Physical Outcrop Characteristics of the Mawrth MSL Candidate Landing Site

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Abstract

Background: One of the candidate landing sites for the Mars Science Laboratory is in the Mawrth region of Mars. The candidate landing ellipse is located on highly cratered terrain with extensive bedrock outcrop. Diverse hydrous minerals have been detected from orbit, providing strong motivation for sending a landed mission to this area. However, models for the accumulation of bedrock in the area are poorly constrained.

Method: To evaluate the physical characteristics of light-toned bedrock in Mawrth area, I described features from and mapped relationships on HiRISE images, anaglyphs, and DTMs in the context of CTX images.

Conclusion: Light-toned bedrock near the Mawrth candidate landing site is highly fractured and brecciated. Several fracture patterns and breccia types are consistent with shock deformation due to impacts. Very few areas near the landing ellipse have layers that are laterally continuous for more than 100 m. This lack of continuity can be attributed to impact-induced disruption of layers as well as inhomogeneous rock accumulation.

A new depositional model is proposed for the effects of impact processes on accumulation of rock that is relevant to rock formation on early Mars. Rocks that accumulated during the phase of martian history with frequent impacts should: 1) be heavily fractured; 2) show highly heterogeneous characteristics laterally and vertically; 3) lack laterally continuous stratification; 4) contain breccia as well as finer-grained units; and 5) be highly altered geochemically if water was available. These characteristics are consistent with our current understanding of the Mawrth region. Thus, it is likely that many of the characteristics of Mawrth light-toned bedrock were shaped by impact processes.

Introduction

The Mawrth candidate landing site for NASA’s Mars Science Laboratory (MSL) is located on the western edge of Arabia Terra, on the heavily cratered Noachian highland terrain where it slopes NNW into Acidalia Planitia (Fig. 1). The proposed landing ellipse is nestled between a north-trending segment of Mawrth Vallis and Oyama Crater (Fig. 1; Grant et al. Planetary Space Sci, in press). It is a very attractive landing site due to its diverse clay mineralogy and an abundance of hydrous phases that reflect water-mineral interactions (Poulet et al. 2005, Loizeau et al. 2007, Wray et al. 2008, 2010, Bishop et al. 2008, Mustard et al., 2008; Poulet et al. 2008, McKeown et al. 2009, Farrand et al. 2009, Noe Dobrea et al. 2010). In addition, the Noachian age of the heavily cratered highlands (e.g. Tanaka 1986; Hartman and Neukum, 2001; Michalski and Noe Dobrea 2007) suggests that Mawrth will provide insights into very early processes shaping the surface of Mars.

The hydrous minerals at Mawrth show a stratigraphic zonation. The topographically lowest units in small craters near the landing ellipse show hydrous bands but no absorption features suggestive of clay minerals (Wray et al., 2008, 2010). Mg and Fe-rich clay mineral absorption features characterize overlying materials (Wray et al. 2008, Mustard et al. 2008, Bishop et al. 2008, McKeown et al. 2009), with Al-rich clays mixed with other hydrous minerals capping the clay-rich sequence (Wray et al. 2008, Mustard et al. 2008, Bishop et al. 2008, McKeown et al. 2009). Although finer compositional subunits are suggested by color variations (Loizeau et al., 2007), this stratigraphic sequence of clay minerals is observed throughout the Mawrth candidate landing site area (McKeown et al. 2009).
These clay-rich units are draped by a partially eroded dark mantling unit (Loizeau et al., 2007, 2010, Michalski and Noe Dobrea 2007, McKeown et al. 2009, Noe Dobrea et al. 2010) and are overlain by irregular patches of impact ejecta. Erosion of an overlying dark mantling unit and impact ejecta resulted in the exposure of the bedrock with extensive hydration bands in spectra observed from orbit.

Although extensive studies of the mineralogy in the Mawrth area have been published, the geomorphology of outcrops within and near the landing ellipse have not been extensively characterized with the notable exception of comparisons of meter-scale surface textures with mineralogic units (McKeown et al., 2009). Several early studies suggested that many Mawrth outcrops were finely layered based on MOC-resolution images (Malin and Edgett 2000, Poulet et al. 2005, Loizeau et al. 2007, Michalski and Noe Dobrea 2007). However, recent studies focusing on HRSC and HiRISE images have suggested that compositional and color variations in outcrops do not strictly follow physical layering (Loizeau et al., 2010). Thus, outcrop geometries have provided few clues to the processes leading to such clay-rich rocks. By characterizing the complicated relationships among fractured rock units exposed on near-horizontal surfaces where clay mineral signatures are strongest and on slopes where stratal geometries are better expressed, it may be possible to better understand the origins and distribution of hydrous minerals.

