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Thermal effects of impact bombardments on Noachian Mars

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ABSTRACT

Noachian (prior to ca. 3700 Ma) terranes are the oldest and most heavily cratered landscapes on Mars, with crater densities comparable to the ancient highlands of the Moon and Mercury. Intense early cratering affected Mars by melting and fracturing its crust, draping large areas in impact ejecta, generating regional-scale hydrothermal systems, and increasing atmospheric pressure (and thereby, temperature) to periodically re-start an otherwise moribund hydrological cycle. Post primary-accretionary bombardment scenarios that shaped early Mars can be imagined in two ways: either as a simple exponential decay with an approximately 100 Myr half-life, or as a “sawtooth” timeline characterized by both faster-than-exponential decay from primary accretion and relatively lower total delivered mass. Indications are that a late bombardment spike was superposed on an otherwise broadly monotonic decline subsequent to primary accretion, of which two types are investigated: a classical “Late Heavy Bombardment” (LHB) peak of impactors centered at ca. 3900 Ma that lasted 100 Myr, and a protracted bombardment typified by a sudden increase in impactor flux at ca. 4100–4200 Ma with a correspondingly longer decay time ($\leq$400 Myr). Numerical models for each of the four bombardment scenarios cited above show that the martian crust mostly escaped exogenic melting from bombardment. We find that depending on the chosen scenario, other physical effects of impacts were more important than melt generation. Model output shows that between 10 and 100% of the Noachian surface was covered by impact craters and blanketed in resultant (hot) ejecta. If early Mars was generally arid and cold, impact-induced heating punctuated this surface state by intermittently destabilizing the near-subsurface cryosphere to generate regional-scale hydrothermal systems. Rather than being deleterious to the proclivity of Noachian Mars to host an emergent biosphere, this intense early impact environment instead enhanced the volume and duration of its surface/subsurface geophysical habitable zone.

1. Introduction

It is widely recognized that in the solar system’s first billion years, impact processes greatly affected the surfaces of the solid planetary bodies, be they composed of ices or silicates (Melosh, 1989). As such, investigations formulated to explore the effects of early bombardment to Earth’s initial thermal, mechanical, chemical and biological state have long been a fertile area of study (e.g. Öpik, 1960; Hartmann, 1966; Sleep and Zahnle, 1998). Profound chemical and mechanical modifications of its ancient crust are expected to have occurred due to impacts. All the more so for a small (0.107 $M_{\oplus}$), old (Dauphas and Pourmand, 2011) and cold (e.g. Carr and Head, 2010) world like Mars that has always been situated at the outer edge of our solar system’s habitable zone (Hart, 1979), the early bombardment regime imposed strong controls on planet-wide geophysical states. Compared to Mars, Earth’s crust is very young and consequently records practically nothing of the bombardment epoch (e.g. Trail et al., 2007); the average age of terrestrial oceanic crust is only about 70 Ma, whereas that of the continents is close to 2500 Ma (e.g. Taylor and McLennan, 1995). On Mars, however, about 60% of the crust dates from before about 3700 Ma (e.g. Neumann et al., 2004). At an average crustal depth of about 60 km (Wieczorek and Zuber, 2004), this corresponds to a theoretical Pre-Noachian/Noachian crustal volume of approximately 5×10^9 km^3. On Earth, the equivalent late Hadean–Eoarchean (4000–3650 Ma) crustal inventory is a mere 1×10^{-5}

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of the total volume of continental crust (Nutman et al., 2001), which leads to a rough estimate of ~1.5×10^4 km^3. Evidently, Mars preserves hundreds of thousands of times (~340,000×) more "Hadean" crust than does Earth. Aside from the lifeless Moon, Mars is the most accessible repository in our solar system of processes to have operated on the inner (terrestrial-type) planets in the first half-billion years. It shows abundant evidence for how intense modifications from bombardment strictly controlled a rocky world's capacity to host environments suitable for the emergence and sustainability of a biosphere. Its richness and variety of fluvial features (e.g. Carr, 1999) as well as evidence for long episodes of aqueous alteration (e.g. Ehlmann et al., 2009) demonstrates conclusively that Noachian Mars was episodically wet before about 3700 Ma (Carr, 2012). In this context, the combination of water and impact-delivered heat (and to a lesser degree, volcanism) should have driven long-lived extensive and ubiquitous hydrothermal systems on early Mars (e.g. Abramov and Kring, 2005).

