



Direct thermal effects of the Hadean bombardment did not limit early subsurface habitability

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ABSTRACT

Intense bombardment is considered characteristic of the Hadean and early Archean eons, yet some detrital zircons indicate that near-surface water was present and thus at least intervals of clement conditions may have existed. We investigate the habitability of the top few kilometers of the subsurface by updating a prior approach to thermal evolution of the crust due to impact heating, using a revised bombardment history, a more accurate thermal model, and treatment of melt sheets from large projectiles (>100 km diameter). We find that subsurface habitable volume grows nearly continuously throughout the Hadean and early Archean (4.5–3.5 Ga) because impact heat is dissipated rapidly compared to the total duration and waning strength of the bombardment. Global sterilization was only achieved using an order of magnitude more projectiles in 1/10 the time. Melt sheets from large projectiles can completely resurface the Earth several times prior to ~4.2 Ga but at most once since then. Even in the Hadean, melt sheets have little effect on habitability because cooling times are short compared to resurfacing intervals, allowing subsurface biospheres to be locally re-established by groundwater infiltration between major impacts. Therefore the subsurface is always habitable somewhere, and production of global steam or silicate-vapor atmospheres are the only remaining avenues to early surface sterilization by bombardment.

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1. Introduction

The Hadean eon, formally defined as beginning with Earth's accretion ~4.6 Ga and ending at 4.0 Ga (International Commission on Stratigraphy, 2017), has long been visualized as a calamitous time in Earth's history. By its original definition, no rocks were thought to be preserved from the Hadean (Cloud, 1972). Planetary bombardment was still relatively intense; indeed, the Hadean includes late accretion due to ongoing collisions with numerous planetary embryos >100–1000 km in diameter (e.g., Bottke et al., 2010). Impact rates decreased in the early Archean eon, although there may have been a terminal cataclysm or Late Heavy Bombardment (LHB) at ~3.9 Ga (see Kröner and Cohen, 2002, for a review). Accretional heat and radioactive heating were maximized, perhaps causing a global geodynamic style different from plate tectonics (O'Neill and Debaille, 2014). Nonetheless, some detrital zircons with Hadean crystallization ages have $^{18}\text{O}/^{16}\text{O}$ compatible with clay minerals (Mojzsis et al., 2001; Wilde et al., 2001), implying that liquid water existed near the surface of the Earth. The Hadean apparently was a time of both calamity and complexity.

The bombardment history, near-surface temperatures, and existence of water in the Hadean and early Archean are important constraints on habitability, the conditions suitable for the emergence and sustenance of life. Sleep and Zahnle (1998) performed pioneering basic calculations on the effects of impacts on early habitability. They concluded that global distribution of ejecta (including transient silicate vapor atmospheres) was the chief danger for Earth and Mars. For Earth, thermal radiation could be absorbed by ocean boiling, whereas for a dry Mars, the surface was inferred to be frequently melted (see also Abramov and Mojzsis, 2016). In contrast, Ryder (2002) argued that much of the Hadean proper was relatively peaceful since the early lunar impact flux appeared to be concentrated into the LHB, and even the LHB was insufficient to produce ocean-evaporating, globally sterilizing events. Abramov and Mojzsis (2009) and Abramov et al. (2013) performed detailed global thermal-history models due to LHB heating, including effects on habitability. They found no plausible situation in which subsurface habitable zones were fully sterilized. Marchi et al. (2014) developed a new bombardment model for the Hadean and early Archean. They refined the timing and size of impactors, including during the LHB, and also determined that projectiles with diameters >100 km can produce melt sheets that cumulatively resurface the Earth.

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In this paper, we reassess the influence of post-Moon-forming impacts on subsurface microbial habitability of the Earth for three reasons. First, we incorporate an updated bombardment history that has a more gradual decline and a “sawtooth” LHB instead of a spike (Marchi et al., 2014). Second, we demonstrate that the thermal model of Abramov and Mojzsis (2009) and Abramov et al. (2013) was spatially under-resolved, and we seek to determine how this may have influenced their conclusion that even a short, intense LHB would not fully sterilize the subsurface. Third, we wish to determine thermal effects and implications for habitability of emplacement of the huge melt sheets that are formed by the largest projectiles.

2. Methods

Our approach consists of five principal steps: (1) specify alternative bombardment histories (projectile diameter and time of impact, with both quantities in discrete bins or steps), (2) calculate the initial axially symmetric heating due to impacts for each diameter bin, (3) compute the axisymmetric cooling history for each diameter and expand to local Cartesian coordinates, (4) insert each impact’s thermal history at the appropriate time at a random location into a 4D (x, y, z, t) Cartesian array representing the entire Earth surface, and (5) assess the subsurface habitability by summing the volumes of temperature intervals representing different microbial tolerances. Steps 1, 2, and 5 closely follow the methods of Abramov and colleagues; our different approach to the thermal history in Steps 3 and 4 makes minor assumptions of linearity that both significantly improve resolution and vastly decrease computing time.

