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Ages of very large impact basins on Mars: Implications for the late heavy bombardment in the inner solar system

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[1] A sharp peak in both relative crater retention ages and inferred model absolute ages for the largest impact basins on Mars may be a Martian equivalent of a late heavy bombardment (LHB) terminal lunar cataclysm (TLC). If so, it supports a NICE-type LHB, provides an important temporal connection between lunar and Martian chronologies, and suggests the current Martian chronology overestimates the age of large basins and perhaps other events in early Martian history. **Citation:** Frey, H. (2008), Ages of very large impact basins on Mars: Implications for the late heavy bombardment in the inner solar system, *Geophys. Res. Lett.*, *35*, L13203, doi:10.1029/2008GL033515.

1. Introduction

[2] Although MOLA-found buried basins [*Frey et al.*, 2002] combined with visible impact basins provide a self-consistent timeline for early events in Martian history [*Frey*, 2006], crater retention ages derived from visible and buried "Quasi-Circular Depressions" (QCDs) alone are minimum ages. There certainly must be impact basins buried so deeply they have no topographic expression. *Edgar and Frey* [2008] showed that crustal thickness data [*Neumann et al.*, 2004] reveal a large population of "Circular Thin Areas" (CTAs): thin crust surrounded by rings of thicker crust. We believe these may be another manifestation of sometimes previously unrecognized impact basins because many correspond to QCDs, either visible or buried, they are widely distributed around Mars, and have a size-frequency distribution like that of QCDs [*Edgar and Frey*, 2008]. Many CTAs do not correspond to QCDs; these may be additional deeply buried impact basins. If so, most buried surfaces are even older than previously thought.

[3] The same crustal thickness data suggest several new very large ($D > 1000$ km) impact basins, mostly in areas of great burial (lowlands or Tharsis) where topography alone might not reveal deeply covered features. The largest, a 2780 km wide feature in Amazonis Planitia, is marked by a faint narrow ring of thicker crust surrounding generally thinner crust, within which are numerous smaller CTAs (Figure 1). The lowland portion of the Utopia Basin main ring has a similar character. A smaller ($D \sim 1155$) well-defined CTA lies within Amazonis (IA in Table 1); this feature was recognized in the crustal thickness data early on [*Neumann et al.*, 2004] and separately in gravity models as a pronounced circular anomaly [*Lemoine et al.*, 2001].

[4] Combined with those previously recognized from image or topographic data, the total population of impact basins >1000 km diameter now numbers 20. Figure 2 shows these; the new candidate basins (see below) are shown as the dashed circles. Basin characteristics are given in Table 1. There is a slight concentration of basins at northern latitudes: 60% (and three of the five largest) have centers at positive latitudes while 40% have centers south of the equator. But 11/20 (55%) lie within the highlands, 7 (35%) in the lowlands, and 2 may exist in the Tharsis region. This distribution is similar to that of the relative areas of the three regions. Note 3 of the 4 largest lie within the lowlands.

2. Crater Retention Ages of Large Basins

[5] To determine the crater retention ages of the large basins, we counted the QCD and non-QCD CTAs superimposed on the rim or interior of the 20 large basins. The resolution of the crustal thickness data limits this to features >300 km. Because the smallest members of the large basin population could appear young because it is hard to fit 300 km wide features inside a 1000 km wide basin, we plot in Figure 3 the N(300) crater density versus basin diameter. There appears to be no systematic bias introduced by small size; both large and small values of N(300) are found for smaller basins.

[6] Figure 4 shows the distribution of N(300) ages. The obvious peak in the basin crater retention ages (CRAs) contains over half the population, ALL the lowland and Tharsis basins, and 3 of the 4 largest basins (see Figure 3). If the "peak" is extended to $5.0 < N(300) < 2.0$, then 4 of the 5 largest basins fall into the time period when 65% of the basins formed (if the crater retention ages represent formation time as opposed to, for example, the time of some large scale resurfacing event).

