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Distribution of rocks on the Gusev Plains and on Husband Hill, Mars

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[1] The population of rocks larger than 15 cm in diameter was measured at 36 locations imaged by the Spirit rover over ∼ 4 km of the traverse across the Gusev plains and Husband Hill in Gusev crater on Mars. The rock population observed on plains surfaces is consistent with impact fragmentation of rubbly/fractured volcanics and reveals little evidence for modification by secondary processes or weathering. Interpretation of counts from Husband Hill suggest an influence by bedrock for rocks larger than 0.5 m across, but the distribution of smaller rocks is consistent with ejecta possessing contributions from pre-plains impact events. Results indicate plains surfaces experienced only tens of centimeters of eolian erosion/deposition since the Hesperian, whereas meters rather than tens of meters of erosion modified Husband Hill since the early Hesperian. **Citation:** Grant, J. A., S. A. Wilson, S. W. Ruff, M. P. Golombek, and D. L. Koestler (2006), Distribution of rocks on the Gusev Plains and on Husband Hill, Mars, *Geophys. Res. Lett.*, *33*, L16202, doi:10.1029/2006GL026964.

1. Introduction

[2] The population of rocks on a geologic surface records information about the processes responsible for its evolution [e.g., *Malin*, 1988; *Bulmer et al.*, 2005]. Primary rock populations, such as those evolved on impact [*Melosh*, 1989] and volcanic landscapes [*Anderson et al.*, 1998; *Bulmer et al.*, 2005], are often modified (e.g., sorted) by weathering and/or secondary geomorphic processes [*Malin*, 1988], and these effects can be measured [*Bulmer et al.*, 2005] to constrain processes affecting a surface.

[3] Gusev crater was selected as the landing site for the Spirit rover with the intention of sampling sedimentary deposits emplaced during discharge from Ma'adim Vallis, which breaches the southern rim of the crater [*Cabrol et al.*, 1996, 1998a, 1998b; *Kuzmin et al.*, 2000; *Irwin et al.*, 2002; *Golombek et al.*, 2003a; *Grant et al.*, 2004]. The surface traversed by the Spirit rover after landing (14.5692°S, 175.4729°E), however, is characterized by impact-modified volcanic plains of late Hesperian age [*Milam et al.*, 2003; *Squyres et al.*, 2004; *Grant et al.*, 2004; *McSween et al.*, 2004; *Crumpler et al.*, 2005; *Golombek et al.*, 2006] and Husband Hill to the southeast that is older than the surrounding plains (at least early Hesperian [*Kuzmin et al.*, 2000, *Greeley et al.*, 2005], but perhaps Noachian) and of uncertain origin [*Squyres et al.*, 2006; *Arvidson et al.*, 2006]. We examined the rock population of the surfaces at regular intervals along the traverse of the Spirit rover (Figure 1) to determine whether there was any significant variability among presumably different geomorphic surfaces that might reflect a fluvial/alluvial contribution to the impact-derived blocks and/or modification by weathering or alternate geomorphic processes.

2. Measuring the Rock Population

[4] The rock population was characterized by measuring the maximum visible axis of all rocks larger than 15 cm at 36 locations, including 27 across the plains and 9 on Husband Hill (Figure 1). Counts completed on the plains were grouped into the following geomorphic surfaces: 1) crater rims (within 0.5 crater radius of a crater rim crest), 2) crater ejecta (near a crater rim to approximately 1 crater diameter from a rim crest), and 3) plains (located more than a crater diameter from the nearest impact structure larger than 30–40 m). These boundaries become blurred in some locations because the look direction of the images used for the counts was sometimes biased towards or away from a particular surface and three of the counts were made at locations where images incorporate multiple viewing directions (Figure 1). In addition, crater rims encompass large craters whose preservation state ranges from relatively pristine (e.g., Bonneville crater) to degraded (e.g., Missoula crater) [*Grant et al.*, 2006].

[5] Rock populations were measured using Pancam images collected at the end of rover drives and the majority of these images were taken looking toward the southeast (Figure 1). Images covered an average azimuth wedge of 45 degrees and only rocks from 8 m up to 20 m from the rover were considered, typically resulting in areas covered by the rock counts of 80 to 100 m^2 (Table 1). Rocks closer than 8 m were often not covered in the images and waning confidence in the ability to accurately resolve rocks beyond 20 m led to their exclusion. To minimize error, the dimension of individual rocks was measured across the face visible at a constant distance from the rover. Some individual rocks and entire scenes were measured multiple times by more than one person and produced comparable results, thereby providing confidence in the methods employed as well as the validity and reproducibility of the results.

