VERY LARGE VISIBLE AND BURIED IMPACT BASINS ON MARS: IMPLICATIONS FOR INTERNAL AND CRUSTAL EVOLUTION AND THE LATE HEAVY BOMBARDMENT IN THE INNER SOLAR SYSTEM.
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Introduction: Buried impact basins revealed by MOLA topography have significantly changed our view of the age of major events in early Mars history. Crustal thickness data indicate the population of buried impact basins is even larger than previously thought, suggesting the buried surfaces are even older than previously estimated. This same data set reveals several new very large (>1000 km diameter) impact basins, bringing the total population to ~20. Their spatial distribution and relative ages provide important information on the possible nature of the basement below Tharsis, the relative age of the highlands and lowlands, the rapidity with which the global magnetic field died, and a possible "spike" in large impact cratering during the Late Heavy Bombardment which may have been the martian equivalent of a "terminal lunar cataclysm".

More Buried Basins: MOLA topography revealed a very large population of likely buried impact basins everywhere on Mars [1,2] which suggested both the highlands and lowlands of Mars were older than previously thought [2,3]. Although the MOLA-found buried basins (in combination with visible impact basins) provided a self-consistent timeline for early events in martian history [3] it was always clear that crater retention ages derived from these visible and buried "Quasi-Circular Depressions" (QCDs) were minimum ages, because there almost certainly must be impact basins buried so deeply that no topographic expression of their presence remains. Edgar and Frey [4,5] showed that crustal thickness data [6] reveal a population of "Circular Thin Areas" (CTAs): circular areas of thin crust surrounded by a ring or extended region of thicker crust. Many correspond to QCDs, either visible or buried, so these CTAs are another manifestation of impact craters. But many CTAs do not correspond to recognized QCDs. These may be additional impact basins buried so deeply that MOLA data alone cannot reveal their presence. If so, many of the buried surfaces are even older than previously thought, and the lowlands may be as old as the highlands [4,5] unless the density of impact craters $\geq$ 300 km has reached a state of saturation [7] (see below).

Very Large Basins: The same crustal thickness data [6] suggest the presence of several additional very large (D>1000km) impact basins [8]. Combined with those previously recognized from image or topographic data [3] the total population of likely large impact basins now numbers ~ 20. Figure 1 shows these; the new candidate basins (see below) are shown as the dashed circles. Basin characteristics are given in Table 1.

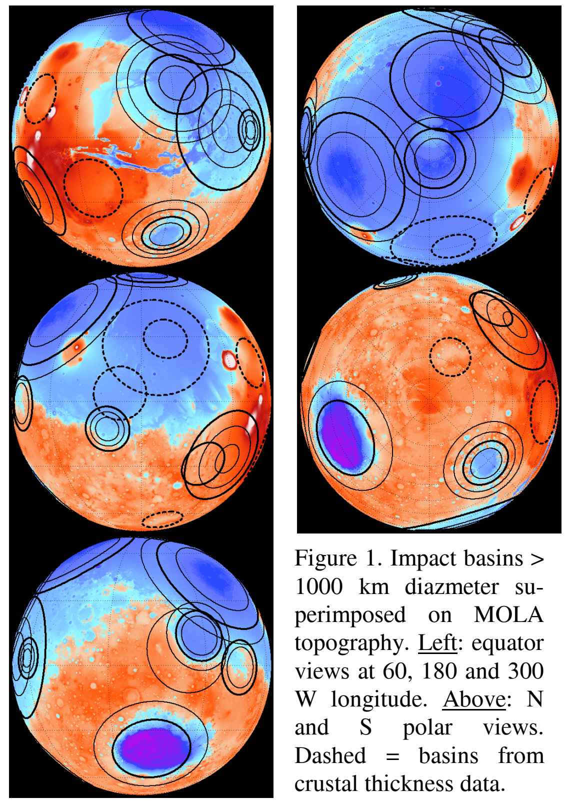

Figure 1. Impact basins > 1000 km diazmeter superimposed on MOLA topography. Left: equator views at 60, 180 and 300 W longitude. Above: N and S polar views. Dashed = basins from crustal thickness data.

There is a slight concentration of basins at northern latitudes: 60% 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, to first order, similar to the relative areas of the three regions. What is unusual is that 3 of the 4 largest basins lie within the lowlands, including the largest of the possible newly identified candidates.

