JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, E08S91, doi:10.1029/2005JE002449, 2006

Impact constraints on, and a chronology for, major events in early Mars history

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Received 14 April 2005; revised 25 October 2005; accepted 8 November 2005; published 23 August 2006.

[1] Large-diameter visible and buried impact basins, seen as ‘‘quasi-circular depressions’’ (QCDs) in MOLA gridded data, provide a self-consistent chronology for major events on early Mars in terms of N(200) crater retention ages. On the basis of a conversion to model absolute ages, this chronology extends back hundreds of millions of years into a previously unknown ‘‘pre-Noachian’’ epoch during which a now buried highlands surface was established, in which several very large impact basins formed while the global magnetic field was still present. A cluster of very large ‘‘lowland-making’’ basins occurred at a model age of about 4.13 GY (or earlier), forming the fundamental topography of the Mars crustal dichotomy at a time prior to the age of the oldest visible highland crust. This early event in Martian history marks the transition from the ‘‘pre-Noachian’’ to the Early Noachian when the well-preserved Hellas, Argyre, and Isidis basins formed, all after the global magnetic field died.

Citation: Frey, H. V. (2006), Impact constraints on, and a chronology for, major events in early Mars history, *J. Geophys. Res.*, *111*, E08S91, doi:10.1029/2005JE002449.

1. Introduction

[2] MOLA data have revealed a large population of ‘‘quasi-circular depressions’’ (QCDs), many with little or no visible expression in image data. On the basis of their widespread occurrence, general absence from areas of extensive volcanic resurfacing, and especially their cumulative frequency curves, these ‘‘invisible’’ QCDs are likely buried impact basins [*H. V. Frey et al.*, 1999, 2002]. If true, they have important implications for the true relative ages of the highland and lowland crust, and when and how the crustal dichotomy may have formed [*Frey*, 2003a, 2003b, 2004b, 2005]. Based on an earlier survey it appeared the buried lowlands are of Early Noachian age, likely slightly younger than the buried highlands but older than the exposed (visible) highland surface [*H. V. Frey et al.*, 2002].

[3] In this paper we consider a global population of large QCDs, both visible and buried, and use total population (visible + buried) crater retention ages to develop a chronology of major events (sequence of large basin formation, loss of the global magnetic field, likely formation of the crustal dichotomy) on early Mars. We find evidence in the cumulative frequency curves for a loss of large visible basins at diameters 800 to 1300 km which suggests some global-scale event early in Martian history. If lack of magnetic anomalies in well-preserved impact basins indicates they formed after the core dynamo died, then the global magnetic field appears to have disappeared at about the time the lowlands formed. The topographic crustal dichotomy was produced very early in Martian history by processes which operated very quickly. A northern lowland has existed throughout nearly all of Martian history, predating the last of the really large impacts (Hellas, Argyre and Isidis) and their likely very significant environmental consequences.

2. QCDs > 200 km Diameter

[4] Figure 1 shows an area just north of Hellas in which visible craters and QCDs not visible in images occur together. QCDs are best seen in stretched MOLA data, but contouring helps reveal their quasi-circular nature. As with visible craters, the buried features sometimes overlap (or are overlapped by younger visible features); identification of these is subjective. We normally assign a quality factor to the candidate QCDs so that weak cases can be excluded from statistical studies. In Figure 1 we identify several subtle QCDs which were not included in the final compilation discussed in this paper.

[5] We searched 64 pixel/degree MOLA data [*Smith et al.*, 1999] for QCDs larger than 200 km diameter. Features of this size are difficult to bury completely (rim heights 1–1.5 km, depths ~4 km based on data from *Garvin et al.* [2002]) and therefore might survive over most of Martian history. This is also a size appropriate for comparison with gravity and magnetic anomalies [*Lemoine et al.*, 2001; *Acuna et al.*, 1999; *Connerney et al.*, 2001]. Of the 560 found, the great majority (>85%) have little or no obvious visible structure (such as basin rims, isolated knobs or massifs that might mark those rims, etc.). Figure 2 shows these as dashed circles; visible basins in this size range are shown as the solid circles. There is an obvious hemispheric dichotomy in the density of QCDs which corresponds

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Published in 2006 by the American Geophysical Union.

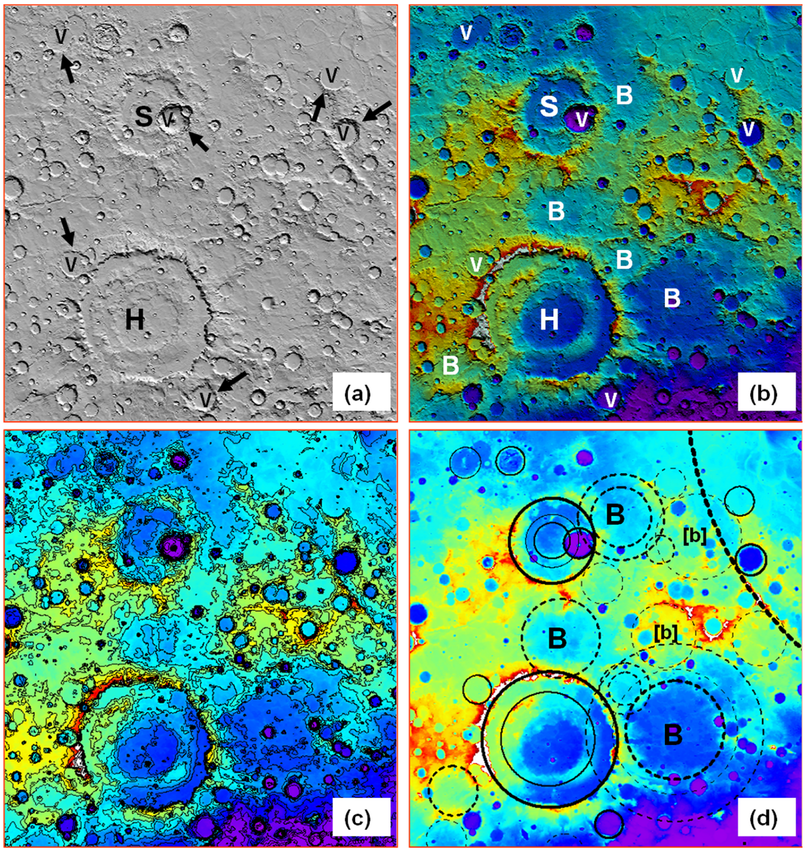
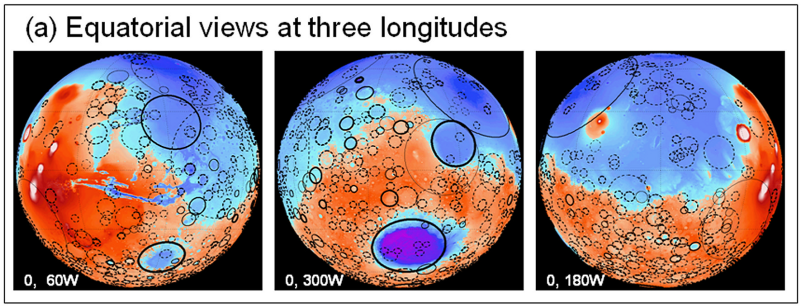


