Constraints on the origin and evolution of the layered mound in Gale Crater, Mars using Mars Reconnaissance Orbiter data

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A R T I C L E   I N F O

Keywords:
Mars, Surface
Geological processes
Cratering
Infrared observations

A B S T R A C T

Gale Crater contains a 5.2 km-high central mound of layered material that is largely sedimentary in origin and has been considered as a potential landing site for both the MER (Mars Exploration Rover) and MSL (Mars Science Laboratory) missions. We have analyzed recent data from Mars Reconnaissance Orbiter to help unravel the complex geologic history evidenced by these layered deposits and other landforms in the crater. Results from imaging data from the High Resolution Imaging Science Experiment (HiRISE) and Context Camera (CTX) confirm geomorphic evidence for fluvial activity and may indicate an early lacustrine phase. Analysis of spectral data from the CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) instrument shows clay-bearing units interstratified with sulfate-bearing strata in the lower member of the layered mound, again indicative of aqueous activity. The formation age of the layered mound, derived from crater counts and superposition relationships, is 3.6–3.8 Ga and straddles the Noachian–Hesperian time-stratigraphic boundary. Thus Gale provides a unique opportunity to investigate global environmental change on Mars during a period of transition from an environment that favored phyllosilicate deposition to a later one that was dominated by sulfate formation.

1. Introduction

Layered sedimentary sequences with repetitious bedding are of particular interest in planetary exploration because they constitute one of the key differences between bodies that possess an atmosphere or hydrosphere and those that lack them. Specifically, these types of sedimentary deposits require suitable transport media such as wind or liquid water to form. Thick, laterally extensive sedimentary sequences with finely stratified materials may require an extended period of time for formation, particularly if sediment flux and accumulation rates were low during deposition. Therefore, such thick sequences have the potential to capture secular, episodic, or cyclical environmental changes that may have occurred in their depositional settings. The overall objective in studying such deposits is to determine (or more broadly, place constraints upon) the environmental conditions that prevailed when the sediments were laid down.

Gale Crater hosts a sequence of layered deposits that exceeds several kilometers in thickness. Analysis of visible to near-infrared reflectance spectra (0.4–4 μm) from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument indicates strata in the lowermost section of the mound exhibit an upward transition from clay- and clay/sulfate-bearing beds to predominantly sulfate-bearing beds (Milliken et al., 2010). Such a transition in mineralogy is broadly consistent with the proposed global environmental shift from circum-neutral/alkaline conditions to more acidic conditions inferred from analysis of OMEGA (Bibring et al., 2006) and CRISM spectral data (Murchie et al., 2009).

In this paper, we analyze the impact crater population and stratigraphic relationships to better constrain the time frame within which the layered strata in Gale Crater were deposited. Images from the High Resolution Imaging Science Experiment (HiRISE) taken at 25 cm/pixel scale and Context Camera (CTX) taken at 6 m/pixel scale onboard the Mars Reconnaissance Orbiter (MRO) are...
used to map and characterize the layered deposit within Gale Crater in detail to help unravel the complex geologic history of this region. By placing the layered deposits in Gale in a more tightly confined temporal context, this analysis will help establish scientific objectives and testable hypotheses that may help guide potential future landed exploration.

2. Background and regional context

2.1. Physiography

Gale Crater is a large (152 km diameter) impact crater centered at 5.3°S latitude, 222.3°W longitude in the Aeolis Mensae region (Fig. 1). Within the crater lies a slightly off-centered mound of layered material that measures approximately 45 km by 90 km in areal extent. This deposit has a maximum relief—meaning the elevation difference between the highest point on the mound and the lowest portion of the surrounding crater floor—of ~5.2 km and an average height of 3.8 km. This corresponds to a total mound volume of about 1.7 × 10^4 km^3 of sedimentary material. By comparison, the average depth of the Grand Canyon on Earth (~1.6 km) is less than half the average exposed stratigraphic thickness of the Gale mound (e.g., Webb et al., 2008).

2.2. Relationship to dichotomy boundary

Gale Crater lies on the southern, upland margin of the martian hemispheric dichotomy boundary, which is the topographic dis-continuity that divides the heavily cratered uplands from the smoother and lower-elevation northern lowlands. Along the dichotomy is a zone of disruption dubbed fretted terrain where intact cratered terrain has been partially disrupted into mesas, hummocks, and knobs (Sharp, 1973). As pointed out by Irwin et al. (2004), fretted terrain in the equatorial zone near Aeolis Menase (~10°N–10°S, 240°W–210°W) differs from fretted terrain in the midlatitudes north of Arabia Terra (~25°N–50°N, 350°W–260°W). The former lacks indicators of ice-facilitated mass wasting that are present in the latter, such as lineated valley fill and lobate debris aprons. Gale crater straddles the transition from crat ered highland surfaces to disrupted surfaces of Aeolis Mensae. Whereas the southern rim of the crater is largely intact, the terrain immediately adjacent to the northern rim has been heavily dissected in conjunction with the formation of fretted terrain (Fig. 2). Due to the downward pre-existing slope of the planetary dichotomy boundary, the northern rim lies several km lower than the southern rim (e.g., see Irwin and Watters, 2010 Fig. 6B and D). The central layered mound is also topographically higher than the low-lying northern rim, giving the appearance from certain perspectives that the mound elevation exceeds the crater rim elevation. In fact, there are a few points along the southern edge of the crater rim that slightly exceed the current maximum mound elevation. Regardless, the mound height and volume suggest that the entire crater was once largely filled with sediment, and it is even possible that the entire crater was previously buried and has since been exhumed.

2.3. Other large crater-hosted sedimentary mounds

While Gale Crater is noteworthy in terms of the size and volume of its interior layered deposit, it is not an isolated example: several other large impact craters in the vicinity also possess central layered material of a similar nature. Examples include Reuyl Crater (86 km in diameter, 9.8°S, 193.2°W) and Nicholson Crater (103 km in diameter, 0.2°N, 164.6°W). In each of these cases, the craters host massive central mounds of light-toned, layered sedimentary that may have once been part of more extensive deposits, though the original maximum extent and heights of those deposits remains unknown. Given the proximity and similarity of character of these remnant layered mounds (of which Gale Crater is the largest) to the Medusae Fossae Formation (MFF), it is possible that Gale Crater may be a remnant of a formerly more extensive MFF (e.g., Schultz and Lutz, 1988). Craters act as sedimentary traps, and in addition to being depositional foci, the crater walls offer a measure of protection against subsequent erosion. Based on detailed geologic mapping and the distribution of pedestal craters around the present extent of the MFF, Schultz and Lutz (1988) inferred that these deposits were formerly more extensive and have undergone

![Fig. 1. Topographic map of Mars (Robinson projection). Location of Gale Crater is indicated with red star; prior Mars landing sites are labeled with black dots. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image-url)
significant erosion and deflation. In addition to physical proximity, many of these layered deposits are also similar in their surficial spectral properties (i.e., they are dust-dominated), low thermal inertia, number and spacing of layers, and presence of yardangs (wind-carved ridges) (e.g., Bradley et al., 2002).