Possible New Large Basins: The crustal thickness data [6] suggest 5 new very large basins [8]. Not surprisingly, all of these are in areas of great burial (lowlands or Tharsis) where topography alone might not reveal deeply buried features. The largest of new candidates lies in Amazonis, which previously was the only very large region of lowlands in which a large impact basin had not been identified [9]. As shown in Figure 2, the large (D~2870 km) Amazonis (Az in Table 1) feature is marked by a narrow ring of thicker crust surrounding generally thinner crust, within which are numerous smaller CTAs. Note that the lowland portion of the Utopia Basin main ring has a similar character. A smaller (D~1155) well-defined CTA ("Inside Amazonis", IA in Table 1) lies within Amazonis; this feature was recognized in the crustal thickness data early on [6] and in gravity models which predate the current crustal thickness model [10].

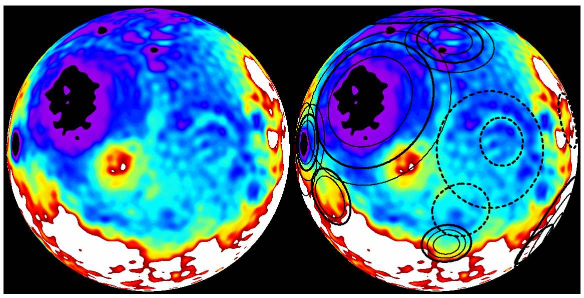

Figure 2. Stretched crustal thickness of eastern Mars, with the newly identified Amazonis Basin (large dashed circle) and previously recognized Utopia Basin (large thick solid circle) indicated (right). Utopia is an obvious topographic feature; Amazonis is not. Amazonis was the only large expanse of lowlands in which a large impact basin had not been previously recognized. Based on the number of superimposed smaller QCDs and CTAs (note small circular areas in lower right panel , Amazonis is older than Utopia.

Two possible new large basins (D~1350, 1660 km) in the Tharsis region are suggested by the crustal thickness data. As described below, determining if these are real is important for understanding the likely nature of the basement below the Tharsis volcanics.

Nature of the Tharsis Basement: Figure 3 shows cumulative frequency curves for the highlands, lowlands and Tharsis regions based on a combined data set of QCDs and non-QCD CTAs [4,5]. The cumulative number per unit area at 300 km diameter is the same for the highlands and lowlands, suggesting they are the same age (but see below). The green Tharsis curve lies below that for the lowlands and highlands, and drops off at large diameters as would be expected for a younger surface. The simple interpretation is that Tharsis is indeed new, younger crust throughout. But our search for very large impact basins revealed two candidates in the Tharsis region (see Figure 3). If these are real, they are moderately old (Table 1) with a crater retention age similar to that of many lowland and some highland basins. Figure 3 also shows the cumulative frequency curves with the two large basins added. Tharsis is still overall younger, but at large diameters, the curve looks like that for the ancient highlands. If this is this case, Tharsis could be built on older crust.

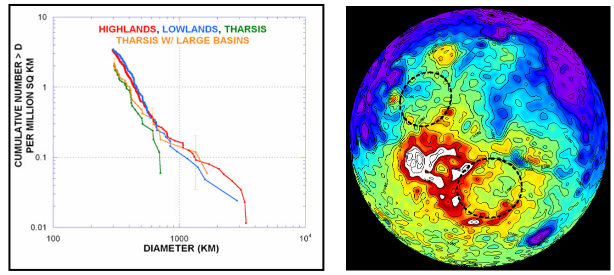

Figure 3. Cumulative frequency curves based on QCDs and CTAs for the highlands, lowlands and Tharsis, without (green) and with (orange) the two proposed large basins in the Tharsis region (right, shown as the dashed circles on stretched and contoured crustal thickness data). In both cases the N(300) crater retention age of Tharsis is younger than that of the highlands and lowlands, but if the two proposed basins are real, the large diameter end of the cumulative frequency curve is very similar to that of the highlands.

Relative age of the highlands and lowlands: The cumulative frequency curves (Figure 3) for the highlands and lowlands are essentially identical for D<800km; the N(300) crater retention age for the two regions appears to be the same. If true, this would have important implications for formation of the crustal dichotomy. But the similarity of the two curves, and the fact that the low diameter end follows the same -2 power law slope as the large diameter end (see Figure 4) suggest caution. A -2 power law slope may indicate impact saturation.