Figure 1. Quasi-circular depressions (QCDs) in heavily cratered highlands north of Hellas. The area is about 1500 km across. (a) Grayscale MOLA shaded relief shows the obvious two-ring Huygens (H) and Shroeter (S), basins. Huygens outer ring is ~475 km wide, Shroeter's is ~300 km across. Arrows and "V" indicate craters >~100 km diameter visible on image data. Hints of other depressions are seen in this rendition, which is actually superior to image data at the same scale. (b) Highly stretched MOLA color shaded relief. Reds are high and blues are low elevations. "B" indicates a very obvious QCD not visible in image data, interpreted to be a buried impact basin. (c) Colored MOLA topography (stretched) with 250-m contours revealing the quasi-circular nature of the low topography. (d) Interpretation of Figure 1c. Solid lines represent visible craters, and dashed show QCDs not visible on images. Thick lines indicate more obvious features. "B" indicates buried features included in the data described in this paper; "[b]" indicates two additional more subtle QCDs > 200 km diameter not used in this study.

roughly with the topographic dichotomy. In the highlands, buried basins outnumber visible basins by a factor 6. In the lowlands, buried basins are 20 times more abundant than visible basins in this size range.

[6] A significant number of very large or giant basins (D > 1000 km) exist, roughly equally divided between the two hemispheres. The most obvious of these are Hellas, Argyre and Isidis (all in the highlands), but other QCDs previously suggested to be giant impacts include Chryse, Acidalia and the now well accepted Utopia [*Schultz and Glicken*, 1979; *Schultz et al.*, 1982; *McGill*, 1989a, 1989b; *Schultz and Frey*, 1990; *Stockman and Frey*, 1995]. These latter three features account for much of the northern lowlands, and in Table 1 and elsewhere are designated "lowland-making basins" (see below). Two very large Utopia-size features are found in the highlands. One is near but not identical to an earlier proposed "Daedalia Basin" [*Cradddock et al.*, 1990; *Schultz and Frey*, 1990] and, like other basins previously suggested on the basis of photogeologic mapping, is considered a "visible" basin. The other, not previously recognized, is centered near 4°N, 16°W, near the head of the Ares Vallis. This "Ares" basin may have influenced early fluvial drainage from Argyre through the Uzboi-Ladon-Arden Valles and Margaritifer-Iani Chaos depressions [*Frey*, 2003b]. The superimposed Chryse Basin promoted drainage out of Ares NW through Ares Vallis around the northern rim of the Aram Chaos basin [*Schultz et al.*, 1982], which lies just west of the center of the much larger basin. Daedalia and Ares are very subtle (topographic) features, both have a high density of superimposed smaller basins, and are likely older than most of the other giant basins.

[7] Large basins may have multi-ring structure [*Schultz and Glicken*, 1979; *Schultz et al.*, 1982; *Pike and Spudis*, 1987; *Schultz and Frey*, 1990; *Spudis*, 1993] and for many can be seen in the topographic data. Table 1 lists the QCDs larger than 1000 km and their possible topographic "rings." Generally the most prominent of these is taken as the actual "diameter" of the basin for plotting the cumulative frequency curves described below. Where no ring is clearly


(a) Equatorial views at three longitudes

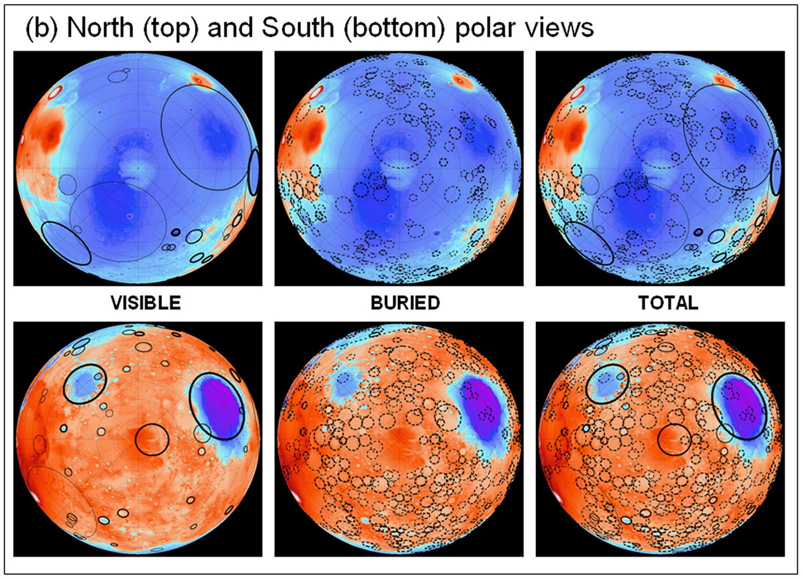

(b) North (top) and South (bottom) polar views

Figure 2. QCDs on Mars > 200 km in diameter over colored MOLA topography. Blues are lowlands, and reds are highlands. Solid circles show "visible" (on images) features known to be impact basins. Dashed circles represent features not visible on images and are believed to be buried impact basins. (a) Equatorial views at 60°W, 300°W, and 180°W. (b) Polar views. Buried features outnumber visible basins by a factor 6 in the highlands and a factor 20 in the lowlands. Note the greater density of QCDs in the Southern Hemisphere, corresponding to the cratered highlands.

dominant, the largest recognized ring is used as the basin diameter.

