AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Planets

RESEARCH ARTICLE

10.1002/2014JE004699

Key Points:
- The first field geologic map on Mars
- Large volumes of water circulated through fractures in the crust
- The first in situ traverse on the rim of a complex impact crater

Correspondence to:
L. S. Crumpler,
larry.crumpler@state.nm.us

Citation:
Crumpler, L. S., et al. (2015), Context of ancient aqueous environments on Mars from in situ geologic mapping at Endeavour Crater, *J. Geophys. Res. Planets*, *120*, 538–569, doi:10.1002/2014JE004699.

Received 18 JUL 2014
Accepted 9 FEB 2015
Accepted article online 11 FEB 2015
Published online 24 MAR 2015

Context of ancient aqueous environments on Mars from in situ geologic mapping at Endeavour Crater

L. S. Crumpler[1], R. E. Arvidson[2], J. Bell[3], B. C. Clark[4], B. A. Cohen[5], W. H. Farrand[4], R. Gellert[6], M. Golombek[7], J. A. Grant[8], E. Guinness[2], K. E. Herkenhoff[9], J. R. Johnson[10], B. Jolliff[2], D. W. Ming[11], D. W. Mittlefehldt[11], T. Parker[7], J. W. Rice Jr.[12], S. W. Squyres[13], R. Sullivan[14], and A. S. Yen[7]

[1]New Mexico Museum of Natural History and Science, Albuquerque, New Mexico, USA, [2]Department of Earth and Planetary Sciences, Washington University in Saint Louis, St. Louis, Missouri, USA, [3]School of Earth and Space Exploration, Arizona State University, Tempe, Arizona, USA, [4]Space Science Institute, Boulder, Colorado, USA, [5]Marshall Space Flight Center, Huntsville, Alabama, USA, [6]Department of Physics, University of Guelph, Guelph, Ontario, Canada, [7]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, [8]Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, District of Columbia, USA, [9]U.S. Geological Survey, Astrogeology Science Center, Flagstaff, Arizona, USA, [10]Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland, USA, [11]Johnson Space Center, NASA, Houston, Texas, USA, [12]Planetary Science Institute, Tucson, Arizona, USA, [13]Department of Astronomy, Cornell University, Ithaca, New York, USA, [14]Center for Radiophysics and Space Research, Cornell University, Ithaca, New York, USA

Abstract Using the Mars Exploration Rover *Opportunity*, we have compiled one of the first field geologic maps on Mars while traversing the Noachian terrain along the rim of the 22 km diameter Endeavour Crater (Latitude −2°16′33″, Longitude −5°10′51″). In situ mapping of the petrographic, elemental, structural, and stratigraphic characteristics of outcrops and rocks distinguishes four mappable bedrock lithologic units. Three of these rock units predate the surrounding Burns formation sulfate-rich sandstones and one, the Matijevic Formation, represents conditions on early Mars predating the formation of Endeavour Crater. The stratigraphy assembled from these observations includes several geologic unconformities. The differences in lithologic units across these unconformities record changes in the character and intensity of the Martian aqueous environment over geologic time. Water circulated through fractures in the oldest rocks over periods long enough that texturally and elementally significant alteration occurred in fracture walls. These oldest pre-Endeavour rocks and their network of mineralized and altered fractures were preserved by burial beneath impact ejecta and were subsequently exhumed and exposed. The alteration along joints in the oldest rocks and the mineralized veins and concentrations of trace metals in overlying lithologic units is direct evidence that copious volumes of mineralized and/or hydrothermal fluids circulated through the early Martian crust. The wide range in intensity of structural and chemical modification from outcrop to outcrop along the crater rim shows that the ejecta of large (>8 km in diameter) impact craters is complex. These results imply that geologic complexity is to be anticipated in other areas of Mars where cratering has been a fundamental process in the local and regional geology and mineralogy.

1. Introduction

Mars Exploration Rover *Opportunity* crossed the geologic contact between Meridiani Planum and older Noachian terrain when it arrived at the 22 km diameter "Endeavour" impact crater rim on its 2681st Mars day ("sol") after landing ("sol 2681," 9 August 2011). Examination of outcrops of greatly differing age on both sides of the contact represents one of the first in situ documentations of conditions on Mars over widely separated periods of geologic time, a fundamental mission task for the Mars Exploration Rovers (MER) Program [*Squyres et al*., 2003].

