**THERMAL EFFECTS OF IMPACT BOMBARDMENTS ON EARLY MARS.** O. Abramov[1] and S. J. Mojzsis[2,3,4], [1]U.S. Geological Survey, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001 (*oabramov@usgs.gov*), [2]University of Colorado, Geological Sciences, 2200 Colorado Ave., Boulder, CO 80309-0399, USA, [3]Center for Lunar Origin and Evolution (CLOE), NASA Lunar Science Institute, [4]Hungarian Academy of Sciences, RCAES, Institute for Geological and Geochemical Research, 45 Budaörsi ut, H-1112 Budapest, Hungary.

**Introduction:** Noachian (pre ~3.7 Ga) terranes are the oldest and most heavily cratered on Mars, with crater densities comparable to ancient lunar and Mercurian highlands. A variety of fluvial features [e.g., 1] and evidence for aqueous alteration [e.g., 2] indicate that Mars was wet, at least partially and/or episodically, in the Noachian. This combination of water and impact-delivered heat (and, to a lesser degree, volcanism) likely drove hydrothermal systems [e.g., 3] and increased the temperature of the Martian atmosphere via injection of water vapor [e.g., 4].

Two impact bombardment periods that likely affected early Mars are (i) post-accretionary elevated impactor flux, commonly known as the "heavy bombardment" and (ii) a putative increase in the number of impact events around 4.0 Ga, commonly known as the "late heavy bombardment" (LHB) [5,6]. A comprehensive assessment of how these bombardments affected the Martian crust is important for evaluating its geological history and biological potential.

**Bombardment parameters**: We model two types of post-accretionary bombardments: (i) an exponential decay as described by [7] and (ii) a sawtooth timeline, characterized by faster-than-exponential decay and reduced total mass [8].

Likewise, two types of LHB are modeled: (i) a baseline scenario representing a classic "spike," centered at 3.9 Ga and lasting ~100 Myr [5,6,9,10], and (ii) a more recent concept of a "sawtooth" LHB, characterized by an near-instantaneous increase in the number of impacts at ~4.1 Ga, overall lower delivered mass, and a longer duration, with exponential decay extending into the Archean [8, 11].

Simulations of a stirred asteroid belt [12], suggest that the impact flux (impacts per area per time) may have been higher on Mars than the Earth by a factor of ~4.5 during the LHB. However, that would suggest that all observed Martian impact basins, including some equivocal quasi-circular depressions, formed as a result of the LHB [13]. Instead, we use a more conservative Mars/Earth impact flux ratio of 2.76 [14], which represents a long-term average and thus broadly applicable to post-accretionary bombardment as well.

The total mass delivered to Mars by the baseline model post-accretionary and LHB bombardments was $1.9 \times 10^{21}$ kg [7] and $1.6 \times 10^{20}$ kg [15], respectively. For the sawtooth scenarios, that mass is smaller by a factor of 4 [8]. There are indicators that both post-accretionary and LHB impactors were dominated by a population similar to present-day main belt asteroids [8, 16], whose size/frequency distribution is unlikely to have changed significantly since then [17]. The duration of the LHB is taken to be ~100 Ma for the baseline scenario, and ~400 Myr for the sawtooth scenario. The duration of the post-accretionary bombardment is ~400 Myr (from ~4.5 to ~4.1 Gyr).

**Technique summary**: We apply the global cratering model described in [15] to Mars (Fig. 1). For each crater in the model, a temperature field is calculated using analytical expressions for shock deposited heat and central uplift [15]. After the crater's thermal field is introduced into a three-dimensional model representing the Mars lithosphere, it is allowed to cool by conduction in the subsurface and radiation/convection at the atmosphere interface. Volumes within temperature ranges of interest are monitored and recorded.

**Results:** With a surface area 0.28x that of Earth, and approximately same mass delivered, Mars experienced a cratering density ~3 times higher during both post-accretionary and LHB bombardments Most of Mars' surface area would have been resurfaced by the baseline LHB and all of it would have been resurfaced by the baseline post-accretionary bombardment, with cratering at saturation. The average impact velocity on Mars is about ½ that of Earth, and thus, average energy delivered per unit area would have been somewhat smaller. As was the case for Earth [15], most of the Martian crust would not have been melted by either a post-accretionary bombardment or the LHB. From the mass and size-frequency distribution constraints, the largest impactor in the baseline LHB model is 310 km in diameter, generating a crater ~2300 km in diameter, approximately the same as Hellas Basin. The largest impactor in the baseline post-accretionary model is ~490 km in diameter.

Thermal effects of impact bombardments were also important on local scales associated with smaller craters. For example, the heat in a ~60-km impact crater could have denatured pre-existing phyllosilicates [18], making them undetectable by spectroscopy. It also would have released significant amounts of water vapor into the atmosphere, both as a result of the impact itself and post-impact hydrothermal activity, temporarily warming the climate [e.g., 4].