3. Cumulative Frequency Curves and Crater Retention Ages

[8] Figure 3 shows cumulative frequency curves for the visible, buried and total (visible plus buried) QCD populations of the planet as a whole (Figure 3a) and separated into highlands (cratered terrain, CT) and lowlands (smooth plains, SP) (Figure 3b). Dashed lines show -2 power law trends in the log-log plots. A small number (~10) of very large (mostly visible) basins (D = 1300–3000 km) follow a -2 power law slope in the global population (Figure 3a), but the visible population shows a significant depletion at $D < 1300$ km before recovering the -2 trend at $D < 600$ km. This depletion may represent a major, global scale resurfacing event [*Frey*, 2003b]. The buried population does not show this depletion. The visible global population at $D < 600$ km appears to have several branches, perhaps indicating a series of smaller scale global resurfacing events or regional variations in the crater density.

[9] The large-scale depletion (resurfacing event) is seen in Figure 3b in the visible and total population for the highlands, whose curves mimic the character of the planet-wide visible and total basins in Figure 3a. The individual lowland and highland buried populations, like the buried population of the planet as a whole, does not show this

Table 1. Visible and Buried Quasi-Circular Depressions Greater Than 1000 km Diameter[a]

Basin	Center	Possible Diameters	Notes
Hellas	42°S, 294°W	**2070**, 3085	H/V
Scopolus	7°N, 278°W	**2250**	H/V
Isidis	13°N, 273°W	1048, **1352**, 1845	H/V
Unnamed	1°S, 249°W	**1070**, 1435	H/B
Utopia	45°N, 245°W	2360, **3380**, 4210	L/V[b]
Unnamed	12°S, 196°W	630, 916, **1193**	H/V
N Polar	76°N, 185°W	810, 1220, **1660**	L/B
Unnamed	29°S, 146°W	**1278**	H/B
Daedalia	26°S, 131°W	842, 1821, **2639**	H/V
Argyre	49°S, 43°W	905, **1315**, 1798, 2350	H/V
Chryse	25°N, 42°W	995, **1725**, 2635, 3225	L/V[b]
Acidalia	58°N, 19°W	2020, **2790**	L/V[b]
Ares	4°N, 16°W	1260, 2075, **3300**	H/B
Hematite	3°N, 2°W	480, 760, **1065**	H/B

[a] Main topographic ring (diameter) indicated by boldface. H, highland; L, lowland; V, visible; B, buried. "Visible" includes basins suggested prior to MOLA based on photogeologic studies.

[b] "Lowland-making" basin counted as highland.

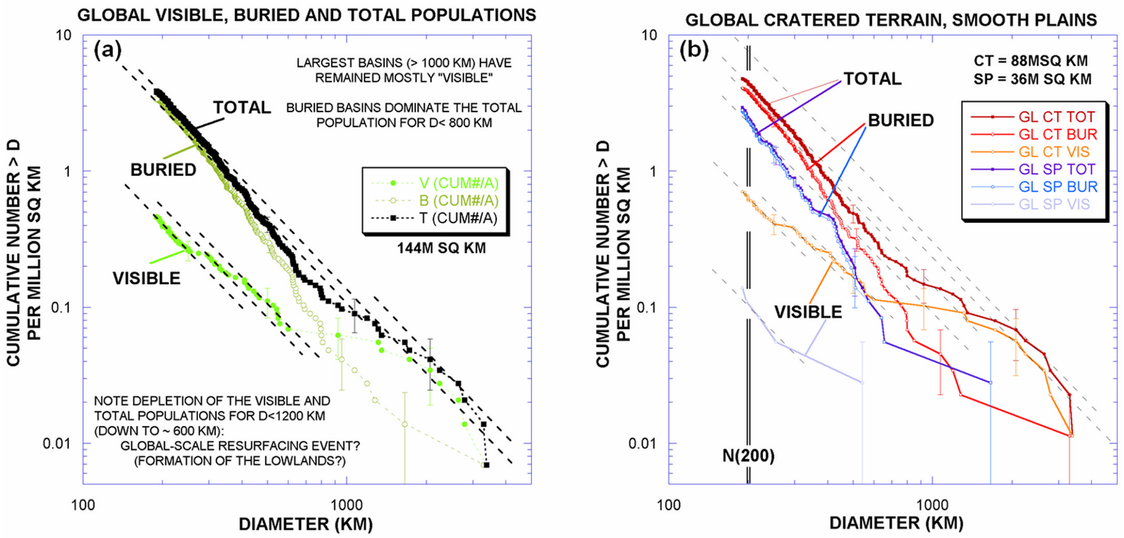


Figure 3. Cumulative frequency curves for visible, buried, and total (visible + buried) populations of QCDs > 200 km diameter. (a) Global distributions. (b) Distributions separated into cratered highlands (CT) and smooth lowland plains (SP). The global visible and total populations (Figure 2a) show a depletion of large basins at D < 1200 km diameter. At larger diameters, these counts closely follow a −2 power law slope (dashed lines), as do the visible, buried, and total populations at smaller diameters. This depletion occurs in the cratered highland visible and total populations (Figure 2b) but not in the lowland populations. It may represent some global-scale resurfacing, perhaps the formation of the lowlands (see text). Note that in Figure 2b the lowlands buried and total populations plot higher than the visible highland population for D < 500 km, but lower than the buried and total highland population for all diameters. The N(200) crater retention age (CRE) is used later to establish a chronology of major events on Mars. The total population N(200) CRE for the highlands is 4.5, and for the lowlands is 2.5.

depletion at D < 1300 km. In Figure 3a and in Table 1, most of the large basins are considered to be highland basins, including the "lowland-making basins" (Chryse, Acidalia, Utopia) on the assumption the lowlands were not present before the basins formed them. The impacts that formed very large basins like Utopia, Acidalia and Chryse would likely destroy large numbers of preexisting smaller basins. Thus formation of the lowlands could explain the observed loss of basins in the 600- to 1300-km size range in Figure 3 [*Frey*, 2003b, 2004a]. An alternative might be an early formation of Tharsis if that involved the destruction of a large area of previously cratered terrain like that which survives outside of Tharsis.

[10] At D < ~500 km the buried and total population lowland basins plot above the buried highland basins, indicating the lowland basement below the smooth plains is older than the exposed visible highland surface. This result, based on a global distribution of QCDs, is consistent with our earlier result comparing the lowlands with just a portion of the highlands [*H. V. Frey et al.*, 2002]. The buried and total population in the lowlands is, however, younger than the buried and total population of the highlands. We have shown elsewhere by direct comparison with the oldest exposed surface units on Mars, *Nh*$_1$, SE of Hellas [*Frey and Frey*, 2002] and elsewhere [*E. L. Frey et al.*, 2002] that the buried lowland crust is Early Noachian (EN) in age [*Frey et al.*, 2002]. Both locally and planetwide there is buried highland crust older than this. The buried highland population represents an even earlier epoch of (intense) cratering (and resurfacing) than was previously recognized on Mars. We later refer to this as the "pre-Noachian" epoch [*Frey*, 2003a, 2004b, 2005] (see Table 2).