Initial traverses in this new terrain occurred on Cape York, an isolated segment of the Endeavour crater rim that is partially buried in regional late Noachian to early Hesperian age sulfate-rich sands of the *Burns formation* [*Squyres and Knoll*, 2005] (Figure 1). A sequence of several distinctive bedrock lithologic units separated by marked unconformities was examined in situ by Opportunity along the traverse in this terrain [*Arvidson et al*., 2014]. These bedrock units contain variations in elemental abundances, mineralogy, and petrography that are documented in a rover-based geologic map presented here. Stratigraphic control

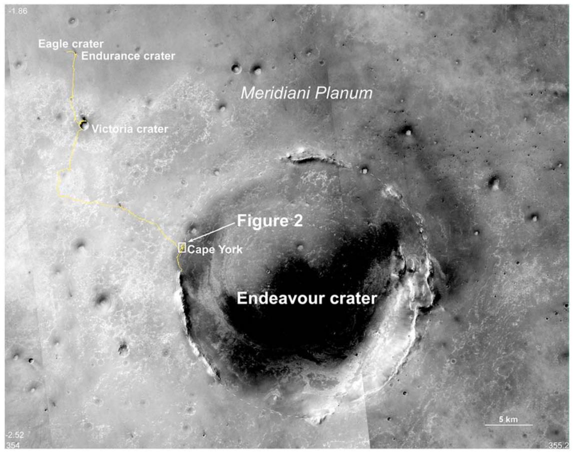

Figure 1. Map of Opportunity traverse from landing site to the rim of Endeavour Crater. The traverse around Cape York occurred between sols 2681 and 3315. Image source, MRO/Context Camera images B02_010486_1779_XN_02S005W, P15_006847_1770_XN_03S005W, and P13_006135_1789_XN_01S005W. Image width, 45 km.

together with interpretations of the origin and significance of variations in petrography, mineralogy, and chemistry are sufficient to validate some of the previously inferred characteristics global Martian climatic history defined from global photogeologic mapping and remote sensing [*Scott and Carr*, 1978; *Scott and Tanaka*, 1986; *Greeley and Guest*, 1987; *Sharp and Malin*, 1984; *Bibring et al*., 2006; *Tanaka and Hartmann*, 2008]. Similar methods were applied previously at the MER Spirit site [cf. *Crumpler et al*., 2011] and identified distinct differences in rates of apparent weathering across large unconformities in the stratigraphic record at Gusev Crater. Compilation of the results along the rim of Endeavour crater also represents the first field reconnaissance geologic map on the topographic rim of a complex (>8 km diameter on Mars) impact crater.

2. Traverse and Strategic Science Narrative

The Cape York Crater rim segment is a hill 770 m long and 250 m wide located on a gentle slope into the interior of Endeavor Crater. It is asymmetric in profile, the western flank low to completely level with the surrounding plains and the eastern side sloping up to 12° toward the crater interior. A broad bench encircles Cape York and grades from the interior to the contact with the plains and the Burns Formation. A low escarpment is present in a few places near the contact between this bench and the interior outcrops. Opportunity made local traverses into the interior to investigate outcrops, but most of the 2.6 km circumnavigation of Cape York was executed using the relatively planar surface of the encircling bench (Figure 2).

The traverse began at the southwestern end of Cape York (Figures 2a and 2b) where a 20 m diameter impact crater (*Odyssey Crater*) had excavated blocks suitable for investigation as samples of the bedrock. A bright slab-like rock a few meters southeast of the rim of Odyssey crater, *Tisdale* 2, was the site of the first in situ analysis of Cape York material (sols 2696–2706, 25 August 2011 to 4 September 2011). After examining Tisdale, Opportunity traversed east and north partly up the slopes of Cape York to a broad light-toned outcrop feature, named *Chester Lake* (sols 2707–2735, 5 September 2011 to 4 October 2011) followed by the in situ analysis of the target *Salisbury*. Initial results are reported in *Squyres et al*. [2012].

Outcrops northward along the crest of Cape York, informally named *Shoemaker Ridge*, are coarse assemblages of lithic fragments embedded in a fine-grained matrix. Along the traverse north a brief stop was made (sols 2765–2771, 4–10 November 2011) at the western contact between the plains and the slopes of Cape York (Figure 2c) where Opportunity examined one of the widely distributed small light-toned veins (*Homestake*, sols 2769–2771, 8 November 2011). Opportunity spent its fourth winter (sols 2795–2946, 5 December 2011 to 8 May 2012) on the ridge crest at the north end of Cape York (*Greeley Haven*) (Figure 2c) situated on one of the coarse, clast-rich outcrops.

In the following spring Opportunity continued to the northern marginal contact with the surrounding Meridiani Planum where an important lithologic type example, *Grasberg* (sols 2989–3007, 21 June 2012 to 10 July 2012) was examined (Figure 2d). The traverse continued in a clockwise direction around the north margin of Cape York visiting two "fractures" or graben-like traces (*Mount Goldsworthy*, sol 3008–3009 11–12 July 2012 and *Whim Creek*, sols 3019–3039, 22 July 2012 to 11 August 2012). These two fractures cut across both the plains and the apron surrounding Cape York (Figure 2d) where the measurements of contact displacement provided some simple tests of stratigraphic sequences.

