Reconstructing the distribution and depositional history of the sedimentary deposits of Arabia Terra, Mars

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A R T I C L E   I N F O

Article history:
Received 10 January 2012
Revised 3 May 2012
Accepted 3 May 2012
Available online 14 May 2012

Keywords:
Mars
Geological processes
Mars, Surface
Mineralogy

A B S T R A C T

The sedimentary deposits of Meridiani Planum formed during the martian climate transition at the Noachian–Hesperian boundary between warm–wet and cold–dry conditions, and give valuable insight into how and when this transition occurred. We show that these deposits share characteristics with sedimentary outcrops across Arabia Terra. Despite near-ubiquitous dust cover across much of Arabia Terra, spectral signatures of polyhydrated sulfate minerals resembling those in Meridiani were identified in Schiaparelli and another unnamed crater. An erosional morphology analysis using both image and topographic data was then used to identify morphologies characteristic of Meridiani-type deposits and catalogue their occurrences throughout Arabia Terra. The occurrences of deposits with compositions and morphologies resembling the Meridiani deposits throughout Arabia Terra suggest that Meridiani-type sedimentary rocks were once more widespread. Elevations of the eroded remnants were used to reconstruct the pre-erosional paleo-surface of the deposits. Within this study area, these deposits once covered ~2.5–3.6 × 106 km2 and represent an eroded volume of 0.9–1.7 × 106 km3 of sediment. Crater retention ages using craters of a range of preservation states and stratigraphic levels reveal that the deposits were laid down and subsequently eroded during a ~270 Myr period between ~3.83 and 3.56 Ga. The deposits formed following the transition from fluvial dissection to evaporite deposition at the end of the Noachian. The high erosion rates (~3 × 10−6 m/yr) suggest that Mars may have maintained a thick atmosphere relative to today even as it dried out in the Early Hesperian.

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1. Background and introduction

The nature and timing of the transition of Mars’ climate from its early warmer and wetter state to the cold and dry environment of today remains one of the most significant outstanding questions in the geologic history of Mars. The end-member states of the climate are well represented in the geologic record, but the transition itself is not as well documented. This climate transition occurred roughly around the Noachian–Hesperian boundary and was characterized by major shifts in geologic processes. The Noachian period was characterized by the formation of fluvial valley networks (Hynek et al., 2010), phyllosilicate minerals such as montmorillonite, saponite, and Fe-chlorites (Murchie et al., 2007b; Mustard et al., 2008), and elevated erosion rates relative to those of today (Golombek et al., 2006). The formation of dendritic valleys likely required the stability of liquid water at the surface and a thicker atmosphere to facilitate precipitation and high erosion rates.

At the end of the Noachian and beginning of the Hesperian epochs (~3.7–3 Ga; Hartmann and Neukum, 2001), the climate began to shift toward more arid conditions as evidenced by a switch from phyllosilicate- to sulfate evaporite-dominated mineral formation. In addition to the aridification of the climate, the atmosphere was likely being stripped away throughout early Mars’ history due to a combination of impact ejection, solar wind sputtering (perhaps facilitated by loss of the dynamo; Dehant et al., 2007), adsorption onto the regolith, and collapse onto the polar caps (Brain and Jakosky, 1998). The changing climate led to lower erosion rates and dropping temperatures, ultimately leading to the cold and hyper-arid conditions of the Amazonian. The transition from Noachian to Hesperian climatic conditions was likely complicated, with changes in surface temperature, pressure, and humidity likely occurring at different rates over different time scales. Elucidating these intricacies requires a geologic record of the conditions present during the climate transition. However, over much of the planet this transition manifested itself only in a slowing and cessation of aqueous activity, and thus did not leave a distinct imprint on the surface. However, in some locations the changing climate resulted in a transition from erosion to deposition, allowing
the preservation of a geologic record of the changing conditions. Such a record is present in the sedimentary rocks of Meridiani Planum and the surrounding Sinus Meridiani region, which formed during this climatic transition at the Noachian–Hesperian boundary (Arvidson et al., 2006).

The Opportunity Rover documented reworked evaporite deposits within Meridiani Planum that are generally inferred to have formed in a playa environment (McLennan et al., 2005; Grotzinger et al., 2005; Squyres et al., 2006) and span the Late Noachian to Early Hesperian periods (Arvidson et al., 2006; Lane et al., 2003). The rover-observed outcrop, named the Burns Formation, is a sulfate- and hematite-rich sandstone unit exposed in crater walls beneath the hematite lag deposit now covering Meridiani. The Burns Formation was found to be layered on various scales (<1 mm laminations to >1.5 m dune cross beds) and to contain up to 40% sulfates in both the grains and cements (Squyres et al., 2006; Glotch et al., 2006). The rocks were interpreted as having formed in an active playa/dune field depositional setting based on the composition and sedimentary structures (Squyres et al., 2006). Geochemical and elemental evidence from the sulfates indicated an evaporitic origin and also supports the interpretation of an arid playa environment (Grotzinger et al., 2005). Opportunity's investigations also detected jarosite $[\text{KFe}_3\left(H_2\text{O}\right)_6\text{SO}_4]$, which precipitates from acidic solutions (rather than the water of neutral to high pH suggested by many of the phyllosilicates; Mustard et al., 2008) and provides unambiguous evidence that the sulfate salts precipitated from liquid water (Squyres et al., 2006). Extensive diagenesis is documented by the presence of hematitic concretions, the presence of crystal molds, and a diagenetic contact in outcrop view (McLennan et al., 2005). The hematite concretions cover the plains around the Opportunity landing site and are interpreted as an erosional lag deposit within Meridiani Planum (Golombek et al., 2006).

Collectively, these observations indicate that aeolian grains were sourced from an evaporite-cemented altered basalt, deposited in a playa/dune field environment, and then cemented in dunes and inter-dune areas by sulfate evaporites and groundwater. The groundwater moving through the system later caused substantial diagenesis. Such characterizations of the environments present in Meridiani are important, but provide direct information for only a small portion of the martian surface over the brief time period of their deposition. To better understand the broader implications of these deposits, it is necessary to relate these relatively well-characterized sulfate outcrops explored by Opportunity in Meridiani Planum with orbital remote sensing observations covering a much broader area, in order to identify the full suite of related sedimentary deposits formed during this crucial climate transition.

Outside of Meridiani, layered sedimentary rock outcrops are observed throughout much of the Arabia Terra region (Malin and Edgett, 2000; Edgett, 2005). These abundant outlier deposits suggest that the Meridiani etched terrain was once more laterally extensive, but was subsequently eroded (Hynek et al., 2002; Hynek, 2004). Superficially, these outcrops share many similarities with the layered outcrops of the etched terrain (Hynek et al., 2002; Hynek, 2004) associated with the well-characterized Meridiani deposits. A geomorphic study of one subset of these layered deposits in northeastern Arabia Terra found evidence that they have experienced significant erosion, including pedestal craters and inverted relief (Fassett and Head, 2007). However, it is not known whether these widely distributed deposits across Arabia Terra shared a similar origin with the Meridiani deposits.

In this study, we examined outcrops throughout the Arabia Terra region of Mars with the objective of determining if they are related to those in Meridiani. The study area (black outline, Fig. 1a) consists of the majority of Arabia Terra, but excludes areas known to have experienced significant later modification such as the outflow channels and chaos regions to the west and fretted terrain to the north. We used Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) data to characterize the mineralogy of the Meridiani-type deposits and then to find similar spectra in outlying deposits across Arabia Terra. The sulfate evaporites of Meridiani formed in a unique depositional setting (McLennan et al., 2005; Grotzinger et al., 2005) and the presence of sulfates in other outcrops is evidence that those outcrops may share a similar depositional history to Meridiani.

However, over most of the region the spectral evidence for the mineralogy of the deposits is obscured by dust (Fig. 1b). We thus performed a morphological analysis to relate outlying deposits to those in Meridiani. The Meridiani deposits, because of their distinctive depositional and erosional environments and variable induration levels, produce distinctive erosional morphologies. The presence of these erosional morphologies in outlying deposits indicates similar induration, deposition, and erosion histories.

Linking outlying deposits with those in Meridiani shows the vast extent of Meridiani-type deposits across Arabia Terra. These remnant deposits were used to reconstruct the original extent and eroded volume of the Meridiani-type deposits. The results indicate that many sedimentary rocks across Arabia Terra are genetically related to those in Meridiani Planum, and that a depositional environment similar to the playa environment inferred for Meridiani Planum once covered up to $3.6 \times 10^9$ km$^2$. Crater age dating was performed to better place the depositional and erosional history of the Meridiani-type deposits within the geologic history of Mars. By focusing on a sediment-filled basin with a large concentration of preserved pedestal craters, we are able to constrain the main deposition and erosion period to between ~3.8 and 3.5 Ga. Combined with evidence from other studies, this
indicates a transition from valley network incision to evaporite deposition at the Noachian–Hesperian boundary, and erosion rates following the end of sulfate deposition comparable to those inferred for the Noachian period of Mars. By linking these outlying deposits to those in Meridiani, we are able to shed light on the distribution, timing, and implications of Meridiani-type sulfate deposition on early Mars.

2. CRISM hyperspectral image analysis

2.1. Background and methods

The presence of sulfate minerals in Meridiani Planum and northern Sinus Meridiani is well documented from both rover and orbital observations (McLennan et al., 2005; Gendrin et al., 2005; Wiseman et al., 2007). These minerals are a defining characteristic of these rocks, related to their formation as evaporitic playa deposits, and thus may be used to identify rocks of similar type and origin. CRISM hyperspectral data in the visible and near-infrared wavelengths can be used to identify sulfate minerals from orbit (Murchie et al., 2007a) and thus relate outlying sedimentary rocks in Arabia Terra to those in Meridiani.

We used CRISM data to identify exposures of hydrated sulfates in the Arabia Terra sedimentary deposits. Previous studies identified the spectral signature of both mono- and polyhydrated sulfates associated with the Meridiani deposits (Gendrin et al., 2005; Wiseman et al., 2007). Monohydrated sulfates are characterized by spectral absorptions at 2.1 and 2.4 μm (e.g., kieserite, Fig. 2), while polyhydrated sulfates show absorptions at 1.9 and 2.4 μm (e.g., magnesium sulfate, Fig. 2) (Cloutis et al., 2006). Absorptions at 1.9 μm indicate hydration in minerals (Cloutis et al., 2006). Unfortunately, CO₂ in Mars’ atmosphere has a strong absorption feature around 2 μm (Smith et al., 2009) that is not always completely removed by atmospheric correction (McGuire et al., 2009). This absorption band can obscure or mask detections of 1.9 and/or 2.1 μm features and make positive identification of sulfate or hydrated minerals difficult. The abundance of dust in Arabia Terra is also an issue. A thermal inertia map (Putzig and Mellon, 2007) of the study region (Fig. 1b) shows that much of the northeast portion of Arabia Terra has low thermal inertia, indicating unconsolidated, fine-grained dust at the surface. Even a few tens of microns-thick layer of dust will prevent detection of the bedrock below it.