[11] We can use the cumulative density of craters at D = 200 to establish a basic (relative) chronology for visible and buried surfaces, and for large scale features such as giant impact basins (see below and Table 2). From Figure 3b, the total population N(200) age for the lowlands is 2.5, for the highland is 4.5. An extrapolation of the −2 power law trend for the very largest basins (D > 1300 km diameter) gives a total large basin population N(200) of about 8.5, perhaps the oldest crater retention age observable on Mars.

4. Comparison With Magnetic Anomalies

[12] Impact basins >200 km diameter are of a size where their distribution can be compared directly with geophysical signatures such as gravity and magnetic anomalies [*Frey*, 2003a, 2003b, 2004a]. Gravity anomalies derived from tracking of orbiting spacecraft [*Lemoine et al.*, 2001] provide information on today's distribution of mass, and there is no guarantee that today's mass distribution accurately describes that of early Mars. On the other hand, the lack of a present-day global magnetic field on Mars [*Acuna et al.*, 1999] indicates that the magnetic anomalies discovered and mapped by Mars Global Surveyor are remanent in nature [*Acuna et al.*, 1999; *Connerney et al.*, 2001], and so likely reflect conditions in the ancient crust while a presumed core dynamo was still active and able to magnetize the crust. The lack of magnetic anomalies in some of the most prominent large impact basins (Hellas, Argyre) and

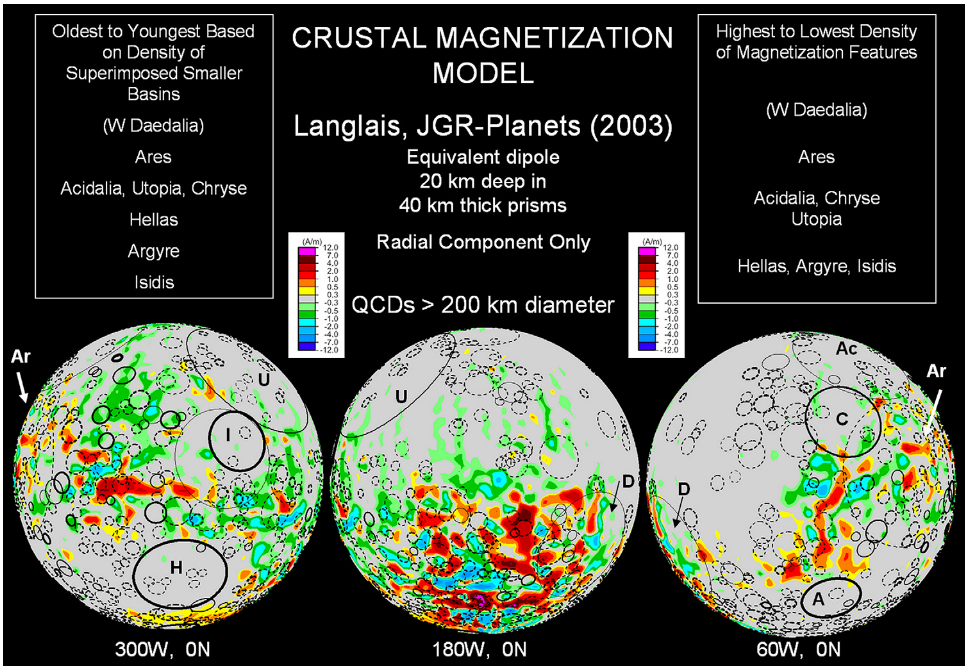


Figure 4. Magnetization anomalies from *Langlais et al.* [2004] compared with the distribution of visible and buried impact basins. For the very largest basins, those with the largest number of superimposed smaller basins (and therefore oldest), Ares (Ar) and W Daedalia (D), have more magnetic anomalies of greater amplitude. The youngest large basins, Isidis (I), Argyre (A), and Hellas (H) have no magnetic features, while the intermediate age ("lowland-making") basins have a few weak anomalies.

even smaller features has been cited as evidence that these basins formed after a presumed global magnetic field disappeared [*Acuna et al.*, 1999; *Nimmo and Gilmore*, 2001; *Hood et al.*, 2003; *Langlais et al.*, 2004]. The MOLA-based evidence for a much larger population of very large impact basins provides the opportunity to extend this kind of study and perhaps develop better constraints on when the magnetic field died (relative to the sequence of large impact basin formation).

[13] Figure 4 compares QCDs (both buried and visible) and magnetization anomalies [*Frey*, 2003a, 2003b, 2004a] from a model by *Langlais et al.* [2004] based on an equivalent dipole formation, using 40-km-thick prisms buried 20 km deep in the crust. Only the radial component is shown. This is but one of many models of the magnetic field [*Arkani-Hamed*, 2001, 2002; *Connerney et al.*, 2001; *Purucker et al.*, 2000; *Cain et al.*, 2003] and while different models vary in small details (such as anomaly amplitude, depending on the elevation at which they are computed), they are virtually identical in distribution of the anomalies [*Nimmo and Tanaka*, 2005]. In Figure 4 there is no compelling correlation between magnetization anomalies and smaller impact basins.

[14] Among the largest impact basins, those that are most prominent (Hellas, Isidis and Argyre) have no obvious anomalies, as has been described before [*Acuna et al.*, 1999; *Nimmo and Gilmore*, 2001; *Hood et al.*, 2003; *Langlais et al.*, 2004]. Less obvious but previously recognized large basins like Utopia, Chryse and Acidalia (the "lowland-making" basins) have at most a few weak anomalies. Only the two most subtle large basins, Daedalia and Ares, have prominent anomalies lying within their main rings [*Frey*, 2003a, 2003b, 2004a]. Solely on the basis of their "visibility," it appears only the oldest basins retain significant magnetization features in their interiors.