Here, I address the issues of the geometry of layering and the relationships between breccia in flat-lying outcrops within the context of crater formation and bedrock fracturing. I hypothesize that the outcrops are heavily influenced by impact processes, including the processes of impact debris emplacement, base surge deposits, and impact-induced fracturing.

Fracture Patterns Associated with Craters
The Noachian age of the heavily cratered highlands (e.g. Hartmann and Neukum 2001) and Mawrth (Tanaka 1986; Michalski and Noe Dobrea 2007) suggests that the site will provide insights into how impacts affected the surface of Mars. Within the Mawrth area, abundant craters reflect this old age. Many craters are embedded in the lower part of the stratigraphy, suggesting a long accumulation time for the older parts of the section (Michalski and Noe Dobrea 2007; Wray et al. 2008; Loizeau et al. 2010). The more finely layer upper section contains fewer syndepositional craters (Wray et al., 2008; Loizeau et al., 2010). However, the upper section is still younger than a significant number of currently exposed craters, making it prudent to understand the effects of cratering on the stratigraphy.

Impacts fracture host bedrock in addition to forming craters. They produce an initial compression wave that is followed by a rarefaction wave, producing substantial stress variations in the bedrock over very short time scales. The waves expand away from the impact site, and they reflect off the upper free surface, producing substantial variations in shear stress (e.g. Collins et al. 2004; Senft and Stewart 2009). These stresses deform the bedrock, producing melts, breccias, and fractures (e.g. Melosh, 1989). For simple craters (up to ~4 km diameter on Earth and ~7 km diameter on Mars), stresses are dominated by the compression and rarefaction waves associated with the impact and subsequent rebound. Complex craters have similar initial stresses, but are large enough that the transient crater walls collapse, creating a more complicated temporally and spatially varying stress field. The response of bedrock to the stress-induced shock waves can be observed around terrestrial craters (e.g. Shoemaker, 1963; Ackermann et al., 1975; Kumar, 2005; Kumar and Kring, 2008; Henkel et al., 2010), reproduced in experiments (e.g. Polanskey and Arhens, 1990; Arhens et al., 2002), and computationally modeled (e.g. Collins et al., 2004; Senft and Stewart, 2009). Fracture patterns reflect the interaction of the bedrock with the shock waves, producing fractures that approximately parallel the ground surface, radiate away from the crater, and form concentric rings. The extent of fracturing around craters often extends at least one crater diameter from the crater rim (e.g. Ackermann et al., 1975; Pohl et al., 1977; Pilon et al., 1991; Vermeesch and Morgan, 2004; Kumar, 2005; Salguero-Hernandez et al., 2010).

Data and Methods
Analysis of fracture patterns and layering was performed on images and DTMs from the High Resolution Imaging Science Experiment (HiRISE) and the Mars Reconnaissance Orbiter Context Camera (CTX). DTMs were draped with images and visualized using the virtual globe program Crusta (Bernardin et al., 2010a, 2010b), developed through the
Keck Center for Active Visualization in Earth Sciences (KeckCAVES) at the University of California, Davis. Crusta allows real-time manipulation of global-scale Mars data, which allows investigation of regional to local data. Features, such as layering, can be mapped in oblique views, allowing excellent evaluation of the three-dimensional characteristics of geologic features.

**Physical Features Observed in the Mawrth Candidate Landing Ellipse**

The Mawrth candidate landing site is situated on Noachian heavily cratered terrain (Fig. 1), and impact-related fracturing is to be expected in the bedrock. The site is immediately adjacent to the ~100 km diameter Oyama crater. Also, both fresh and degraded small craters are common, and evidence for cratering during accumulation of the lower section of bedrock is abundant regionally (Michalski and Noe Dobrea 2007; Wray et al. 2008; Loizeau et al. 2010). Extensive evidence for impact-related deformation is visible in CTX and especially HiRISE images in the form of fractured rock and breccia. Exposed rocks are brecciated with various geometries. In contrast to the diverse and abundant breccia types, continuous layering is rare. In this section, I first describe and interpret five classes of breccia and then document the paucity of laterally continuous layering.

**Diverse Fracture and Breccia Types**

Most of the exposures within the Mawrth candidate landing ellipse consist of light-toned bedrock with mesas of younger dark-toned “mantle” deposits (Fig. 1). The light-toned units show either relatively smooth but fractured outcrop surfaces or breccia textures. Here, I focus on the fracture patterns and breccia types in the light-toned bedrock. Dark-toned materials also consist of several units, some of which contain impact ejecta.