Impact melt volumes, as well as habitable volumes for potential microorganisms, were measured throughout the course of the simulations. As the bombardments progressed, habitable volumes for mesophiles (20-50 °C) generally decreased, and habitable volumes for thermophiles (50-80 °C) generally increased. The habitable volumes in active impact-induced hydrothermal systems increased as bombardments progressed, reaching maximums of ~4 × $10^7$ and ~3 × $10^6$ $km^3$ for baseline post-accretionary bombardment and LHB, respectively. Total thermophilic and hydrothermal habitable volumes were smaller by approximately a factor of 5 compared to the Earth [9], due mainly to a combination of reduced surface area and lower impact velocities.

The above estimates assume a surface temperature of 1 °C and a thermal gradient of 13 °C $km^{-1}$. However, even if the average surface temperature was comparable to today's Mars (-63° C), life may have persevered in a global aquifer underneath a layer of permafrost termed the cryosphere [19]. Over $10^5$-$10^6$ of the impact craters that formed during the LHB and post-accretionary bombardment, respectively, would have accessed the global aquifer, providing a subsurface plumbing network between individual impact-induced hydrothermal systems.

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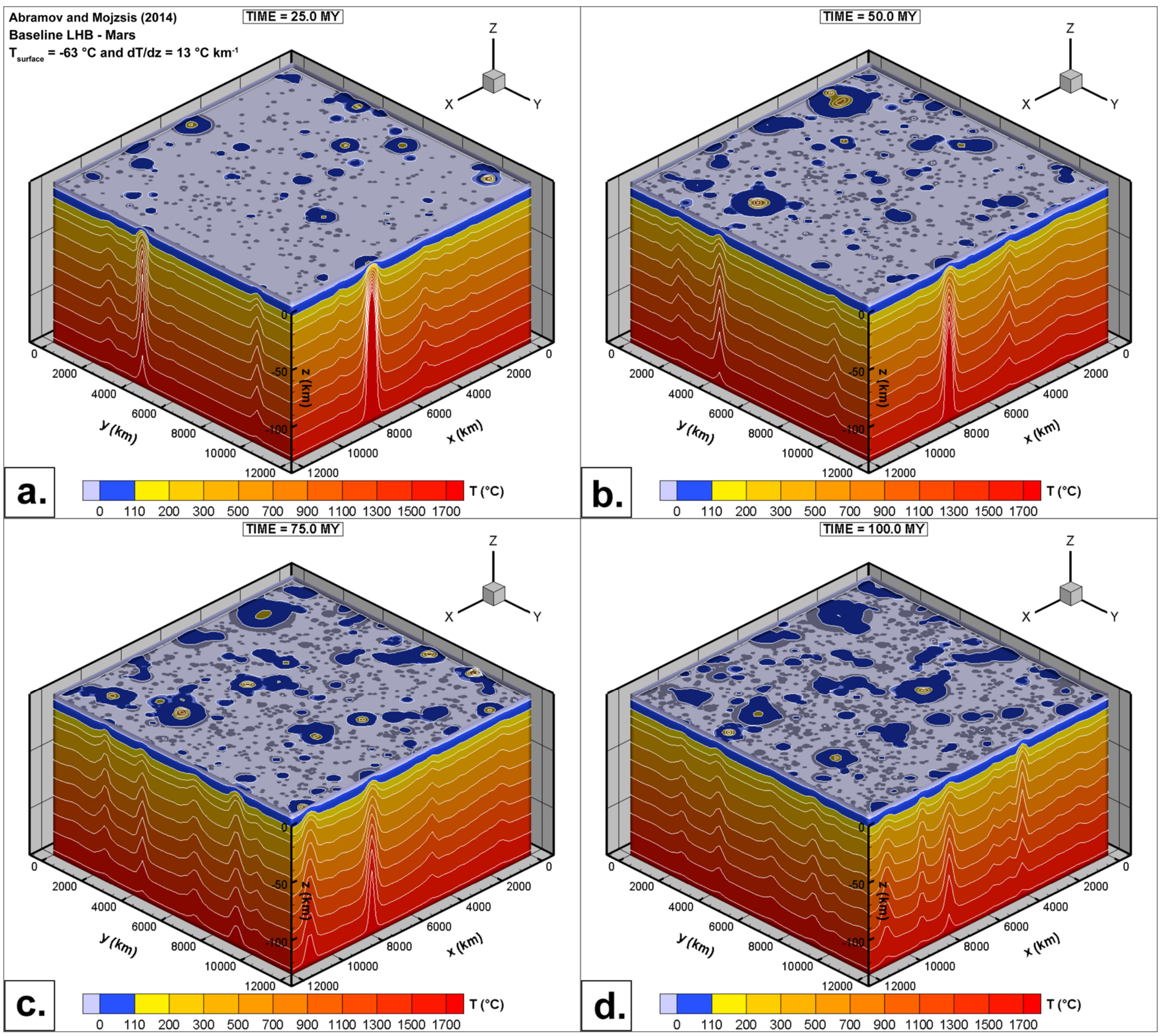


**Figure 1.** A 3-dimensional model representing the Mars lithosphere at (a) 25 Myr, (b) 50 Myr, (c) 75 Myr, and (d) 100 Myr out of the 100 Myr baseline LHB. Only impactors larger than 10 km are included. Dark areas denote crater imprints. Upper surface shows temperatures at a depth of 4 km. Light blue represents the cryosphere, dark blue represents the habitable zone.