2.4. Previously proposed origins

Numerous interpretations of the layered deposits in Gale Crater and the potentially similar units of the Medusae Fossae Formation have been advanced. Given the low thermal inertia of these deposits and thin bedding, many have suggested eolian-related formative processes, including volcanic ash (Scott and Tanaka, 1982; Greeley and Guest, 1987; Bradley et al., 2002; Hynek et al., 2003) or eolian dust plus ice (Schultz and Lutz, 1988; Watters et al., 2007). A lacustrine origin was proposed on the basis of horizontal to subhorizontal layering and terraces, the channel system that cuts the southern rim of the crater and debouches onto the western crater floor, and numerous other small, inward-draining channels identified in Viking Orbiter images (Cabrol et al., 1999). Using higher-resolution MOC images, a subaqueous origin of this and other layered material was reasserted based on the affinity of the layered materials for impact craters, their thickness, regular layering, bed orientations, and apparent lack of cross beds (Malin and Edgett, 2000). Conversely, a stated lack of evidence for classic lacustrine features such as terraces, deltas, and fans in Gale was cited as evidence in support of formation of the layered central mound instead as a hydrothermal spring deposit (Rossi et al., 2008). Although not addressed to Gale Crater specifically, in a similar vein it has been proposed that many crater-hosted and intra-crater sedimentary deposits such as Meridani may be due to groundwater upwelling and evaporation, resulting in evaporite precipitation and cementation of eolian sediment (Andrews-Hanna et al., 2007). Additionally, it has been suggested that there may be a genetic link between the mineralogy of light-toned deposits and aqueous processes. Specifically, accumulations of buried evaporitic hydrated salts can create thermal anomalies (due to their low thermal conductivities) that may have sustained hydrologic activity in the more recent past (Kargel et al., 2007).

2.5. Previous age determinations

Establishing the formation ages of the layered deposits in Gale Crater and elsewhere has proved challenging. In planet-wide geologic mapping efforts using Mariner 9 data, Gale Crater and its interior deposits were mapped as unit Nplc (Noachian cratered plateau material), implying the crater’s maximum age is Noachian (Scott and Carr, 1978). A unit of HNpd (deflation plains material) abuts the eastern edge of the crater, interpreted as older (Noachian) surfaces exhumed in wind erosion of relatively soft, younger (ca. Hesperian) materials. Later mapping with higher-resolution Viking images placed the central layered mound in the Hesperian (grouped with other isolated exposures of smooth plains material in unit Hpl3) (Greeley and Guest, 1987). Some workers have inferred that the mound is much younger, perhaps as young as the Late Amazonian (Scott and Chapman, 1995; Cabrol et al., 1999). Others have contended that on the basis of evidence for widespread crater exhumation, Gale and other layered sedimentary strata were originally deposited in the Noachian Period (Malin and Edgett, 2000). Finally, an analysis of the regional geology of Gale and its contributing watershed suggested that the Gale impact occurred near the Noachian/Hesperian boundary after the period of widespread crater degradation (based on its relatively pristine morphology) but before the development of adjacent fretted terrain (Irwin et al., 2005). The crater interior deposits were inferred to have formed soon thereafter but prior to the terminal phase of highland valley network activity.

In global to regional scale geologic maps, some of the conflicting ages reported for Gale and its interior deposits may have been due to the fact that its time-stratigraphic position was largely inferred from its general morphology rather than assigned via direct measurement of its crater size–frequency distribution (due to the
relatively small area and lack of large craters on the mound). Craters were measured directly using Viking images of the floor and interior mound (Cabrol et al., 1999), but both the crater floor material and layered mound material were combined into a single count area in that study, thus lowering the overall apparent crater density and inferred age. In this study, we use revised crater counts and newly revealed details about the stratigraphic relationships between mapped units to place firmer constraints upon the period of time in which this layered sequence was deposited.

3. Methodology

3.1. Mapping technique

Using all available HiRISE images of Gale Crater as well as a mosaic of CTX images acquired through July 2010, we identified and delineated geologic units at a scale of 1:50,000. Unit identifications were made on the basis of geomorphic expression, surface texture, tone (approximation of albedo), and contact
relationships with other mapped units (e.g., Wilhelms, 1990). Because the type areas of beds in the Gale layered stack lack formal or even provisional names, we have assigned them names based on physical characteristics (e.g., layered material). This becomes potentially problematic due to the fact that some unit names may reflect both primary characteristics (those that occurred during deposition) and secondary features due to post-emplacement processes (e.g., weathering, diagenesis; see further discussion in Hansen (2000)). Thus we have limited our discussion of relative age inferences to those units for which we infer a parallelism between rock and time units, particularly those in the NW quadrant of the mound. Despite these limitations, the central mound is bounded on all sides by erosional scarps and therefore Gale Crater presents an opportunity to assess the full three-dimensional geometry of the beds.

3.2. Geometric measurements

The geometry of selected geologic contacts was measured using data extracted from individual Mars Orbiter Laser Altimeter
(MOLA) profiles. First, a unit’s traceable extent was mapped using HiRISE and CTX images. Using GIS software, we identified points where the mapped contact intersect the MOLA profiles. The elevation of these intersection points was estimated by assuming a linear slope between the two adjacent MOLA elevation points on either side of the intersection point along a given profile (e.g., Beyer and McEwen, 2005). MOLA observations have a footprint ~168 m in diameter and are spaced ~300 m along the spacecraft ground track (Smith et al., 2001). Uncertainty associated with MOLA elevation measurements has been assessed through an analysis of crossing profiles (Neumann et al., 2001), which yield a RMS error of 1.8 m. For purposes of fitting a surface to the network of xyz points, the x and y locations were given as meters in a simple cylindrical coordinate system with (0, 0) given at an arbitrary local reference point. z-Values were also given in meters.

In addition to determining the attitude of mapped contacts, we also examined characteristics of individual beds within our mapped units. The high resolution and high signal-to-noise ratio of HiRISE images provide unprecedented detail about the expression of individual beds and have revealed that several units previously characterized as massive in lower spatial resolution images actually consist of finely stratified beds with minimal erosional contrast. Stereo pairs of HiRISE images have been analyzed using photogrammetric software by the USGS to produce extremely high quality topographic maps with 1 m grid spacing (e.g., Kirk et al., 2008), although labor-intensive manual editing of the resulting Digital Terrain Model (DTM) is necessary to remove processing artifacts. Here, we use topographic profiles extracted from single lines of stereo pairs of HiRISE images to infer the thickness and apparent dip of individual layers.