Within the landing ellipse, HiRISE images show 100 to >200 meter-long fractures that are linear and partially define >100 m polygons; conjugate fracture sets with linear fractures spaced ten meters or less; meter-scale polygonal fractures; arcuate pods of breccia; and irregular breccia with numerous textures that is not subdivided.

1. **Long Fractures in Sparse Networks.**

Linear fractures that are longer than 100 m are common in some areas (Fig. 2). These fractures occasionally abut each other and change direction abruptly, defining incomplete polygons. Rarely, they are oriented parallel to each other. Fractures are typically <5 m wide, although some are 10 m or more in width. Sometimes they form topographic ridges and are clearly composed of rock that is darker than the surrounding bedrock (Fig. 2B). In other cases, they form lows and may be filled with dark debris or rock. Most fracture fills are dark and some have light halos in the bedrock surrounding them; for most, it is difficult to determine whether they are filled with dark sediment or rock. However, the linear geometry and steep walls of high-standing fractures suggest that they are vertically oriented, nearly planar features.

**Interpretation:** The ridge forming cracks have geometries and weathering properties consistent with them being igneous dikes that intruded into bedrock lacking differential regional stress or to paleo-fluid flow through bedrock fractures (Wray et al., 2008). The parallel orientation of rare long fractures could reflect either: 1) differential stress during intrusion or 2) preexisting aligned bedrock weaknesses that templated the geometry of intrusions or fluid flow. The similarity of long fractures throughout the landing ellipse suggests that all such fractures may have the same origin even though only a few are planar and filled with resistant materials.

2. **Conjugate Linear Fracture Sets.**

Many outcrop areas contain parallel fracture sets that are co-linear over 100 to >200 m (Fig. 2B). Commonly two orientations are present within the bedrock, representing

![](figure2.jpg)
conjugate fractures sets. Additional unoriented fractures are also common in these areas. The spacing of individual fractures ranges from >10 m to 1 m or less, but they are commonly consistent within areas of several hundred square meters.

**Interpretation:** Conjugate fracture sets probably represent bedrock fracturing in response to differential horizontal stresses. Pervasive fracturing could be due to either proximity to an impact or tectonic stresses. The lack of orientation of fracture sets over areas on the order of square kilometers suggests that tectonic stresses were not uniform regionally, if present at all. Thus, fracturing in response to impact shock waves is a preferred interpretation. If this interpretation is correct, one would expect the fracture patterns to reflect the orientations of shock waves associated with nearby craters.

3. **Polygonal Fractures.**

There are two classes of polygonal fractures in light-toned units. The first class consists of approximately hexagonal blocks less than a few meters in diameter (Fig. 3A). Most consist of light colored polygons with darker fracture fill, but a few consist of dark colored polygons and light-colored fracture fill. Most polygons have >4 sides, and fractures defining them show little to no orientation on a scale of 10’s to 100’s of meters. The second class consist of approximately rectangular blocks less than a few meters in diameter (Fig. 3B). Through-going, oriented (first order) fractures define two edges of the blocks, whereas cross fractures are discontinuous. First order fractures in these polygonal areas are oriented across 100s of square meters of exposure. Both classes of polygonal fractures occur on irregular outcrop surfaces with meters of relief; they do not represent fracturing of specific layers within the bedrock (Fig. 3B).

**Interpretation:** Polygonal fracture patterns commonly reflect contractional processes such as cooling or water loss (e.g. Lachenbruch, 1962; Spry, 1962; Allen, 1985; Chavdarian and Sumner, 2010). Cracks propagate perpendicular to the local maximum tensile stress. Thus, uniform contraction in a homogenous material with no external stresses produces polygonal fractures that are not oriented on a scale of 10s of meters. In contrast, inhomogeneous materials, e.g. fractured rocks, have zones of weakness that will preferentially fail during contraction, and first order cracks will following these zones of weakness. Similarly, if the contracting material experiences an external stress, the direction of maximum tensile stress will be oriented by the external stress, and first order cracks will reflect this orientation. In both cases, second order cracks will subsequently accommodate contraction perpendicular to the first order cracks (e.g. Jagla and Rojo, 2002). Angles between first and second order cracks tend to be close to 90°, promoting rectangular polygons.