3. "Absolute" Basin Ages

[7] N(300) crater retention ages can be converted to model "absolute ages". Figure 5 shows N(300) ages for the major stratigraphic boundaries, extrapolated from *Tanaka*'s [1986] small diameter counts (averaged where N(5) and N(16) differ) using a -2 power law, plotted against Hartmann-Neukum (H-N) (2001) model ages for these boundaries. Hesperian and Amazonian H-N ages were also averaged because the authors differ on their values [*Hartmann and Neukum*, 2001].

[8] The relationship between N(300) and H-N ages shows two distinct branches, both of which can be very well approximated by straight lines (in the log-linear plots shown) which cross at the Early Hesperian-Late Hesperian boundary. Extrapolating a fit for the steeper line into the Early Noachi-

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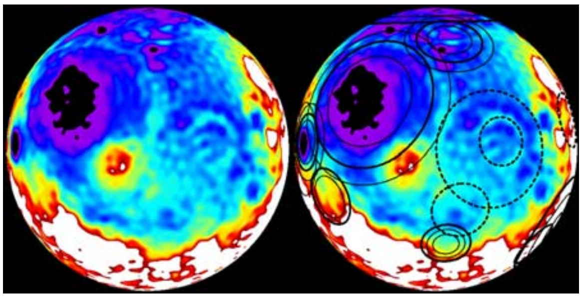

Figure 1. Stretched crustal thickness of eastern Mars, with the newly identified Amazonis Basin (large dashed circle) and previously recognized Utopia Basin (large thick solid circle) indicated (right). Reds and white = thick crust, purples and black = thin crust. Utopia is an obvious topographic feature; Amazonis is not. Based superimposed smaller QCDs and CTAs, Amazonis is older than Utopia.

an, it is possible to calculate "absolute" Hartmann-Neukum ages in billions of years (gigayears, Gy) from the N(300) ages for the large basins (Table 1). This is shown in the outlined portion of Figure 5 (top), enlarged as Figure 5 (bottom) and shown as a histogram of ages in Figure 6.

[9] Note that 80% of the large basins fall within the narrow age range 4.10–4.25 Gy; only the younger Hellas, Argyre and Isidis Basins lie outside this range. There is an even stronger concentration of many basins in Figure 5(bottom) in the narrower interval 4.12–4.14 Gy: this contains ALL the Tharsis and lowland basins except Utopia (the largest and most recently formed). If the derived absolute ages are correct (which assumes the N(300) ages determined are correct AND the conversion to H-N model ages is appropriate), then the "absolute" ages for the largest basins appear sharply peaked in a very narrow time interval (~150 MY) in Martian history.

4. Discussion

[10] The distributions of both crater retention and inferred model absolute ages for the largest impact basins on Mars have important implications not only for the early history of Mars, but for that of the inner solar system as well. It is tempting to correlate the strong peak in ages with a "spike" in impact production, analogous to the proposed "terminal lunar cataclysm" (TLC) [*Tera et al.*, 1974]. The inferred Martian time interval (~150 MY) is consistent with both the TLC and the duration suggested by the NICE model [*Gomes et al.*, 2005; *Bottke and Levison*, 2007; *Bottke et*