The HiRISE instrument uses Time Delay Integration (TDI) to integrate the exposures of each line of ground observed up to 128 times to increase the signal-to-noise ratio (Delamere et al., 2003). A linear array of 10 overlapping CCDs provides a ~6 km swath width at red wavelengths (center wavelength is 694 nm). Each line of a compiled HiRISE image is essentially like a separate image, and two HiRISE observations of the same ground target with different look angles can be used to compute the relative

Fig. 5. (A) HiRISE image PSP_006855_1750 centered over large chasm on the western margin of Gale Crater’s layered mound (image centered at ~5.09°N lat, 222.77°W lon). White boxes give locations of B–D. (B–D) Subsets of (A) centered on inverted channel-like features cut into chasm walls. Arrows indicate down gradient direction.
heights of features in a given line of pixels using a variation of the basic stereo equation:

\[ h = \frac{p}{(\tan \theta_{1B} + \tan \theta_{2B})} \]  

(1)

Here, \( h \) is the height of the feature of interest, \( p \) is the measured parallax, and \( \theta_{1B} \) and \( \theta_{2B} \) are the respective emission angles of the two HiRISE images that constitute the stereo pair (accounting for their position in the CCD array). This single-line stereo technique is only applicable near the martian equator where the projection of the MRO spacecraft’s orbital tracks onto the surface are near-parallel (further details are given in Appendix A). Fortunately, Gale Crater is centered within about 5° of the equator. Other obvious limitations of this technique are that the resulting small-baseline heights are known only in a relative sense, e.g., the height of a feature such as scarp above a designated point in its surroundings. Also, no compensation has been made for spacecraft jitter or potential small misregistrations of the CCD array. Repeated measurements of beds using multiple pairs of line profiles suggests that the resulting profile data is accurate to within a few meters (~3–5 m) in a relative sense.

3.3. Measuring crater size–frequency distributions

Determining the impact crater size–frequency distribution of a surface remains the principal means of assessing relative age (specifically crater retention age) in the absence of returned samples. Within the study area, all craters not grouped into obvious
secondary clusters or chains were visually identified and recorded. HiRISE, CTX, and THEMIS (Thermal Emission Imaging System) visible and daytime infrared images were used to analyze the crater population within the study area. We also obtained nested crater counts for crater counts contained within a single mapped unit. In nested counts, all craters greater than a certain cutoff diameter are recorded using images with a range of resolutions. In small representative sub-region(s), smaller craters are recorded down to the limit of confident identification (which varies depending on surface roughness, lighting conditions, etc. but is generally ~5 pixels (Schultz et al., 1977)). These nested counts from different image data sets can be combined on a single plot if the surface areas over which the counts were performed are taken into account.

Summary plots of the incremental crater size–frequency distribution were made according to established techniques and conventions and were overlain on modeled production functions (Hartmann and Neukum, 2001; Hartmann, 2005). The measured crater densities of the martian time-stratigraphic boundaries (Tanaka, 1986) were also included on the summary plots for comparison.

4. Results

4.1. Preliminary geologic mapping results

In the central layered mound, we have identified 22 distinct geologic units (Fig. 3), not including the crater’s walls and relatively flat crater floor. This sequence can be divided into two major components: a Lower mound (Lm) formation and an Upper mound (Um) formation (consistent with the provisional names assigned in Milliken et al. (2010)). Layered strata in the Lower mound formation are generally horizontal to sub-horizontal (as measured from single-line stereo profiles). The Upper mound formation, in contrast, consists of more finely layered units that have higher-angle bounding surfaces, at least within certain units. An erosional unconformity, initially recognized by Malin and Edgett (2000), separates these two formations in the NW quadrant of the mound (Fig. 4C). The interpretation of contact relationships elsewhere is somewhat complicated by the unconsolidated mantling units that are prevalent throughout the mapped area. Eolian bedforms are especially abundant on units in the Upper mound formation (Fig. 4D). The more informal and general term “unit” is used over “member” to describe subdivisions of these provisional formations as strict lithostratigraphic definitions cannot be uniformly assigned to all mapped units (e.g. Tanaka et al., 2005).

Abundant geomorphic evidence for aqueous activity is present in multiple units in the Lower formation of the layered mound. Polygonal ridge networks (Fig. 4A and B) are observed to emerge from beneath light-toned layers with fractured surface textures. We interpret these ridge networks as evidence for subsurface fluid flow and preferential cementation along fracture zones. Similar evidence for fracture-controlled fluid flow has been observed in layered deposits in Candor Chasma (Okubo and McEwen, 2007). Numerous channels and inverted channels are also present in numerous locations in the Gale deposits. Inverted channels appear to be limited to the Lower mound formation (Fig. 5). These positive relief structures are erosional remnants of indurated channel-fill deposits that are often located in larger incised (negative relief) channels. Recent comprehensive mapping efforts in Gale by Anderson and Bell (2010) also identified large numbers of sinuous channels on the crater floor interpreted as inverted channels.

4.2. Geometry of layers and layer contacts

The attitude of a portion of the erosional contact between the Upper and Lower formations of the layered mound was determined by attempting to minimize the residual offset between a modeled planar surface and the observed xyz points as interpolated from individual MOLA topographic profiles. As depicted in Fig. 6, the contact at this location is best described by a planar surface with a strike and dip of N45E, 12.1°NW (i.e., inclined to the NW).

Using the single-line stereo technique, the geometry of individual beds was derived. In Figs. 7 and 8, two examples of single-line stereo profiles are plotted: one from the Lower formation of the central mound (Fig. 8) and another from the Upper formation (Fig. 8). The six layers in the profile given in Fig. 7B are between 10 and 30 m thick and have an apparent dip of ~2°. Individual layers have variable geomorphic expressions—many appear to have a coarse zone of rubble at their base and fine upwards, while others may be topped with coarse rubble zones (depending on where the boundaries between layers are drawn). Note these rubble zones may just be the result of in-place fracturing rather than being representative of a coarsening-upward sequence. Layers in the Upper formation, in contrast, are between 3 and 7 m thick and have apparent dips >5° and <10° (Fig. 8). No differences in constituent grain size (as observed at HiRISE image resolutions) are apparent in the weathering characteristics across bed boundaries, and the beds appear to be near-uniform in tone and texture.

4.3. Alteration mineralogy in the near-IR: Evidence of phyllosilicates and sulfates

Visible and near-infrared spectral data from the CRISM instrument have revealed the presence of a diverse suite of alteration minerals in the Lower formation of the layered mound where...
Fig. 8. (A) Single-line stereo profile location on HiRISE image PSP_009927_1750 (2nd image used for stereo is PSP_008002_1750). (B) Topographic profile derived from single-line stereo. Elevations are referenced to arbitrary zero value at point d.