[15] It is possible to use the number of superimposed smaller basins to calculate an N(200) crater retention age for the large basins and therefore place them in a relative age sequence [*Frey*, 2003a, 2004a, 2004b]. Daedalia and Ares are the oldest, Utopia, Chryse and Acidalia are younger but similar in age, and Hellas, Argyre and finally Isidis are the youngest. As shown in Figure 4, this is the very same sequence of highest to lowest density of magnetization features. The oldest two are those with strong magnetic anomalies, the youngest three are those without any anomalies, and the middle three (which all have a similar N(200) age of 3–3.2) have at most a few very weak anomalies. This is consistent with the idea that the most recent basins formed after the main magnetic field shut off, as previously suggested by others [*Acuna et al.*, 1999; *Nimmo and Gilmore*, 2001; *Hood et al.*, 2003; *Langlais et al.*, 2004]. If true, the corollary is that Daedalia and Ares have numerous relatively strong anomalies because they formed well before the global magnetic field died, in time for their cooling crust (or any materials filling them) to become remagnetized. The lowland-making basins probably formed at about the time the field was shutting down, or shortly after the dynamo turned off (depending on how long it would take the field to decay to where it could no longer magnetized the cooling crust).

5. A Relative Age Chronology of Major Events in the Early History of Mars

[16] The N(200) ages used to place the largest basins in a temporal sequence can be compared with N(200) ages for

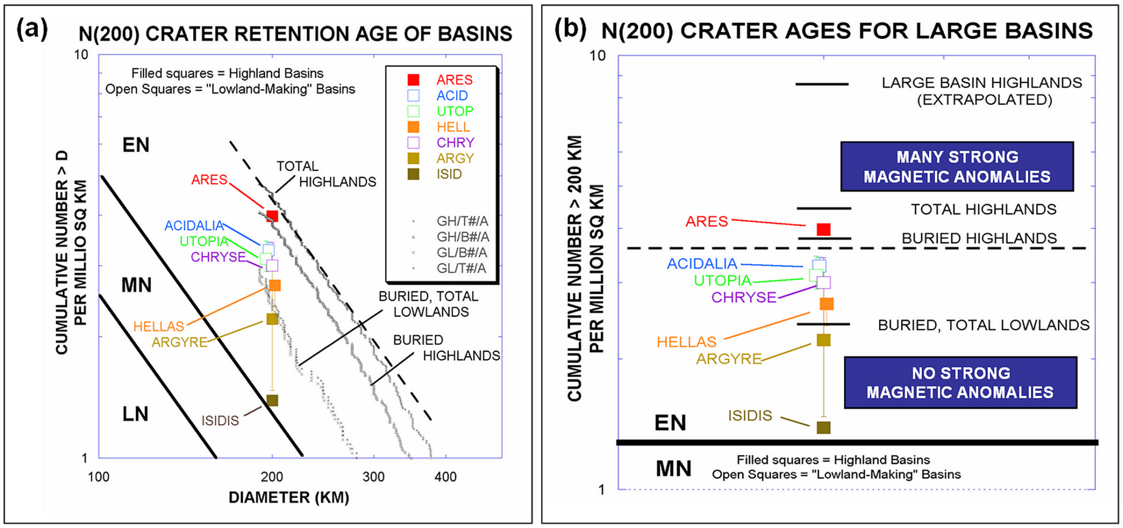


Figure 5. N(200) ages for very large basins and surfaces. (a) Basin N(200) ages compared to cumulative frequency curves for visible and buried surfaces (from Figure 2). Note that Ares is slightly older than the buried (but not total) highlands, and that the "lowland-making" basins (Chryse, Acidalia, and Utopia) are older than the buried and total lowlands, as they should be. The N(200) ages for both basins and surfaces provide a self-consistent chronology for early Mars. (b) N(200) ages from Figure 5a shown in relation to two epochs on Mars which bracket when the global magnetic field may have died. If the field died at N(200) about 3.5 (dashed line), basins forming at that time or shortly after (Chryse, Acidalia, and Utopia) would at most have weak anomalies from a partial remagnetization in a decaying field. Basins formed even later (Hellas, Argyre, and Isidis) would have no magnetic anomalies, as is observed. However, Ares, forming before the hypothetical demise of the magnetic field, would have a floor that had time to be remagnetized before the field died. The chronology shown here is consistent with the observed distribution of magnetic anomalies in different basins (Figure 4).

highland and lowland buried and visible (as well as total age) surfaces [*Frey*, 2003a, 2004b]. Figure 5 shows basins plotted on the lower diameter end of the Figure 3 cumulative frequency curves. Stratigraphic boundaries Early Noachian (EN)-Middle Noachian (MN) and Middle Noachian–Late Noachian (LN) (thick black lines) are derived from *Tanaka*'s [1986] crater counts at small diameters on type surfaces extrapolated to the larger diameter range appropriate for basins using a −2 power law.

[17] The Daedalia basin is not shown in this plot because it is difficult to accurately determine an N(200) age for it, as the eastern half of the basin, and probably most smaller basins superimposed on it, are completely obscured by Tharsis volcanics. The Ares Basin is slightly older than, or about the same age as, the buried highlands (as it should be, since its interior includes a large area of buried highland crust), but is younger than the total crater retention age of the highlands (as it must be if it formed in the highlands). The lowland-making basins are older than the buried (and total) lowlands, as they should be if they formed the lowlands. Hellas too is slightly older than the lowlands, Argyre slightly younger, and Isidis younger yet. The N(200) ages for basins and surfaces provide a self-consistent relative chronology of events in early Mars history.

[18] Figure 5b connects this N(200) chronology to the magnetic field observations in terms of two major epochs: an early period during which there was a global magnetic field capable of producing strong magnetic anomalies (which includes the origin of the Ares basin and the ancient original highland surface on which it formed), and a later epoch where major basins like Hellas, Argyre and Isidis (as well as the buried lowlands) have no strong anomalies, presumably because the global magnetic field had disappeared. If the core dynamo on Mars died at N(200) ~ 3.5 (shown by the dashed line), slightly before or at about the time the lowland-making basins formed, then the presence of at most a few weak anomalies in the interiors of Utopia, Acidalia and Chryse could be explained in terms of partial remagnetization of the cooling crust in a decaying but nearly dead main field. The relative absence of magnetic anomalies in the northern lowlands, with the exception of a few near the north pole [*Hood and Zakharian*, 2001], could be due mostly to demagnetization of the crust from large-scale impacts, as is suggested to be the case in the highlands at Hellas and Argyre [*Nimmo and Gilmore*, 2001; *Hood et al.*, 2003; *Rochette et al.*, 2003; *Mohit and Arkani-Hamed*, 2004], though other processes may have (also) played a role [*Nimmo and Tanaka*, 2005; *Solomon et al.*, 2005].