In the Mawrth landing ellipse, unoriented polygonal fractures are interpreted as forming from uniform contraction of hydrous bedrock as it lost water to the atmosphere. Polygonal fracturing during cooling seems less likely due to the abundance of hydrous mineral signatures observed from orbit in polygonally fractured materials (Loizeau et al. 2007, Wray et al. 2008, Bishop et al. 2008, McKeown et al. 2009).
Polygons with oriented first order fractures are also interpreted as contraction of hydrous bedrock due to water loss. In this case, the orientation of first-order fractures could be due to several processes. First, the contracting material could have been damaged prior to contraction, with first order cracks propagating along oriented zones of weakness. In contrast, first order crack orientations could be controlled by external processes. An applied stress from tectonics could have induced orientation of maximum tensile stresses, leading to oriented first order cracks. Alternatively, if the contracting layer overlies rock with a preferential fracture pattern, friction coupling between the contracting rock and underlying units could lead to first-order cracks following the orientation of the underlying bedrock fabric. Any or all of these processes could have influenced first order crack orientations in Mawrth bedrock. The second order cracks are interpreted to have formed to accommodate contraction parallel to the first order cracks.


Elongate areas of brecciated rock are common in the Mawrth landing ellipse (Fig. 4). They are often 20 to 50 m wide and 30 to >100 m long with ends that pinch to <1 m wide. These pods consist of blocks that often systematically vary in size from one edge to the other. The contact between brecciated and unbrecciated bedrock on one edge of the pod is gradational. Near this edge, the breccia consists of up to 4-10 m diameter blocks, and fractures separating blocks extend into unbrecciated bedrock (Fig. 4). Away from this contact, the blocks gradationally decrease in size, sometimes to below the resolution of HiRISE images. The contact between the smallest blocks and bedrock is sharp on the scale of 1 m (Fig. 4, 5). This contact is arcuate on the scale of meters to 10s of meters. Individual sharp contacts can extend for 100s of meters with multiple pods of breccia extending off either side of the surface. The arcuate sharp contacts also diverge and merge along strike and crosscut topography (Fig. 5B).

The blocks are angular and most of the larger ones show a fitted texture, i.e. the edges of neighboring blocks are parallel to each other. This relationship is less obvious or breaks down with the decrease in block size.

Interpretation: The similarity of blocks and surrounding rock as well as the extension of fractures from between blocks into intact bedrock suggest that the breccia formed via the in situ fracturing of bedrock. Several processes that brecciated bedrock include: 1) partial collapse of layers; 2) fault motion; 3) hydraulic pressure; and 4) shock stresses.

Partial collapse of layers can be caused by undercutting of a layer followed by gravitational collapse. This produces downslope transport of blocks with fractures sometimes extending into bedrock. This model predicts that blocks should either be topographically at or extend down slope from their layer of origin. If layers are steeply dipping, and they are undercut on the uphill side, one would expect a different geometry of brecciation than layers undercut on the downhill side. Within the Mawrth landing ellipse, breccia pods extend both up and down slope from the more intact bedrock with no difference in texture (Fig. 4B). Some of the blocks are clearly up slope from the associated fractured bedrock. Thus, gravitational collapse cannot account for many breccia pods. In addition, breccia pods can be more than 40 m wide in areas with less than 5 m of topographic relief. It is unrealistic for beds on the order a few meters thick to be undercut by tens of meters on nearly flat terrains.

Motion along faults can cause brecciation of host rocks. However, relationships between the edges of breccia pods and topography demonstrate that zones of brecciation are highly arcuate. In some cases, they extend over topographic highs as linear features, but show arcuate geometries within 20 meters along strike (Fig. 5B). Thus, the boundaries of the breccia pods are far from planar on the spatial scales required for fault motion. If the breccia pods did form in response to fault motion, faulting must have caused spatially variable shattering of the bedrock. Such a geometry is not consistent with the organized fault systems characteristic of tectonic-induced faulting.
Hydraulic brecciation can occur when fluid pressures are greater than the minimum principle stress on the bedrock (e.g. Phillips, 1972). The fluids induce tension fracturing and walls of fractures can explode inward if there is a sudden reduction of fluid pressure (Phillips, 1972). This type of brecciation is commonly associated with normal faults and hydrothermal systems. However, breccia zones almost always extend steeply upward due to the low density of fluids compared to rock (Phillips, 1972). In contrast, breccia pods commonly do not dip steeply into underlying bedrock.

Figure 5. Arcuate breccia pods defining apparent layering from HiRISE image PSP_006676_2045. A) Context image showing apparent layering at low resolution. B) Breccia pods crosscut topography and apparent layering continues into the smooth, unbrecciated rock in the lower left, but with a sinuous geometry (dashed line indicated by arrow). Light blue lines represent 2 m elevation contours. C & D) Breccia pods define apparent layering, but are not laterally continuous either on surfaces with low relief (C) or sloping surfaces (D) (figure5.jpg).
Also, their asymmetric geometry is not characteristic of hydraulic breccia, where both walls commonly shatter.