Analysis of orbital remote sensing by the *MRO/CRISM instrument* (*Mars Reconnaissance Orbiter Compact Reconnaissance Imaging Spectrometer for Mars*) suggested the presence of broadly exposed phyllosilicates

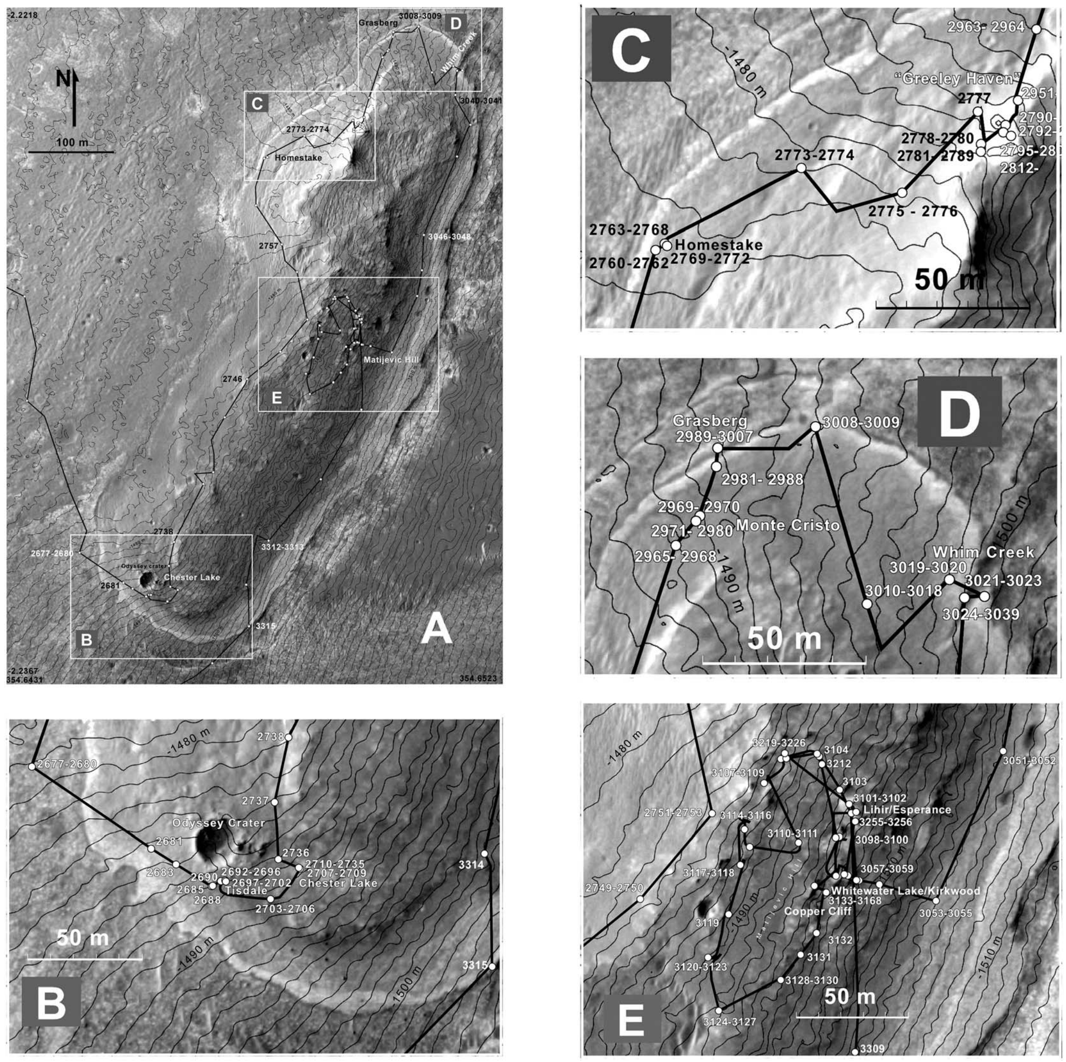

Figure 2. (a) Overview of the traverse at Cape York. Outlined boxes identify locations of areas shown in Figures 2b–2e. Image width, 586 m. (b) Southern point of arrival at Cape York near the 20 m diameter Odyssey Crater. (c) Location of Homestake, a light-toned vein observation, and (right) the site of the fifth winter, Greeley Haven. (d) Traverse on the bench around the northern end of Cape York, site of Grasberg and Whim Creek observations. (e) The outcrop walk about at Matijevic Hill, a circuit of the interior of Cape York in search of outcrop evidence for phyllosilicates. Image source, MRO/HiRISE, ESP_018846_1775. Contours (1 m) are based on MRO/HiRISE DTM data using images ESP_018701_1775 and ESP_018846_1775. White dots on black line indicate the successive locations occupied by Opportunity during the traverse.