Fig. 9. Comparison of Mars CRISM spectra and laboratory spectra showing the presence of hydrated sulfates and clay minerals in Gale Crater. All CRISM spectral ratios are 7 x 7 pixel averages. (A) CRISM spectral ratios for an Fe-smectite (nontronite) deposit near the base of the Gale Crater mound compared to a lab reflectance spectrum of nontronite. (B) CRISM RGB composite (RGB = 0.749, 0.501, and 0.449 μm, respectively) image FRT000086F1 with locations of spectra presented in (A) marked with colored circles. The red CRISM spectrum in (A) represents a ratio of the region marked by the green circle divided by the region marked by the red circle. The black CRISM spectrum in (A) represents a ratio of the green circled region divided the black circled region. The choice of the denominator affects the spectral slope for wavelengths less than 1.5 μm but does not affect the presence or position of absorption features at longer wavelengths. (C) CRISM spectral ratios for sulfate deposits in Gale Crater. Some regions are consistent with monohydrated sulfate (kieserite; black spectra) whereas others are consistent with polyhydrated sulfate (likely MgSO₄·nH₂O; red spectra). (D) CRISM RGB composite (RGB = 0.749, 0.501, and 0.449 μm, respectively) image FRT000095EE with locations of spectra presented in (C) marked with colored circles. The red CRISM spectrum in (C) is a ratio of the region marked by the red circle divided by the region marked by the white circle. Black CRISM spectrum in (C) corresponds to the black circled region divided by the white circled region.” (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
the moderate dust cover permits identification of the surface composition (Milliken et al., 2010). Following standardized atmospheric correction procedures (Murchie et al., 2009), spectra of individual geologic units were divided by the spectrum of a nearby spectrally neutral (dusty) region. These spectral ratios were then compared with laboratory mineral spectra (Fig. 9). Moving from the lowermost stratigraphic units upwards in Fig. 10A and B, there are sulfate-bearing rocks possibly mixed with smectite, a thin but distinct smectite-bearing unit (specifically the iron-rich phyllosilicate nontronite), a layer with a mixture of smectite and olivine in which the latter is associated with unconsolidated eolian material, a unit with a mixture of sulfate and smectite, sulfate-bearing beds, and finally the absence of hydrated minerals in the layers of the upper member of the central mound (i.e.,
the beds are spectrally similar to dust). Thus, the mineralogy transitions from mixed sulfate-clay assemblages to a dominantly sulfate alteration assemblage upsection. The sulfates do not exhibit spectral characteristics common of Ca and Fe-sulfates and are instead most consistent with Mg-bearing sulfates (e.g., kieserite, hexahydrite, etc.).

4.4. Mid-infrared results and thermal inertia

The surficial geology of Gale Crater has been mapped in detail by Pelkey et al. (2004) using 100 m/pixel daytime and nighttime thermal data from the Mars Odyssey THEMIS (Thermal Emission Imaging System) instrument supplemented with THEMIS visible and MOC (Mars Orbital Camera) images. Seven surface types were identified and mapped on the basis of their thermal characteristics, including 3 units of floor materials, central mound material, sand sheets, crater wall material, and material in the surrounding undivided terrain (dubbed plateau material). Material on the northern floor of Gale Crater, including the proposed MSL landing ellipse, were found to have high temperatures and corresponding high thermal inertias. This thermal signature was attributed to bedrock or extensively indurated material (Pelkey and Jakosky, 2002).

Fig. 11 is a plot of THEMIS nighttime temperatures. The data indicate that temperatures decrease upslope on the central mound. Regions with the lowest temperatures are found at the highest elevations, and are consistent with dust cover in excess of a few cm thick (i.e., exceeding a diurnal thermal skin depth in thickness). The dust cover appears to taper downslope to reveal more indurated units, which is consistent with stronger near-infrared absorption features being evident in the lower, less dust-covered units in the Lower formation compared to the units of the Upper formation.
4.5. Crater size–frequency distribution results

4.5.1. Direct age measurement of the layered mound

The most straightforward method to determine the age of the layered units in Gale is to determine the crater retention age of the mound itself. This is problematic given the apparent material properties of these units. Most of the exposed surfaces do not appear to retain craters, and overall measured crater distribution (Fig. 12A and B) yields a young age near the Late Hesperian/Early Amazonian boundary. However, much like the layered deposits in the north and south polar regions (e.g., Herkenhoff and Plaut, 2000), this young age likely represents an exposure age or resurfacing age that reflects recent erosion, and it is not necessarily indicative of the depositional age of the material. Unit lm3 of the Lower formation contains a significant number of craters that appear to have been exhumed from underneath subsequently deposited layers that are now being stripped back (see example given in Fig. 13).

4.5.2. Minimum age constraint: Superposed floor units and valley network deposits

A more accurate constraint upon the minimum formation age of the layered units in Gale can be obtained by using basic superposi-
tion relationships. As evidenced by the geologic cross-section given in Fig. 3B, it is clear that the units on the floor of Gale Crater overlap and embay the lower units of the layered deposits. Thus, these floor units are topographically lower but stratigraphically higher, and therefore younger, than the Lower formation of the Gale mound. By determining the age of this floor unit we can place a firm minimum age constraint upon the layered mound. The measured crater size–frequency distribution of the floor unit is given in Fig. 12C and D, indicating an age of Early Hesperian. Therefore, the lower portions of the mound can be no younger than the Early Hesperian. Evidence differentiating this result was noted by Irwin et al. (2005), who observed that the inlet channel breaching the southern rim diverges into two small terminal deposits on either side of the eastern lobe of the central mound. Such a configuration requires that the lower portions of the mound have been in place prior to the terminal phase of activity of this channel.

4.5.3. Maximum age constraint: Gale ejecta crater distribution

In order to bracket the age of the deposits in Gale, it is necessary to determine an upper age boundary that marks the maximum potential age of the deposits. For this study, we used the age of Gale Crater itself as a time-stratigraphic marker. Fig. 12F is a plot of the crater size–frequency distribution of craters superposed on Gale’s ejecta. The outer terminus of Gale ejecta is gradational in nature and its exact extent is difficult to pinpoint, so we have measured the crater distribution within the estimated continuous ejecta blanket using the relation $R_{ce} = (2.348 \pm 0.5)R^{1.006}$ (Moore et al., 1974). Here, $R_{ce}$ is the radius of continuous ejecta and $R$ is the apparent crater radius. Although this relationship was empirically determined for lunar craters, it has been used to provide first-order estimates of martian ejecta (e.g., Grant et al., 2008). An outline of the area counted is given in Fig. 12E and the count data are given in Fig. 12F. Data from the two largest crater size bins suggest that the Gale impact occurred in the Late Noachian, although the density of smaller-sized craters (2–16 km in diameter) are more consistent with an age that straddles the Late Noachian/Early Hesperian boundary. Error bars in a few diameter bins (e.g., centered at 9.51 and 13.45 km diameter) subtend epoch boundaries, adding some degree of uncertainty to the age assignments given above. Two potential factors may account for the apparent discrepancy between the larger and smaller crater size bins. First, this might be due to differential erosion such that smaller superposed craters were degraded more efficiently than larger ones (e.g., Chapman and Jones, 1977; Craddock and Howard, 2002). Second, although we have endeavored to exclude craters that predate the Gale impact from the count (mapped with unfilled circles in Fig. 12E), it is possible that a few older craters were included, resulting in a slightly older apparent age in the largest size bins.