3. Rock Population Characteristics

[6] The size frequency distribution of rocks counted on crater rims, crater ejecta, and plains are fairly similar and largely independent of proximity to most craters larger than 100 m in diameter (Figure 2). In general, there are more rocks near crater rims, fewer on the plains, and fewest

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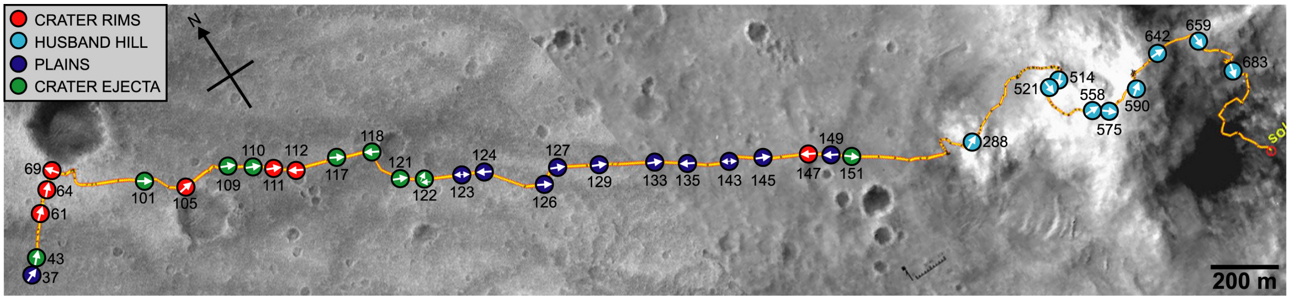

Figure 1. Map (on MOC image base) of the Spirit Rover traverse from the landing site to the rim of Bonneville crater and across the plains to Husband Hill. Rock populations were measured at the 36 locations denoted by circles that correspond to assigned geomorphic surfaces (Table 1). Populations were measured using "end of drive" Pancam images and the average look direction of the images is denoted by arrows within each circle.

exposed on crater ejecta. Nevertheless, the distribution of rocks on these surfaces show an exponential increase in number with decreasing size (Figure 2a), consistent with what has been observed elsewhere on Mars [*Golombek and Rapp*, 1997], and with a distribution commonly associated with single and multiple fragmentation processes during impact cratering events [*Melosh*, 1989; *Grant et al.*, 2006]. The size distribution of rocks on Husband Hill is similar to the other three surfaces at diameters less than ~0.5 m, but has relatively more rocks at larger diameters (Figure 2a).

[7] Data for individual counts of the rock population on a local geomorphic surface are similar to the cumulative population for that geomorphic surface, thereby implying they are representative of the total populations. The average axis of the measured rocks on all surfaces varies between 22 and 29 cm with associated standard deviations of 8 to18 cm (Figure 3). The average number of rocks larger than 15 cm per square meter was slightly more variable, ranging between 0.20 on the crater ejecta to 0.30–0.35 on the plains and on Husband Hill to just over 0.5 for counts along crater rims. The sizes of the largest measured rocks show the greatest variation in the cumulative counts and range from 0.8 m on crater ejecta and plains to close to 2.0 m around crater rims and on Husband Hill (Figure 3). On all surfaces investigated, an increase in average rock size is accompanied by an increase in standard deviation (Figure 3), suggesting that the presence of larger rocks is not accompanied by a paucity of smaller ones (for rocks larger than 15 cm).