[*Arvidson et al*., 2014] approximately halfway along the east flank of Cape York. So Opportunity traversed south along the eastern margin of Cape York with the goal of examining outcrops in the interior of Cape York (subsequently named *Matijevic Hill*). During the southward traverse (sols 3042–3055, 15–28 August 2012), a series of Panoramic Camera (Pancam) and Navcam panoramas were acquired to continue mapping the structural arrangement and lithologic characteristics of Cape York on its east margin. The texture and apparent structure of many outcrops along the east margin from these panoramas appear similar to the rough, clast-rich breccias typical of that seen along the crest of Cape York.

Opportunity executed a prospecting circuit or geologic "outcrop walk about" of the interior of Matijevic Hill (Figure 2e) in search of outcrops relevant to the CRISM phyllosilicate detections. At the start of this circuit an unusual dark fin-shaped outcrop consisting of unusually high concentrations of small spherules was identified on the east edge of the interior outcrops (the outcrop *Kirkwood*, Matijevic Hill Outcrop Campaign, sols 3056–3307, 29 August 2012 to 14 May 2013) [*Arvidson et al*., 2014]. The traverse ultimately returned to the starting point of the loop where outcrops of extremely altered rocks were examined. These outcrops were determined to be the stratigraphically lowest unit and probable source of the phyllosilicate detections in CRISM observation [*Arvidson et al*., 2014].

After completion of the Matijevic Hill prospecting campaign, Opportunity exited southward driving again along the smooth eastern apron surrounding Cape York. It departed the southern end of Cape York on sol 3316 (23 May 2013) making observations of the contact between the Grasberg Formation on the edge of Cape York and the surrounding Burns Formation before continuing the traverse southward to the next rim segments of Endeavour Crater, *Nobby Head*, and *Solander Point*.

3. Field Geologic Mapping Method on Mars

The methods used in this study are modified versions of the techniques of traditional field geologic mapping on the Earth. Experience in geologic mapping from Mars Exploration Rovers Spirit and Opportunity over the past decade has shown that the methods of geologic mapping are similar on foot in the field on Earth and in situ on Mars with a rover. The dimensions of the mappable geologic units on Mars and that of geologically complex areas on Earth are both similar and occur at a "human scale" of observation, that is, centimeter to meter length scales. Erosion can expose geologic sections allowing direct determination of stratigraphic successions, measurements of the attitude of bedding, fractures, and faults, and identification of unconformities and other hiatuses. The principal differences in mapping with a rover on Mars are those associated with the restricted view of surroundings and the lower sampling rate of both the context scenes and of the rocks along the traverse. With rovers, there is little information between observation stations, and stations can be separated by tens of meters. The result is analogous to mapping on the Earth in areas of poor outcrop exposure where the geology must be inferred between outcrops.

The hypothesis-testing methodology at the core of field geologic mapping is also similar on Mars and on Earth, although the number of tests that can be done with a rover is restricted because a rover is slower. On Earth, geologic documentation of outcrop observations can include traverse of a large area over which several outcrops might be examined, traversing in a "zigzag" pattern to many outcrops in the vicinity of a general traverse line to sort out several competing geologic hypotheses. With a rover, short side trips to surrounding outcrops are not often feasible within available strategic and mobility constraints, so a much smaller number of tests can be accommodated. Because the traverse proceeds without excursions to surrounding exposures, the observations are confined to a narrow corridor. The final map based on these observations is a geologic transect map or a geologic "strip map" differing only in shape and very little in geologic content from the broad rectilinear study areas of traditional terrestrial quadrangle mapping.

Data downlink rates, the frequency of communication, and the comparatively limited speed and terrain manageability are the principal restrictions limiting the rover speed and the number of sites visited and the corresponding level of mapping detail. But there are other limitations related to the robotic process, including the communal character of the platform. Rover science operations have been compared to a busload of field geologists going from outcrop to outcrop with corresponding differences of opinion about what observations to make, where to go to make them, and the interpretation and significance of the observations made. Despite these limitations, the findings from a rover-based in situ mapping exercise provide stratigraphic context for materials of disparate position and variable elemental composition that otherwise would be uncorrelatable from remote sensing alone. These results are "ground truth," invaluable to interpretation of more expansive data sets provided from orbital remote sensing.