The hyperspectral datasets analyzed here comprise 25 full-resolution targeted (FRT) and 19 half resolution long targeted (HRL) CRISM images. These images have spatial resolutions of approximately 18 m/pixel and 36 m/pixel, respectively, and spectral resolutions of ~6.55 nm/channel with 545 separate channels between 362 and 3920 nm (Murchie et al., 2007a). CRISM observations were obtained in I/F (the ratio of the measured intensity to the solar flux at the top of the atmosphere) format. Data sets were atmospherically corrected by making use of observations over the Olympus Mons volcano, with the large amount of relief allowing for the calculation of the atmospheric spectrum due to the difference in path lengths of the light through the atmosphere (McGuire et al., 2009).

Spectral parameter maps were then created for each CRISM image as a first-order indicator for sulfate or hydrated minerals, using band depth calculations to detect known absorption features at the wavelengths of interest for sulfates and other hydrated minerals (Pelkey et al., 2007). The SINDEX parameter highlights the concavity caused by absorptions at 2.1 and 2.4 μm signifying the presence of polyhydrated sulfates:

\[
\text{SINDEX} = 1 - \frac{R_{2100} + R_{2400}}{2 R_{2290}}
\]

In this and all subsequent equations, the “RXXXX” terms indicate the surface reflectance value in the atmospherically corrected CRISM band at the nearest wavelength in nanometers (e.g., R2400 is the surface reflectance at 2400 nm or 2.4 μm).

The 1.9 μm band depth parameter calculates the absorption due to the presence of water:

\[
D_{1900} = 1 - \frac{R_{1973} + R_{1927}}{R_{2006} + R_{1874}}
\]

In this and all subsequent equations, the “DXXXX” term signifies the band depth calculated at that wavelength, in nanometers. The 2.1 μm band depth calculation performs the same operation, but around the 2.1 μm value:

\[
D_{2100} = 1 - \frac{0.5 (R_{2120} + R_{2140})}{0.375 R_{1930} + 0.625 R_{2250}}
\]

Parameter maps were made for over 70 CRISM observations by placing the SINDEX parameter in the red channel, the 2.1 μm band depth in the green channel, and the 1.9 μm band depth in the blue channel. In these parameter maps, red to purple/magenta colors indicate the presence of polyhydrated sulfate minerals only, bright green indicates the presence of monohydrated sulfate minerals only, blue indicates the presence of generally hydrated minerals, and yellow indicates the presence of mixed polyhydrated and monohydrated sulfate minerals.

Images that showed promising parameter maps for sulfates and other hydrated materials were then marked for detailed spectral analysis. The possible presence of incompletely removed atmospheric effects requires that spectra be viewed as ratios in order to elucidate their composition. To create a ratioed spectrum, a spectrum from the material of interest was simply divided by a “spectrally neutral” portion of the scene from the same data column (ensuring that they were obtained by the same CCD chip on the detector and therefore have similar instrument effects). This reduces the background noise and remaining atmospheric effects, leaving only the signature of the surface material.

2.2. Northern Meridiani Planum

In order to link the CRISM spectra to outcrops near the Opportunity Rover, we produced a type-locality parameter map over a previously documented sulfate occurrence in northern Meridiani (Wiseman et al., 2010). The surface materials in this scene are part of the large etched terrain deposits that are contiguous with the well-documented sulfates at the MER Opportunity landing site (Hynek, 2004), and thus link the orbital observations to ground truth. The scene (Fig. 3a) is shown as a false color1 image with

![Fig. 2. Library spectra of magnesium sulfate (a polyhydrated sulfate) and kieserite (a monohydrated sulfate) from the CRISM Analysis Tool spectral library.](image-url)
the 2.5295 μm band in the red channel, the 1.5066 μm band in the green channel, and the 1.0800 μm band in blue. The stars and Xs correspond to the numerator and denominator spectra, respectively, of the ratioed spectra in Fig. 4. All parameter maps (bottom row) are represented with the SINDEX parameter in red, the 2.1 μm band depth in green, and the 1.9 μm band depth in blue. Red areas indicate polyhydrated sulfates, yellow areas a mix of monohydrated and polyhydrated sulfates, and blue to purple areas indicate hydration. All scale bars are 250 km. (a and d) False color image and parameter map of FRT00004616. Inset map at lower right shows the scene (black dot) in relation to the etched terrain (shaded areas). (b and e) False color image and parameter map of FRT0000931E. Inset map at lower right shows the scene (black dot) in relation to Schiaparelli crater. (c and f) False color image and parameter map of HRL000005F7. Inset map at lower right shows the scene (black dot) in relation to Crater X.

Two ratioed spectra were extracted from areas identified as polyhydrated (red) and mixed monohydrated and polyhydrated (yellow) in the spectral parameter map (Fig. 4a and b, respectively). The polyhydrated spectrum shows an absorption at 1.9 μm, while the 2.4 μm feature is more of a shelf than a defined absorption band, consistent with minerals like polyhydrated magnesium sulfates (Fig. 2). The spectrum from the mixed monohydrated and polyhydrated sulfates exhibits a prominent 2.1 μm absorption, indicating that the mix is likely dominated by monohydrated sulfates. This spectrum also shows a well-defined
absorption band at 2.4 µm rather than a shelf, which is characteristic of kieserite (Fig. 2). The northern Meridiani location provides a reference for what characteristics are most useful in identifying rocks with similar mineral signatures to those in Meridiani. Using these spectra from well-characterized surfaces in the Meridiani etched terrain region as a guide (Wiseman et al., 2010), we examined CRISM data from outlying areas in Arabia Terra in order to search for additional exposures of sulfates.

2.3. Schiaparelli crater

We used CRISM data to look for evidence of hydrated sulfate signatures outside of the known Meridiani deposits in more distal reaches of Arabia Terra. Schiaparelli crater is a 460 km diameter impact basin in southeastern Arabia Terra. It is centered at 3°S 16°E, over 400 km to the southeast of the edge of the Meridiani etched terrain. The false color image (Fig. 3b) shows a bright white cap unit and a green (in false color) unit that is less pronounced and darker in color than in that in Fig. 3a. The scene is mostly covered by dark gray material that forms dunes in the northwest portion of the image and covers the white cap unit in the southern and eastern portions. The aeolian deposits and/or dust making up this gray material obscure the spectral signature of the underlying bedrock. The red or magenta coloring in the parameter map (Fig. 3e) indicates a 2.4 µm absorption and thus the presence of polyhydrated sulfates within and on the slopes below the bright white cap material. The lack of yellow or bright green in the parameter map indicates that there are no monohydrated sulfates detected in this parameter map.

The prevalence of aeolian material made finding a clean outcrop for spectral analysis difficult. The area that provided the clearest detection of sulfates occurs in a patch of underlying material in the western portion of the false color image (star in Fig. 3b). This looks to be an erosional window where the white cap material has been removed exposing green material beneath. The ratioed spectrum (Fig. 4c) was identified as a polyhydrated sulfate signature. It has a prominent absorption band just above 1.9 µm and a drop around 2.4 µm that flattens into a shelf at longer wavelengths. The continuous slope across the 2.1 µm region of the spectrum supports the absence of monohydrated sulfates as seen in the parameter map. The detection occurs in a similar textured and colored material as the polyhydrated sulfate detection in the Meridiani scene. The two locations share a similar mineralogy, as well as comparable morphological characteristics that suggest related depositional environments may have existed in both locations.

2.4. Unnamed crater at ~9.0°N 12.3°E (Crater X)

An unnamed crater located at 9.0°N 12.3°E (hereafter referred to as Crater X) was also examined. The unit of interest is located near the northeast edge of the scene and appears teal in the false color image (Fig. 3c). This scene is noticeably different from the previous two scenes in that there is no white cap unit and the target unit isn’t green in false color. Therefore, the position in the stratigraphic column here may differ from that in Meridiani and Schiaparelli. Crater X is very degraded and partially filled with dark sand or dust. The deposit of interest is a small remnant left on the crater floor. The tealt outcrop in the false color image is red or magenta in the parameter map (Fig. 3f), indicating the presence of polyhydrated sulfates. No monohydrated sulfates were detected in this scene. The large blue patches in the parameter map indicate areas of high hydration within the dark sand area. The parameter map may be detecting outcrops of hydrated bedrock that are not distinct in the false color image due to poor color contrast between bedrock and the dark crater fill at the wavelengths of the false color image.

Spectra from this scene exhibited variability in data quality. The best sulfate detection spectrum obtained from the teal unit (Fig. 4d) shows a typical 1.9 µm hydration feature (a shelf centered on 1.9 µm that ranges from about 1.85 to 1.95 µm wavelengths) for polyhydrated sulfates. This unit displays a 2.4 µm feature that is slightly atypical for polyhydrated sulfates, having the same initial sloping shelf starting at ~2.39 µm wavelength but then dropping off more steeply and in a more convex downward shape. This detection is therefore less robust than the one in Schiaparelli crater, but is sufficiently similar to laboratory spectra to support its identification as polyhydrated sulfate material.

2.5. CRISM analysis summary

Analysis of CRISM data aided in the identification of hydrated sulfate minerals both north of the Meridiani Planum region and elsewhere in Arabia Terra. The low thermal inertia of most of northeastern Arabia Terra indicates that the surfaces here are dust covered and therefore impede the use of CRISM data. However, two confident sulfate detections were made outside of Meridiani Planum despite nearly ubiquitous dust cover. Analyses identified hydrated sulfate deposits in Schiaparelli crater and Crater X that are compositionally similar to those in the well-characterized Meridiani deposits. These new sulfate identifications are located ~400 and 480 km from the edge of the Meridiani etched terrain, respectively, and demonstrate that deposits with polyhydrated sulfate mineralogies may have been much more widely distributed across Arabia Terra than previously recognized. In addition to these detections, Andrews-Hanna et al. (2010) also identified polyhydrated sulfates within crater fill deposits in Arabia Terra located 375 km from the eastern edge of the Meridiani etched terrain. The sulfate-rich rocks in Meridiani were interpreted as having formed in an evaporative playa environment, and the similar mineralogies at these more distant localities suggest that similar environments may have also existed in these areas. This is in turn evidence for an active hydrologic cycle across the Arabia Terra region during the time these evaporites were forming.