6. Absolute Ages for Major Events in the Early History of Mars

[19] The N(200) relative crater retention ages can be converted into "absolute ages" [*Frey*, 2004b] using the Hartmann-Neukum (H-N) model chronology [*Hartmann and Neukum*, 2001]. Figure 6 shows schematically how this was done. *Tanaka*'s [1986] crater counts were used to convert his N(16) ages for major epoch boundaries (Early Noachian/Middle Noachian (EN/MN), etc.) to N(200) ages assuming a −2 power law. *Hartmann and Neukum* [2001]

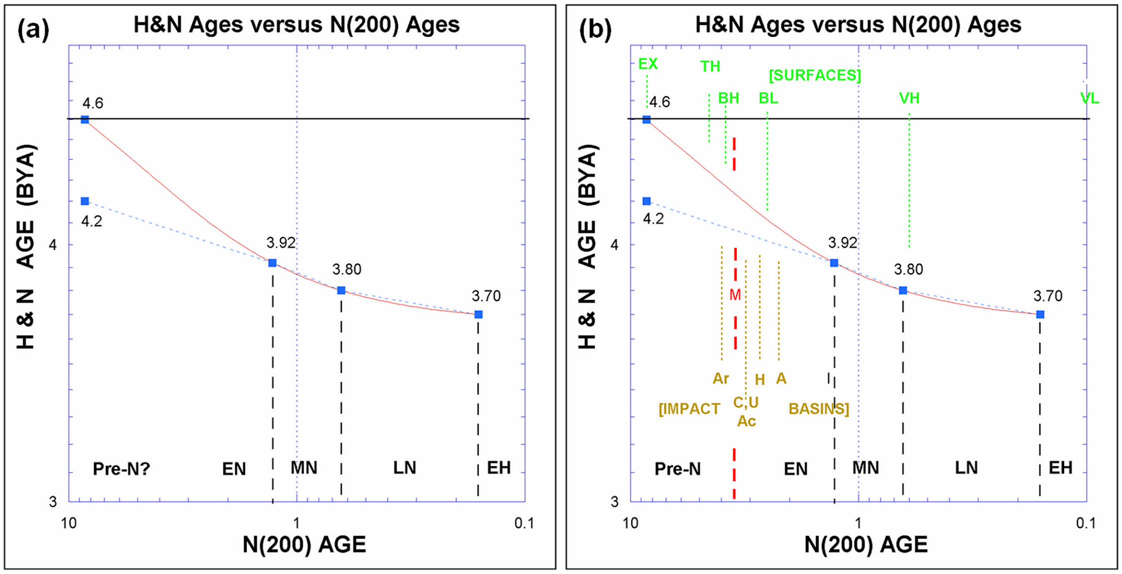


Figure 6. Crater retention ages (CRE) and "absolute ages." (a) Conversion of N(200) crater retention ages to Hartmann-Neukum [*Hartmann and Neukum*, 2001] absolute ages. Hartmann and Neukum have model absolute ages for the major stratigraphic boundaries Early Middle Noachian (EN-MN), Middle-Late Noachian (MN-LN), Late Noachian-Early Hesperian (LN-EH), etc. These are plotted versus N(200) ages derived by extrapolating *Tanaka*'s [1986] counts done at smaller diameters to D = 200 (dashed lines in Figure 5a). No ages are provided for periods earlier than the EN-MN boundary at 3.92 GY. We assume the earliest possible N(200) age we observe (based on a −2 power law extrapolation for the very largest impact basins (D > 1000 km) can range between 4.6 GY (the maximum possible) or 4.2 GY (a linear extrapolation from the EN-MN and MN-LN points. With these curves, any N(200) age (derived from Figures 2 and 4) can be plotted and the corresponding Hartmann-Neukum model absolute age determined, as shown in Figure 6b. Surfaces: TH, total highlands; BH, buried highlands; BL, buried lowlands; VH, visible highlands; VL, visible lowlands. Impact basins: Ar, Ares; C, Chryse; AC, Acidalia; U, Utopia; H, Hellas; A, Argyre; I, Isidis. "M" indicates a possible time for the demise of the global magnetic field.

give a model absolute age for each of these boundaries, so a plot of H-N ages versus N(200) ages can be made (Figure 6a).

[20] However, the buried highlands and total highlands crater retention ages are earlier than even the oldest known Early Noachian surfaces [*Frey and Frey*, 2002; *E. L. Frey et al.*, 2002; *Frey*, 2003b] and probably represent a "pre-Noachian" epoch [*Frey*, 2003b, 2004b; *Tanaka et al.*, 2005]. In addition, there is a much older N(200) age derived by a −2 power law extrapolation of the largest impact basin points in Figure 2b, which may represent the oldest observable crater retention age on Mars, N(200) ∼ 8.5. We consider

Table 2. A Proposed N(200) Timeline for the Early Crustal Evolution of Mars[a]

N(200)	Feature	Event	Epoch	H/N Age
∼0.1	visible lowlands		EH	3.65
0.16	**EH/LN boundary**		**EH/LN**	**3.70**
>∼0.6	visible highlands		LN/MN	>3.79
0.64	**LN/MN boundary**		**LN/MN**	**3.80**
1.28	**MN/EN boundary**		**MN/EN**	**3.92**
>∼1.3	Isidis	impact	EN	>3.92
>∼2.2	Argyre	impact	EN	>4.00–4.07
>∼2.5	buried, total lowlands		EN	>4.04–4.11
>∼2.7	Hellas	impact	EN	>4.05–4.13
>3.0–3.2	Chryse, Utopia, Acidalia	lowlands formed?		>4.08–4.18
∼3.5?		core field dies?		4.10–4.21
>∼3.8	buried highlands		pre-N	>4.11–4.25
>∼4.0	Ares	impact	pre-N	>4.12–4.26
>∼4.5	total highlands		pre-N	>4.14–4.33
∼8.5	**large basin highlands (ext)**	**impacts**	**pre-N**	**4.26–4.60**

[a] Entries in bold are tie points for conversion from N(200) ages to the absolute chronology of Hartmann-Neukum [*Hartmann and Neukum*, 2001] [H/N Age].

two cases for the absolute value for this earliest (large basin) age: a linear extrapolation from the EN/MN and MN/LN points, and the unlikely case that the origin of Mars at 4.6 BYA is the upper limit for preservation of large impact basins. These are shown as two possible endpoints at the left of Figure 6a. With this plot it is then possible to convert any N(200) age to an "absolute" H-N (model) age or to a possible range of ages for Early Noachian or older features. These are shown in Figure 6b and listed in Table 2.