4. Discussion

[8] Broad similarities in the populations of rocks on what were presumably different geomorphic surfaces (Figures 2 and 3) encountered by the rover on its traverse across the floor of Gusev crater reflect the dominant role of impact fragmentation in modifying the basaltic surface [*Squyres et al.*, 2004; *Grant et al.*, 2004, 2006; *Crumpler et al.*, 2005; *Golombek et al.*, 2006]. This statement is consistent with the occurrence of abundant small craters across these surfaces and ranging in size from less than 1 m to more than 200 m in diameter [*Crumpler et al.*, 2005; *Grant et al.*, 2006; *Golombek et al.*, 2006]. Cubing the diameter of rock sizes comprising the rock size-frequency distribution curves and using a density of 3000 kg/m^3 for basalt [*Johnson and Olhoeft*, 1984] serves as a proxy for rock mass [e.g., *Grant et al.*, 2006] and enables comparison to the rock distribution associated with fragmentation processes [*Melosh*, 1989]. A plot of derived rock mass versus cumulative number of rocks yields slopes of 0.9 up to 1.2 (Figure 2b) for rocks on crater rims and plains and ejecta surfaces, respectively, that are broadly consistent with multiple fragmentation processes [*Melosh*, 1989; *Grant et al.*, 2006]. Elevated crater rims often expose more numerous and larger rocks [*Melosh*, 1989], but the relatively higher derived slopes for the distributions measured on crater ejecta and plains may be the result of local drift accumulations that bury some rocks and/or the presence of an initially rubbly or fractured substrate.

[9] Eolian processes influence the observed rock populations to some degree as drift accumulations locally bury rocks on some surfaces while deflation exhumes rocks on others. Drift deposits were frequently observed along the rover traverse (Figure 4a) and reflect the redistribution of tens of centimeters of fine-grained sediments by the wind [*Grant et al.*, 2004; *Greeley et al.*, 2004; *Golombek et al.*, 2006]. Local deposition of as little as 20–30 cm eolian drift along crater rims can bury many smaller rocks and partially bury larger ones, effectively decreasing the apparent number of rocks (Figure 4a). Increased roughness associated with

Table 1. Summary Characteristics of Rock Populations on Different Geomorphic Surfaces

Geomorphic Surface	Sols Considered[a]	Total Number of Rocks Measured (>15 cm)	Average Rocks/m^2	Counts Completed in Azimuth Wedge 0–90°	90–180°	180–270°	270–360°
Crater Rims	7	317	0.50	3	1	0	3
Plains	11	519	0.33	2	6	0	5
Crater Ejecta	9	263	0.22	1	6	0	2
Husband Hill	9	334	0.31	3	4	2	0

[a]Refers to the number of scenes examined.

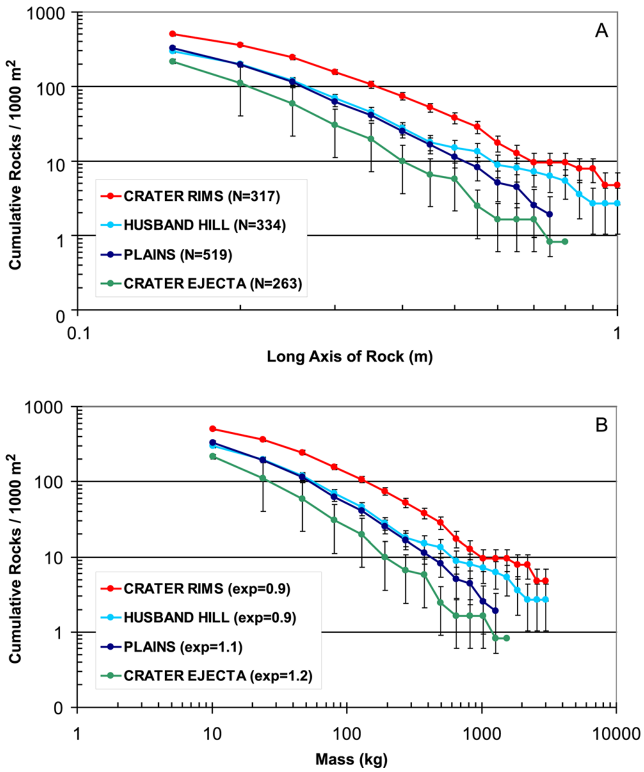

Figure 2. (a) Cumulative distribution of rock sizes (larger than 15 cm) for crater rims, crater ejecta, plains, and Husband Hill. (b) Cubing the rock diameters and multiplying by an assumed density of 3000 kg/m^3 [*Johnson and Olhoeft*, 1984] as a proxy for rock mass yields populations whose slopes range from 0.9 to 1.2, which is broadly consistent with multiple fragmentation processes [*Melosh*, 1989]. Distributions incorporate the effects of tens of centimeters of eolian deposition and/or deflation of initially rubbly or fractured volcanic substrates across the plains that may influence the population of smaller rocks. Error bars represent ± square root of the number of craters in each bin.