3. Morphology analysis

3.1. Introduction

Given the limitations inherent in spectral analyses due to the ubiquitous dust cover over much of Arabia Terra, it is necessary to rely on other methods to identify sedimentary deposits that share characteristics with those in Meridiani. The composition, erosional properties, and geological setting of the Meridiani deposits led to those rocks having distinguishing erosional morphologies. These can be used as identifying characteristics in comparing outlying deposits with those in Meridiani. These morphologies may be evident even in cases where a thin cover of dust obscures the surface spectra, making them more widely applicable than CRISM analysis. However, while the composition and degree of induration of the rocks likely strongly controls the erosional style, such relative erosional styles should be used with caution.

Both the Meridiani etched terrain (Hynek et al., 2002; Hynek, 2004; Edgett and Malin, 2002; Edgett, 2005) and layered deposits previously identified in northeastern Arabia Terra (Fassett and Head, 2007) exhibit evidence for significant erosion. We here perform a systematic analysis of the erosional morphologies both in Meridiani and throughout Arabia Terra using a variety of datasets. As erosional morphologies of interest occur at many scales, HiRISE 25 and 50 cm/pixel data (McEwen et al., 2007) were supplemented with Thermal Emission Imaging System (THEMIS) 230 m/pixel daytime infrared (Christensen et al., 2004) and Mars Orbiter Laser Altimeter (MOLA) topography data (Smith et al., 2001). Eight classifications of erosional morphologies were defined from the
Meridiani Planum and Sinus Meridiani regions: etched terrain, distinctive layering, buttes, knobs, scaly terrain, pedestal craters, inverted craters, and intra-crater deposits. Distinctive layering morphologies were further broken down into six sub-classifications. Several of the erosional and layering morphologies detailed here have been previously identified as characteristic of Meridiani Planum (Edgett, 2005; Hynek, 2004).

In the following sections, the erosional morphologies typical in the Meridiani region are described and then compared with occurrences throughout Arabia Terra. This analysis is limited to an area encompassing much, but not all, of Arabia Terra (study area shown by the solid line in Fig. 1), as a result of both the availability of data and prevalence of observed sedimentary outcrops. Starting in the Meridiani region and working outward, 375 HiRISE images in the study area were examined for the presence of any of the eight unique erosional morphologies. At least one of the eight erosional morphologies was catalogued in 241 of those images. Many images contained more than one type of erosional morphology. In these cases, all types of erosional morphologies present were documented, but the resulting maps of their distribution (Fig. 5) only show the most prevalent type.

3.2. Erosional morphology descriptions

3.2.1. Etched terrain

The Etched terrain (ET) unit is recognizable by its high thermal inertia and warm nighttime temperature in THEMIS thermal infrared images (Hynek, 2004), and by its erosional morphology (Fig. 6a and b). The high thermal inertia indicates that the sediments are consolidated and likely cemented. The thermal inertia is not widely useful in identifying ET occurrences as a result of the widespread dust cover in Arabia Terra. The ET unit displays a complex pattern of pits, mesas, and polygonal to rounded erosional features, resulting from the differential erosion of the semi-horizontal layered material that makes up the unit. The unique erosional morphology and texture of ET units is identifiable even through moderate dust cover, and this visual appearance is therefore useful in identifying occurrences of ET units outside of Meridiani Planum.

Fig. 5. (a–f) MOLA hill shade maps of the approximate locations of HiRISE-scale erosional morphologies, showing (a) etched terrain, (b) distinctive layering, (c) buttes, (d) knobs, (e) scaly terrain, (f) HiRISE-scale inverted craters. (g) Map of the locations of HiRISE images in Fig. 6 (upper case letters) and 7 (lower case letters). (h) Map of the study region with large-scale pedestal craters outlined in black, intra-crater deposits in red, and inverted craters in blue. Boxes indicate extents of Figs. 8a and 11. The latitude and longitude extents of each panel are the same as in Fig. 1.
The ET unit is confined primarily to the sedimentary deposits that are directly contiguous with Meridiani Planum (Hynek, 2004) or to a ring of occurrences that may indicate where the benches at the western side of Meridiani Planum have been eroded back (Fig. 5a). There are a few instances of ET erosional morphologies elsewhere in Arabia Terra. This terrain is sometimes associated with heavily scalloped layers. The few occurrences of ET units outside of Meridiani Planum are strong indications of Meridiani-type rocks.

### 3.2.2. Distinctive layering

The sedimentary deposits of Arabia Terra were first identified on the basis of their layering (Malin and Edgett, 2000). Most Meridiani-type sedimentary rocks are layered, but distinct erosional conditions are required to expose that layering. Identified layered outcrops (Fig. 5b) are divided into a number of sub-types of layer morphologies that are associated with the Meridiani deposits (Table 1; Fig. 7). Semi-horizontal layering exposed in eroded outcrops of sedimentary rocks (Fig. 7a) is seen in the Meridiani region and throughout Arabia Terra. Slight disparities in layer strength often cause small ledges or benches to form from erosion. In some cases, the layering can be either rhythmic (having a regular and repeatable layer thickness), or bundled (having two scales of periodicity in the layer thickness or strength as indicated in HiRISE stereo topography or image data, resulting in layers grouping into packets of 10), as seen in Becquerel crater (Lewis et al., 2008) (Fig. 6d). The bundling of layers into packets of 10 is noteworthy.
as this has been correlated with the 1.2 Myr modulation of the 120 kyr obliquity cycle, demonstrating a climatic control of the deposition (Lewis et al., 2008). The identification of similar rhythmic layering, with a strong suggestion of bundling at the limit of resolution, in eastern and northern Meridiani (Figs. 6c and 7b, respectively) suggests a similar depositional mechanism. The layering may also be expressed as whirled, closed loop patterns (Fig. 7c). These whirls may arise from either differential erosional exposure of sub-horizontal sediments or from bedding patterns or from erosion of sedimentary structures such as large-scale paleo-dunes (Okubo et al., 2009). Layers can also be scalloped, showing distinct crenulations on the exposed edge (Fig. 7d). In some cases, scalloped layers grade into eroded terrain, suggesting a continuum of erosional morphologies. Layers that were exposed specifically in the walls of craters were delineated into a separate group (Fig. 7e). These layers are often of poor exposure and may be covered by mass wasting and/or erosion products and dust, obscuring their true morphology.

The semi-horizontal layering morphology was the most abundant identified, and is spread evenly across Arabia Terra. A somewhat higher concentration of layered morphologies in the immediate Meridiani Planum region is in part due to a higher concentration of available images. These layer morphologies in outcrop view provide yet another line of evidence to link the sedimentary deposits in Arabia Terra with those in Meridiani. However, as with all of the erosional morphologies, the existence of layering alone does not prove a similar formation mechanism. Although layered lava flows exhibit different morphologies and can be excluded, layered ash deposits such as the Medusae Fossae formation may result in a similar surface expression.

3.2.3. Buttes and knobs

Buttes, as defined here, are flat-topped packages of rocks that stand above surrounding terrain and are isolated from other high-standing packages. Use of this term here also includes structures that may technically be mesas or tables, as distinguished by their height relative to their width. Buttes vary in size and shape, and may or may not have defined layering visible on the sides (Fig. 6e and f). Buttes occur when a more resistant layer caps underlying weaker layers (Huggett, 2003, p. 92) leading to differential erosion. As such, buttes are related to pedestal craters, but do not require impact ejecta to be the resistant cap layer. Buttes are a somewhat rare morphology in the Meridiani region (Fig. 5c), though they have been previously documented within Meridiani (Edgett, 2005) and are important in the identification of Meridiani-type deposits. They are often left as a residual outlier at the retreating edge of the eroding deposit, as also observed on Earth (Ahnert, 1998, p. 242).

Buttes are found throughout Arabia Terra in low abundance (Fig. 5c), though like pedestal craters they often occur at scales larger than HiRISE images but smaller than MOLA scales making them under-represented in this erosional morphology analysis. They are often associated with pedestal craters, and in these cases may be the result of discontinuous ejecta coverage. Several intra-crater

<table>
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<th>Layer type</th>
<th>Basic characteristics</th>
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<td>Semi-horizontal layering</td>
<td>Semi-horizontal, may have slight to pronounced erosional benches</td>
</tr>
<tr>
<td>Rhythmic and bundled layering</td>
<td>Layering periodicity on two scales, with large bundles composed of smaller beds (Lewis et al., 2008)</td>
</tr>
<tr>
<td>Whirled layering</td>
<td>Layering exposed on the surface in loops and whirls, possibly indicating cross bedding (Okubo et al., 2009)</td>
</tr>
<tr>
<td>Scalloped layers</td>
<td>Semi-horizontal layers eroded into pronounced benches form deeply curved and scalloped shapes</td>
</tr>
<tr>
<td>Layers in crater walls</td>
<td>Layers exposed by the excavation of impact craters</td>
</tr>
</tbody>
</table>

Fig. 7. Examples of the five layering types described in Table 1. Locations are given in Fig. 5g. All scale bars are 500 m. (a) Semi-horizontal layering. HiRISE image ESP_017118_1790. (b) Bundled layers. Some of the detail here is obscured by dust. HiRISE image PSP_007440_1845. (c) Whirled layers that may indicate cross bedding (Okubo et al., 2009). HiRISE image PSP_003418_1865. (d) Scalloped layering in a different portion of the image in Fig. 6h. HiRISE image PSP_007070_1915. (e) Layers exposed in a crater wall. HiRISE image ESP_017382_1825. (f) Close-up of boxed area in (e) showing thicker, ridge forming layers and thinner layering in crater wall. All image credits: NASA/JPL/University of Arizona.
deposits also have nearby buttes. The association of buttes with these two classic Meridiani-type erosional morphologies makes them important in identifying the deposits, despite their relative scarcity.

Knobs are a type of erosional morphology closely associated with buttes, differing in that they tend to be smaller and have pointed to rounded tops (Fig. 6g and h). They are also a product of differential erosion and denudation that likely represents a further stage of erosion after large buttes have been dissected. On Earth, knobs may also be known as isolated towers, rounded peaks, or jagged peaks (Huggett, 2003, p. 93). They may occur as relatively isolated forms, or be part of large knob fields. Some of the knobs may technically be classified as yardangs, but no distinction is made here between these two forms. The knobs very often, but not always, exhibit layering on their sides.

Knobs are common throughout Arabia Terra (Fig. 5d). They are frequently associated with intra-crater deposits and likely result from aeolian erosion of those differentially indurated deposits. They are not often found on the inter-crater plains, which may suggest that the wind patterns within craters create an erosional environment ideal for forming this type of morphology. Alternately, the hydrologic focusing within craters (Andrews-Hanna et al., 2010) could cause a unique induration environment. The abundance of this morphology in the Meridiani region and its association with intra-crater deposits makes it an ideal proxy for identifying Meridiani-type deposits throughout Arabia Terra.