Shock stresses induced by impacts cause bedrock to fracture. The geometry of the breccia pods is at least superficially consistent with networks of fractures produced by impacts, including pseudotachylites, e.g. breccia with zones of impact-induced melt (e.g. Reimold, 1995; Dressler and Reimold, 2004; Riller et al., 2010). In this impact-brecciation model, the well defined surfaces would represent major fractures or dikes of impact-induced melt, and the breccia blocks extending away from these surfaces would be separated by smaller fractures or veins of melt. The gradational change in block size toward intact bedrock would reflect decreasing shear with distance from the main shear surface. The arcuate nature of the brecciation and its irregular lateral distribution would require spatially heterogeneous strain distributions on the meter to decameter scale. Heterogenous fracture distributions form when the rate of fracturing approaches the speed of compression waves in rock (e.g. Sagy et al., 2004), and computational model results suggest fractures are associated with impact craters (e.g. Collins et al., 2004; Senft and Stewart, 2009). However, the gradation in clast size and arcuate geometry have not been documented in impact-induced brecciation at the scales observed at Mawrth. In the absence of a geometrically similar model at the appropriate scale, an impact origin for the breccia remains speculative.

5. Irregular Large Block Breccia.
Irregular bodies of breccia are common within the Mawrth landing ellipse. These breccia bodies range in size from a few meters to more than 100 m across, and they have irregular shapes (Fig. 6). In some places, they cover large areas whereas in others, breccia is patchy. The boundaries of the breccia bodies can be both gradational and abrupt with surrounding less brecciated bedrock. Blocks within the breccia are irregular in size, commonly with clasts larger than several meters in diameter. Similar sized clasts can be concentrated into specific areas, but sometimes the blocks are poorly sorted. They can also exhibit fitted textures, but non-fitted fabrics are common as well. Relationships among breccia body shape, block sizes, and block textures are not sufficiently understood to divide these textures into multiple breccia types.

Interpretation: The large block breccia bodies may have multiple origins. Some have a geometry sufficiently similar to breccia pods that shock brecciation is a reasonable interpretation. Shock brecciation immediately below an impact is expected and might have formed some of these breccia bodies. In addition, fracturing due to other processes, such as hydraulic brecciation or forces related to deposition of impact ejecta on the bedrock, might also have formed some of the breccia. Finally, some of the breccia lacking fitted textures might consist of impact ejecta. Substantially more characterization of clast and fracture relationships is required to constrain these processes.

Stratification Styles
Stratification is poorly expressed in the Mawrth landing ellipse, although some layering is present in the walls of small craters and on the western slope of Mawrth Vallis.

Stratification on Low Relief Areas
Within nearly flat-lying light-toned bedrock, layering is
suggested locally in images with resolution of lower than 1 m/pixel, but inspection at maximum HiRISE resolution demonstrates that these areas are dominated by breccia between arcuate fractures (Fig. 5). Occasionally, a single change in albedo with a layer-like geometry can be traced for ~200 m, but multiple layers in the same area have not been identified in spite of extensive investigation. The low topographic relief of only a few meters over square kilometers does make identifying layers challenging if layering is present but poorly expressed in the bedrock.

Interpretation: The ubiquity of breccia and the absence of multiple layers within a single area suggests that there is little evidence for stratification in low relief areas, including most of the landing ellipse. The absence of evidence does not demonstrate the absence of stratification in these areas, however. The interpretation of the origin(s) arcuate breccia pods has substantial bearing on the interpretation of whether or not stratification is present and preserved. If the arcuate breccia pods represent impact deformation, stratification is likely not expressed in most of the landing ellipse outcrop patterns.

Stratification in Small Crater Walls
Small craters provide more topographic relief that allow evaluation of layering. In the two 1-2 km diameter craters within the ellipse, stratification is suggested in the outcrop patterns (Fig. 7, 8). When these areas are mapped in detail, however, most apparent layering either 1) does not represent planar features or 2) is not laterally persistent for more than a few 10s of meters.

Example 1: A prominent bench within the north, smaller crater shows very rapid changes in elevation over a few 10s of meters (Fig. 7). If this bench did represent a layer in the bedrock, the apparent dip based local topography points radially inward; the strike also rotates in the space of a few meters. On the east and northeast sides, the crater walls step back and dip very gently above this bench. Interpretation: The inward dip of the bench is not consistent with deformation associated with craters, which tend to warp surrounding layers upward. Rather, its ring geometry and inconsistent elevation is more consistent with it being an erosional remnant reflecting an ancient infill level in the crater. The infill top may not have had a constant elevation if deposition or previous erosion was dominated by eolian
depositional environments, neither channels nor lenses are apparent as expected for laterally variable depositional environments, and no systematical up—indicating features such as truncation surfaces or gradational outcrop textures are present as expected for environments that alternate between deposition and erosion. Rather, the apparent layering is consistent with the visual expression of fractures that extend obliquely through the outcrop. The only distinction between the features is their orientation. Thus, it is reasonable to interpret the more nearly horizontal features as fractures. The rare exceptions of laterally continuous, nearly horizontal layers could reflect depositional layering, although fracture or dike interpretations can not be excluded.

