EARLY MARS REVISITED BY NEW GLOBAL GEOLOGIC MAPPING AND CRATER COUNTING.

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Introduction: Our new geologic map of Mars at 1:20M scale represents the most thorough characterization of global stratigraphic units since the Viking-based 1:15M-scale maps [1]. The mapping is primarily based on a Mars Orbiter Laser Altimeter (MOLA) digital elevation model at 463 m/pixel spatial resolution and Thermal Emission Imaging System (THEMIS) infrared images at 100 m/pixel. The mapping is stored as a geographic information system (GIS) geodatabase permitting spatial queries of map units and features with other data sets. In addition, our global and local detailed inventories of crater locations and diameters permit us to date outcrops and units more thoroughly and accurately than previously possible. Here, we reassess the earliest geologic evolution of Mars, noting degrees and styles of resurfacing and other surface modification.

Stratigraphy: Geologic units are discriminated by age (noted in the unit symbol by epoch or period(s); e.g., Early Noachian is indicated by eN), geographic setting, and morphogenetic attributes. Major geographic categories for earliest rocks include highland (h), lowland (l), basin (b), transition (t), and polar (p). Morphogenetic units consist of volcanic (v), edifice (e), and undivided (u; layered, and thus undivided as stratigraphic sequences).

The ages of the map units and larger outcrops are determined by superposition relations and local, precise crater counts, as well as outcrop intersections with a new global database of craters >1 km diameter [2]. The latter approach, using a specially crafted version of the map in which impact crater unit outcrops have been removed, enables counts to be determined digitally for every outcrop. However, the crater data need to be carefully scrutinized, because some surfaces have been significantly modified to the extent that smaller craters have been obliterated and/or the size of the crater sample is too small for adequate statistical accuracy. We have addressed the amount of resurfacing implied by crater rim obliteration by noting the minimum diameters at which craters appear fully preserved assuming that their size-frequency distributions are in accord with the Ivanov production function [3] for several representative surfaces for each of the most ancient Martian epochs (Table 1). These data confirm that older surfaces tend to be increasingly degraded (see also [4]) and that cumulative crater density intercepts for relatively better-preserved surfaces assigned to date them by [5-6] for the most part can yield reliable ages. In two cases, Early Noachian surfaces have noticeably deficient numbers of craters larger than the epoch-defining diameter (16 km), indicating that erosion reached a few hundred meters (Table 1); one site is the extremely rugged, mountainous eastern rim of Hellas basin and the other is a faulted plateau within Noachis Terra northwest of Hellas basin.

Table 1. Minimum non-obliterated crater diameter ranges and estimated resurfacing thicknesses based on diameter-rim height relationships [2] for selected Noachian and Early Hesperian sites.

Epoch (and crater density boundary diameter(s) (km))	*No. sites*	*Min. crater diam, (km)*	*Resurfacing thickness (m)*
Early Hesperian (5)	6	2 to 4	27-67
Late Noachian (5, 16)	5	1.1 to 5	12-89
Middle Noachian (16)	8	3 to 14	46-218
Early Noachian (16)	4	5 to 30	89-407

Table 2. Mean crater densities for largely Noachian to Early Hesperian units (age indicated by first one or two letters in symbol), where N(x) = no. craters > x km diameter/10^6km^2.

Unit symbol	*Area (10^6 km^2)*	*N(5)*	*N(16)*
eHb	0.42	187±21	38±9
eHh	1.91	186±10	34±4
eHt	3.94	238±8	50±4
eHv	6.28	247±6	74±3
lNh	9.42	389±6	118±4
lNv	2.53	257±10	73±5
mNh	32.79	587±4	180±2
eNh	16.80	650±6	239±4
eNb	3.98	529±12	181±7
HNt	3.11	325±10	99±6
HNb (lN to eH)	0.65	203±18	53±9
ANa	0.29	219±27	55±14
Nhu	2.63	239±10	66±5
Nve	0.16	351±47	38±15
Nhe	0.21	723±59	182±30

Hesperian and Amazonian units in particular tend to be insufficiently thick to completely bury larger craters and their rims on underlying surfaces. Other circular depressions likely form due to collapse or deformation above buried crater rims. In these cases, the buried craters predate the surface unit and thus must be removed from the crater count to obtain an accurate age of the unit. This explains why N(5) densities tend to be high for Early Hesperian units (Table 2) vs. assigned density values (Table 3), whereas in the Early and Middle Noachian, N(5) values tend to be low due to obliteration.

Table 3. Epoch crater density, N(x), and age boundaries based on Ivanov (Iv) and Hartmann (Ha) chronology size-frequency distributions [5].