3.2.4. Scaly terrain
Scaly terrain is an erosional morphology composed of numerous points and troughs that are densely clustered and resemble scales or sharkskin (Fig. 6i and j). While the term “scaly” has been used to describe other terrains on Mars (e.g., Mest, 2007; Michalski et al., 2007), it is here used as a descriptive term specific to the Meridiani and Arabia Terra regions. Although this morphology is observed within the Meridiani deposits (Fig. 5e), it is also common near Mawrth Vallis (outside of the study region) in terrains generally thought to contain phyllosilicates (Carter et al., 2009). The prevalence of scaly terrain both in Meridiani and in areas with phyllosilicate spectral detections suggests that the texture may be only weakly related to composition. However, several craters in known Meridiani-type deposits have phyllosilicate detections (Poulet et al., 2008). Therefore, the scaly terrain erosional morphology is used as a proxy for Meridiani-type deposits only in conjunction with other evidence such as additional distinctive erosional morphologies or mineralogical evidence.

3.2.5. Pedestal craters, inverted craters, and intra-crater deposits
Differential erosion and denudation can lead to three crater-form erosional morphologies: pedestal craters, inverted craters, and intra-crater deposits. Pedestal craters occur when the continuous ejecta blanket from an impact protects underlying deposits from erosion, leading to the formation of a raised pedestal surrounding the crater when the surrounding deposit is eroded (Fig. 8a and b). It should be noted that this formation mechanism differs from that inferred for pedestal craters in the high latitudes of Mars, in which impact-generated heat partially melts the ice in the regolith in such a way as to protect the underlying areas from sublimation (Kadish et al., 2009). This mechanism is not plausible to form pedestal craters in the low latitudes, where large amounts of ice cannot currently exist in the near surface due to warmer temperatures. Instead, the ejecta creates a physical barrier from erosion of the weaker underlying sedimentary deposits, similar to buttes and table mountains on Earth.

The prevalence of pedestal craters in the Meridiani region (Hynek et al., 2002) warrants the use of this morphology as an indicator of other Meridiani-type deposits. Arabia Terra exhibits the largest concentration of pedestal craters outside of the high latitude regions. Pedestal craters can be distinguished by their abnormally thick ejecta, as determined by the thickness of the ejecta in relation to the crater size (Housen et al., 1983). In cases where MOLA topography is ambiguous in regards to ejecta thickness, the presence of a distinct bench at the edge of the ejecta blanket expressed in either topography or image data can be used to identify a pedestal crater. Craters that do not meet either of these characteristics may be classified as pedestals if the bottom elevation of the crater lies above the elevation of the surrounding plains and there is a visible ejecta blanket (distinguishing them from inverted craters). Pedestal craters must be distinguished from the similar looking rampart craters, which form from fluidized ejecta after an impact into a volatile-rich target (Barlow et al., 2000; Mouginis-Mark and Baloga, 2006). These craters can also have a raised rim at the edge of the ejecta, which may resemble a bench around a pedestal crater in the absence of topographic data.

Small pedestal craters (≤1 km) are rare in HiRISE images, but large (≥3 km) pedestal craters are common throughout Arabia Terra (Fig. 5h). This may be due to the fact that larger craters excavate more deeply and have thicker ejecta which is more likely to contain deeply excavated bedrock, and thus more likely to preserve underlying sediments. In several locations, multiple large pedestal craters and benches with similar elevations (Fig. 8b) confirm the prior existence of a once more extensive deposit surface, consistent with the interpretations of Edgett and Malin (2002).
Inverted craters are those in which the crater itself is expressed in positive relief (Fig. 6k and l). Inverted craters likely form when well-lithified sediments that fill a crater subsequent to the impact are more resistant to erosion and remain intact as the surrounding surface deflates. Following regional erosion, they sometimes retain crater-like profiles, except that the fill rises above the surrounding area. Inverted craters preserve sediments that were deposited within an impact crater, rather than under the ejecta as in a pedestal crater. These features are more common at the HiRISE scale (Fig. 5f) than at MOLA- and THEMIS-scale (Fig. 5h). More frequently, craters are too shallow for their width (based on depth-to-diameter ratio (Melosh, 1996) indicating that they have been partially filled but not inverted. However, the simple shallowing of craters is common on Noachian-aged surfaces, and is not diagnostic of infilling by Meridiani-type deposits.

Intra-crater deposits consist of rounded mounds of layered material that are preserved in craters. They can cover almost the entire crater floor (often with a characteristic moat around the edge as observed in the crater near 2°N 10.6°E), form a symmetric mound in the center of the crater (e.g., Crommelin and Henry craters), or be eroded into a small irregular mound (e.g., Becquerel crater). They often exhibit signs of aeolian erosion (i.e., the associated knobs, see Section 3.2.4) which indicate that the intra-crater deposits were once more extensive. In addition, some intra-crater deposits rise to or above the rim of their enclosing crater (Fig. 8b), suggesting that they once overtopped that level and therefore could not have formed as lacustrine deposits. Intra-crater deposits tend only to occur at large (>5 km) scales and were thus identified solely from MOLA data (Fig. 5h). Intra-crater deposits were distinguished from central peaks (which form during the crater excavation and modification and are non-sedimentary) by their smooth, mound-like morphology, and the fact that they may rise above the rim. A coarse global survey found a concentration of intra-crater deposits within Arabia Terra (Andrews-Hanna et al., 2010), supporting their relationship to the Meridiani-type deposits.

Pedestal craters, inverted craters, and intra-crater deposits preserve remnants of eroded sedimentary deposits. This makes them important tools in finding outlying deposits of possible Meridiani-type rocks. All three morphologies were instrumental in the generation of interpolated surface reconstructions in Section 4, because the large relief often associated with them is important in reconstructing the pre-erosional sediment thickness.

3.3. Distribution of erosional morphologies

Eight types of erosional morphologies common in the Meridiani region were examined and used as type examples for identifying similar deposits throughout Arabia Terra. The strongest morphological evidence for a particular deposit being related to the Meridiani deposits is the presence of distinctive layering. Given that the differential induration and erosion of these layered deposits is a main factor in determining their erosional morphology, similar morphologies likely suggest similar rock properties in terms of the layering and induration. Within the Meridiani deposits, this induration arises as a result of the presence of cementing sulfate salts that formed in an evaporitic playa environment (McLeman et al., 2005).

The distribution of erosional remnants of deposits indicated by the morphological analysis is wide spread across Arabia Terra (Fig. 5a–f). Etched terrain morphologies are more restricted (87 occurrences), occurring mainly in Meridiani itself. There is a cluster of etched morphologies in the Crommelin crater area and one identification within Henry crater over 1500 km from Meridiani (using 0°N 0°E as the reference location for Meridiani). Distinctively layered morphologies are found across the study region (184 occurrences), up to ~2200 km away from Meridiani. Knobs were the second most common erosional morphology identified in this study, with 103 locations mapped as far as ~2200 km from Meridiani Planum. Buttes are much less common than knobs, identified in only 20 locations, up to ~2200 km from Meridiani Planum in a location near Luzin crater. Scaly erosional morphologies occur across Arabia Terra in 54 locations as far as ~2500 km from Meridiani Planum. Pedestal craters were the least common erosional morphology at the HiRISE scale, with only eight identifications. As discussed above, an examination of THEMIS and MOLA data revealed many more pedestal craters (Fig. 5h). Small-scale pedestal craters, though rare, are widespread, with the furthest location ~2000 km from Meridiani. Inverted craters were identified in 21 HiRISE images, as well as several examples at larger scales in MOLA and THEMIS data. They are also restricted mostly to the Meridiani area, though three occurrences are documented in the east of the study area up to ~2100 km away from Meridiani.
to these widely separated points is justified by the constant dip angles measured for the Meridiani deposits over hundreds of km, following the regional dip of Arabia Terra (Hynek and Phillips, 2008). These uniform dip angles are consistent with the hypothesized origin of the Meridiani deposits as a groundwater-fed playa (McLennan et al., 2005). Hydrological models predict a smoothly varying water table, producing sub-planar deposit surfaces with consistent dip directions and angles both within Meridiani and throughout Arabia Terra (Andrews-Hanna et al., 2010). The expected sub-horizontal nature of a water table surface under arid conditions suggests that a smooth planar or smoothly varying surface would best approximate the water table surface, where cementation is likely occurring.

A regional example of the concept can be seen in west Meridiani, where several pedestal craters preserve the same paleo-surface level, also coincident with an erosional bench at the edge of Meridiani Planum (Fig. 8b). This level also matches the elevations of a nearby inverted crater and intra-crater deposit. A pre-erosional surface could logically be reconstructed by interpolating between these points of similar elevation on these remnant deposits. Subtracting the modern topography from the reconstructed paleo-surface would show how much material had been removed from the area. In this section, this concept is applied to the remnant sedimentary deposits over the whole of Arabia Terra. Two types of surface reconstructions, least-squares plane and kriging, were chosen in order to best fit the elevations of the remnant deposits and represent the pre-erosional surface of the deposits.

4.2. Methods

The pre-erosional deposit surface was calculated by first building a set of data points consisting of the elevations of remnant sedimentary deposits. It is unlikely that the remnant deposits at these points escaped erosion entirely while the surrounding areas underwent denudation, and thus the data points represent lower bounds on the pre-erosional topography and thickness of the deposit. The first points selected were those within the known deposits of Meridiani Planum and the surrounding etched terrain. Points were chosen at the edge of the deposit, where a distinct bench was produced as the deposits eroded back. Nearby pedestal craters and an inverted crater were also chosen. Data points were then chosen successively further away on features interpreted to be remnants of Meridiani-type rocks due to mineralogical and/or morphological similarities with the type locality. Occurrences of Meridiani-type rocks were not always large enough to be seen distinctly in the MOLA topography data. In cases where deposits could be identified visually but not topographically (e.g., small-scale knobs), a best-estimate location was chosen to represent the occurrence height.

Each data point was assigned a confidence level of 1, 2, or 3. A confidence level of 1 was assigned to those points that were most confidently identified as Meridiani-type deposits. The most typical locations in this category are large intra-craters deposits and large, flat-topped pedestal craters. This high degree of confidence is based upon the fact that many pedestal craters and intra-craters deposits preserve layering, most intra-crater deposits have associated small-scale Meridiani-type erosional morphologies, and that there have been sulfate identifications in some intra-craters deposits (Andrews-Hanna et al., 2010). These large remnant deposits are also more likely to represent the pre-erosional deposit thickness, whereas the other geomorphic indicators discussed in Section 3 may in some cases preserve more deeply eroded deposits. Locations in this category also include those in the Meridiani region itself, since these are the type specimens.