**Stratification in a 17 km Diameter Crater Wall**

Several 5-17 km diameter, relatively young craters occur near the landing ellipse (Fig. 1), providing the opportunity to examine layering. Layering is present in the walls of at least two of these craters (Wray et al., 2008; Loizeau et al., 2010). The 17 km diameter crater south of the proposed landing ellipse formed after Oyama Crater as demonstrated by the preservation of impact debris on the modern surface (Fig. 1).

The northern wall exposes several hundred meters of section (Fig. 9). (True stratigraphic thickness depends on bedding dip which can not yet be obtained for this section). The lowest well exposed strata for a resistant ledge that extends almost 4 km along the crater wall. To the east, it is buried by younger sediment and the west it extends beyond the edge of the HiRISE image. Layering within this unit is discontinuous on the scale of 100s of meters with beds pinching together and thinning out. At least one large-scale truncation of a package of layers is also present (Fig. 9B). Strata are upturned into this truncation, and the strata above it thicken into the low, suggesting syn-sedimentary erosion for the origin of the truncation rather than later deformation.

The well stratified interval is overlain by more than 100 m of poorly layered rock with abundant fractures (Fig. 9A). One dark band within this interval may be laterally persistent. This unit is in turn overlain by a set of resistant strata that can also be traced, with covered intervals, for ~4 km (Fig. 9). Again, individual stratigraphic packages within this unit are not laterally continuous even though the stratigraphic interval is laterally persistent. Above the upper resistant unit, outcrop consists of light-toned rock with patches that are well laminated that grade laterally into unlaminated zones with extensive fracturing. This unit is extensively faulted and folded in places (Fig. 9C). This deformation does not appear to extend into lower strata.

**Interpretation:** The lateral persistence of some stratal units for kilometers around the crater wall suggests intervals of consistent rock accumulation across the local landscape. In contrast, the lateral discontinuity of stratal subunits with the resistant units suggests that sedimentary processes varied within that landscape. The large-scale truncation of ~20 m of upturned strata suggests that the strata were deformed soon after being deposited. The syn-sedimentary timing of such deformation is demonstrated by the infilling of
topography by the overlying strata (Fig. 9B). Overall, these features imply a regionally persistent environment with variable conditions, including possible deformation of layers. The origin of the poorly layered bedrock between the resistant units is unclear as no features were identified to distinguish between a massive origin and post-depositional destruction of layering.

The deformation of the upper half of the stratigraphic column can be attributed impact processes related to the formation of the crater exposing the strata. The increase in deformation upward is consistent with the response of bedrock to impact stresses near the surface where there is little overburden pressure. This deformation is laterally variable, with better preservation of layering in the center of the north wall and overprinting of all layering to the east (Fig. 9A).

**Stratification in the West Bank of Mawrth Vallis**

The west bank of Mawrth Vallis immediately east of the Mawrth candidate landing site is stratified (Fig. 10). This region slopes from west to east, and exposes bedrock with apparent layering over a wide area. When these areas are examined at maximum HiRISE resolution, the apparent layering is sometimes defined by albedo variations and sometimes by zones of breccia (Fig. 10 A, C). Albedo variations define a few apparent layers that dip to the east more steeply than the slope of the vallis. Most well defined layers are slightly darker gray. However, one prominent dark band is present throughout the outcrop. In places, it is broadly folded, and forms short dip slopes with down to the east (Fig. 11). This band cuts up and down topography and is deformed around knolls. Most other layering is defined by breccia with three different textures. Some layers consist of narrow zones of broken rock with an even apparent width (Fig. 10A). These breccia-layers are most common on slopes and define fairly laterally continuous layers, sometimes more than 100 m. Elsewhere, layers are defined by laterally continuous subparallel fractures (Fig. 10C). These do not precisely parallel layers defined by color variations, and they merge and split, creating an irregular network of fractures that are distinct from bedding. Finally, large breccia blocks in arcuate pods define a coarse apparent

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**Figure 9.** Stratification in a 17 km diameter crater from HiRISE image ESP_016829_2040. A) A 50 m thick package of strata extends for almost 2 km near the base of the outcrop. A second continuous resistant interval is indicated by arrows. B) Detail of lower stratified unit, with bedding planes (outlined) truncated and overlain by subsequent beds. C) Detail of the upper stratigraphy showing the extensive brecciation. This brecciation is consistent with deformation of the strata due to the impact that formed the 17 km diameter crater (figure9.jpg).
layering in topographically flat areas (Fig. 11A). As described above, the arcuate breccia pods do not define continuous layers even though these are sandwiched between two zones with better layering.

