THERMAL STATE OF THE TERRESTRIAL LITHOSPHERE DURING THE LATE HEAVY BOMBARDMENT: IMPLICATIONS FOR HABITABILITY.

O. Abramov and S. J. Mojzsis, Department of Geological Sciences, University of Colorado, 2200 Colorado Ave., Boulder, CO 80309.

Introduction: Hypervelocity impacts of large bolides result in a significant but localized temperature increases 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 doubtlessly 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. 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].

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., 9]; (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., 10]; (iii) potentially constraining the rate and duration of the LHB by laboratory analysis of terrestrial Hadean zircons [11-13]; 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 are also investigated.

For each crater in the model, a temperature field is calculated using analytical expressions for shock deposited heat and central uplift [17]. 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.

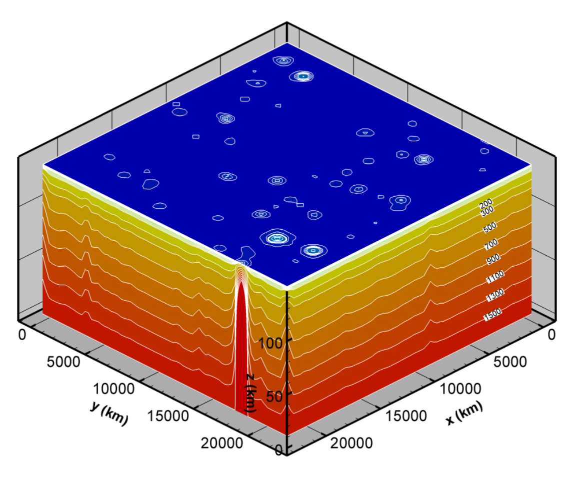

Figure 1. A 3-dimensional model representing the Earth's lithosphere at the end of the 100 Myr LHB. Only impactors larger than 10 km in diameter are included in this model.

Results: Most of the mass (and energy) during LHB was likely delivered by a relatively few very large impactors. 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. 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. Although smaller impactors (1 - 10 km) were as important as gigantic basin formers (100+ km) in terms of sterilizing the surface (Table 1), large craters are nonetheless more biologically significant because they take a far longer time to cool. The LHB scenario in our main model is insufficient to extinguish microbial life (Fig. 2). This model does not explicitly incorporate thermal shock from a global layer of hot ejecta following a large impact [18]; however, the maximum sterilization depth for such a process is only a few hundred meters, and is further reduced or eliminated by the presence of the oceans. The largest impactor in our model (~300 km in diameter) is insufficient to vaporize the oceans [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%

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.

In addition to our baseline model, we explored the parameter space to evaluate the effects of different LHB durations, mass fluxes, impact velocities, temperature gradients in the crust, and the presence of oceans. In the case of 10 Myr LHB, the mesophile curve in Fig. 2 crosses the themophile curve, indicating that the overall conditions are more favorable for thermophiles. The same effect can be achieved by doubling the impact velocity from 20 to 40 km/s. Either increasing the total mass delivered by a factor of 10, from 2.0 $\times 10^{23}$ g to 2.0 $\times 10^{24}$ g, or doubling the geothermal temperature gradient from 12°C to 24°C results in approximately equal habitable volumes (~6 $\times 10^{8}$ km^{3}) for mesophiles, thermophiles, and hyperthermophiles towards the end of the LHB. However, it is important to note there is no plausible scenario in which the entire terrestrial habitable zone is fully sterilized.

If oceans are present, heat is lost from the upper boundary up to 10 times faster, and habitable conditions are re-established up to an order of magnitude more rapidly after crater formation. For craters of ~200 km, colonization by thermophiles in the central regions is possible after ~20,000 years [19,20]. This observation further favors the survival of subsurface microbial life throughout the bombardment.

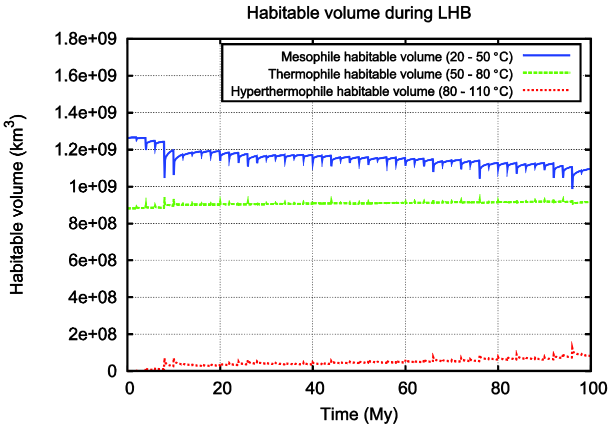

Figure 2. Evolution of habitable volumes during the 100 Myr LHB in the habitable zone within ~4 km of the surface. Only impactors larger than 10 km in diameter are included.

Acknowledgements

This work is funded by the NASA Postdoctoral Program and the NASA Exobiology program. The use of office space and computer resources at the Department of Space Studies of the Southwest Research Institute is gratefully acknowledged.

References: [1] Turner G. et al. (1973) *Proc. Lunar Sci. Conf.*, 4, 1889–1914. [2] Tera F. et al. (1974) *Earth Planet. Sci. Lett.*, 22, 1–21. [3] Cohen B. A. et al. (2000) *Science*, 290, 1754-1756. [4] Ryder G. (1990) *Eos Trans. AGU*, 71(10) 313, 322-323. [5] Zahnle K. J. and Sleep N. H. (1997) in *Comets and the Origin and Evolution of Life*, pp. 175-208, Springer-Verlag, New York. [6] McKeegan K.D. et al. (2007) *Geology*, 35, 591-594. [7] Pace N. R. (1997) *Science*, 276, 734-740. [8] Moorbath S. (2005) *Applied Geochem.*, 20, 819-824. [9] Strom R. G. et al. (2005) Science, 309, 1847-1850. [10] Gomes R. et al. (2005) *Nature*, 435, 466-469. [11] Mojzsis S.J. et al., this meeting. [12] Mojzsis S. J. and Harrison T. M. (2002) *Earth Planet. Sci. Lett*, 202, 563-576. [13] Trail D. et al. (2007) *Geochim. Cosmochim. Acta*, 71(16), 4044-4065. [14] Hartmann W. K. et al. (2000) in *Origin of The Earth and Moon*, pp. 493-451, Univ. Arizona Press, Tucson. [15] Ryder G. et al. (2000) in *Origin of The Earth and Moon*, pp. 475-492, Univ. Arizona Press, Tucson. [16] Bottke W. F. et al. (2005) *Icarus*, 175, 111-140. [17] Abramov, O. and Mojzsis S. J (2008) *LPSC XXXIX*, abstract 1036. [18] Sleep, N.H. and Zahnle K. (1998) JGR, 103, 28,529-28,544. [19] Abramov O. and Kring D. A. (2004) *JGR*, 109, doi:10.1029/2003JE002213. [20] Abramov O. and Kring D. A. (2007) *Met. Planet. Sci.* 42, 93-112.