A confidence level of 2 was assigned to modified intra-craters deposits, smaller pedestal craters, and any deposits that display modified Meridiani-type morphologies. This category was created for those locations that closely resemble those in classification 1, but have undergone more substantial erosion and may underestimate the pre-erosional deposit surface elevation. Including heavily eroded locations tends to reduce the overall predicted surface height and the resulting eroded volume. Many locations in this category are flat, low relief intra-craters deposits. This category also includes pedestal craters with fresher, blockier ejecta, indicating a younger age and preservation of a later, lower surface level. Some data points on the edges of the Meridiani Plano region were also placed here if they had a smooth, down sloping morphology rather than a distinct bench.

A confidence level of 3 was assigned to the remaining locations. These locations were interpreted to be the last erosional remains of Meridiani-type deposits, and are often composed of only yardangs or knobs. The confidence of the common formation mechanism of the these deposits with those in Meridiani is lower than for confidence levels 1 and 2 deposits, and they may represent deeper erosional levels that significantly underestimate the original deposit elevation. These locations helped to show the areal extent of the eroded remnants, but were often so eroded that inclusion of their elevations greatly decreased the reconstructed surface height and eroded volume. There were many points where this simple approach fell short and the classification level assignment became necessarily more subjective.

The data points are concentrated around the Meridiani Planum region. A general trend of more identifiable outcrops runs northeast from Meridiani. The data points are more sparse to the southeast and northwest of this trend (near Schiaparelli and Becquerel craters, respectively), due in part to a lack of higher-resolution data. In addition, Noachian terrain indicators, such as valley networks (Hynek et al., 2010) and increased phyllosilicate detections (Carter et al., 2009) in these areas show that many surfaces exposed in the northwest and southeast are very old basement exposures. This indicates these areas were either never covered by Meridiani-type sedimentary rocks, or any deposits that may have been present have been completely removed. Some sporadic outcrops are still visible in these areas, though usually are of poor preservation and/or are dust covered. These contribute to classification 3 data points in these regions. The reconstructed deposit models are less accurate and more sensitive to error in areas of reduced data point concentration.

The data points were then used to generate a continuous surface using both kriging and a best-fit plane. Three models were created for each surface type using confidence level 1 points, levels 1 and 2 points, and all points. The planar fit and kriging interpolation based on the confidence level 1 points only are the most data-conservative (use the fewest, most confident, and most tightly clustered data points), but also result in higher predicted surface heights and greater eroded deposit thicknesses and volumes. The planar fit and kriging interpolation based on all data points have a greater areal confidence as there are is a greater number of data points, but these models are the most volumetrically conservative as the inclusion of highly eroded data point elevations reduced the overall reconstructed elevation (see Table 2). In order to best balance the two data extremes, models constructed using data points with confidence levels 1 and 2 are used as the representative examples.

The resulting models of surface elevation are shown in Fig. 9a and c. The areas in which the predicted pre-erosional deposit surface is below the present-day ancient cratered surface of Arabia Terra (areas of no color in Fig. 9a and c) represent regions predicted to be originally lacking deposits, possibly resulting from a paleo-water table that remained at depth below the surface. No correction was made for craters that are younger than the deposits, resulting in a relatively small over-estimation of deposit thickness in places. However, young craters are surrounded by ejecta
blankets approximately equal in volume to the crater cavity, so the net error in total deposit volume due to young, post-deposit craters is small. The fitted and interpolated surface reconstructions were clipped to the study area polygon (black outlines in Fig. 9), coinciding with the spatial extent of the greatest concentration of erosional remnants. The MOLA topography elevations were subtracted from the reconstructions in locations where the interpolated surface was above the present-day surface, giving the estimated eroded thickness. The eroded deposit thickness was integrated over the area in which the reconstructed sediment surface lies above the present-day surface to yield the total estimated eroded volume and average thickness of the eroded deposits across the Arabia Terra region (Table 2). Though this approach has many uncertainties, it provides a first-order estimate of the original extent, thickness, and volume of sedimentary material that once covered Arabia Terra.

4.3. Planar surface models

The planar surface fit represents the geometrically simplest interpretation of the data points. This model is a best-fit scenario, with some of the data points lying above the plane and some below, which will underestimate or overestimate the deposit thickness in places. The advantage of the planar fit is that the surface

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**Table 2**

Eroded volumes, GELs, and surface areas (colored areas in Fig. 9a–d) predicted by models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Eroded volume (km$^3$)</th>
<th>GEL (m)</th>
<th>Surface area (km$^2$)</th>
<th>Avg. thickness (m)</th>
</tr>
</thead>
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<td>Krigge: Confidence Level 1</td>
<td>$1.67 \times 10^6$</td>
<td>11.5</td>
<td>$3.6 \times 10^8$</td>
<td>464</td>
</tr>
<tr>
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<td>7.3</td>
<td>$2.9 \times 10^8$</td>
<td>366</td>
</tr>
<tr>
<td>Krigge: All Confidence Levels</td>
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<td>6.2</td>
<td>$2.6 \times 10^8$</td>
<td>347</td>
</tr>
<tr>
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<td>11.6</td>
<td>$3.4 \times 10^8$</td>
<td>494</td>
</tr>
<tr>
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<td>9.2</td>
<td>$2.9 \times 10^8$</td>
<td>462</td>
</tr>
<tr>
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<td>7.0</td>
<td>$2.5 \times 10^8$</td>
<td>404</td>
</tr>
</tbody>
</table>

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**Fig. 9.** A comparison of the interpolated surface elevations (left; referenced to martian datum) and predicted eroded deposit thickness (right) from this study and the hydrologic model of Andrews-Hanna et al. (2010). (a and b) Interpolated surface and deposit thickness using a least squares planar fit of the confidence level 1 and 2 data points. Black circles represent confidence level 1 data points, squares level 2, and triangles level 3. (c and d) Interpolated surface and deposit thickness using a krig fit of the confidence levels 1 and 2 data points. (e and f) Predicted surface elevations and deposit thickness from hydrologic model of Andrews-Hanna et al. (2010). The same color bar applies to each figure within a column. All images on MOLA hill shade background.
is not forced to match the elevations of all data points, and thus will naturally exclude outlier points that may have been incorrectly identified or that coincide with more deeply eroded portions of the deposit. Although this surface is only strictly a plane in latitude–longitude–elevation space, it provides a simple surface that does not over-fit the data. The planar fit model using confidence levels 1 and 2 points reaches a maximum of 881 m in elevation. It dips to the north–northwest at 0.089° with a dip direction of 322° azimuth measured clockwise from north. This dip falls within the range of the data of Hynek and Phillips (2008) for the etched terrain only, who calculated 0.05°–1.0° dips at 300°–345° azimuth, and slightly exceeds the hydrological model results of Andrews-Hanna et al. (2010) with predicted dips of 0.035 ± 0.008° at 296°–332° azimuth.

The thickest deposits are predicted in the northeast and southwest of the study area, with zero eroded deposit thickness predicted in the area northwest of Meridiani Planum (Fig. 9b). Several of the craters in this area are shown to be filled, though some are likely more recent than the deposits causing a slight over-estimation in these areas. The predictions of thickest deposits occur in Pasteur (19.20°N 24.50°E), Tikhonravov (13.35°N 35.80°E), and Henry (10.78°N 23.30°E) craters, while Crater X and several other craters in the center of the study region and in the south also show significant deposit thicknesses. Craters and other low-lying areas are the most logical places for thick sedimentary stacks cemented by groundwater to accumulate, as the craters act as sediment sinks and hydrologic drawdown points (Andrews-Hanna et al., 2010).

The confidence level 1 model reaches a maximum of 1017 m in elevation. It follows the general trend of Arabia Terra, dipping to the north–northwest with a dip angle of 0.090° and a dip direction of ~331° azimuth. The deposits cover a larger area than those from the confidence levels 1 and 2 model because the more highly eroded data points included in the model of levels 1 and 2 points force the overall surface elevation to be lower. The planar fit model made using all of the data points (levels 1–3) has an even more restricted areal distribution than the second model. This surface has a maximum elevation of only 626 m, and dips at 0.082° to the north–northwest (324° azimuth).

The planar model of confidence levels 1 and 2 points leads to a calculated volume of the eroded sedimentary deposits in this region of 1.34 × 10^6 km^3 (Table 2). This volume would represent a ~9.2 m layer of material evenly distributed on the surface (global equivalent layer, GEL). The model of confidence level 1, having a larger areal distribution, gives a larger eroded volume estimate of 1.68 × 10^6 km^3, equivalent to a ~11.6 m GEL. The final planar surface interpolation, utilizing all of the data points, leads to an estimated eroded volume of 1.01 × 10^6 km^3 and a GEL of ~7.0 m. These volumes indicate that the sedimentary deposits of Arabia Terra have undergone a massive amount of erosion.

4.4. Krige surface models

Kriging is an optimal interpolation method used to predict spatial data based on known data points (Stein, 1999). It differs from the planar model in that it keeps all of the data points at the interpolated surface, while fitting the area in between with a smooth surface based on the semivariogram of the data. The same three sets of data points at varying confidence levels were used to create the kriging models. Because the kriged surfaces are not flat, a single dip and dip direction cannot be calculated. Instead, the general slope trend for each surface is noted.

In general, the kriging surfaces have higher maximum elevations and lower minimum elevations (1745 and ~3423 m, respectively) than their planar counterparts, but have similar total areas. The model surface of confidence levels 1 and 2 points (Fig. 9c) produces a noticeably different areal distribution of reconstructed deposits in comparison with the planar model, with deposits missing from most of the southern area and less coverage to the north and northeast of Henry crater. As in the planar models, the deposits are thickest within the large impact basins, with the thickest accumulation within Pasteur crater and Crater X. The reconstructed eroded deposit thickness (Fig. 9d) over Meridiani Planum is thinner than in the plane model, because these deposits are still present on the surface and thus show a smaller eroded thickness. There are few deposits predicted in the southern part of the study area west of Schiaparelli crater. However, the areas southwest of Henry crater, northwest of Gill crater, and at the western tip of the study area all have increased coverage and thickness of deposits relative to the plane surfaces. The slope is generally to the northwest, but cannot be described by a single dip direction and angle. The krig model surfaces from the confidence level 1 only, or from all three confidence levels, resemble the level 1 and 2 model.