5. Discussion and interpretation

5.1. Summary of the nature of the layered material

Images and data from observations of Gale Crater by the MRO spacecraft have verified and expanded previously recognized characteristics and also revealed a wealth of previously unknown details. The Upper and Lower formations of the mound have distinct morphologic and mineralogic characteristics, and they may have been formed by separate processes (e.g., Milliken et al., 2010). The erosional surface between these two members is non-horizontal, but this does not necessarily constrain its origin. Such a surface could be the result of a landslide (perhaps an exposed footwall following normal faulting) or alternatively could be the result of eolian erosion. Given the lack of debris directly attributable to mass wasting processes downslope of this contact, this suggests that eolian erosion may control this and other surfaces of omission.

CRISM data have revealed an intriguing suite of alteration minerals in the Lower formation of the mound, including an upward transition from a series of phyllosilicate-bearing to a group of sulfate-bearing layers (Milliken et al., 2010). If formed in situ, these alteration minerals hint at the former presence of water in Gale, and the morphology of numerous inverted channels are also evidence a significant role for local aqueous processes.

5.2. Formation time constraints

Key considerations of any geologic site are determining when the processes inferred occurred and their duration. In the case of Gale Crater, salient questions are when was the layered material deposited, and when were the channel systems active? We have attempted to answer these questions by measuring the crater population in combination with superposition relationships to establish an upper and lower time boundary for the formation of the layered material. Direct measurement of the crater size–frequency distribution on the entire layered mound yields a Late Hesperian age (Fig. 12A and B), but the widespread occurrence of exhumed craters indicates that this age only represents an exposure or resurfacing age. Exhumed craters represent only a fraction of the total crater population given that an indeterminate number of impact structures must have been lost with removal of the overburden.
A more accurate minimum formation age in the Early Hesperian Period is obtained by an analysis of the crater size–frequency distribution on the floor units that overlap the lowermost units of the layered mound (Fig. 12C and D). It is also true, however, that the erosional unconformity that separates the Upper and Lower formations represents an unknown hiatus in the depositional history recorded in Gale. There is also a distinct change in material properties above and below this boundary. Below this unconformity, many units contain evidence of exhumed craters (e.g., unit L3 in Fig. 3), while above this boundary the material appears to be more friable and retains craters poorly. The age of the units in the Upper formation are therefore unclear based on both stratigraphic relationships or their measured crater distribution. This uncertainty parallels the disparate ages estimated for the Medusae Fossae Formation, which has been alternatively placed in the Amazonian due to on the basis of its low crater retention age (Greeley and Guest, 1987; Tanaka, 2000; Bradley et al., 2002) or the Hesperian based on an analysis of the number density of surrounding large pedestal craters (Schultz and Lutz, 1988). Units in the Upper formation, if connected to the MFF, are plausibly consistent with either of these proposed chronologies.

An additional constraint can be obtained from the age of the last dated activity in valley networks around Gale. Studies of valley networks using a buffered crater count technique (Fassett and Head, 2008) indicate that no valley networks in the cratered southern highlands are younger than the Late Hesperian (younger valley networks exist, but they are exclusively confined to volcanic terrains). Numerous small valley networks debouch onto the crater floor from all sides, and a sizable percentage of the floor material appears to have been fluvially transported. It is no coincidence, then, that the age of the floor units matches the age of last activity of the surrounding valley networks. The small inverted channel on the mound itself may also be a valley network-like feature. Because this feature superposes all of the units in the Lower formation of the mound, if its age is comparable to the rest of the more traditional valley networks, it would place firmer constraints upon the relative age of the Lower formation.

A maximum formation age for the layered deposits near the Noachian/Hesperian boundary (Fig. 12E and F) is provided by the age of Gale itself as dated by superposed craters on its ejecta. This age is consistent with the general morphology of Gale, which is less degraded than many other craters of comparable size in the Noachian highland terrain. Using computer models of terrain degradation by a variety of processes (Forsberg-Taylor et al., 2004), it has been shown that craters follow a predictable sequence of morphologies as erosion proceeds. Many of the craters in Noachian terrain have flat, infilled floors relative to their diameters and exhibit shallowed wall slopes. Gale Crater, despite containing a large mound of layered material, still retains some elements of more pristine wall morphology (excluding the degraded terrain adjacent to the northern crater rim).

We are therefore able to constrain these layered deposits as having formed sometime between near the end of the Late Noachian Period and Early Hesperian Period (Fig. 14). This general time frame still represents a possible \( \sim 0.2 - 0.3 \) Ga window within which these deposits were lain down. But even these loose constraints pin down the Gale deposits to an interesting and little explored time-stratigraphic boundary in martian history. Results from the OMEGA instrument suggest a potentially global-scale transition from environmental conditions that favored phyllosilicate formation to conditions that favored sulfate formation (Bibring et al., 2006), potentially due to the extensive outgassing of volcanogenic sulfur coupled with a rapid, global drop in atmospheric pressure and loss of water. Alternatively, co-deposition of both phyllosilicates and sulfates are known from terrestrial analogs, for example where diverse mineralogies occur in close proximity in evaporation-dominated, ephemerally wet playa systems (e.g., Baldridge et al., 2009). Both morphologic and mineralogic evidence indicates that Gale Crater captured a stratigraphic record of this apparent transition (Milliken et al., 2010), making this locale one of the few recognized sites that would allow in situ exploration of this transition at a scale accessible to a rover.

5.3. Origin(s) of layered materials

Of the myriad proposed origins for the layered deposits, a few can be set aside or deemed unlikely. It is clear, for example, that the Gale mound consists of a stratified sequence of sedimentary layers. Additionally, as evidenced by the thermophysical data (Fig. 11), the lack of a lag deposit despite significant evidence for eolian deflation necessitates that the layered material consist of fine-grained sediments with little to no coarse fraction. While stratified sedimentary deposits can form in high-energy environments such as those near impact craters or explosive volcanic vents, a thick accumulation of a finely layered, repetitive sequence of sedimentary strata generally requires a lower-energy depositional environments such as an eolian sand sheet or a lacustrine/marine basin (turbidite deposits are one notable exception to this generalization, however). Therefore we consider it unlikely that volcanoclastic processes alone are responsible for the observed characteristics of the deposits, particularly the fine regular layering revealed in HiRISE images. The diverse alteration mineralogy of the layered stack is also difficult to explain in a volcanic scenario without evoking radically different fluid chemistries affecting only certain portions of the mound.