Impact-induced effects on Mars included: (i) structural modifications to the lithosphere including some that involved an entire hemisphere (e.g. Andrews-Hanna et al., 2008; cf. Melosh, 2008); (ii) melt production at the regional (10 s to 100 s of km) to global scale (1000 s of km); (iii) melt mixing and differentiation of impact melt sheets; (iv) implantation of shock-deposited heat that lingered on in the lithosphere and mantle for millions of years (Abramov and Mojzsis, 2009); (v) generation of thick and overlapping regional and global layers of hot ejecta (e.g. Sleep and Zahnle, 1998); (vi) compositional changes and resultant modifications to the surface zone via delivery of cometary and asteroidal materials (e.g. Flynn, 1996) that probably included the supply of prebiotically important molecules (e.g. Wright et al., 1989); and (vii) changes to primordial atmospheric compositions and densities, and thereby of paleoclimate (e.g. Toon et al., 1982), which involved the catastrophic release of water vapor into the atmosphere from heating of Mars' surface/sub-surface cryosphere (e.g. Segura et al., 2002).

The earliest styles of bombardment to have affected Mars immediately following its formation are modeled in this work as either a:

(i) *Classical* post-accretionary bombardment characterized by an exponential decay of the impactor flux with a 100 Myr half-life (Ivanov et al., 2002)
(ii) *"Sawtooth"* post-accretionary bombardment with a faster-than-exponential decay from primary accretion compared to the *Classical* modality, and relatively lower total accreted mass. This model was introduced by Morbidelli et al. (2012; cf. Turner, 1979) and developed further by Marchi et al. (2014).

We also focus on two later enhancements to the bombardment flux superimposed on a long post-accretionary decline:

(i) *Classical* "late heavy bombardment" spike in impactors, centered at 3900 Ma with a duration of approximately 100 Myr (Turner et al., 1973; Tera et al., 1974; Wetherill, 1975; Ryder, 1990, 2002).
(ii) *Sawtooth*-like late heavy bombardment scenario distinguished by a sharp rise in the number of impacts at ca. 4100–4250 Ma (e.g. Hopkins and Mojzsis, 2015) with overall relatively lower delivered mass than the *Classical* model, followed by a shallow ramp in the flux with correspondingly longer duration of bombardment (~400 Myr). Afterwards, there is a long tail of decay of the impactor population (e.g. Bottke et al., 2010) that extended well into Earth's Proterozoic eon (corresponding to Mars' middle Amazonian period; Tanaka, 1986).

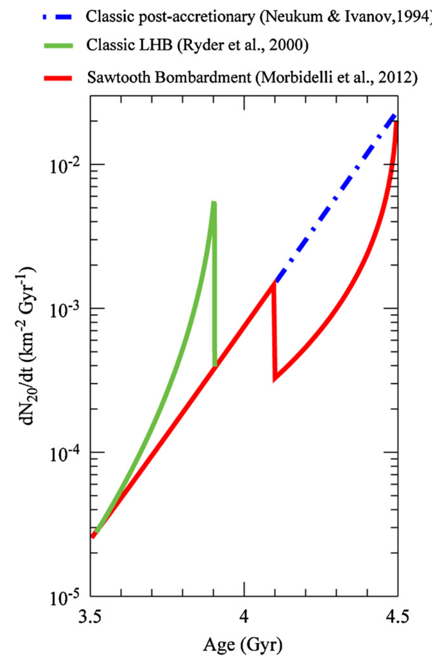

Fig. 1. Timeline of martian bombardment scenarios modeled in this work. The Sawtooth bombardment timeline includes both Sawtooth post-accretionary (sPA, pre-4.1 Ga) and Sawtooth LHB (sLHB, 4100 Ma and later) scenarios. This figure has been modified from Morbidelli et al. (2012) for fluxes to Mars.

A timeline illustrating the relationships between the bombardments outlined above is presented in Fig. 1.

Next, we review the four different bombardment scenarios outlined above: two early bombardments and two late bombardments, by comprehensively assessing the thermal effects of each to the martian crust (Table 1). The output of our global bombardment models is thereafter used to evaluate the thermal state of Mars' crust in the Noachian and to gauge its past ability to have accommodated an alien biome.

1.1. Modeled bombardments

1.1.1. Classical post-accretionary (cPA)

After the major planet-building phase of accretion ceased, numerous leftover planetesimals populated the solar system and

Table 1
Summary of statistics for the four bombardment scenarios on early Mars. Total melting in the upper 20 km of the crust during the bombardment is shown, and is calculated using the high-resolution static model. Mean values between the 1 °C and −63 °C surface temperatures are shown. Resurfacing is calculated based on the area of the final crater.

Bombardment type		Start time (Ga)	End time (Ga)	Total mass delivered (kg)	Largest impactor (km)	Percent of crust melted	Percent resurfaced
Post-accretionary	Classical (cPA)	4.5	4.1	6.5×10^{20}	492	3.9%	100%
	Sawtooth (sPA)	4.5	4.1	1.6×10^{20}	310	1.1%	46%
Late heavy bombardment	Classical (cLHB)	3.9	3.8	1.0×10^{20}	246	0.8%	36%
	Sawtooth (sLHB)	4.1	3.7	2.8×10^{19}	196	0.2%	10%