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 \(\sim 4 \times 10^7\) and \(\sim 3 \times 10^6\) 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.

**References:**


**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.