An intriguing possibility is that Gale may have once hosted a lacustrine phase of activity. Evidence of aqueous processes are abundant, including: widespread exposure of alteration minerals, evidence of subsurface fluid flow in the form of polygonal ridge networks, and evidence for fluvial activity in the form of both positive and negative relief channels. But it seems unlikely that lacustrine evolution alone is solely responsible for the entirety of the layered mound. First, many of the benches and terraces inferred to be wave-cut platforms in lower resolution data (Cabrol et al.,
1999) turn out to be stratigraphic contacts between distinct layers, some of which are clearly non-horizontal (e.g., Fig. 6). Second, given that the height of the mound exceeds the rim height except in all but a few small locations, Gale would have to have been filled to a level above the rim, which also necessitates complete inundation of the surrounding terrain. Indeed, Gale's location along the dichotomy boundary means that the entire northern plains would have to be filled with water were Gale to be filled (e.g., Parker et al., 1989; Head et al., 1999). On the other hand, if only the lower mound units were completely submerged, the implied inundation extent of the surrounding terrain would be much less.

A variant of a lacustrine formation scenario is that the water may have been sourced by groundwater rather than overland flow. Motivated by the interpretation of Meridiani as a former playa deposit containing eolian-reworked evaporites (Grotzinger et al., 2005), a geophysical model was proposed in which an upwelling groundwater table intersects the surface, evaporates, and cements eolian sediments into place (Andrews-Hanna et al., 2007, 2010). Requiring an extended time period with surface temperatures above freezing, the proposed model envisions repeated wetting and evaporative episodes that build up a substantial thickness of sedimentary material in locales with favorable hydrologic conditions (such as deep craters). A potential obstacle to this hypothesis is that the limited degree of weathering seen at Merididiani is more consistent with closed system alteration (Niles and Michalski, 2009) rather than the open system origin required by an interconnected groundwater system. But as the full mineralogic diversity at Gale is only beginning to be unraveled (e.g., Milliken et al., 2010), it remains to be seen if additional geochemical data will support or disfavor an open system model.

In their analysis of sedimentary deposits on Mars using MOC images, Malin and Edgett (2000) concluded that the sediments were most likely deposited in a quiescent environment; specifically, they favored subaqueous, lacustrine depositional processes over subaerial, eolian processes. Part of their reasoning was that the inferred age of the deposits implies that the formative processes are no longer operative today, at least with the same vigor. While it is true that these deposits do not seem to be forming contemporaneously in the equatorial zone, one need not look too far afield to find a modern day martian process that produces deposits potentially analogous to those laid down in the past. Both polar regions contain sequences of stratified deposits that consist of frozen volatiles mixed with a small percentage of dust (e.g., up to 10% in the south polar layered deposits (Plaut et al., 2007). These deposits unconformably overlie the basement terrain, contain layers traceable for tens to hundreds of kilometers in horizontal extent, and show an affinity for craters (e.g., Byrne and Ivanov, 2004; Fishbaugh and Hvidberg, 2006; Milikhov and Plaut, 2008). The location of Gale Crater and other layered deposits in non-polar regions that straddle the equator obviously require further explanation. Due primarily to the lack of a stabilizing satellite like the Earth's Moon and the larger influence of nearby Jupiter, the obliquity of Mars has been shown to exhibit chaotic behavior and may frequently reach values as extreme as 60° or greater (Laskar et al., 2004). During periods of high obliquity, the increase in insolation at polar regions may initiate a planet-wide redistribution of polar surface and subsurface volatiles to lower latitudes. It is possible that Gale is a remnant of one of these periods of high obliquity. A related possibility is that the rotation axis of Mars may have migrated to its present position (i.e., through true polar wander) (Murray and Malin, 1973; Schultz and Lutz, 1988). Numerous studies of Mars' remnant magnetic field have inferred past polar wander (e.g., Spenke and Baker, 2000; Frawley and Taylor, 2004; Boutin and Arkani-Hamed, 2006), and the long-wavelength topography of northern plains-encircling geologic contacts have been calculated to better fit an equipotential surface if ~30–60° of true polar wander has occurred (Perron et al., 2007). However, the occurrence of polar wander has been challenged on the basis of expected tectonic features (e.g., Grimm and Solomon, 1986) and disputed geologic ages of sedimentary units (Tanaka, 2000). Despite these potential objections to polar wander, either high obliquity or polar wander may yet explain the equatorial concentrations of sedimentary rock and the unexpected concentrations of near-surface hydrogen in non-polar locations; in this case the mineral signatures would likely represent diagenetic processes (Niles and Michalski, 2009).

One remaining possibility is that the entire stack of sediments could be the result of dry eolian deposition. If this were the case, then the diverse suite of alteration minerals detected would have to be formed elsewhere, transported, and deposited within Gale. It is known, for example, that soil deposits in the extremely arid Atacama Desert on Earth contain salts accumulated from atmospheric influx (Ewing et al., 2006). Yet given the mineralogical diversity at Gale, a single source region seems unlikely. It would appear that multiple source regions (or an evolving source) are required to supply and sequester these altered minerals in distinct layered units. The potential source region(s) remain unidentified. Furthermore, the geomorphic evidence of fluid flow on and within the mound (channels, inverted channels, and filled fractures) seems at odds with a completely anhydrous depositional environment. Lithification of individual sedimentary layers is also difficult to accomplish in a completely anhydrous environment.

In sum, we are left with two overarching alternative explanations: an aqueous chemical and clastic deposit (consistent with moderately deep inundation), or a stratified dusty or high obliquity (polar-like) deposit; or some combination of the two. For example, the mound may have a polygenetic origin in which the Lower formation of the mound formed by one set of processes that included a lacustrine phase whereas the Upper formation was dominated by eolian airfall. Regardless of the exact formation scenario, however, the mound captures an important mineralogic and potentially climate-related transition in martian history near the Noachian–Hesperian boundary.