The eroded volume predicted by the model of confidence level 1 and 2 data points is ~1.06 × 10^6 km^3, or a GEL of ~7.3 m. The total surface area of the predicted deposit above the modern topography was calculated as ~2.9 × 10^5 km^2 giving an average thickness of ~0.36 m. The krig surface of confidence level 1 points leads to an eroded volume calculation of ~1.67 × 10^6 km^3, or a GEL of ~11.5 m very similar to the first planar model. The final kriged model, using all of the data points, leads to an eroded volume calculation of 9.03 × 10^5 km^3, or a GEL of ~6.2 m. Thus, while some differences in the reconstructed distribution of the deposits exists, estimates of the total eroded volume from all models lie in the range of 0.90–1.67 × 10^6 km^3. The eroded volumes of all models are summarized in Table 2. It must be noted that these volumes are lower bounds, as the reconstructed sediment surfaces indicate that the pre-erosional deposit extended beyond the edges of the study area.

4.5. Comparison with hydrologic modeling

The reconstructed deposit surfaces and thicknesses derived from the physical remnants of the Meridiani-like deposits were compared with the predictions of hydrologic models (Fig. 9e and f), which build the deposits from an a priori representation of topography-driven groundwater flow (Andrews-Hanna et al., 2010). Both the reconstructed deposits and the hydrologic model-predicted deposits are predicted to have covered large areas of Arabia Terra, with a sediment surface dipping gently to the northwest. Overall, the thickness prediction maps concur, with the best agreement in craters and basins, where both models predict the thickest deposits. The northeast portions of both surface reconstructions have the best fit with the hydrologic model. The planar surface is visually closer to the elevations predicted by the hydrologic model.

The largest area of discrepancy with the krig model of elevation is northeast of Schiaparelli crater where the hydrological model under-predicts the coverage and thickness of deposits versus the reconstructed deposit surface. The apparent misfit in Meridiani Planum is caused by the fact that the krig model restricts the surface to the data point elevation in Meridiani Planum, which gives it a predicted eroded thickness near zero (as the deposits are still present there). The hydrologic model removed the current Meridiani deposits before predicting thicknesses, so they naturally reform there. Likely reasons for the misfit between the reconstructed surface and the hydrological model predictions lie in the fact that the hydrological model doesn’t take into account factors such as spatial variations in precipitation. For example, the under-prediction of the deposits thickness in southeast Arabia Terra in the hydrological models may arise because of an area of enhanced precipitation and aquifer recharge not included in the model.
assumptions. Alternately, spatial variations in the hydraulic properties of the aquifers would alter the predicted distribution and thickness of deposits (Andrews-Hanna et al., 2010), as would a permeability contrast between the forming sedimentary deposits and the underlying regolith. Thus, by comparing these two independent approaches, it may be possible to shed light on the regional details of the climate and hydrology within Arabia Terra.

4.6. Summary and discussion of the deposit reconstruction

The eroded remnants of Meridiani-type sedimentary rocks are spread across Arabia Terra. Using the elevations of these points, planar fits and krige interpolations were used to reconstruct the pre-erosional surface and thickness of these deposits. These models predict that the deposits once covered between 2.5 and 3.6 \( \times 10^6 \) km\(^2\), prior to the erosion of between 0.90 and 1.68 \( \times 10^6 \) km\(^3\) of material. Such large predicted pre-erosional deposit thicknesses and volumes indicate that the processes that formed these deposits were active over a widespread area. Furthermore, the vast majority of this deposit was subsequently eroded.

Given the large volumes of eroded sedimentary materials calculated above, the ultimate fate of this material cannot be overlooked. The immense amount of material removed from Arabia Terra must have been redeposited elsewhere on Mars, or otherwise reworked into the geologic system. One possible repository is the Vastitas Borealis Formation of the northern lowlands. This is an extensive sedimentary deposit that blankets the topographic low of the northern lowlands to thicknesses of \( \sim 100–170 \) m (Campbell et al., 2008) lying on top of a ridged plains unit of Early Hesperian age (Head et al., 2002). The estimated volumes of the eroded deposit of 0.90–1.68 \( \times 10^6 \) km\(^3\) fall below the estimated volume of the Vastitas Borealis Formation of 3 \( \times 10^6 \) km\(^3\) (Head et al., 2002), though there are significant uncertainties in both volumes. A similar problem exists regarding the fate of the eroded interior layered deposits from within Valles Marineris (Andrews-Hanna, 2012). The volume of sediments eroded from within Valles Marineris of \( \sim 2 \times 10^6 \) km\(^3\) could also be contained with Vastitas Borealis. Although the Vastitas Borealis Formation has been interpreted as outflow channel sediments (Head et al., 2002), it is unlikely that the expected course-grained sediment from the catastrophic flooding could have been transported up to 8000 km across the lowlands to form the distal parts of this deposit. While the sediments carried by the Missoula floods were transported distances possibly exceeding 1000 km into the ocean, this occurred in channelized turbidity currents driven by a topographic gradient of 0.1%, with fans forming where the flows overspilled the channel levees (Brunner et al., 2000; Normark and Reid, 2003). In contrast, formation of the Vastitas Borealis Formation from outflow channel sediments would require low energy unchannelized sediment transport over distances of up to 8000 km to cover an area of 1.7 \( \times 10^7 \) km\(^2\), although there is some topographic gradient to drive this transport proximal to the channel mouths, substantial upslope transport would be required to reach the distal parts of the deposit. Aeolian redeposition of the eroded Arabia Terra sedimentary deposits may provide a simpler explanation for this unit. The age constraints developed in the next section indicate erosion of the deposits during the early to middle Hesperian, consistent with the possibility that the eroded deposit materials could comprise some part of the Vastitas Borealis Formation. While the spectral signature of sulfates have not been detected in association with this deposit, sulfate signatures have also been notably absent from exposed outcrops within Meridiani that are known to be sulfate rich.

The eroded deposit materials could also have been globally redistributed and reworked into the regolith by impacts. McLennan et al. (2010) calculated the distribution and concentration of sulfur in the soil using the Gamma Ray Spectrometer aboard the Mars Odyssey spacecraft. Concentrations are higher in the equatorial latitudes and there is a relatively high concentration of sulfur just to the east of Arabia Terra (McLennan et al., 2010). However, the high sulfate concentrations of the Meridiani-type deposits (up to \( \sim 40 \) wt.%; Squyres et al., 2006; Clotht et al., 2006) and a global equivalent layer at least 6.2 m deep would lead to roughly 11% sulfur in the upper 25 m of regolith. This is significantly higher than the maximum concentration of \( \sim 3\%\) seen by the Gamma Ray Spectrometer, suggesting that the entirety of the eroded material was not likely simply reworked into the regolith unless the deposits contained a significantly lower sulfate fraction on average than that observed in Meridiani. Some of the volume could have been removed by dissolution of sulfates, as suggested by the 35% secondary porosity observed in the Burns Formation (McLennan et al., 2007). Alternatively, eroded and altered deposits may have been incorporated into other sulfate-rich deposits observed on the surface, such as the north polar gypsum dunes of Olympia Undae (Langevin et al., 2005). It may be that the eroded deposits can be accounted for by a combination of the sinks described above, or that other processes and repositories must be considered. Thus, the fate of the eroded Meridiani-type deposits remains an unanswered question.

5. Timing and rates of deposition and erosion

5.1. Background and methods

The previous section demonstrated that large volumes of sedimentary materials similar to those in Meridiani were deposited and subsequently eroded in the Arabia Terra region. In order to better constrain the time period during which these deposits formed and eroded, we now use crater age dating on a subset of the deposits in northeast Arabia Terra. Crater size–frequency distributions can be used to estimate absolute ages for exposed surfaces on Mars (Hartmann and Neukum, 2001). This methodology relies on models for the rate at which impact craters have accumulated over the past ~3.9 Ga, so that the crater size–frequency distribution can be used to estimate the exposure age of the surface (Michael and Neukum, 2008). This is an important distinction from the actual age of the rocks in deposits like the Meridiani-type rocks because they have undergone burial and exhumation. It is more accurate to think of areas as cratered volumes rather than cratered surfaces (Edgett and Malin, 2002) since craters form, are buried, and can be exhumed, all while continued cratering is occurring (Fig. 10). This can complicate the interpretation of the crater population on a surface, but also has the potential to allow reconstruction of the history of a sedimentary deposit through consideration of the full crater population.

In this section, the crater population in a basin in northeast Arabia Terra (Fig. 11) is examined to reconstruct the erosion and deposition history of the deposits. This basin was chosen as it contains an abundance of pedestal craters, which offer a unique opportunity to date the deposit in intermediate stages of deposition and erosion. These intermediate ages are lower bounds, however, as not all craters were likely to have been preserved as pedestals. The spread of individual crater ages ranging from before deposition of the sediments to after their erosion, also provides the opportunity to constrain ages for the onset and cessation of deposition in this area.

All craters within the basin that were larger than \( \sim 1 \) km were assigned ages in relation to the deposits as pre-, syn-, or post-deposit. These classifications were based on the state of the ejecta, relief of the rim, and the presence of fill. Pre-deposit craters were identified as those lacking visible ejecta blankets, with highly
degraded rims, and that may be filled with layered deposits (Fig. 12a). Syn-deposit craters include pedestal craters and others that formed while the sediments were being deposited or eroded based on stratigraphic relationships or crater fill (Fig. 12b). The scene is dominated by three large pedestal craters, as well as a large number of smaller pedestals. While large craters can be surrounded by secondary crater fields, secondary craters are unlikely to excavate deeply enough to generate an armoring layer of bedrock ejecta to protect the sedimentary deposits in order to produce a pedestal. Thus, we interpret both small and large pedestal craters as primary craters. Post-deposit craters were those with ejecta that overlies adjacent deposits, or those that have extremely fresh appearances (e.g., with well-preserved ejecta and sharp rims; Fig. 12c). Post-deposit craters were minimally filled, if at all, by aeolian accumulations.

The relative ages of many craters were ambiguous. The primary age estimates were based only on those craters that could definitively be placed in one category or another. Craters of ambiguous relative age were then used for error estimates. Many of the small craters were classified as ambiguous due to a lack of ejecta. This is likely not because this population of small craters is old (pre-deposit), but rather because their small size makes their ejecta more susceptible to erosion. Erosion rates and modification of small rayed crater ejecta has likely been significant even in the past several 100 Ka (Golombek et al., 2010). Most of the small craters are likely post-deposit, though the uncertainty introduced by this crater population is not significant since the age estimates are based on fits to the larger crater population.