**Interpretations:** The albedo variations are consistent with compositional layering, which could be bedding. Alternatively, igneous dikes intruded along a structural trend can not be excluded. In either case, the layering is deformed around knolls. The rounded geometry of the knolls and the deformation of strata suggest that they might represent bedrock deformed below impact craters that are now eroded away. Alternatively, the deformation could have been widespread at a topographically higher level than most of the exposure today, leading to the apparent folding around the topographically high knolls.

Variations in breccia texture likely reflect variations in lithology and brecciation processes. Most of the breccia textures are similar to those observed in crater walls. However, the arcuate breccia pods provide a particularly interesting constraint. Layering dips to the east both east and west of the low containing the pods. Thus, if layers were present in the bedrock intersecting the flat area, they should intersect the surface and be visible. The absence of any layering in these flats strongly suggests that the bedrock with the arcuate breccia pods is not layered.
Overall, the stratification expressed in the slope of Mawrth Vallis, as well as impact craters and other exposures in the area, gives a consistent story of variable accumulation processes and substantial deformation. Deformation is expressed in both brecciation of the bedrock and by faulting and folding of layers, particularly in association with impact processes.

**Discussion**

Rocks near and in the Mawrth landing ellipse contain a number of features that can be used to constrain their origins. The paucity of laterally continuous layers suggests that depositional process were spatially heterogeneous. Vertical variations in outcrop characteristics suggest depositional variations through time. Rare, very coarse depositional
breccia (with blocks >1 m in diameter) suggests high energy transport or gravity collapse of bedrock. Unlayered units suggest very rapid deposition or extensive diagenetic alteration. Extensive brecciation of outcrop suggests substantial post depositional stresses and is consistent with fracturing in response to shock waves. These constraints, as well as the Noachian age of the Mawrth area, strongly suggest considering a depositional model that includes impact processes as an important depositional process.

Impact Model for Rock Accumulation
Impacts were abundant early in the history of Mars, and they disrupted existing geological relationships, redistributed rock, and fractured bedrock. The resulting exhumation, deposition, and deformation can lead to a "cratered volume" of rock (Malin and Edgett 2000; Edgett 2005; Malin et al. 2010), and craters are embedded in the lower stratigraphy of Mawrth (Michalski and Noe Dobrea 2007; Wray et al. 2008; Loizeau et al. 2010). If one considers the effects of these processes, a basic depositional model for a cratered terrain can be developed. Assume the crust initiates as igneous rock; early impacts would brecciate the crust and remelt parts of it (Fig. 12). Lava flows would be produced by larger impacts, as would hydrothermal systems if water is available. Debris excavated from craters would be distributed across the surface, and a zone of fractured rock would surround the crater. Impact debris and shattered rock would provide a source of sediment for wind and/or water reworking. Base surges and fallout from more distant impacts and pyroclastic eruptions likely add sediment to a given site. Through time, impacts would produce effects that vary with impact.

**Figure 12.** Conceptual model for the accumulation of rock in the Mawrth area based on impacts, airfall sediment accumulation, and eolian processes. These schematic diagrams provide the simplest accumulation model based on only three processes: 1) impacts for brecciation and ejecta deposition, 2) air fall deposition, and 3) wind erosion. Additional processes, such as fluvial erosion and deposition, hydrothermal activity, and lacustrine deposition, are likely as well. Because these processes are spatially variable erosion and deposition, they would increase the complexity of stratigraphy if they were active. [figure12.png]
magnitude and host rock characteristics, but would share the basic characteristics of disrupting existing geological relationships, redistributing rock, and fracturing bedrock.