Within the above constraints, the textures, structures, mineralogy, chemistry, and petrography of outcrops were systematically examined in situ at a dozen locations during Opportunity's traverse around and through the interior of the Cape York Endeavour Crater rim segment. Similarities and differences between examined rocks and outcrops were noted and the rock types and relative stratigraphic positions of widely separated outcrops were compared, correlated, and mapped. Instead of depicting the geology over a rectangular area or "quadrangle," the map is restricted to within the limits of detection capability, nominally defined as the distance beyond which it is not possible to resolve the characteristics necessary to identify and distinguish different rock types using Navcam images. Experience has shown that detection and identification of geologically definitive features is limited to about 20 m distance in the MER moderate resolution setting (2 bit) Navigation Camera (Navcam) frames. This limit defines a swath width of 40 m along the traverse for which geologic information is most reliable (Figure 3). In many locations geologic characteristics can be detected beyond 20 m, either due to higher bit count, more

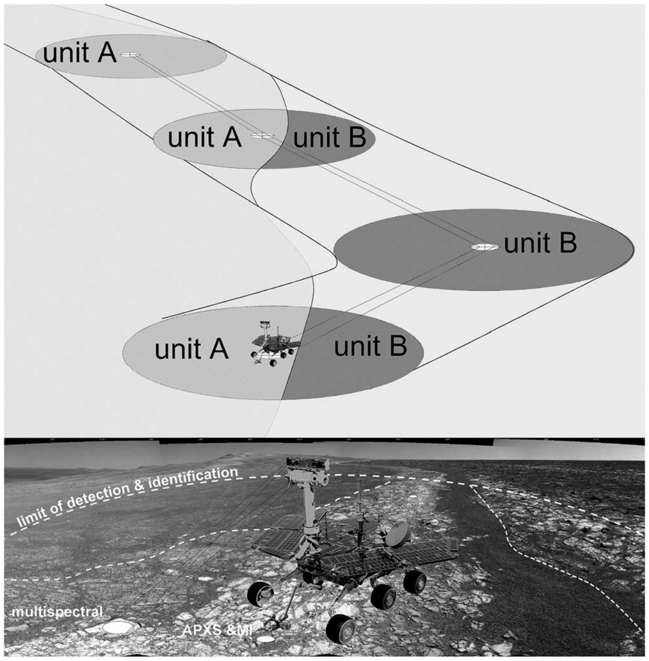

Figure 3. Schematic of in situ geologic mapping as done from a rover. Experience using Spirit and Opportunity shows that detection and identification of lithologic differences is limited to a distance of 20 m from the rovers. Beyond this distance features may be insufficiently resolved for identification or correlation with previously visited outcrops. Petrologic characteristics are determined using the in situ instruments (APXS, MI, and RAT) and mast-mounted cameras (Navcam and Pancam visible and multispectral remote sensing). Following traditional geologic mapping methods in terrains where outcrops are isolated, contacts between units are tracked and interpolated between stations where necessary. The compiled result is a geologic strip map.

favorable lighting, or favorable slope. But in a greater number of settings, mapping beyond this distance is not possible. Therefore, we set 20 m as the most consistent limit on mappability.

Plotting the observed exposures of each lithologic unit, correlation of exposures from site to site and identification of their contacts, respective overlapping characteristics, time series of emplacement, and compilation of their attitudes enabled preparation of a geologic map (see Figure 13) along the traverse in which the geologic units are defined from outcrop studies of the different lithologic units. Because sectional exposures are rare, determination of stratigraphic relationships required using some basic field geologic techniques to resolve geometry, as discussed later in section 5. The availability of topographic relief data from High Resolution Imaging Science Experiment (HiRISE) digital terrain models also allowed construction of simple geologic sections in order to test stratigraphic and structural field interpretations. In some situations, the attitude of bedding has been determined from simple field methods such as along-strike and down-dip viewing and plotting contacts on geologic sections. Another simple, but standard field method, that of contact displacement across vertical faults and intercepting erosion planes was also used to test for a proposed stratigraphic order (section 5.3.1).

The construction of a geologic map from in situ observations is an important development in Mars science because it allows definition of stratigraphic sequence and establishes parameters sufficient to define local structure, and definition of geologic history extending over an interval of Martian time during which several bedrock materials were formed following intervening periods of erosion. The results may be considered ground truth testing some of the fundamental concepts about Martian climatic history postulated from years of orbital remote sensing.

4. Lithologic Units Identified From In Situ Observations

The primary observations that distinguish each lithologic unit are compiled in the following along with the relevant contact and stratigraphic inferences. The discussion below reviews these characteristics in descending stratigraphic order and provides an overview of their distribution, contact relationships, and observations relevant to their significance in understanding the geologic history at Endeavour Crater. While the discussion of each unit is necessarily protracted and a review of earlier work in the case of several units, the intent is to provide some insight into the detail of the observations that went into defining them. Initial discussion of the Shoemaker and Matijevic Formations at Cape York and the surrounding Burns Formation are reported in *Squyres et al*. [2012] and *Arvidson et al*. [2014] and other references as cited throughout the unit descriptions. Here these descriptions are brought together, which together with the geologic map, enable a coherent view of the regional stratigraphy.