The crater retention age from the entire crater population (including those whose age relative to the deposits was uncertain) represents the pre-deposit surface. An intermediate age during which the deposits were present on the surface while being either deposited or eroded is represented by the crater retention age from the syn-deposit and post-deposit craters. The crater retention age from the post-deposit crater population represents the time of cessation of large-scale erosion. However, some craters were likely obliterated by all of the active geologic processes, meaning that the crater retention ages are lower bounds.

The crater retention ages were calculated by fitting the size-frequency distributions from a particular combination of crater
populations with theoretical isochrons (Michael and Neukum, 2008). Formal errors on the individual ages are calculated on the basis of the counting statistics as well as the quality of the fit between the size–frequency distribution and the isochron. The absolute ages are based on the production function of Ivanov (2001) and the chronology function of Hartmann and Neukum (2001) and were produced using the Craterstats software (Michael and Neukum, 2008, 2010). We emphasize that the ages reported here are model ages, and thus represent only estimates of the absolute age based on attempts by previous studies to calibrate martian crater size–frequency distributions to absolute ages of lunar surfaces.

5.2. Crater retention age results and discussion

In order to best fit the isochrons to the size–frequency distribution data, the small crater population (<2 km) was not fitted. This crater population can be seen as a kink in the size–frequency distributions of the syn- and post-deposit craters (Fig. 13), caused by the uncertainty of their relative ages due to their susceptibility to even low rates of erosion. The kinks in the isochrons for the post-deposit craters and the post- and syn-deposit craters suggest that the majority of the small crater population should be placed in the post-deposit category, as would be expected. However, since this determination could not be made based on the morphology of the craters, the isochrons were fit only to the mid-size and large crater populations. The mid-sized craters are the easiest to classify, have the best preservation potential as pedestals, and provide close fits to the theoretical isochrons. The large crater population has a poor fit to the isochrons, due in part to their relative scarcity leading to poor counting statistics. However, the large crater population does not strongly affect the ages due to the large error bars.

The age estimated from post-deposit craters is $3.41^{+0.09}_{-0.25}$ Ga, suggesting that the primary phase of deposition and erosion of the deposits in the basin ceased around this time (Fig. 13). The reported errors above derive from the counting statistics and quality of the fit between the theoretical isochron and the crater size–frequency distribution. Note that these error estimates do not take into account any systematic errors that might arise from miscalibration of the crater production function to the absolute surface age. If all craters that could potentially be classified as post-deposit are included, the post-deposition age is $3.72^{+0.03}_{-0.04}$ Ga. Therefore, there is an additional +0.31 Ga error arising from the ambiguity in classifying the relative age of the craters as post-deposit. In order to represent these errors, we calculate the mean age from the two calculations with the error bars calculated from the absolute maximum and minimum ages possible. Thus, the representative age of the end of deposition is $3.56^{+0.09}_{-0.40}$ Ga. The post- and syn-deposit craters give an age of $3.57^{+0.06}_{-0.05}$ Ga. This age is representative of the deposits in some intermediate stage of deposition and/or erosion. Including the craters with ambiguous relative ages increases the crater retention age to $3.75^{+0.02}_{-0.03}$ Ga. Combing these two ages yields the final estimate of the intermediate deposit age $3.66^{+0.17}_{-0.12}$ Ga. Finally, all of the documented craters in the basin lead to an estimated age of $3.83^{+0.02}_{-0.03}$ Ga, placing an upper limit on the age of the beginning of deposition since we cannot constrain how much time elapsed between the formation of the ridged plains on the floor of the basin and the onset of deposition.

The craters within this basin record the deposition and erosion history of these Meridiani-type sedimentary rocks. The estimated ages indicate that the layered sediments were laid down and subsequently eroded during a 270 Myr period between $3.83^{+0.02}_{-0.03}$ Ga and $3.56^{+0.19}_{-0.10}$ Ga. This spans the late Middle Noachian through the beginning of the Late Hesperian epochs (Hartmann and Neukum, 2001), with a mean deposit age of Early Hesperian. This age coincides with prior estimates of the age of major sulfate deposition (Bibring et al., 2006) and with previous estimates of the age of the Meridiani deposits (Hynek and Phillips, 2008; Lane et al., 2003), but provides a more complete view of the history of the deposits. Such agreement of ages supports the relationship of the outlying deposits we examined to the type locality deposits examined in these previous studies.

As a side note, these deposits were emplaced over a unit mapped as Hesperian ridged plains materials (Greeley and Guest, 1986; Skinner et al., 2006). The full crater population demonstrates that the total age of this surface beginning with the formation of the ridged plains is middle to Late Noachian, and by the Early Hesperian, an accumulation of sedimentary deposits up to 1 km thick had been emplaced over the plains, which were then subsequently eroded. This work suggests that the ridged plains at the base of the sedimentary deposit were covered by a thick sedimentary deposit for ~270 Myr, and thus were not exposed to cratering during this time. Thus, counting only the small and mid-sized craters on the plains between the pedestals results in a significant under-estimate of the age of the plains. Clearly, in areas of potential sedimentation and erosion such as this, crater retention ages must be approached with caution.

Assuming that deposition and erosion of the deposits each took 135 Myr (one half of the total period of erosion and deposition) and a deposit height of ~1.0 km within the basin, the mean deposition and erosion rates equal $7.4 \times 10^{-3}$ m/yr. A minimum estimate of either the deposition or the erosion rate, assuming that either stage lasted the full 270 Myr, is $3.1^{+0.19}_{-0.17} \times 10^{-3}$ m/yr. Lewis et al. (2008) calculated the deposition rate for the Bepcquerel Crater deposits by correlating the layer periodicity with orbital periodicity time scales to estimate rates of ~3 $\times 10^{-5}$ m/yr. Hydrological models predict the rate of groundwater upwelling and sedimentation within Bepcquerel to be ~3 $\times$ higher than the rate within this basin (Andrews-Hanna et al., 2010), bringing the range in minimum depositional rates within this basin calculated from

![Crater size–frequency distributions showing post-deposit craters (blue), post- and syn-deposit craters (red) and all craters (black). Ages are calculated using the chronology of Hartmann and Neukum (2001) and the production function of Ivanov (2001).](image-url)
The lower formation of the Gale Crater deposit has been formation and erosion of the Gale Crater sedimentary deposit. Late Middle Noachian (3.7–3.6 Ga) based on stratigraphic relationships, while the Late Noachian–Early Amazonian (~3 Ga) exposure age of the surface of the remnant sedimentary mound indicates that the km-scale erosion ceased at that time (Thomson et al., 2011). The similar depositional and erosional histories of these two widely separated sedimentary deposits supports the inference that the climatic and hydrologic transitions recorded in Arabia Terra were global in extent.

These rocks therefore record important information about the duration and nature of the climate transition at the end of the Noachian. The ages estimated here indicate that the transition from a warmer, wetter Mars towards the cold, dry climate of today may have been more complicated than previously assumed. The significant deposition rates require active evaporation and replenishment of ground water with mean surface temperatures near or above freezing, as well as the ability of the wind to move aeolian grains into areas to be cemented. However, the lack of obvious fluvial dissection of the deposits requires that the climate at this time must have been much drier than at the time of valley network incision in the Late Noachian. The relatively high erosion rates following the main period of deposition indicate that the atmosphere must have been thick enough to sustain winds with enough power to erode and move sand-sized grains. However, significant aeolian erosion could not have taken place until deposition largely ceased and the water table dropped below the surface, likely due to a weakening hydrologic cycle. This indicates that major atmospheric loss continued after the hydrologic activity shut down. This series of events suggests that the transitions from warm to cold temperatures, and from wet to dry surface conditions, and from thick to thin atmosphere were neither instantaneous nor synchronous. Instead, mean surface temperatures remained above freezing until sometime after the transition from wet to arid conditions, a process that likely occurred over a period of tens to hundreds of Myr. Furthermore, a substantial atmosphere persisted after the drying of the climate in order to facilitate the erosion of the deposits.

6. Conclusions

6.1. Summary and discussion

The sedimentary rocks of Meridiani and Arabia Terra are inferred to be part of a unique hydrological and depositional environment that spans the transition from Noachian to Hesperian climates on Mars. This study brought together evidence from spectral and morphological data to show that outcrops across Arabia Terra are likely related to those in Meridiani Planum and thus the Meridiani-type deposits were once more extensive. Hyperspectral analyses of the Meridiani-type rocks and possibly related outliers were performed using CRISM data to identify outcrops of Meridiani-type rocks based on the unique sulfate mineralogy found in the Meridiani Planum deposits. However, dust cover in much of the Arabia Terra region and instrument noise impeded this analysis. Despite these challenges, two confident sulfate detections were made in Arabia Terra in regions far removed from Meridiani: in Schiaparelli crater and Crater X, located distances of ~400 and 420 km, respectively, from the edge of the Meridiani etched terrain. Assuming the outlying sulfates formed in the same way as those in Meridiani, these locations reveal that groundwater-fed playas existed over a large area.

The CRISM analysis was augmented by an erosional morphological analysis to identify additional outcrops related to those in

the crater population into agreement with the scaled rate from Beccquerel of \( \approx 1 \times 10^{-5} \) m/yr.

The constraint on the erosion rate is also in agreement with previous estimates of the erosion rates for the Noachian period (Golombek et al., 2006). This result is important, considering that cessation of deposition and onset of erosion likely occurred due to a decrease in hydrologic activity as the climate was drying out. This may require the atmosphere to have remained sufficiently thick, despite the aridity, in order to sustain such erosion rates through \(~3.66–3.56\) Ga. Subsequent to this time, though, erosion rates must have dropped significantly. If erosion had continued at the rate estimated, the ensuing \(~3.5\) Gyr would have seen up to \(~10\) km of sedimentary material removed, yet extensive deposits remain unarmored in the Meridiani etched terrain and elsewhere. Estimates of large-scale Amazonian erosion rates on Mars of order \(<1\) m/yr (Golombek et al., 2006) show that erosion rates subsequent to large-scale denudation of the Meridiani-type deposits were low. It should be noted, however, that modern erosion rates may be orders of magnitude higher on localized scales, such as around fresh ejecta blocks (Golombek et al., 2010). However, these small-scale higher erosion rates may not be relevant to the regional erosion of the Meridiani-type deposits.