5.4. Implications for future landed exploration

The layered sedimentary material in Gale Crater presents an opportunity to explore one of the largest and best-exposed stratigraphic sections accessible by the MSL landing system and payload. The flat, northern crater floor presents a relatively safe landing ellipse on a terrain similar to that landed on by MER Spirit in Gusev Crater. Within the nominal landing ellipse is an alluvial fan from a small valley network incised into the crater's northern rim. This fan presents the opportunity to assess some basic paleo-hydrogeologic questions about valley networks, including the sediment load and constraining the water-to-rock ratio of valley networks, which remain unconstrained. At the southern edge of the ellipse is a traversable route with a moderate grade up through the layered stack of sediments in the central mound (e.g., Bridges, 2001, 2006; Bell et al., 2006; Thomson et al., 2007; Anderson and Bell, 2010). These deposits appear to have been lain down across the Noachian–Hesperian boundary, and as such capture an environmental record of the conditions that initially favored phyllosilicate formation and deposition and later shifted to a sulfate-dominated system. If the phyllosilicates were formed by surface processes, this transition may reflect a loss of an initially denser and more clement early martian atmosphere.

Another, more philosophical issue is whether it is better to direct future landed exploration to a site that represents typical Mars (or perhaps a site that typifies a process) versus directing exploration to a unique site that may be atypical of Mars. But because recently landed exploration by the MER rovers has revealed an increasing complex picture of Mars' evolution, it has become more difficult...
to state definitively what “typical” really means. Furthermore, the most unambiguous evidence of ancient life on the Earth often requires somewhat anomalous preservation conditions, for example, “Konservat-Lagerstätten,” rare deposits known for the exceptional preservation of fossilized organisms such as the Jurassic Solnhofen Limestone (e.g., Barthel et al., 1990), Cambrian Burgess Shale (e.g., Gould, 1989; Briggs and Fortey, 2005), or earlier life traces in Archean Warrawoona Group (e.g., Hofmann et al., 1999; Brown et al., 2004). Thus, Gale Crater is perhaps a type example — one of a class of craters containing interior layered deposits — that bear witness to an extended sedimentary record that will likely be vital to understanding the history of past habitability on Mars.

6. Conclusions

From crater count data and superposition relationships, units in the Lower formation of Gale Crater layered materials can be reliably constrained to have been deposited near the Early Hesperian/Late Noachian boundary. Spectral analyses of layers in the lower mound indicate an upward transition from phyllosilicate-bearing to sulfate-bearing layers, albeit with some evidence of interfingering (Milliken et al., 2010). Formative scenarios consistent with the observed mound properties include lacustrine (sourced from either groundwater or overland flow) or eolian deposition in a paleo-polar or high obliquity environment. It is also possible that units in the Upper and Lower mound formations do not share the same mode of origin. Nevertheless, an important role for aqueous processes is demonstrated by positive and negative-relief channels and valley network-like deposits, evidence for fluid movement and cementation along fracture zones, and the simple presence of mineralogic signatures of alteration. The lithification of layers may also point to a role for water, although this criterion alone is not definitive.

An erosional surface or surface of omission separates the upper and lower portions of the mound, and this inclined interface represents a fundamentally unknown length of time. It is possible that it is the result of a brief depositional interlude, or alternatively it may represent a significant gulf of time. If the Upper formation of the Gale layered deposits is genetically related to the Medusae Fossae Formation (MFF), then Gale presents an opportunity to explore a unique martian puzzle. Specifically, what are the MFF layers composed of, and how did they form? Are they eolian dust deposits, volcanic ash deposits, paleo-polar deposits, or something else? Recent radar sounding data indicates that they have an anomalously low density and may even be ice-rich (Watters et al., 2007). Irrespective of any potential connection to the MFF, spectral evidence for phyllosilicates and geomorphic evidence for fluvial activity and subsurface fluid flow in the Lower formation of the mound suggest a prior history that involves water in Gale Crater. In situ investigation of the nature and origin of these alteration minerals and host sediments will allow us to determine the role of aqueous activity and how it fits into the larger evolution of layered deposits of Mars.

Acknowledgments

This manuscript was improved by thoughtful reviews from Rossman Irwin and an anonymous reviewer. This research was supported in part by a NASA Interdisciplinary Exploration Science grant to Simon J. Hook.

Appendix A. Single-line stereo method

In the text, we presented a method for rapidly measuring terrain heights (specifically the thickness of layers exposed in stair-step fashion) using manual measurements on a single line extracted from each image of a stereo pair of HiRISE images. Here we explain this methodology in greater detail and compare the results with topographic points extracted from a DTM created by the USGS (Kirk et al., 2009) using advanced stereo-matching algorithms contained in SOCET SET (BAE Systems).

The fundamental stereoscopic parallax equation is well known and is used to derive terrain heights from aerial photography (e.g., Jensen, 2000).

<table>
<thead>
<tr>
<th>Point ID</th>
<th>1488 nomap x-pixel</th>
<th>1488 nomap y-pixel</th>
<th>Lon (E)</th>
<th>Lat (N)</th>
<th>Single-line Elev (m)</th>
<th>DTM Elev (m)</th>
<th>Norm. DTM Elev (m)</th>
<th>Elev diff (m)</th>
</tr>
</thead>
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<td>B’</td>
<td>842</td>
<td>15,444</td>
<td>137.344260</td>
<td>-4.868115</td>
<td>51.3</td>
<td>-3342.92</td>
<td>48.0</td>
<td>3.3</td>
</tr>
<tr>
<td>A</td>
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<td>15,444</td>
<td>137.344726</td>
<td>-4.868061</td>
<td>58.3</td>
<td>-3332.65</td>
<td>58.3</td>
<td>0.0</td>
</tr>
<tr>
<td>B</td>
<td>613</td>
<td>15,444</td>
<td>137.345297</td>
<td>-4.867996</td>
<td>50.0</td>
<td>-3349.79</td>
<td>41.2</td>
<td>8.8</td>
</tr>
<tr>
<td>C</td>
<td>542</td>
<td>15,444</td>
<td>137.345616</td>
<td>-4.867959</td>
<td>31.4</td>
<td>-3364.23</td>
<td>26.7</td>
<td>4.7</td>
</tr>
<tr>
<td>D</td>
<td>507</td>
<td>15,444</td>
<td>137.345774</td>
<td>-4.867840</td>
<td>20.5</td>
<td>-3366.21</td>
<td>24.7</td>
<td>-4.2</td>
</tr>
<tr>
<td>E</td>
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<td>15,444</td>
<td>137.345988</td>
<td>-4.867917</td>
<td>15.0</td>
<td>-3372.64</td>
<td>18.3</td>
<td>-2.3</td>
</tr>
<tr>
<td>F</td>
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<td>137.346132</td>
<td>-4.867900</td>
<td>9.4</td>
<td>-3375.56</td>
<td>15.4</td>
<td>-6.0</td>
</tr>
<tr>
<td>G</td>
<td>380</td>
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<td>137.346350</td>
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<td>0.0</td>
<td>-3383.69</td>
<td>7.3</td>
<td>-7.3</td>
</tr>
</tbody>
</table>

* Elevation values normalized to elevation of point A obtained using single-line stereo method.
In Eq. (A.1), $h$ is the height of the object being measured, $H$ is the altitude of the sensor, $P_b$ is the absolute stereoscopic parallax between the two stereo images, and $dP$ is the differential parallax between two reference points of interest. The single-line stereo technique is a variation on this formulation (Eqs. (A.2) and (1) in main body of the text):

$$ h = H \times \frac{dP}{P_b + dP}. $$

Re-arranging (A.5) yields Eq. (A.2). Elevation values obtained with the single-line stereo technique compared to those obtained directly from a full stereo DTM product (produced from the same HiRISE images PSP_001488_1750 and PSP_001752_1750) are given in Table A.1 and plotted in Fig. A.2. The RMS error of the normalized elevation values is 5.3 m. This result indicates that to a first-order, the single-line technique yields reasonable results.