2.1. Projectile size and time distribution

Our baseline impactor population (Case 1a) is a representative, single realization from a Monte Carlo simulation of the interplanetary planetesimal population hitting the Earth subsequent to the Moon-forming impact (Marchi et al., 2014). The time interval is 4.5 to 3.5 Ga, spanning the Hadean and early Archean. Impacts are discretized at 25 Myr intervals (multiple impacts are applied at each step). The total mass 7.0×10^{22} kg (density 2700 kg m^{-3}) is dominated by the two largest planetesimals, or embryos (diameters 1700 and 3500 km), that impact at 4.475 Ga (the first post-4.5 Ga time step); the remainder of the population contains 2.8×10^{21} kg and has a size–frequency distribution (SFD) roughly following an incremental power law with slope between -2 and -3 , down to a minimum diameter of 15 km (Fig. 1). Note that the total projectile mass is $\sim 1\%$ of Earth’s mass, which is compatible with a “late veneer” of highly siderophile elements (see Walker, 2009, for a review). After the initial two large projectiles, the mass flux decreases with a $1/e$ time constant ~ 120 Myr but includes a “sawtooth” LHB in which the impact rate peaks at ~ 4.1 Ga. Impact velocities are 16 km s^{-1} prior to 4.15 Ga and 25 km s^{-1} afterward, representing planetesimal stirring due to planetary migration (Bottke et al., 2012; Morbidelli et al., 2012). We also consider an alternative (Case 1b) that eliminates the three largest projectiles and has a total mass 2.1×10^{21} kg.

We compare (Case 2a) to the SFD and time interval used by Abramov and Mojzsis (2009). Our implementation of their SFD includes projectiles > 5 km in diameter and has a total mass 1.6×10^{21} kg (Fig. 1). The impacts occur at 20 km s^{-1} and are randomly distributed over an LHB interval of 100 Myr—note that this time interval models only the LHB and not the entire late accretion. Following Abramov and Mojzsis (2009), we also treat an alternative (Case 2b) with tenfold mass in each bin. This last scenario is arbitrary and intended to test the upper limits of the effects of bombardment on habitability.

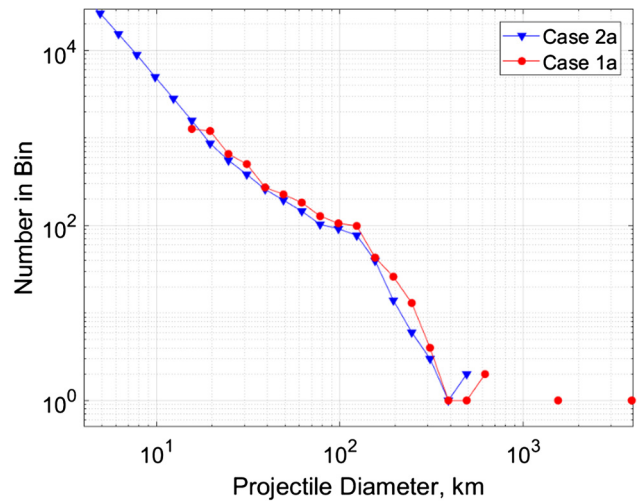


Fig. 1. Impactor size–frequency distributions (SFDs). Case 1a follows Marchi et al. (2014); Case 2a is rebinned from Abramov and Mojzsis (2009). Note two large remnant planetary embryos in Case 1a; the three largest projectiles are deleted in Case 1b. Case 2b uniformly scales Case 2a by $10\times$.

2.2. Impact heating

Subsurface heating due to impacts follows the detailed analytic treatment of Abramov et al. (2013), and Abramov and Mojzsis (2009), and we do not reproduce it here. The key steps are (1) calculation of a radial power law for peak shock pressure from impactor density, velocity, and impact angle, (2) conversion to waste heat using a Murnaghan equation of state, (3) structural uplift, and (4) topographic correction. Abramov et al. (2013) discussed validation of the predicted melt volumes against numerical models. We performed a rudimentary comparison of the heating predicted from the analytic model with a numerical model and found reasonable agreement (Appendix A).

The topographic correction involves shifting the isotherms at the transient crater elevation to the original horizontal surface and proportionately pulling up the isotherms below (Fig. 2). This is intended to reflect that heating length scales are large compared to topography so the latter can be conveniently considered flat. We derive slightly different results from Abramov et al. (2013) because they remove topography before applying structural uplift, whereas we do the reverse. Both are incorrect as sequences: future scaling should be done directly from hydrodynamic impact simulations and the final crater shape after the modification stage adopted for topographic correction. Here and in Abramov et al. (2013), the topographic correction sharply bends isotherms upwards below the former transient cavity: this defines the fundamental horizontal length scale as the transient cavity diameter D_{tc} .

2.3. Thermal evolution

For each projectile diameter (bin) d_p , the axially symmetric post-impact thermal anomaly $\Delta T(d_p, r_p, z_p)$ (where the subscript p indicates local, projectile coordinates) was expanded by Abramov and Mojzsis (2009) to Cartesian coordinates. Individual impacts were randomly placed into a 22 500-km square grid, with wrapping, representing the surface area of the Earth. Since depths affected by the impacts considered here are small compared to the planetary radius, the simpler Cartesian geometry can be efficiently used to track the overlapping thermal effects and to compute the integrals for habitable volumes. The model depth was 140 km, corresponding to a postulated lithospheric thickness. Transient 3D thermal conduction was simulated over this global grid (x, y, z) with the initial thermal disturbance of each impact added

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