[21] Two important caveats about these model ages must be kept in mind: (1) The H-N timescale is uncertain by probably a factor 2 (W. K. Hartmann, personal communication, 2002). (2) All the buried and total N(200) ages shown are likely to be too low, so all the corresponding H-N ages should be considered minimum model ages. This is because we almost certainly do not see all the buried impact basins bigger than 200 km diameter in the MOLA data. Additional basins likely exist that are so deeply buried that they retain no relic topographic relief.

[22] Table 2 shows the N(200) and model "absolute ages" in billions of Hartmann-Neukum years for major events in Martian history. The corresponding stratigraphic epochs are also shown. For time periods well before the Early Noachian, we use the term "pre-Noachian." We take the dividing line between pre-Noachian and Early Noachian to be the formation of the large lowland-making basins at N(200) about 3–3.2 [see also *Nimmo and Tanaka*, 2005; *Tanaka et al.*, 2005]. The buried highlands are slightly younger (4.11–4.25 GY) than the Ares Basin (4.12–4.26 GY), and distinctly older than the buried lowlands (4.04–4.11 GY). The buried (and total) lowlands are younger than the "lowland-making" basins Utopia, Acidalia and Chryse (4.08–4.18 GY), as they should be. The last of the large impact basins considered here, Isidis, formed at about 3.92 GY, at the Middle Noachian–Early Noachian boundary.

[23] In this model, the lowlands form at ~4.13 ± 0.05 GY or perhaps slightly earlier. We take this to be the age of the formation of the crustal dichotomy, and also the boundary between Early Noachian and "pre-Noachian" time. This is also close to the time when the global magnetic field died, based on which basins do and do not have anomalies within their main rings. It may be that the two events, formation of the fundamental crustal dichotomy and the demise of the global magnetic field, are related. In any event, it appears N(200) ~ 3–3.2 (~4.13 GYA?) was an important time in early Martian history.

7. Discussion

[24] The discovery of buried impact has pushed knowledge about early Mars back to epochs far earlier than we could previously study. There is clear evidence for a cratering history earlier than the oldest visible surface units [*Frey and Frey*, 2002], a "pre-Noachian" [*E. L. Frey et al.*, 2002; *Frey*, 2003b, 2004b, 2005] that, based on Hartmann-Neukum [*Hartmann and Neukum*, 2001] model ages, includes recoverable information hundreds of millions of years prior to that visible at the surface [*Frey*, 2003b, 2004b].

[25] The N(200) relative crater retention ages described in Table 2 provide a self-consistent chronology of major events in early Martian history, even though the model absolute ages must be treated with caution. Although we occasionally use Hartmann-Neukum [*Hartmann and Neukum*, 2001] model ages below for convenience, it must be emphasized that the model ages themselves are uncertain by at least a factor 2 and all are likely too young, because the N(200) ages are minimum ages. Things are likely older than shown in Figure 5 and Table 2.

[26] The oldest age recoverable from the large diameter QCDs is that derived from extrapolation of the cumulative frequency curve for the largest impact basins, which follow a −2 power law trend from 1300 to over 3000 km (Figure 3). This N(200) ~ 8.5 has the most uncertain absolute age (Figure 6). It cannot be older than Mars itself, and probably no younger than about 4.26 GY. This extrapolated N(200) age is significantly greater than the CRA of the total highland population (N(200) ~ 4.5) (Figure 5b, Table 2), perhaps indicating a considerable gap between the (extrapolated) oldest possible CRAs for the largest basins and that for the preserved highlands (an average over the whole of the highlands).

[27] What is not clear is how differences in N(200) ages relate to absolute age differences. It could be argued that the relationship between N(200) and H-N ages (Figure 6) is not likely to be linear in the earliest part of Mars history, when the impact flux was probably declining rapidly. There is still considerable uncertainty about the very earliest time of Martian history, and no guarantee that we have any observable crust dating from just after the origin of the planet. The possibility of saturation in the total population crater densities for ancient highland terrains is suggested by the convergence of their cumulative frequency curves to the same −2 power law slope, following a saturation trend in an incremental frequency plot [*E. L. Frey et al.*, 2002; *Frey*, 2003a]. If true, there may be a wall behind which the earliest part of Martian history is hidden.

[28] A major event (or cluster of events) appears to have occurred at around N(200) = 3.0–3.2 ~4.13 ± 0.05 GY), when three very large impact basins, Utopia, Chryse and Acidalia, formed what are now much of the lowlands of Mars. The impacts actually occurred before this time, as this N(200) age is that determined by superimposed smaller basins. There must have been some period of time between the formation of the basin and the stabilization of that surface. The same, of course, is true for Ares and the other large basins, all of which are likely older than indicated by their N(200) ages (Table 2).

[29] While we cannot rule out that lowlands may have existed before and then been modified by these impacts [e.g., *Nimmo and Tanaka*, 2005; *Kiefer*, 2005], it is clear that lowlands must have been present following them. We take this cluster of "lowland-making" basin impacts to be the latest time when the lowlands, and therefore the fundamental Martian crustal dichotomy, formed [*Frey*, 2002a, 2004b, 2005]. This is very early in Martian history, in the earliest part of the Early Noachian, likely hundreds of millions of years before the formation of the youngest large basins (Hellas, Argyre and Isidis) and the average age of the exposed (visible) Middle-Late Noachian highland crust. This constraint on the time of formation of the lowlands has important implications for the possible origin of the crustal dichotomy, which remains a major controversy. End-member endogenic [*Wise et al.*, 1979; *McGill and Dimitriou*, 1990; *Sleep*, 1994; *Zhong and Zuber*, 2001;

Lenardic et al., 2004; *Roberts and Zhong*, 2004] and exogenic [*Wilhelms and Squyres*, 1984; *Frey and Schultz*, 1988, 1990; *Frey*, 2002, 2005] processes continue to be invoked. There is little direct observational evidence that uniquely supports endogenic processes, and it may be hard to form the lowlands by endogenic processes in the short time available. Most mechanisms suggested [e.g., *Sleep*, 1994; *Zhong and Zuber*, 2001] take many hundreds of millions of years to operate and result in a relatively late formation of the lowlands (Late Noachian-Early Hesperian [e.g., *McGill and Dimitriou*, 1990]). For example, even with a very steep viscosity gradient, *Zhong and Zuber* [2001] required 400 million years to establish the degree-1 mantle convection thought necessary. Still unknown and unmodeled [*Roberts and Zhong*, 2004] is how much longer it takes to reduce the topography in the north by 3–5 km [*Frey et al.*, 1998], presumably by crustal thinning or subcrustal flow. At present there are no quantitative models that demonstrate that the required volume of crust can be lowered by the required amount, in whatever time may be available.