Over hundreds of millions of years, impacts would lead to the accumulation of an irregular mix of sediment. Layering would frequently be discontinuous because impact debris deposition is spatially heterogeneous and impact related damage would disrupt layering (Fig. 12). Craters also truncate preexisting layers. Eolian processes would redistribute bedrock and, if the landscape was topographically complex, as expected for cratered terrains, the distribution of eolian deposits would also be variable. Thus, the only processes that might produce continuous layers would be base surge or air-fall deposits from volcanic eruptions, distant impacts, or dust storms. These would drape the irregular landscape and be subject to subsequent reworking (Fig. 12). Additional processes affecting stratigraphy could include melting induced by impacts, hydrothermal activity induced by impacts, and other sedimentary processes such as fluvial transport or lacustrine deposition in craters. Because these processes should vary locally, they would likely increase the complexity of stratigraphy if they were active. The net results would vary depending on the details of deposition and deformation at any given site, producing heterogeneous deposits that accumulate over hundreds of millions of years.

Water probably affects most characteristics of impact-related rock accumulation. Fractured crust is an effective aquifer for either liquid water or ice. Impacts excavating bedrock with substantial water would produce water-rich impact ejecta. Impact-derived heat would more easily melt bedrock because water lowers melting temperatures. Heat would induce convection in the aquifer, with hydrothermal activity within the crater. Combined heat and increased water flow would accelerate alteration reaction rates in both neighboring bedrock and ejecta. These processes would occur in the vicinity of each impact, leading to early alteration of impact materials and progressive alteration of bedrock with each subsequent impact. The extent of alteration and the composition of alteration products would vary spatially and depend on water composition, water availability, temperature, and bedrock composition. Unless impact induced alteration was regionally extensive due to sufficient warm water flow, this model predicts heterogeneous alteration. And heterogeneous physical properties are also predicted by the impact model for rock accumulation. Thus, most deposits that accumulated during the early solar system, e.g., during the period of heavy bombardment, would be spatially heterogeneous and show evidence for diverse depositional and alteration processes.

Evaluation of the Impact Model for Mawrth

Outcrops in the region of the Mawrth candidate landing ellipse show significant brecciation, discontinuous layering, depositional breccia, and pervasive alteration. Thus, they are generally consistent with the proposed model for impact-influenced rock accumulation. In other words, they may be a case example of a heavily cratered volume of rock (sensu Malin and Edgett 2000; Edgett 2005; Malin et al. 2010). None of the observations made to date are inconsistent with this model.

In addition to the general expectation that Mawrth bedrock was influenced by impacts, Oyama crater lies immediately west of the Mawrth candidate landing ellipse. This ~100 km diameter crater should have fractured surrounding bedrock for at least 10’s of km, well into Mawrth Vallis to the east. Thus, it is extraordinarily unlikely that the bedrock in the Mawrth landing ellipse escaped brecciation from the impact creating Oyama crater. The effects of such large impacts on bedrock are complicated, so it is difficult to determine how many of the features observed in the area can be attributed to the Oyama impact. However, abundant remnant craters throughout the area suggest that impacts have been a significant factor in shaping bedrock in the Mawrth region. Better characterization of the distribution and orientations of fracture patterns and brecciation may help distinguish the effects of the Oyama impact from those of the numerous smaller impacts.

In contrast to the physical layering, the distribution of clay minerals shows a more systematic regional pattern with Al-rich clay minerals overlying Fe, Mg-rich clay minerals (Wray et al. 2008, Mustard et al. 2008, Bishop et al. 2008, McKeown et al. 2009). Various models have been proposed for the distribution of hydrous minerals including deposition of layers of different composition, post depositional alteration of bedrock by surface water, and post depositional alteration of bedrock by groundwater (Michalski and noe Dobrea, 2007; Loizeau et al., 2007, 2010; Bishop et al., 2008; Wray et al., 2008; McKeown et al., 2009; Michalski and Fergason, 2009; noe Dobrea et al., 2010). The impact model for rock accumulation is consistent with all of them except deposition of hydrous minerals from sedimentary processes such as in a standing body of water or by regional fluvial systems. Alteration by groundwater and hydrothermal processes are both expected with the proposed model for rock accumulation, making widespread alteration of bedrock likely. In addition, alteration from surface waters could occur both between impact events and after accumulation of the existing rock. Clay minerals could also locally accumulate in crater lakes. Thus, the impact model for rock accumulation complements and supports previous models for origins of the hydrous minerals, with the exception of those that require clay mineral deposition in a regional lake or sea.

Conclusions

Bedrock near the Mawrth candidate landing site is highly fractured and brecciated. Several fracture patterns and breccia types are consistent with shock deformation due to impacts. Very few areas near the landing ellipse have layers that are laterally continuous for more than 100 m. This lack of continuity can be attributed to impact-induced disruption of layers as well as inhomogeneous deposition. Rare beds of breccia with very large blocks suggests occasional very high energy depositional processes. Thus, it reasonable to
consider an impact-dominated depositional model for the physical features of outcrops in the Mawrth region.

**Directory of supporting data**

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