An additional constraint on the onset of deposition of these sediments is provided by the timing of valley network formation. The observed Meridiani-type deposits are not dissected by dendritic fluvial valleys, and the Meridiani etched terrain itself forms a sedimentary fill within some valley networks (Hynek and Phillips, 2008). This indicates that the deposits were laid down after valley-forming environmental conditions had ceased. Fassett and Head (2008) found that the ages of dendritic fluvial valley networks in the highslands are clustered tightly around the Noachian–Hesperian boundary with a mean age of \(~3.75\) Ga, and a range of 3.69–3.93 Ga (see Appendix A of Fassett and Head (2008)). These ages represent the cessation of fluvial activity in the individual valley networks, and suggest that valley network activity ceased globally near the Noachian–Hesperian boundary. This is consistent with ages from other studies that found valley network ages clustering in the Late Noachian (Hoke and Hynek, 2009; Irwin et al., 2005). Therefore, the Meridiani-type deposits must have formed after this period of intense fluvial dissection. The upper bound age constraint produced by crater age dating from this study places deposition beginning sometime after the late Middle Noachian (\(3.83\) \(+0.01\) / \(-0.00\) Ga), which indicates the basement age and places only an upper limit for the onset age of deposition. If deposition began after the cessation of valley network formation at \(~3.75\) Ga, the calculated deposition rates would increase somewhat.

Another constraint derives from the post- and syn-deposit crater age (\(3.66\) \(+0.11\) / \(-0.11\) Ga), which indicates that the deposits were present in some form in the Early Hesperian. Therefore, taking into account the constraint from valley networks, the window for onset of deposition can be narrowed to between approximately 3.75 and 3.66 Ga, a period of only \(~90\) Myr. The intensity of valley network formation around the Noachian–Hesperian boundary, followed so closely by evaporite formation, suggests that there was a relatively rapid environmental and geological shift from runoff and fluvial dissection to arid conditions conducive to playa formation. This transition, as well as the later drying of the climate that ended the period of sulfate deposition, may have resulted from the combined effect of atmosphere loss and the sequestering of ice in the polar caps and cryosphere, together with more abrupt climate changes driven by shifts in the mean obliquity of Mars (Andrews-Hanna and Lewis, 2011).

This history is consistent with constraints on the timing of the formation and erosion of the Gale Crater sedimentary deposit. The lower formation of the Gale Crater deposit has been interpreted as having formed by similar processes to the Meridiani Planum and Arabia Terra deposits (Andrews-Hanna et al., 2012). The Gale deposit was inferred to have a minimum formation age of Early Hesperian (\(~3.7–3.6\) Ga) based on stratigraphic relationships, while the Late Hesperian–Early Amazonian (\(~3\) Ga) exposure age of the surface of the remnant sedimentary mound indicates that the km-scale erosion ceased at that time (Thomson et al., 2011). The similar depositional and erosional histories of these two widely separated sedimentary deposits supports the inference that the climatic and hydrologic transitions recorded in Arabia Terra were global in extent.
Meridiani. The morphological assessment showed that eight distinct types of erosional styles occur in the well-characterized sedimentary deposits in the Meridiani area, and that these same styles can be found throughout Arabia Terra. While some of these erosional styles may occur elsewhere, their abundance, concentration, and association with each other make them important and reliable tools for identifying Meridiani-type sedimentary rocks.

It must be acknowledged that not all of the layered deposits in Arabia Terra are necessarily composed of Meridiani-type sediments. In western Arabia Terra, light-toned layered deposits in the vicinity of Mawrth Valles are dominated by phyllosilicate mineralogy (Noe Dobrea et al., 2010; Michalski et al., 2007). Phyllosilicates are in some places observed stratigraphically below the sulfares (Wiseman et al., 2008; Wray et al., 2009) and thus represent an earlier phase of aqueous alteration. However, it appears possible that some layered deposits could be transitional between the phyllosilicate and sulfate end-member deposits, as suggested by the Al-rich phyllosilicates possibly formed by alteration by acidic groundwater, overlying Fe/Mg-phyllosilicates indicative of a neutral precipitation-dominated environment (Noe Dobrea et al., 2010). Nevertheless, the thick stacks of finely layered deposits investigated in this study are not consistent with known phyllosilicate deposits and are strongly indicative of Meridiani-type deposits.

The distribution of sedimentary deposits identified above provides only a partial view of the original distribution of the inferred Meridiani-type deposits of Arabia Terra. The elevations of pedestal craters, intra-crater deposits, and other remnant sedimentary deposits were used to reconstruct the pre-erosional deposit surface, and map out the eroded deposit thickness, showing the potential paleo-extent of the Meridiani-type deposits. The eroded volume estimates calculated in this study show that 0.90–1.68 × 10^6 km^3 of sedimentary material was eroded from Arabia Terra, equivalent to a global layer 6.2–11.6 m deep. The pre-erosional deposit would have covered 2.5–3.6 × 10^6 km^2. Extrapo lating from the inferred groundwater-fed playa at Meridiani, the predicted pre-erosional distribution of these related deposits indicate widespread hydrological activity in Arabia Terra. The depositional environment of a groundwater-fed playa also suggests that liquid water had to be stable, at least intermittently, over the depositional time span of the Meridiani-type deposits. Andrews-Hanna et al. (2010) present a groundwater model driven by evaporation and precipitation that could account for the large volumes of sedimentary rocks predicted by this study. Their model-predicted deposits agree well with the reconstructed distribution and thicknesses of this study.

The crater age dating of a basin once filled by Meridiani-type sedimentary rocks gave insight into the detailed geologic history of the deposits. The deposits were estimated to have been laid down and subsequently eroded over a 270 ± 25 Myr time span between 3.83 ± 0.02 Ga and 3.56 ± 0.19 Ga. In addition to constraining the timing of deposition and erosional processes, the crater chronology can be used to calculate a lower bound on the erosion or deposition rates of 3.1 ± 1.7 × 10^-6 m/yr. This range of rates encompasses the scaled deposition rate from Beccuerel crater based on a direct correlation of the layering periodicity with Mars’ orbital evolution (Lewis et al., 2008). The lower bound on the erosion rates from these deposits are in agreement with those estimated for the Noachian (Golombek et al., 2006). However, the bulk of the erosion must have taken place during the Hesperian, which may require the persistence of a thick (relative to today) atmosphere after the demise of the active hydrological cycle.

6.2. Proposed geologic history

Based upon the geomorphic classification, spectral analysis, topographic reconstruction, and crater age dating of this study, together with the results of previous studies, we propose the following generalized scenario for the history of this region. During the Noachian, the basement rocks were dissected by valley networks and altered to phyllosilicates. In the Late Noachian, volcanic plains flooded the basin in northeast Arabia Terra. The climate at this time was relatively warm and wet, and liquid water was consistently stable at the surface. Between ~3.75 and 3.66 ± 0.11 Ga, around the end of the Noachian, the climate experienced a transition to arid conditions. This triggered a cessation of fluvial dissection and shift in the dominant mineralogy from phyllosilicate to sulfate generation. The erosion during the Noachian was likely a result of higher precipitation rates and hydrological activity dominated by overland flow and fluvial incision (e.g., Irwin et al., 2005). The transition from erosion to evaporite deposition can be explained by declining precipitation rates, leading to infiltration, long-distance groundwater transport in the deep subsurface, and zones of focused evaporite formation in regions of groundwater upwelling (Andrews-Hanna and Lewis, 2011).

Depressions such as craters would have filled with Meridiani-type sediments first, and then sediments would spillover and cover much of the Meridiani and Arabia Terra regions (Andrews-Hanna et al., 2010). Eventually, the plains and much of the Arabia Terra basement were covered by the Meridiani-type deposits as they continued their growth. The groundwater table during this time must have been high enough to produce the evaporites that cement aeolian materials in dunes and inter-dune areas, and form diagenetic sulfate minerals and hematite in the subsurface. Hydrologic activity continued with sufficient hydraulic head to drive the ground water table to the continually rising sediment surface to generate stacks of sediments over 1 km thick.

Sometime prior to 3.56 ± 0.19 Ga, the hydrologic cycle began to wane and new deposits were no longer forming. Instead, large-scale aeolian erosion took place, deflating the entire area. The deposits were differentially indurated causing differential erosion into distinct morphologies. Well-armored craters within the deposits became pedestals, filled craters were scoured so that only intra-crater mounds remained, and layers eroded first into benches and then etched terrain and other erosional morphologies. Over a kilometer of sediments were removed in some areas, with a total estimated volume of 0.90–1.68 × 10^6 km^3 of sediments eroded from an area of 2.5–3.6 × 10^6 km^2. The atmosphere at this time must still have been relatively thick in order to sustain such large-scale denudation. After 3.56 ± 0.19 Ga, major erosion and modification of the region ceased. This was likely due to the thinning atmosphere, though topography may have reached large-scale equilibrium with the aeolian modification regime of the landscape (e.g., Golombek et al., 2010). Subsequently, only a steady rate of impact cratering and low rates of erosion have modified the surface in this region.

The long-term trends in erosion, deposition, and aqueous mineralogy are here interpreted as reflecting long-term trends in temperature, aridity, and atmospheric conditions. However, the analyses in this study cannot distinguish between the effects of sustained conditions and those of transient conditions in a more variable climate (e.g., Head, 2012) at any one stage during the climatic and hydrologic evolution of Mars. The fluvial geomorphology of the Noachian valley networks is more consistent with long-term aridity punctuated by transient wetter periods of runoff and incision (Stepinski and Stepinski, 2005; Irwin et al., 2005). It is also possible that the sulfate deposition in the Late Noachian to Early Hesperian may have been accomplished during transient arid periods with low rates of precipitation, punctuating an otherwise hyper-arid climate. Similarly, the erosion of the sedimentary deposits in the Early to Late Hesperian may have occurred in brief episodes, requiring even higher rates than the lower bounds from this analysis. Although we cannot determine if the long-term
average temperatures were above freezing during any one stage in Mars' evolution, the average conditions must have been conducive to significant periods of time in which the surface was above freezing during both fluvial dissection and evaporite deposition. Such transient episodes of warmer–wetter conditions may have been driven by orbital variations (Andrews-Hanna and Lewis, 2011), impacts (Segura et al., 2002), volcanic outgassing (Haley et al., Johnson et al., 2008), or other unknown processes.

The history of these deposits is essential in understanding the transition of Mars from warm and wet to cold and dry. This work indicates that this change may have occurred in a more complicated manner than previously suggested. The transition began with a pulse of valley network formation in the Late Noachian, followed by a shift to an arid, sulfate-producing environment over perhaps as little as ~120 Myr. The temperature was likely above or transiently above freezing during most of the ~270 Myr depositional period. After deposition ceased, the atmosphere remained thick enough to sustain substantial erosion, perhaps until as recently as ~3.56 Ga. The climate transitions on Mars during the Late Noachian and Early Hesperian were an important time in Mars' geologic history, the details of which we are only beginning to unravel.

Acknowledgments

We are grateful to Caleb Fassett and an anonymous reviewer for their thorough and thoughtful reviews. This work was supported by a grant to J.C.A.-H. from the NASA Mars Data Analysis Program.

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