the low-relief ejecta surrounding newly formed craters may lead to more efficient trapping of eolian sediments [*Greeley et al.*, 2006] that bury more rocks, creating the appearance of fewer larger rocks on these surfaces. By contrast, local deflation and exhumation of as little as 20–30 cm on the plains can expose more, larger rocks than might be expected (Figure 4b). Hence, the population of rocks on some crater rims can appear similar to that exposed on locally stripped plains and locally buried ejecta can appear similar to average plains surfaces (Figure 4).

[10] The population of rocks larger than 15 cm on all plains surfaces is a good match with what is expected from impact fragmentation [*Melosh*, 1989] and is consistent with the widespread occurrence of numerous small craters. There is an absence of a mode or other characteristic associated with the population that could represent sorting by alternate processes and demonstrates that the measured rock population is little modified by contributions from alternate primary or secondary processes. These results indicate little geomorphic modification beyond minor eolian redistribution of fine sediments by non-impact processes subsequent to the formation of the Hesperian-aged volcanic surface.

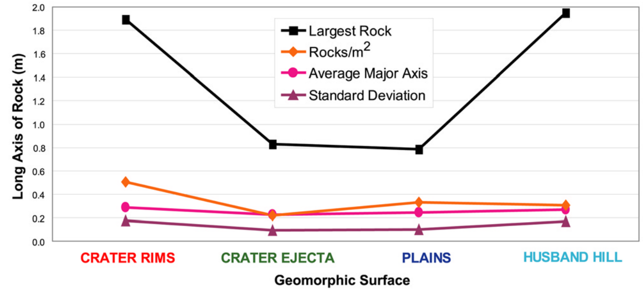

Figure 3. Summary of the largest rock, average major axis for the rocks, standard deviation, and number of rocks per square meter for each geomorphic surface.

[11] The conclusion that there has been little modification of plains surfaces is consistent with previous work elsewhere on Mars and highlights the predominant role of impacts relative to alternate geomorphic processes in shaping rock populations on many surfaces since the Hesperian [*Golombek et al.*, 2003b; *Golombek and Rapp*, 1997]. What little modification has occurred can be accounted for by eolian redistribution of fines and suggests the occurrence of only tens of centimeters of erosion/deposition of the impact fragmented volcanic plains surfaces [*Grant et al.*, 2004; *Greeley et al.*, 2004; *Crumpler et al.*, 2005; *Golombek et al.*, 2006].

[12] On Husband Hill, the overall size-frequency, average rock size, standard deviation, and number of rocks per square meter are fairly comparable to surfaces on the plains, highlighting the importance of impact processes in creating

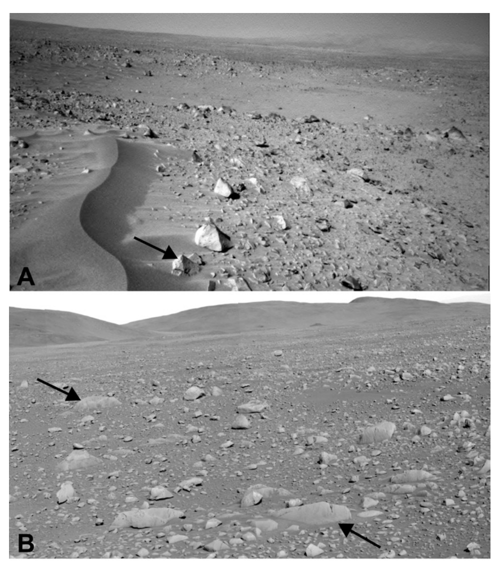

Figure 4. (a) Local accumulation of eolian drift can bury some rocks as in this Navcam view of Lahontan crater (D = 90 m, 4.5 m deep). For scale, the arrow denotes a ~0.2 m rock. Navcam image 2N137028119FFL4100P1827L. (b) Local deflation can expose more, larger rocks (arrows denote 0.65 m and 1 m rocks in the foreground and background, respectively). Eolian redistribution of sediments helps account for similarities in rock populations on crater rims (Figure 4a), crater ejecta, and plains (Figure 4b). Pancam image 2PP126IOF47CYL00P2425L777C1.

the rocks on the Hill. Similarly, when rock sizes on the Hill are adjusted as a proxy for mass, the slope of the resultant curve is 0.9 (Figure 2b), consistent with a population derived via multiple fragmentation events [*Melosh*, 1989]. Like rocks on the plains surfaces, rocks on Husband Hill do not show any evidence of sorting or significant reworking by non-impact processes.

