THERMAL MODELING OF THE TERRESTRIAL LITHOSPHERE DURING THE LATE HEAVY BOMBARDMENT. O. Abramov[1,2] and S. J. Mojzsis[2], [1]Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder, CO 80302 (abramovo@boulder.swri.edu); [2]Department of Geological Sciences, University of Colorado, 2200 Colorado Ave., Boulder, CO 80309.

Introduction: Hypervelocity impacts of a large bolide result in a significant but localized temperature increase in the crust. This process would have been commonplace during the epoch of intense bombardment at ~3.9 Ga [1-3]. This period, commonly termed the Late Heavy Bombardment (LHB), was some 20 to 200 Myr in duration [2,4], and likely resurfaced most of the Earth and may even have vaporized the oceans. Surface habitats for early life would have been destroyed by the LHB. At the same time, however, new subsurface habitats would have been created in the form of impact-induced hydrothermal systems [5], which provided sanctuary to existing life or may even have been the crucible of its origin. Indeed, the timing of the LHB coincides remarkably well with the earliest isotopic evidence of life on Earth by ~3.83 Ga [e.g., 6]. Furthermore, genetic evidence in the form of 16S ssu rRNA and other molecular phylogenies suggests that all terrestrial life arose from a common ancestral population akin to present-day thermophilic or hyperthermophilic organisms [e.g., 7]. 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 survival of any incipient life [e.g., 8, 9].

The underlying purpose of this study is to assess the habitability of early Earth during the LHB by (i) using new studies of impact cratering records of the Moon and terrestrial planets and size distributions of asteroid populations [e.g., 10]; (ii) taking advantage of a new class of early solar system dynamical models that convincingly reproduce impact rates during the LHB defined by the lunar and meteoritic record [e.g., 11]; (iii) potentially constraining the rate and duration of the LHB by laboratory analysis of terrestrial Hadean zircons [12, 13]; and (iv) using numerical modeling to understand the thermal response of the lithosphere to impacts.

Technique summary: The survivability of a nascent biosphere on early Earth during the LHB is assessed by thermal modeling of the lithosphere and 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.

A stochastic cratering model is used to populate all or part of the Earth's surface with craters within a probability field of 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 [11], and 2.2×10^{23} g based on the lunar cratering record [14, 15]. 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 [10], and the size/frequency distribution of the asteroid belt is unlikely to have changed significantly since that time [16]. Thus, we used the size/frequency distribution of the asteroid belt, normalized to the total mass of 2.0×10^{23} g. The duration of the LHB in this preliminary analysis is taken to be ~100 Ma, although other values will be investigated.

For each crater in the model, a temperature field is calculated using analytical expressions for shock deposited heat and central uplift. The shock-deposited heat is calculated using the Murnaghan equation of state for specific waste heat (ΔE_w), as formulated by [17]:

$$\Delta E_w = \frac{1}{2}\left[PV_0 - \frac{2K_0V_0}{n}\right]\left[1-\left(\frac{Pn}{K_0}+1\right)^{-1/n}\right] + \frac{K_0V_0}{n(1-n)}\left[1-\left(\frac{Pn}{K_0}+1\right)^{1-(1/n)}\right]$$

where P is the peak shock pressure, K_0 is the adiabatic bulk modulus at zero pressure, n is the pressure derivative of the bulk modulus, and V_0 is the specific uncompressed volume ($1/\rho_0$). These parameters are well established for the likely target rocks granite and basalt. Shock pressure P drops off with distance r from the impact center according to the power law

$$P = A\left(\frac{r}{R_{pr}}\right)^{-n}$$

where R_{pr} is the radius of the projectile, n is the decay exponent, and A is pressure at $r=R_{pr}$ [e.g., 18]. The decay exponent n varies as a function of impact angle [18], allowing for oblique impacts, and A depends on target and impactor properties. To obtain the final temperature increase, specific waste heat ΔE_w is divided by the heat capacity of the target, which is assumed to be granite. When temperatures are sufficiently high to melt rock, latent heat of fusion is taken into account.

Heat contributed by the central uplift is estimated from the vertical distance of the uplift and the thermal gradient. The height of the stratigraphic uplift, based on observations at terrestrial craters, is estimated by:

$$h_{su} = 0.06D^{1.1}$$

where D is the crater diameter in kilometers [19].

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.

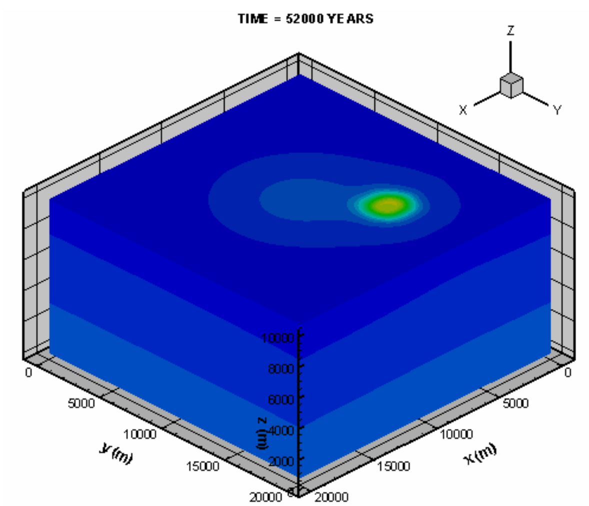

Figure 1. Model snapshot illustrating the formation of two ~5 km craters in the same area within ~50,000 years of each other – an unlikely event.

Results: Most of the mass (and energy) during LHB was likely delivered by a relatively few very large impactors (Fig. 2). Our model predicts ~90 impacts with impactor diameters of 50 km or larger, forming basins ~1,000 km in diameter or greater over the course of a 100 Myr-long bombardment. We find that these impacts would have been temporally separated by over 1 Myr, on average, and would have resurfaced less than 25% of the Earth's surface.

At finer resolution, the largest impactor expected to strike a given 20 × 20 km area shown in Fig. 1 is ~500 m in diameter. This forms a crater ~10 km in diameter. The resulting crater takes up less than 20% of the model's surface area, which is insufficient to sterilize the habitable zone within a few km of the surface everywhere in the model.

In the rare case of a large crater formation in this model area, we find that habitable conditions are established quickly after crater formation, provided that water is present. For craters of ~200 km, colonization by thermophiles in the central regions is possible after ~20,000 years [20,21]. Thus, the preliminary results of this study favor the survival of subsurface microbial life throughout the bombardment.

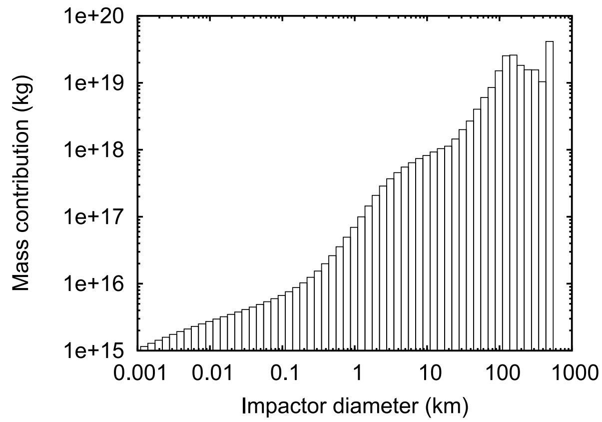

Figure 2. Impactor mass distribution during the LHB, derived from the main belt size/frequency distribution [Bottke et al., 2005] and estimates of the total mass delivered during the LHB [11,14,15].

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