**Appendix B. Preliminary geologic unit descriptions**

<table>
<thead>
<tr>
<th>Unit name</th>
<th>Abbrev.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower mound 1 unit</td>
<td>lm1</td>
<td>Occurs on northern edge of central mound. Forms light-toned layered knobs</td>
</tr>
<tr>
<td>Lower mound 2 unit</td>
<td>lm2</td>
<td>Occurs below lm3 and above lm1; intermediate in tone. Layers exposed in places suggesting conformal bedding with surrounding units, but also some evidence of draped material. CRISM data indicates the presence of phyllosilicates. Occurs immediately below contact with Upper mound units in NW quadrant of mound. Exposures in west are relatively flat-lying and possess numerous craters, some of which appear to have been exhumed. CRISM data suggests weak sulfate signature in upper portion, possibly interbedded with</td>
</tr>
<tr>
<td>Lower mound 3 unit</td>
<td>lm3</td>
<td>Occurs immediately below contact with Upper mound units in NW quadrant of mound. Exposures in west are relatively flat-lying and possess numerous craters, some of which appear to have been exhumed. CRISM data suggests weak sulfate signature in upper portion, possibly interbedded with</td>
</tr>
</tbody>
</table>
### Preliminary geologic unit descriptions (continued)

<table>
<thead>
<tr>
<th>Unit name</th>
<th>Abbrev.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower mound subdued unit 3</td>
<td>lm3s</td>
<td>Occurs along margin of western mound lobe. Contains steep-sided canyon exposure cutting through sequence of Lower mound units.</td>
</tr>
<tr>
<td>Lower mound embayed unit</td>
<td>lmeb</td>
<td>Occurs in NE margin of mound at transition from mound to surrounding plains. Forms ridges of intermediate to light-toned material that are embayed by dark-toned material of floor units.</td>
</tr>
<tr>
<td>Lower mound fractured unit</td>
<td>lmf</td>
<td>Characterized by steep-sided margins exposing layers on both upslope and downslope margins. Interpretation: Erosional fenster exposing underlying layered material.</td>
</tr>
<tr>
<td>Lower mound knobby unit</td>
<td>lmk</td>
<td>Occurs in northern portion of mound. Forms irregular blocky, fractured terrain with locally reworked material distributed between more resistant knobs. Many knobs have streamlined shapes suggestive of eolian erosive control.</td>
</tr>
<tr>
<td>Lower mound subdued knobby unit</td>
<td>lmks</td>
<td>Occurs in northern portion of mound. Similar to unit lmk-forms irregular blocky, fractured terrain with locally reworked material distributed between more resistant knobs. Surface appears mantled with a material similar in tone to underlying material, muting the topographic relief of the knobs.</td>
</tr>
<tr>
<td>Lower mound eastern layered unit</td>
<td>lml</td>
<td>Occurs on eastern lobe of mound. Forms broad, planar surface with variable texture. Some portions smooth and subdued, some portions etched, some eroded; gradational internal contacts observed. Depends on the topography.</td>
</tr>
<tr>
<td>Lower mound mantled unit</td>
<td>lmm</td>
<td>Occurs on eastern margin of mound. Forms chaotic distribution of ridges and knobs with intervening smooth fill. Northern portions of unit have more muted topography, appears to have intermediate-toned mantle partially overlain with dark-toned sand.</td>
</tr>
<tr>
<td>Lower mound marginal unit 1</td>
<td>lmmr1</td>
<td>Occurs along northern and western edge of mound forming contact between layered units and crater floor. Crater floor material clearly onlaps and partially embay unit margin. Numerous dark-toned units also overlie much of the unit.</td>
</tr>
<tr>
<td>Lower mound marginal unit 2</td>
<td>lmmr2</td>
<td>Occurs in thin band in northern margin of mound. Occurs as streamlined ridges of resistant material, presumably yardangs. Are partially embayed by material of crater floor.</td>
</tr>
<tr>
<td>Lower mound marginal unit 3</td>
<td>lmmr3</td>
<td>Occurs along southern margin of mound. Forms intermediate-toned, subdued hummocky material without evident layered, possibly dominated by local mass-wasting and reworking.</td>
</tr>
<tr>
<td>Upper mound chaotic unit</td>
<td>umc</td>
<td>Occurs adjacent to unit ump, forms smaller (1–2 km across) ridges and knobs shedding debris into local valleys. Forms tightly packed array of streamlined erosional ridges and valleys. Valleys are partly filled debris that is presumably locally sourced, but relief remains sharp indicating minimal mantling. Interpreted as erosional yardang-like features.</td>
</tr>
<tr>
<td>Upper mound etched units 1–4</td>
<td>ume1–4</td>
<td>Forms tightly packed array of streamlined erosional ridges and valleys. Valleys are partly filled debris that is presumably locally sourced, but relief remains sharp indicating minimal mantling. Interpreted as erosional yardang-like features.</td>
</tr>
<tr>
<td>Upper mound layered units 1–4</td>
<td>uml1–4</td>
<td>Forms broad, bench-like outcrops of light-toned layered material. The edges of resistant layers are commonly eroded into irregular, saw-tooth like patterns.</td>
</tr>
<tr>
<td>Upper mound layered etched unit</td>
<td>umle</td>
<td>Occurs in western portion of mound. Forms steep-sided linear ridges interpreted as erosional yardangs, oriented predominantly in a N–S direction. Ridges are intermediate to light-toned. Material in between ridges appears darker in tone, locally similar in character to unit lm3.</td>
</tr>
<tr>
<td>Upper mound mantled units</td>
<td>umm1–2</td>
<td>Forms varitextured surface with exposures of layering. Little to no high-angle exposures of erosional knobs are observed as evidenced in other Upper mound layers. Subdued nature of topography implies substantial thickness of light-toned mantling unit that is presumably locally derived.</td>
</tr>
</tbody>
</table>
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