THE POST-ACCRETIONARY DOLDRUMS ON MARS: CONSTRAINTS ON THE PRE-NOACHIAN IMPACT FLUX.

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Introduction: Numerous lines of evidence point toward conditions on Mars during the Noachian epoch that were dramatically different from those of today, but the earliest history of Mars has remained shrouded in mystery. The geological record of this "pre-Noachian" epoch has been largely obscured by the modification of the surface by impacts and erosion during the Noachian [1]. Here we focus on the bombardment history of Mars during the pre-Noachian as revealed by the population of giant impact basins. Four giant impact basins are known to have formed during the Noachian: Hellas, Utopia, Isidis, and Argyre (HUIA). The crustal dichotomy has been interpreted as the hemisphere-scale Borealis Basin [2], formed very early in martian history. In addition, numerous candidate ancient impact basins have been identified based on subtle signatures in topography data and crustal thickness models [3–5].

We use the lack of superimposed basins and the preservation state of the dichotomy boundary to constrain the pre-Noachian bombardment of Mars. We define pre-Noachian basins as those that predate HUIA but post-date the Borealis basin. Our analysis is restricted to crustal-scale basins, defined as those excavating more than 25% of the crust, limiting us to basins >500 km in diameter. Our results indicate that only the well-preserved Hellas, Utopia, Isidis, and Argyre basins post-date the dichotomy, revealing a lull in the bombardment of Mars between ~4.47 and ~4.06 Ga.

Impact modification of the dichotomy boundary: Geophysical evidence supports the interpretation of the northern lowlands of Mars as the ancient Borealis basin. The rim of this 8500×10,600 km elliptical basin is remarkably well preserved, even beneath Tharsis where it is revealed by gravity data [2]. Only the Isidis basin excavates into the dichotomy boundary (Fig. 1a). The lack of major impact modification of the boundary before Isidis provides a statistical constraint on the number of pre-Noachina impact basins.

Treating the dichotomy boundary as a great circle, the probability of a randomly located basin crossing the dichotomy boundary is $\sin(R_b/R_M)$, where R_b is the basin radius and R_M is the radius of Mars. For the HUIA basins, we find a 67% probability that at least one will cross the boundary, in keeping with the observation that Isidis does cross it. For a hypothetical population of 12 pre-Noachian HUIA-like basins, there is a 96% chance that at least one will excavate into the dichotomy boundary, allowing us to reject this putative basin population at the 2-σ confidence level. For comparison, adding 2, 4, 8, 12, and 20 additional HUIA basins in a Monte Carlo model destroyed a median of 0%, 4% (850 km), 12% (2600 km), 16% (3400 km) and 30% (6400 km) of the Borealis rim, respectively (e.g., Fig. 1c). Using the basin diameters from a proposed population of 32 basins [5] and assuming they were produced after the Borealis basin with a random and isotropic distribution, the probability that none would excavate the dichotomy boundary is 0.0039%. Thus, the lack of any large basins other than Isidis excavating the dichotomy boundary limits the number of pre-Noachian crustal-scale basins to be <12.

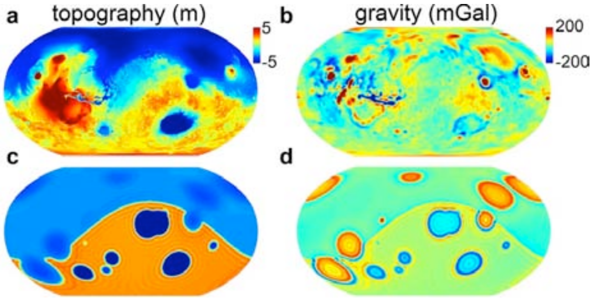

Figure 1. Observed topography (**a**) and gravity (**b**) in comparison to modeled topography (**c**) and gravity (**d**) for synthetic HUIA basins plus an additional population of 12 basins, assuming flexural support of volcanic infill in the northern lowland basins.

Crustal thickness signatures: A more stringent constraint on the number of pre-Noachian basins can be made based on the crustal thickness signatures of HUIA and the dichotomy boundary. The Hellas, Argyre, and Isidis basins have clear signatures in topography data and crustal thickness models (Fig. 2b-d), showing little evidence for relaxation [6] or other forms of modification beyond superficial fluvial erosion and volcanic resurfacing. The gravitational signature of Utopia reveals a basin very similar to Hellas at the time of its infill [7]. The crustal dichotomy boundary has also experienced minimal relaxation [8] and is similar in preservation state to the rims of these much younger impact basins. Thus, any basin comparable to or greater than Argyre in size that formed after the crustal dichotomy should be similarly well preserved. That no such basins are found with comparable topographic and crustal signatures indicates that no crustal-scale basins formed after the dichotomy but before HUIA. This does not rule out the existence of ancient degraded basins with muted signatures [3–5], but requires that any such basins must have formed prior to

Borealis. As an example, the modeled topographic and gravitational signature of a population of 12 pre-HUIA basins in addition to HUIA, assuming flexural support of volcanic and sedimentary fill for the lowland basins, contrasts markedly with the observations (Fig. 1).

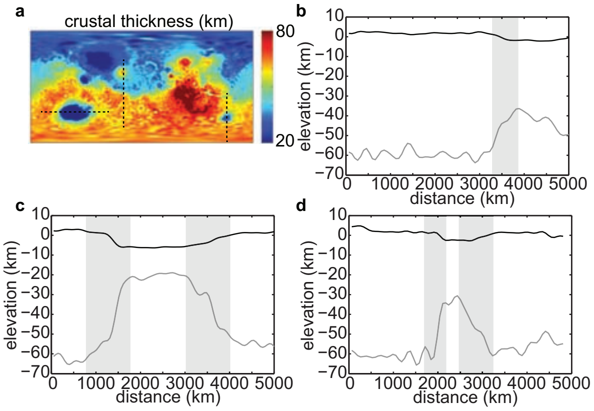

Figure 2. Global crustal thickness model [9] (**a**) and the crustal thickness signatures of the dichotomy boundary (**b**), Hellas (**c**), and Argyre (**d**).