[30] In contrast, the large ''lowland-making'' QCDs (Utopia, Acidalia and Chryse) do account for most of the lowland topography and offer a simple, well-understood, ''instantaneous'' mechanism for the early formation of a topographic dichotomy on Mars by impact [*Frey*, 2003a, 2005]. The preservation of topography indicating that giant impacts did form and can account for much of the existing lowlands means that any endogenic processes were relatively minor players by comparison. The QCD record as well as other considerations [*Solomon et al.*, 2005] strongly suggests that a lowland in the northern third of Mars has been in place since the Earliest Noachian, which favors mechanisms like impacts which operated both early and quickly.

[31] More recently, emphasis has shifted to the possible role of endogenic process in maintaining or modifying the dichotomy, for which there is abundant evidence. Compressional features near the dichotomy [*Watters and Robinson*, 1999] may suggest an endogenic role for boundary modification [*Nimmo*, 2005] rather than origin [*Watters*, 2003a, 2003b], and periods of faulting and resurfacing along portions of the dichotomy boundary, occurring dominantly in the Late Noachian to Early Hesperian, have long been well documented [*Maxwell and McGill*, 1988; *Frey et al.*, 1988]. In the model chronology, this corresponds to a time period of more than 400 million years following the formation of the large lowland-making basins. Post-impact endogenic processes may have played a role here. *Kiefer* [2005] has suggested that buried mass anomalies along the boundary could indicate edge-driven mantle convection controlled by preexisting dichotomy topography, perhaps formed by impact. *Tanaka* [2004] and *Nimmo and Tanaka* [2005] discuss other aspects of dichotomy boundary modification.

[32] The existence of a northern lowland dating from the Earliest Noachian may have provided a topographic sink for the formation of an Early Noachian ocean [*Clifford and Parker*, 2001] and for deposition of the large amounts of western Arabian crust that was apparently stripped and removed, probably by fluvial processes [*Hynek and Phillips*, 2001].

[33] Even after the lowlands were established, large impacts continued to occur, producing the well-recognized Hellas, Argyre and Isidis basins. The global magnetic field may have been gone by this time [*Acuna et al.*, 1999; *Nimmo and Gilmore*, 2001; *Hood et al.*, 2003; *Langlais et al.*, 2004] which would have aided the erosion of the atmosphere. Depending on how long it might take for such a global magnetic field to disappear completely, it is interesting to consider whether the demise of the field is in fact linked to the formation of the three large lowland-making basins. Could the formation of the lowlands by large-scale impact in some way have triggered the demise of the global magnetic field, perhaps by disturbing deep-seated convection and heat loss, which in turn reduced the effectiveness of the core dynamo?

[34] Tharsis was likely growing at this time, having its origin in the early Noachian [*Anderson et al.*, 2001] and having established an early imprint that affected later tectonic and erosional processes [*Phillips et al.*, 2001]. Volcanism associated with this likely provided some compensation for atmospheric loss, increased greenhouse effect, and perhaps creations of a more hospitable climate. *Solomon et al.* [2005] and *Nimmo and Tanaka* [2005] discuss aspects of this based in part on the information provided here.

8. Conclusions

[35] Large diameter visible and buried impact basins, seen as ''quasi-circular depressions'' (QCDs) in MOLA gridded data, provide a self-consistent chronology for major events on early Mars in terms of N(200) crater retention ages. These push back the recoverable part of Martian history by hundreds of millions of years, to an earlier ''pre-Noachian'' epoch not previously recognized, in which the oldest surfaces and giant impact basins formed. The large-diameter crater retention ages provide constraints on the relative age of the largest impact basins, when the lowlands formed, and when the global magnetic field died.

[36] The scenario that emerges for early Mars is as follows: By the time of the Hellas impact (earliest Early Noachian, 4.09 ± 0.04 GY in the model chronology discussed here), the lowlands had already formed because several very large impacts (Utopia, Chryse, Acidalia, perhaps others) had occurred at least 40 million (or more) years before. A crustal dichotomy and dichotomy boundary were already in place, though the total relief between highlands and lowlands may have been different, perhaps somewhat greater than we see today (assuming continuing relaxation and erosion of the boundary, later filling of the lowlands). The lowlands were raw and rough, with a small number of superimposed impacts and perhaps some early sediments, but most of what constitutes the lowland plains today had yet to fill the newly formed, still cooling and relaxing basins. The highlands were already heavily cratered by as much as half a billion years of impact bombardment, including the formation of a couple of very large basins (Ares, Daedalia) that had formed by 4.19 GY, at least 60 million years (and possibly much more) before the lowland-making (Utopia-Chryse-Acidalia) combination. The craters in the highlands were being buried, in part by ejecta from the formation of the northern lowland-making

basins and continued intense bombardment by a very large but diminishing number smaller basin-making objects.

[37] The large lowland which existed in the northern part of Mars and was, by the time of Hellas formation, perhaps already filled or filling with water and sediments transported from the highlands. However, the magnetic field was gone, the dynamo having shut off perhaps 40 (or more) million years earlier (at about the time of impact formation of the lowlands). The loss of the global magnetic field would increase the loss of atmosphere, already diminished by the effects of large impacts like Hellas itself, catastrophes that would be repeated at least twice more when Argyre and Isidis formed 45 and 60 million years in the future. Tharsis, which likely originated in the Early Noachian, was growing but had not yet reached the enormous extent and elevation we see today, and the major Tharsis shield volcanoes had not yet formed. Tharsis growth buried a portion of the older dichotomy boundary in western Mars, and flexed the slowly thickening lithosphere in ways that affected later fluvial drainage. Though the largest shields were not yet apparent, volcanism was extensive, pumping up an impact and solar wind diminished atmosphere with greenhouse gases, producing an environment in which erosion and surface modification were extensive and effective. This was the environment and setting for the subsequent evolution of Mars, that part recorded in its exposed surface, dating from the Early Noachian to the present.

[38] **Acknowledgments.** We thank the organizers of the International Conference of Early Mars for the opportunity to present these ideas at that meeting. Thanks also are owed to two reviewers who provided suggestions for significant improvement in the manuscript, and to James H. Roark for his assistance with the production of the figures for this paper.

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