Boundary	*Iv age (Ga)*	*Iv N(5),* ***N(16)***	*Ha age (Ga)*	*Ha N(5),* ***N(16)***
eH/lN	3.74	200, **51**	3.57	200, **25**
lN/mN	3.86	391, **100**	3.85	787, **100**
mN/eN	3.97	782, **200**	3.96	1575, **200**

New Understanding: Here, we highlight how our new global geologic mapping and crater counting results change the understanding of the early history of Mars as documented in past geologic maps.

Noachian and Early Hesperian surface extents. When we estimate the total amount of surface area by epoch, we note that the eN accounts for about 3.7 times more area than was recognized before in the Viking-based mapping (Table 4). The MOLA topographic data enables us to recognize areas of relatively high relief away from basin rims having high crater density and surrounded by lower-relief, less densely cratered surfaces. Although the proportion of mN remains the same, much of the previously mapped 'mN' is now shown as eN. The eN materials appear to be made up of relatively well-indurated materials based on their preserved relief, perhaps dominated by igneous rocks and impact ejecta.

Table 4. Surface coverage by age

Epoch/ Period	*Area (10^6 km^2)*	*Area (%), this study*	*Area (%), Viking [7]*
eH	16.5	11.5	15.7
lN	13.6	9.4	11.7
mN	34.5	23.9	24.0
eN	22.5	15.6	4.2
N total	70.6	48.9	39.9

Note: Areas include evenly divided portions of units that span more than one epoch; some such units are not represented in Table 2.

Much of the new mN includes former 'lN' and 'eH' ridged plains surfaces that have mN crater densities, although they may display somewhat lower relief and more prominent wrinkle ridges than other mN surfaces. The mNh unit likely includes significant amounts of impact ejecta and mass-wasted and other sedimentary materials. Malea Planum is a large area now mapped as lN, previously identified as 'eH'. Many lN outcrops form intracrater plains fill that appears to consist of fluvial and lacustrine deposits originating by runoff erosion of older, surrounding surfaces, as well as some likely volcanic flows and deposits. Also, a few surfaces previously regarded as lH to eA are now categorized as eH. Overall, there is a net shift in units to older Mars.

Volcanic edifices and flows. Eight recognizable volcanic edifices approaching and exceeding 100 km across date back to the N (unit Nve) and have a mean lN crater age. The majority of N edifices occur peripheral to southern Tharsis and south and northeast of Hellas basin. Twenty of 22 denuded N mountains (unit Nhe) occur south of 30° S. (and mostly peripheral to Tharsis) and may also be volcanic, though lava flows or caldera structures are not observed. These absences may be due to greater denudation at higher latitudes (where mass-wasting may occur at higher rates) as well as their greater mean mN age.

Volcanic flow morphologies are susceptible to obliteration by impact gardening, and the earliest recognizable flows on Mars are lN. Earlier flows likely exist but are difficult to identify. Large shields and widespread lava plains are not evident until the Hesperian (although some N lava sequences may be buried), but the extensive Malea Planum on the south margin of Hellas may be an extensive pyroclastic deposit.

Impact basins: Large impact basins formed in the eN, of which Hellas, Argyre, and Isidis preserve rugged massifs that form their rims and perhaps high-standing ejecta deposits. Linear and arcuate scarps and troughs hundreds of kilometers long and several hundred meters in relief concentric to parts of the rims of Hellas, Argyre, and Isidis basins occur in and/or bound eN outcrops. N basins and craters are degraded and variously infilled with slope debris, fluvial/lacustrine and eolian sediments, and volcanic flows.

Other ancient structures: The southern cratered highlands comprise numerous large-scale topographic features and irregular basins, many of which appear to be structurally controlled and not necessarily tied to impacts, Tharsis development, or global contraction. They largely formed during the eN and mN and were modified by subsequent erosion and sedimentary fill. More work is required to determine whether these features may be spatially or temporally associated with magnetic or gravity anomalies or other crustal signatures.

References: [1] Scott D.H. et al. (1986-87) *USGS Maps I-1802-A-C*. [2] Robbins S.J. (2011) PhD Thesis, CU-Boulder. [3] Ivanov B.A. (2001) *Space Sci. Rev., 96*, 87-104. [4] Robbins S.J. and Hynek B.M. (2012) *LPS 43,* Abs. #1649. [5] Tanaka K.L. (1986) *JGR, 91*, E139-E158. [6] Werner S. and Tanaka K. (2011) *Icarus, 215*, 603-607. [7] Tanaka K.L. et al. (1988) *LPS, Proceedings, 18,* 665-678.