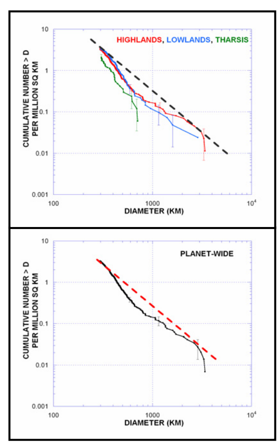

Figure 4. Cumualtive frequency curves for highlands (top left) and for the planet as a whole (bottom left) have a similar character: the same -2 powerlaw slope (dashed lines) roughly fits the large (D> 1000km) and the small (D~ 300 km) diameter end. In between the curves have a shape that suggests depopulation, perhaps due to the formation of the large basins. Where the curves fit the -2 slope, saturation may have occurred.

One interpretation [7] of the shape of the highland and lowland curves, and the total planet-wide curve (Figure 4) is that intense late bombardment by large objects depopulated the surface at D< ~ 1000 km (and likely reset the surface ages). This could explain the downturn in the curves at these diameters. Recovery at smaller diameters has occurred, but may have reached saturation at N(300) ~ 3.5 (average for the planet as a whole; but see below). If true, it is impossible to determine the real crater retention age of the highlands and lowlands.

Relative Crater Retention Ages of Large Basins: The crater retention age of the very large basins can be found by counting the number of sumperimposed smaller basins [7,8]. The coarse resolution of the crustal thickness data limits this to features > 300 km diameter, and even this is likely at the ragged edge of the current crustal thickness model. It is hard to fit many features > 300 km diameter into basins only 1000 km across, so we plot the N(300) crater density versus diameter (Figure 5). The error bars are a percentage error (SQRT[N]/N), and are better for larger features which contain more superimposed craters. But we find both large and small N(300) values for basins of the same size, so it appears there is no signficiant bias introduced by the smaller members of the population even though for the youngest features the number of superimposed features can be counted on one hand.

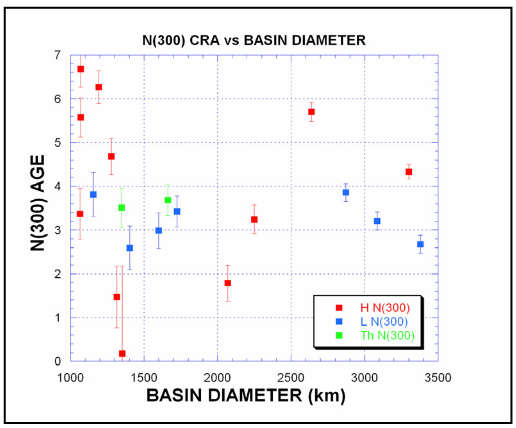

Figure 5. N(300) crater retention age versus diameter for very large basins on Mars. Color code: red = highland basins, blue = lowland basins, green = Tharsis basins

It seems clear from Figure 5 that there is a group of very old basins (N(300) > 5.0), a group of very young basins (N(300) < 2.0) and a much larger group (13/20, 65% of the population) in the middle (5.0< N(300) < 2.0). Figure 6 shows the actual distribution by age.

There is a very obvious peak in the basin CRAs which contains over half the population, all the lowland and Tharsis basins, and 3 of the 4 largest basins (see Figure 5). If the definition of 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. As discussed below, such a peak in crater retention ages, if indicative of formation ages, may imply a "spike" in the impact rate for large objects, perhaps similar to the proposed "terminal lunar cataclysm" suggested by the ages of large lunar basins and the relative absence of lunar sample ages > 4.0 BY [11].

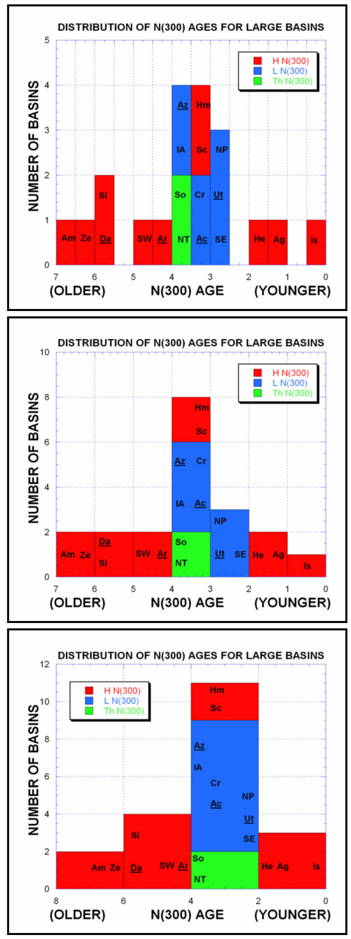

Figure 6. Histograms of large basin N(300) crater retention ages for for bin sizes 0.5 (top), 1.0 (middle) and 2.0 (bottom). Color as in Figure 5. All three plots show the same strong peak at middle ages; this peak contains over half the population and 3 of the 4 largest basins. In the finest (and coarsest) bin size, all lowland and Tharsis basins lie in the 0.4 < N(300) < 2.5 peak (in the coarsest bin the 4.0 < N(300) < 2.0 peak. If CRA corresponds to formation time, > 50% of the population formed in a relatively short time. This may be the martian equivalent of the proposed "terminal lunar cataclysm" [11].