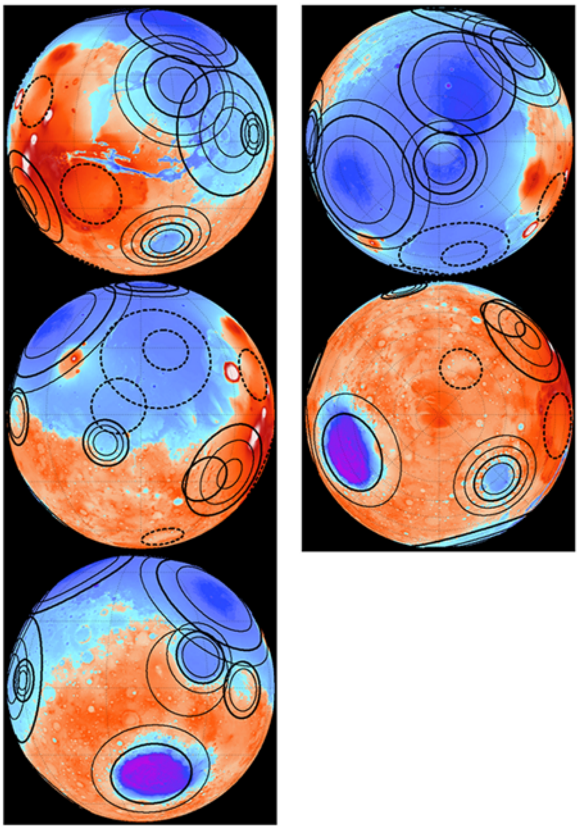

Figure 2. Impact basins >1000 km diameter superimposed on MOLA topography. (left) Equator views at 60, 180 and 300 W longitude. (right) N and S polar views. Dashed = basins from crustal thickness data.

Table 1. Impact Basins on Mars >1000 km Diameter[a]

Name	Symbol	Q/C	Region	Latitude	W Longitude	Diameter	CRA
Amenthes	Am	Q	H	0.9S	249.4	1070	6.68
Zephyria	Ze	Q	H	12.4S	195.7	1193	6.27
Daedalia	Da	Q	H	26.5S	131.7	2639	5.70
Sirenum	Si	C	H	67.4S	154.7	1069	5.57
SW Daedalia	SW	Q	H	29.4S	146.1	1278	4.68
Ares	Ar	Q	H	4.0N	16.1	3300	4.33
Amazonis	Az	C	L	27.1N	172.1	2873	3.86
In Amazonis	IA	C	L	29.3N	167.5	1156	3.81
Solis	So	C	TH	23.8S	84.7	1663	3.68
N Tharsis	NT	C	TH	17.6N	116.4	1347	3.51
Chryse	Cr	Q	L	25.0N	42.0	1725	3.42
Hematite	Hm	Q	H	3.2N	2.2	1065	3.37
Scopolus	Sc	Q	H	6.9N	278.2	2250	3.24
Acidalia	Ac	Q	L	59.8N	17.3	3087	3.21
North Polar	NP	Q	L	80.0N	164.8	1600	2.99
Utopia	Ut	Q	L	45.0N	244.5	3380	2.68
SE Elysium	SE	C	L	3.7N	189.7	1403	2.59
Hellas	He	Q	H	42.3S	293.6	2070	1.78
Argyre	Ag	Q	H	49.0S	42.5	1315	1.47
Isidis	Is	Q	H	13.4N	272.2	1352	0.17

[a] Q, quasi-circular depression (QCD); C, circular thin area (CTA); H, highlands; L, lowlands; TH, tharsis.

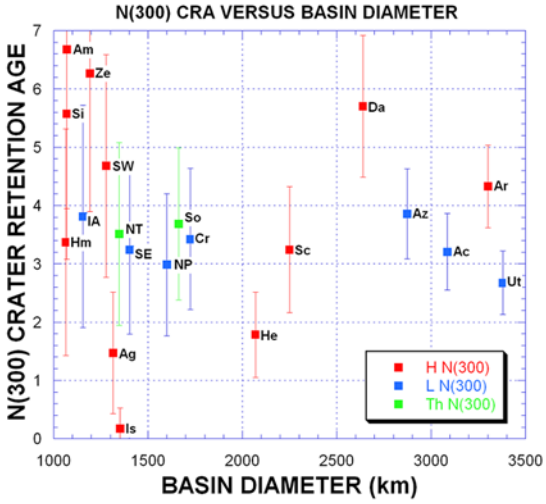

Figure 3. N(300) crater retention age versus basin diameter. Red = highland basins, blue = lowland basins, green = Tharsis basins. Basins keyed to Table 1. Formal counting errors (square root of number/area) are sometimes large because some basins have very few superimposed features >. Note the large number of basins with N(300) ages 2.5–4.0.

al., 2007] for a flux of trans-Neptunian objects deflected into the inner solar system ~800 MY after solar system formation. Such a bombardment would impact all the terrestrial planets at essentially the same time. But the inferred "absolute" age of the Martian peak is different: based on our conversion to Hartmann-Neukum ages, it is 4.1–4.25 Gy on Mars, whereas the TLC is roughly dated at 3.8–4.0 Gy [*Tera et al.*, 1974; *Warren*, 2004; *Ryder et al.*, 2000]. The H-N ages are highly model-dependent and could easily be uncertain by this amount. If the large Martian basins are part of an inner solar system late heavy bombardment, it may be possible to tie the lunar and Martian chronologies together at ~3.9 Gy through the N(300) ages.