Table 1. Lithologic Units Identified on the Rim of Endeavour Crater, the Sols During Which They Were Traversed, and the Mission Sol and Target of Representative Outcrop Observations and Analyses[a]

Map Label	Unit Name	Sols Traversed	Date and Targets Analyzed
a_2	Aeolian ripples	2746 2758–2759 2773–2774 2947–2954 2955–2968	Sol 2957/"North Pole2"
a_1	Soils and regolith	2737–2738 2744–2745 2749–2753 2767 2775–2794 2947–	Not analyzed
B	Burns Formation	0001–26803024–3029	All previous to sol 2681; Sol3027/Rushall
G_2	Grasberg Formation (upper Grasberg)	2681 2760–2762 2989–3007 3019–3023 3042–3043	Sol3001/Grasberg; Sol3021–23/Mons Cupri
G_1	Grasberg Formation (lower Grasberg)	2683–2702 2769–2772 2969–2988 3008–3009 3040–3041 3044–3056	Sol2771/Deadwood Sol2765/Homestake (included veins), Sol2974/Ootsark
cys	Basal Cape York slopes	3056–3059 3240–3245	Not analyzed
S	Shoemaker Formation	2707–2735 2778–2948 3104–3111 3112–3116 3119–3120? 3165–3181 3213–3226	Sol2696/Tisdale 2_Timmons, sol 2702/Tisdale 2_Shaw, sol 2776/Chester Lake_Salisbury1, sol2707-2735/Greeley Haven outcrop (Komati, Boesmankop, Amboy), sol3168/VermillionCliffs1, sol3177/VermillionLake2 sol3158/Onaping, Maley
[b]	"Kirkwood newberry outcrop"	3063–3069 3246–3254	Sol 3067/Kirkwood, sol 3253/SturgeonRiver3
M	Matijevic Formation	3070–3103 3110–3111 3128–3239 3246–3300+	Sol 3070-3096/ Whitewater Lake, Azilda; sol 3187-3194/Sandcherry, Ortiz, Fullerton3/Lihir, Esperance

[a]Units are listed top to bottom from youngest to oldest.
[b]Newberry deposits were not mapped as a separate unit because the exposures are too small.

Two map units consisting of surficial materials and at least four distinct bedrock units (Burns Formation, Grasberg Formation, the Shoemaker Formation, and the Matijevic Formation) are mapped from in situ observations. Each unit meets the criteria required of rock stratigraphic units, including mappability and lithologic constancy [cf. *Krumbein and Sloss*, 1963]. Bedrock units are of particular interest in the context of the missions' goals of understanding past climate because they preserve information about conditions prevailing on early (Noachian to early Hesperian) Martian time when the rocks formed. Two late, mobile fine units are related to later and more recent environments. The slope-forming unit that occurs on the low escarpment encircling the interior relief of Cape York was not examined in situ.

Table 1 provides a brief overview of the geologic units identified from in situ observations and the target names and the sol(s) during which observations were made of each lithologic unit. These are arranged in their approximate stratigraphic order and, for reference, illustrated in columnar section in Figure 17, discussed in a later section. Unit labels (letter abbreviations) are those used on the final geologic maps shown in Figure 13.

4.1. Aeolian Ripples, Unit a_2

Aeolian ripples generally are of two types: (1) megaripples (ripples approximately 1 m in width and 10 cm height) covered with coarse grains generally >1 mm and (2) ordinary ripples (ripples a few centimeters or less in width and height) with much finer grains not resolved by Pancam. Neither ripple type was examined closely in the field area, but we infer properties of each type from earlier encounters elsewhere at Meridiani Planum [*Sullivan et al*., 2005; *Jerolmack et al*., 2006; *Golombek et al*., 2010] and at Gusev Crater [*Greeley et al*., 2006; *Sullivan et al*., 2008].

Megaripples on Earth are distinguished by surfaces of very coarse sand or granules that move downwind in creep driven by saltating finer sand. A bimodal sand supply is required for megaripples to form and migrate [*Bagnold*, 1941, pp. 154–157; *Sharp*, 1963]. Megaripple interiors commonly are dominated by the saltating finer sand but can contain foresets of the same coarse material found covering their surfaces. On Mars, the surfaces of megaripples at both MER sites are resistant to remobilization due to induration of the coarse surface grains. Induration likely occurs during periods between strong wind events or during periods when an upwind supply of saltating finer grains is absent [*Sullivan et al*., 2008]. Megaripples are the most abundant (and durable) ripple type in the Cape York area, similar to other areas explored by Opportunity.