Basin ages: In order to understand the implications of this bombardment history, we must first place constraints on the timing of the Borealis and HUIA impacts. The ages of Hellas, Isidis, and Argyre have been constrained to the intervals 3.86-4.06 Ga or 3.78-3.99 Ga [10], using crater retention ages tied to the absolute timescale established for the Moon. The age of the buried Utopia basin is poorly constrained.

The timing of the Borealis impact is constrained by the crystallization ages of Martian meteorites, since this mega-impact would have reset the age of the entire crust. The Borealis basin must be at least as old as the ~4.43 Ga zircons found in the paired Martian meteorites NWA 7533 and 7034 [11], only slightly younger than the timing inferred from the 4.47-4.50 Ga ages of the shergottite source regions [12, 13]. The age of the Borealis basin can also be constrained using the abundance of highly siderophile elements (HSEs) in Mars's mantle, which are best explained by a late addition of HSEs [14]. The HSEs are well mixed within the shergottite source reservoirs [15], suggesting late HSE delivery to Mars via chondritic projectiles took place after Mars's differentiation but before its final magma ocean crystallization at ~4.47-4.50 Ga [15]. The concentration of Os in the Martian mantle requires an addition of at least ~2.0×10^{21} kg of chondritic material, equivalent to a single projectile with a diameter of ~1100 km [14], or a diameter of 1400-2300 km if we assume accretion of material was only 10-50% efficient. These values match the preferred projectile diameters needed to produce the Borealis basin [16, 17].

Conclusions: The lack of impact excavation of the crustal dichotomy boundary prior to Isidis limits the number of pre-Noachian crustal-scale basins to be <12. The similarity in the preservation states of the dichotomy boundary and the Noachian-aged basins Hellas, Utopia, Isidis, and Argyre requires that no crustal-scale basins formed between Borealis and HUIA. These observations support an impact chronology in which the mega-impact responsible for the Borealis basin at >4.47 Ga was followed by a long quiescent period in which no major basins formed, before the formation of the observed HUIA basins between 3.78 and 4.06 Ga.

This chronology implies a ~400 Myr lull (the "doldrums") in the impact flux between the Borealis impact during the late stages of Mars' accretion and the increased impact flux during the late heavy bombardment [18]. This lull has important implications for Mars during the pre-Noachian. The reduced impact flux in this time period is at odds with common assumptions used in assigning absolute ages from crater counting [19], making the dating of pre-Noachian events difficult [4, 5]. The lull in basin-forming impacts in the pre-Noachian may have enabled a Martian dynamo, before it was terminated by the thermal consequences of the Noachian basin-forming impacts [20]. The reduced pre-Noachian impact flux may have resulted in a more stable but potentially cooler climate, before impact-induced warming of the climate in the Noachian [21]. Alternatively, the pre-Noachian may have been a period in which volcanic outgassing [22] outpaced losses to impact erosion [23], resulting in a thickening atmosphere. The low impact flux during the doldrums also opens up the possibility for the preservation of signatures of other crustal-scale processes at work during the pre-Noachian.

References: [1] Carr M. H. and Head J. W. (2010) *EPSL, 294*, 185–203. [2] Andrews-Hanna J. C. et al., (2008), *Nature, 453*, 1212–1215. [3] Edgar L. A. and Frey H. V. (2008) *GRL, 35*, 1–5. [4] Frey H. V. (2008) *GRL, 35*, 1–4 (2008). [5] Frey H. V. and Mannoia L. M. (2013) *LPSC*, *44*, abstract 2501. [6] Mohit P. S. and Phillips R. J. (2007) *GRL, 34*, 1–6. [7] Searls M. L. et al. (2006) *JGR, 111*, 1–13. [8] Nimmo F. and Stevenson D. J. (2001) *JGR, 106*, 5085-5098. [9] Neumann G. A. et al. (2004) *JGR*, *109*, E08002, doi:10.1029/2004JE002262. [10] Robbins S. J. et al. (2013) *Icarus*. 225, 173–184. [11] Humayun M. et al. (2013) *Nature*, *503*, 513–516. [12] Foley C. N. et al. (2005) *GCA, 69*, 4557–4571. [13] Nimmo F. et al. (2008) *Nature*, *453*, 1220–1223. [14] Bottke W. F. et al. (2010) *Science*. 330, 1527–1530 (2010). [15] Brandon A. D. et al. (2012) *GCA* 76, 206–235. [16] Marinova M. M. et al. (2008) *Nature*, *453*, 1216–1219. [17] Marinova M. M. et al. (2011) *Icarus*, *211*, 960–985. [18] Morbidelli A. et al. (2005) *EPSL, 355*, 144-151. [19] Hartmann W. K. and Neukum G. (2001) *Space Sci. Rev., 96*, 165–194. [20] Roberts J. H. et al. (2009) *JGR, 114*, 1–10. [21] Segura T. L. et al. (2012) *Icarus*, *220*, 144–148. [22] Phillips R. J. et al. (2001) *Science, 291*, 2587–2591. [23] Brain, D. A. and Jakosky B. M. (1998) *JGR 103*, 22,689–22,694.