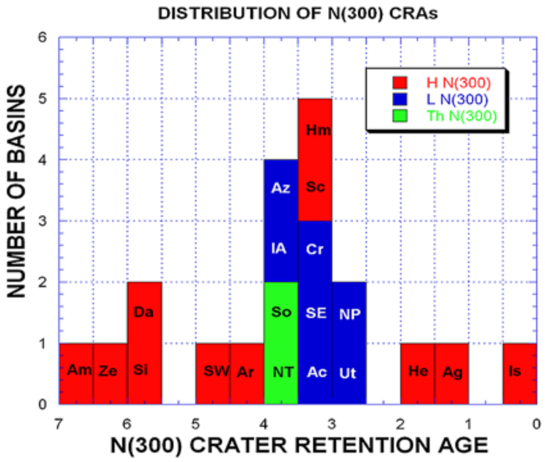

Figure 4. Distribution of large basin N(300) crater retention ages. Color as in Figure 3. The strong peak at middle ages contains over half the population, 3 of the 4 largest basins, and ALL the lowland and Tharsis basins. If CRA corresponds to formation time, >50% of the population formed in a relatively short time.

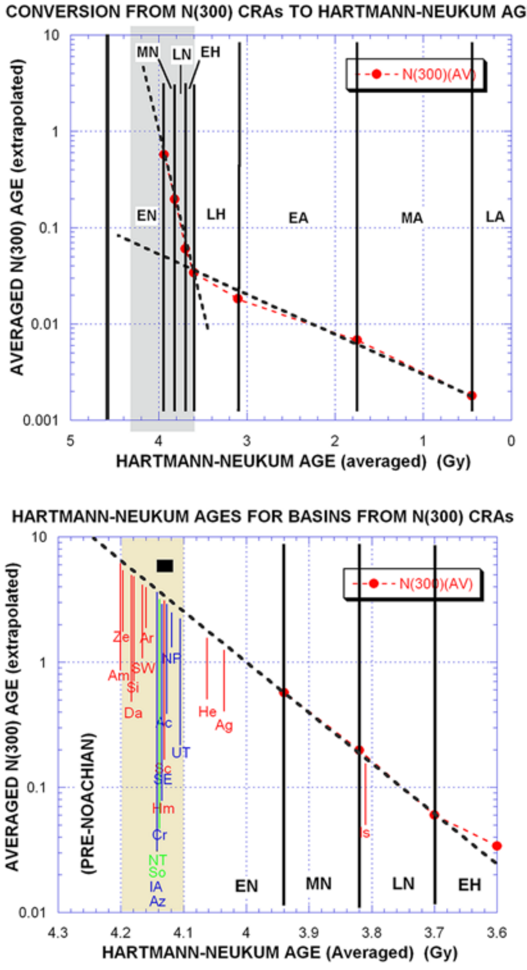

Figure 5. Conversion of N(300) CRAs to Hartmann-Neukum "absolute" ages. (top) Averaged N(300) CRAs for stratigraphic boundaries plotted against H-N "absolute" model ages for the same boundaries. See text. Points are fit by two straight lines in this log-linear plot. Shaded area shown enlarged at the bottom. (bottom) Absolute ages for basins are determined from the N(300) CRAs (Table 1), assuming straight line extrapolation beyond the Early Noachian-Middle Noachian boundary. Note all the basins except the three youngest (Hellas, Argyre, Isidis) lie in a narrow age range of 4.10 to 4.20 Gy, and most (including all those in the lowlands and Tharsis region) in an even narrower time period. Actual distribution of ages shown in Figure 6.