[13] There are subtle differences, however, between the population of rocks on Husband Hill and those on plains surfaces. For example, rocks on the Hill between 0.15 and ~0.5 m across possess a similar distribution to what is observed on the plains, crater rims, and crater ejecta (Figure 2a), as confirmed by plotting the population of that size range. By contrast, there is a slightly greater abundance of rocks larger than ~0.5 m as compared to the plains surfaces (Figure 2a). In contrast to the plains, there are a number of bedrock exposures on Husband Hill that likely account for the increased abundance of larger rocks relative to plains surfaces. Visual inspection of hill surfaces confirms that the largest measured rocks are typically associated with outcrop and indicates most surfaces are mantled by only meters of regolith or less.

[14] Although the rocks on Husband Hill are most consistent with a population dominated by impact fragmentation of local outcrop [*Melosh*, 1989], these rocks are often scattered unevenly across the surface. Some rocks may be buried by eolian drift that is most abundant in topographic alcoves, the lee of outcrops, and on some low relief surfaces. Further, the absence of a thick regolith on Husband Hill, confirmed by numerous bedrock outcroppings, suggests it is possible that gravity-driven slope processes stripped some surfaces of rocks and increased the number of impact fragmented rocks buried by drift within topographic alcoves and elsewhere. The persistence of a rock population characteristic of impact fragmentation coupled with the compositional variety of these rocks, however, suggests that such processes account for not more than meters of modification of Husband Hill's form since before the surrounding plains were emplaced.

[15] The composition of rocks smaller than ~0.5 m on the surfaces of Husband Hill is variable relative to the plains and provides further insight into the amount of erosion occurring over time. As noted, the collective size-frequency distribution of these rocks is most consistent with origin by impact fragmentation and surfaces of the Hill are marked by craters [*Haldeman et al.*, 2006], providing evidence for numerous impacts. The Miniature Thermal Emission Spectrometer (Mini-TES) observed dozens of small rocks on Husband Hill contributing to this population and most are compositionally distinct from visited outcrops (S. W. Ruff et al., The rocks of Gusev crater as viewed by the Mini-TES instrument, submitted to *Journal of Geophysical Research*, 2006, hereinafter referred to as Ruff et al., submitted manuscript, 2006). Some of these rocks (e.g., Adirondack Class exotics) are spectrally equivalent to the basaltic rocks on the plains (Ruff et al., submitted manuscript, 2006) and were likely ballistically emplaced on Husband Hill as ejecta following impact events on the plains. Other rocks (e.g., Backstay and Irvine Class exotics) are found only on Husband Hill and probably represent impact ejecta (although a local origin from dikes or shallow intrusions not visited by the rover cannot be ruled out) [*Squyres et al.*, 2006; Ruff et al., submitted manuscript, 2006]. Ninety-five examples of Wishstone Class rocks are found on Husband Hill, but are not associated with any known outcrop and are compositionally distinct from the plains rocks (Ruff et al., submitted manuscript, 2006).

[16] Because these rocks or exotics contribute to a population of rocks that are almost certainly the result of impact fragmentation and because only the Adirondack Class rocks were detected on the plains, they are likely ejecta materials that are older than the plains rocks. If they are ejecta derived from a large crater tens of kilometers from the landing site that post dates the plains or are from a crater excavating through the plains into underlying materials, then the "exotics" should be observed on the plains. Mini-TES observations on the plains of several hundred rocks, however, show no such examples. Therefore, survival of these exotics as likely remnants of ejecta that predates the plains helps place limits on the erosional modification of Husband Hill since they were emplaced.