Ordinary ripples on Earth generally are much smaller than megaripples and form when winds drive a unimodal sand supply in saltation [*Bagnold*, 1941]. They are ubiquitous among dune fields, for example. In the Cape York field area, ordinary ripples occur only in small, isolated patches, where outcrop or other features (including much larger, indurated megaripples) provide protection from strong winds. The same protection is afforded to air-fall dust, so patches of ordinary ripples commonly are mantled with bright, red dust in areas protected from winds. The dust mantle in these locations must be less than a centimeter thick, otherwise the fine wavelength structure of the underlying ripples would be unrecognizable. The scarcity of ordinary ripple deposits in the Cape York area indicates the supply of fine, saltating sand currently is relatively low, consistent with the more widespread, more prominent megaripples having been indurated and immobile for 10^4 to 10^5 years [cf. *Golombek et al*., 2010].

4.1.1. Interpretation and Significance

Fields of megaripples occur mostly on the western side of Cape York, particularly on the "bench" separating the Burns Formation from the interior outcrops of Cape York, and cover a substantial portion of the northern end of Cape York, as well. Individual megaripples on Earth and Mars can migrate in isolation (where "troughs" between crests are actually intervening ground of different material), so the term "wavelength" is not always applicable and distances between megaripple crests can vary considerably. Spacing between megaripples where these bedforms are most widespread, e.g., the northern end of Cape York, range from tens of centimeters to 3 m or more (Figure 4a). Accumulated wind-blown materials are common immediately eastward of ridge crest outcrops, forming wind-sheltered locations where isolated patches of dust-covered ordinary ripples can be found, such as the target *North Pole* sampled on sol 2957 (19 May 2012).

4.2. Soils (Surficial Sediments and Regolith) (a_1)

Many areas between rocky outcrops generally are topographically smooth, devoid of structure, and covered with debris generally smaller than 10 cm. We refer to this material simply as soil. Aeolian features such as megaripples, ordinary ripples, or drifts are absent. Instead, a mixture of grain sizes is present, apparently with the coarser fractions abundant enough to protect finer materials also present from direct erosion by wind. Consistent with this, yardangs and other outcrop-scale evidence for direct etching or stripping of regolith by wind is lacking. In a few locations, regolith surfaces are dark, suggesting the presence of very fine dark sand by comparison with soils examined more closely earlier in Opportunity's mission. Otherwise, soil surfaces have a mixture of poorly sorted materials generally <10 cm, devoid of obvious bedrock exposures.

The regolith unit was not analyzed during the traverse around Cape York, so neither the elemental composition(s) nor petrographic characteristics are known. Prominent light-toned veins characterize some regolith surfaces, such as at *Deadwood* (sol 2771, 10 November 2011). But in these locations the regolith discontinuously mantles true bedrock with only a few centimeters of unconsolidated material at most resulting in a topographically smooth and bland surface (Figure 4b).

Figure 4. (a) View southwest of small ripples on bench sloping down from Cape York to Meridiani Planum. Rippled materials (unit a_2) are widespread but less than a few centimeters thick. Inset shows direction of view referenced to map view 1NNT63ILFBRCYLFPP0613L000M3. (b) A representative area of regolith (unit a_1) on the west side of Cape York. Particles sizes range from dust to granules, and there is little to no bedrock exposure. This Navcam view is directed south-southwest on sol 2744. Hills in distance are the westernmost rim of Endeavour Crater. Image 1NNR44ILFBOCYLJMP0613L000M2. Rover track width is approximately 1 m.

4.2.1. Interpretation and Significance

The relationship of this regolith with local bedrock lithologic unit may be analogous to that between bedrock, alluvium, and float on Earth. We interpret the soil and regolith unit simply as surficial material consisting of a poorly sorted mixture of aeolian fines of various sizes stabilized by contributions from coarser, local outcrop erosion products. The coarser materials form a surface lag that is stable against strong wind events in the current climate regime.

4.3. Burns Formation, Unit B

The Burns Formation is the principal sandstone forming the rocks of Meridiani Planum and was extensively documented and defined from initial studies at the Opportunity landing site [for example, *Squyres et al*., 2004; *Herkenhoff et al*., 2004; *Soderblom et al*., 2004; *Grotzinger et al*., 2005; *McLennan et al*., 2005]. It is a coarse to medium, well-sorted sand with laminations on the scale of a few millimeters and a fine-grained-binding cement [*McLennan et al*., 2005]. Cross-laminated structures characteristic of aeolian transport are widespread in outcrops of the Burns Formation. Festoon geometry characteristic of water transport is locally present, so the water and wind were likely both involved in the deposition of the original clastic sequence. Unusual textures specific to the widespread diagenesis were identified within the Meridiani Planum rocks, such as the small tabular vugs that crosscut the laminations at random orientations in the outcrops at the type locality near the landing site [*Herkenhoff et al*., 2004] or small veins crisscrossing the surfaces like those in the target *Fruitbasket* (sol 558, 19 August 2005).