[11] It is also tempting to relate the formation of the Martian lowlands to this brief period of concentrated impacts, given that 3 of the 4 largest basins formed at this time now contain much of the lowland crust. The average N(300) age of these "peak" basins (~3.4) is close to but slightly older than the average N(300) age of the lowlands and highlands (~3.2) [*Edgar and Frey*, 2008]. But the two largest basins, Utopia in the lowlands and Ares in the highlands, are separated in time by perhaps as little as ~60 MY, and have very different crustal thicknesses (~14 km below Utopia, ~35–40 km below Ares). It seems unlikely that an impact only a few 10s of millions of years later than one of comparable size could by itself produce the lowland thickness and elevation so obvious in

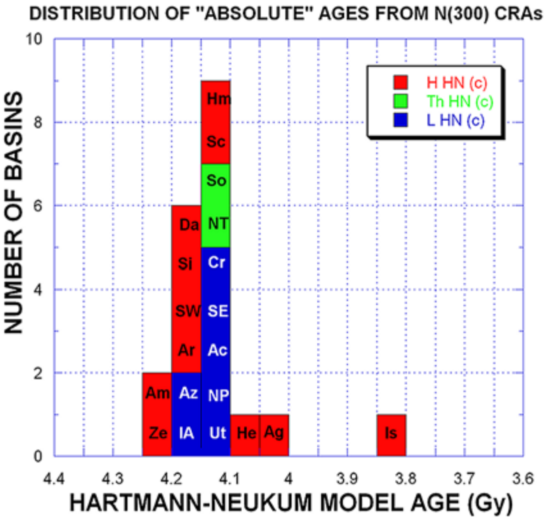

Figure 6. Histogram of model absolute ages for large basins. Color code same as in Figure 4. Bin size 50 MY. The basin ages are sharply peaked between 4.1 and 4.2 Gy. All the lowland and Tharsis basins lie in this bin.

Utopia. It may be Utopia and the other large lowland basins only further thinned crust of already reduced thickness. Whether such "pre-thinned crust" was the result of internal processes [e.g., *Zhong*, 2008] or a single giant impact [e.g., *Andrews-Hanna et al.*, 2008] can still be debated, but by whatever means, the "pre-thinning" must have occurred before the formation of the first of the preserved lowland basins (Amazonis, at 4.154 Gy in Hartman-Neukum years; see Figure 1).

[12] The peak in large basin formation also closely correlates with the apparent demise of the global magnetic field. As discussed in a companion paper [*Lillis et al.*, 2008] basins with N(300) > 4 have strong magnetic signatures, those with N(300) < 2 have no magnetic signatures, and those in the middle age range show a sharply decreasing intensity of magnetic intensity with decreasing age. The global field may have died at about 4.13 Gy if the H-N chronology is correct, or at about 3.85 Gy if the peak represents the Martian equivalent of the terminal lunar cataclysm. In the light of recent simulations by *Kuang et al.* [2008] showing that a 1% reduction in core Reynolds number can cause a subcritical dynamo's magnetic field to weaken by 2–3 orders of magnitude, it is interesting to consider whether a short period of intense bombardment by a number of very large objects may have contributed to the subsequent loss of the global magnetic field by disturbing core-mantle heat flow.

[13] There are implications for the Earth that go beyond the obvious LHB and its likely "impact frustration of life" until after 3.8 Gy. If the total large basin population on Mars is as shown in Figures 4 and 6 (i.e., if there were no very large basins forming earlier than those shown), then throughout the inner solar system the "spike" may have been preceded by several hundred million years relatively free of large impact basin formation. This would support the possibility of a "cool, early Earth" during which early life may have arisen [*Valley et al.*, 2002], conditions suggested by analysis of zircons. Note that the same relatively quiescent pre-LHB period would also have existed on Mars.

5. Conclusions

[14] The very large impact basins which formed early in the history of Mars may have done so in a very short period of time, analogous to the proposed late heavy bombardment "terminal lunar cataclysm". If true, it may be possible to correlate lunar and Martian impact chronologies and therefore absolute ages. The short period of basin formation has implications for the origin of the crustal dichotomy and possible cause of the demise of the global magnetic field on Mars, and the possibility of a several hundred million year period relatively free of the effects of large impacts on both the early Earth and Mars.

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