Basin Ages and Magnetic Anomalies: The peak in CRAs for basins also contains the dividing line between basins which contain strong magnetic anomalies and those that do not. Basins forming after N(300) = 2.0 (Hellas, Argyre and Isidis) have no magnetic anomalies. All the basins with N(300) >4 have strong anomalies. Within the peak of CRAs basins have few to no anomalies, with the change to no anomalies occurring at N(300) ~ 3: Utopia and North Polar have none in the newer, higher resolution map based on the MGS ER experiment [12], but the slightly older Chryse and Acidalia contain moderate anomalies. Lillis et al. [13,14] discuss in more detail evidence for a rapid cutoff of the martian dynamo, based on these basin ages.

Discussion: Large impact basins have a strong influence on the evolution of the lithosphere and crust of a planet, and may have significant effects on the interior as well. We find evidence for about 20 basins > 1000 km in diameter, 5 of which are recognized mostly in crustal thickness data [8], the rest having been identified previously in image or MOLA topographic data

[3]. To first order the number of basins goes with the relative area of the highlands, lowlands and Tharsis regions, but the lowlands contain a disproportionate fraction of the largest basins (3 of the 4). All the lowland basins (and the two candidate basins in Tharsis) have CRAs in the narrow middle range when more than half of the population formed (if crater retention age can be equated with formation time). It remains possible the lowland basins formed on pre-existing lowland and only enhanced the low topography. What seems clear is the basins now containing lowland crust formed in a relatively short period of time when most of the large basins formed on Mars.

It is tempting to correlate this “peak” in crater retention ages for 50-65% of the large basins with a “spike” in impact production, analogous to the proposed lunar cataclysm [11]. If true, it would provide important temporal correlation between events on Mars and on the Moon, because dynamical studies suggest the only source for a “terminal lunar cataclysm” is a flux of objects deflected into the inner solar system [15,16] which would impact all the terrestrial planets at essentially the same time.

It is also tempting to relate the formation of the lowlands to this possible “spike”, given that 3 of the 4 largest basins that formed at this time now contain a significant portion of the lowland crust. The average N(300) age of these “peak” basins is close to the average N(300) age of the lowlands and highlands (~3.5). While lowlands having the same age or even an older age than the highlands might support some endogenic theories for the formation of the crustal dichotomy [17], it is possible that the apparent similarity of the highland and lowland ages in the cumulative frequency curves is the result of saturation. If true, we cannot know the average age of the highlands and lowlands and either could be older than the other.

There are areas of Mars older than N(300) ~3.5: some highland basins including the large Ares and Daedalia features appear to have N(300) > 4. This reinforces the possibility that the average cumulative frequency curves which follow a -2 powerlaw slope may indeed be indicating crater saturation.

The correspondence of a peak in large basin formation with the apparent loss of the magnetic field also makes it tempting to consider possible cause and effect. Could the formation of several very large impact basins (D>2500 km) over a relatively short interval have altered the internal temperature and convective character of Mars in such a way as to disrupt the dynamo in the core? Kuang [18] suggests the dynamo can terminate very rapidly if the Reynolds number decreases below a critical value. Lillis et al. [13,14] describe in detail the evidence that the dynamo terminate rapidly.

Conclusions: The formation of very large impact basins on Mars may have been concentrated in a short period of time, analogous to the proposed “terminal lunar cataclysm”. If true, it may be possible to correlate lunar and martian impact chronologies and therefore absolute ages. The effects of such large impacts were many, and have important implications for the formation of the crustal dichotomy, the nature of the basement below Tharsis, and the timing and perhaps mechanism for the demise of the global magnetic field.

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TABLE 1. IMPACT BASINS ON MARS > 1000 KM DIAMETER

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

Q/C: Q = Quasi-Circular Epression; C = Circular Thin Area

H = Highlands, L= Lowlands,TH = Tharsis

CRA = N(300) Crater Retention Age