[17] The nearest exposed large pre-plains crater to Husband Hill is the partially filled ~23 km-diameter Thira located approximately 20 km to the east-northeast. If Thira postdates the Hills, the expected thickness of ejecta at the range of Husband Hill can be calculated [*McGetchin et al.*, 1973] and is less than 5 m. Surfaces surrounding Gusev crater are early to middle Noachian in age [*Greeley and Guest*, 1987] and may predate the Columbia Hills, but are too distant to have emplaced significant ejecta at Husband Hill. Further, there is no hint of a partially buried crater approaching the size of Thira that predates the plains but is closer to Husband Hill. Hence, it is unlikely that a thick mantle of ejecta (tens of meters) was ever emplaced on the Hills. The absence of thick accumulations of debris flanking Husband Hill and a rock population that reflects the effects of impact fragmentation and little else supports this statement.

[18] Survival of Adirondack Class exotics on Husband Hill indicates minimal erosion has occurred since the plains source rocks were emplaced in the late Hesperian. Moreover, the persistence of some pre-plains ejecta on the Hill pushes the period of low erosion even farther back in time. Although the age of Husband Hill is poorly constrained, the Columbia Hills predate the late Hesperian-aged plains estimated at 3.5 Ga [*Kuzmin et al.*, 2000; *Milam et al.*, 2003; *Greeley et al.*, 2005; *Crumpler et al.*, 2005] and limits erosion occurring since the early Hesperian (~3.6 Ga) and perhaps even the late Noachian to no more than meters. Hence, Husband Hill retains an overall form that is little changed over much of Mars history, pushing the cessation of significant geomorphic activity in Gusev farther back in time, consistent with results from other locations on Mars [e.g., *Grant and Schultz*, 1990, 1993; *Bibring et al.*, 2006]. Our results highlight the importance of impact processes in shaping many surfaces since the early Hesperian (M. P. Golombek et al. Climate change from the Mars Exploration Rover landing sites: From wet in the Noachian to dry and desiccating since the Hesperian, submitted to *Journal of Geophysical Research*, 2006).

[19] The presence of only meters of regolith across much of Husband Hill is counterintuitive considering the younger, surrounding plains [*Crumpler et al.*, 2005; *Arvidson et al.*, 2006] are comprised of harder rocks [*McSween et al.*, 2004;

Arvidson et al., 2006], and were described as being capped by more than 10 meters of unconsolidated debris [*Grant et al.*, 2004; *Golombek et al.*, 2006]. The apparently thicker regolith on the plains, however, likely reflects the occurrence of an initially rubbly and/or fractured substrate, which is commonly associated with primary volcanic surfaces [*MacDonald*, 1972]. Impact fragmentation and mixing of volcanic rubble is consistent with the higher slopes associated with the derived rock mass frequency distribution for rocks on the ejecta and plains units (Figure 2b). Lower mass distribution slopes for the crater rim rocks imply multiple fragmentations of less rubbly materials. The craters larger than 30–40 m in diameter included in the crater rim unit should have sampled rocks to depths exceeding 10 m and may have excavated beneath the rubble into fractured bedrock. If correct, the thickness of regolith on the plains produced by impact may be only meters thick in places [*Grant et al.*, 2004], more consistent with what is observed on Husband Hill.

5. Conclusions

[20] The population of rocks on surfaces visited by the Spirit rover during its traverse across the volcanic plains and Husband Hill in Gusev crater reflects the cumulative effects of impact cratering and associated emplacement as ejecta over much of Martian history. There is minimal evidence for contributions to the measured rock populations by alternate geomorphic processes or by weathering. Minor differences between local plains surfaces can be accounted for by variable erosion and deposition of tens of centimeters of eolian drift while the steeper slopes associated with derived rock-mass distributions for plains and ejecta units may reflect the influence of an initially rubbly surface rather than the occurrence of a thick (>10 m) impact-derived regolith. Collectively, results imply little modification of plains surfaces since the Hesperian other than by impact gardening.

[21] The population of rocks on the surface of Husband Hill is also dominantly the result of impact and retains ejecta contributed from pre-plains impact events. Regolith on Husband Hill is up to meters in thickness and drapes local outcrop. Like the plains, the population of these rocks is slightly modified by eolian and perhaps slope processes. Persistence of some pre-plains ejecta, however, limits erosional modification of the Hill to only meters since at least the early Hesperian and perhaps even the Noachian. Hence, the surfaces explored on the floor of Gusev crater have remained remarkably unchanged over much of Martian history and highlights the early cessation of significant geomorphic activity in at least one location on Mars during the relatively early history of the planet.

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