The sandstones are weakly cemented by terrestrial standards. Rock Abrasion Tool (RAT) used required 30 to 50 times less energy per unit volume to grind Burns Formation rocks than the basaltic rocks examined at the Spirit landing site in Gusev Crater [*Squyres et al*., 2004], implying strength comparable to or less than chalk [*Thomson et al*., 2013]. Concretions occurring as grey spherules 1 to 2 mm in diameter are embedded within the sandstone, erode out, and are concentrated in surficial lag deposits that are characteristic of the soils across Meridiani Planum [*Soderblom et al*., 2004; *Weitz et al*., 2006]. In the vicinity of Endeavour Crater the Burns Formation outcrop exposures tend to consist of upturned and otherwise displaced or rotated cobble to boulder-size fragments such that the plains landscape is relatively rocky and rugged in appearance within the 10 to 100 m adjoining Cape (Figure 5a).

Near-infrared multispectral images acquired by the Panoramic Camera (Pancam) [*Bell et al*., 2003] with center wavelengths from 432 nm to 1009 nm were used to determine the spectral variability of rocks. The details of the methods used for deriving the spectral variability of rocks have been outlined in previous discussions [*Bell et al*., 2003; *Farrand et al*., 2006, 2008], and the multispectral characteristics of the Burns Formation described by *Farrand et al*. [2007]. Both lighter-toned and darker-toned surfaces are common in the Burns Formation outcrops. The former are generally covered by dust or potentially have a thin alteration veneer [*Knoll et al*., 2008]. The darker-toned surfaces generally have had a purple color in L257 color composites made using the 753 nm (L2), 535 nm (L5), and 432 nm (L7) filters. They have a relative reflectance maximum of approximately 750 nm and have a shallow near-infrared (NIR) absorption band with a minimum reflectance occurring at approximately 938 nm (Figure 7). The 535 nm band depth of dark-toned Burns Formation surfaces is variable, but for the spectra considered here, had a mean of 0.21. The lighter-toned surfaces have a buff color in L257 color composites and are like other dust-coated surfaces with a flat to convex shape in the NIR and a moderately high 535 nm band depth.

The only elemental analysis on the Burns Formation conducted during the traverse around Cape York was at the target *Rushall* on the floor of Whim Creek, a fracture cutting across the outcrops of the Grasberg and Burns Formations (see discussion of the Grasberg formation below) at the northern tip of Cape York. With the exception of slightly elevated Ca, which could reflect some contamination by the prevalent $CaSO_4$ exposures around Cape York (section 4.4), the results are similar to most of the Burns Formation outcrops across Meridiani Planum (Figure 8).

SO_3 abundance in the Burns Formation rocks is $>$20 wt % [*Clark et al*., 2005] is present possibly as authigenic sulfate salts forming the cementing agent for the sandstone. Fe abundance is typically in the range of 15 to 18 wt % as FeO. Mg and Ca concentrations are up to several tens of percent. Cl and Br are elevated enough to be detected by the APXS.

4.3.1. Interpretation and Significance

The Burns Formation is a sulfate-cemented, basalt-sourced sandstone [*McLennan et al*., 2005] accumulated in a regionally low area or basin bordering the cratered highlands. The parental rock from which the sand grains originated was fundamentally basaltic and the evaporites are of a composition consistent with weathering of olivine basalt by acidic water [*McLennan et al*., 2005; *Squyres and Knoll*, 2005; *Squyres et al*., 2006]. It may have formed as muds in playas and was then reworked into sands via water and wind. Transport and emplacement occurred through a combination of aeolian and fluvial processes, some reworked, and subsequently authigenic minerals introduced when by rising groundwaters and the grains cemented [*Grotzinger et al*., 2005]. Assessment of the Mössbauer and alpha particle x-ray spectrometer (APXS) results on differing concentrations of the characteristic spherules that litter the surfaces of outcrops indicates that the spherules are 50% hematite (Fe_2O_3) by mass [*Rieder et al*., 2004], and thus the principal reservoir of hematite [*Soderblom et al*., 2004]. The spherules are interpreted to be simple hematite concretions developed through diagenetic alteration of the sandstones [*McLennan et al*., 2005; *Arvidson et al*., 2006; *Calvin et al*., 2008].

At Cape York the Burns Formation is in unconformable contact with the preexisting eroded landscape of Endeavour Crater. The Burns Formation was emplaced largely by a succession of sand deposition that may have initially draped the lower slopes of the Endeavour Crater rim remnants. The fact that no isolated

10.1002/2014JE004699

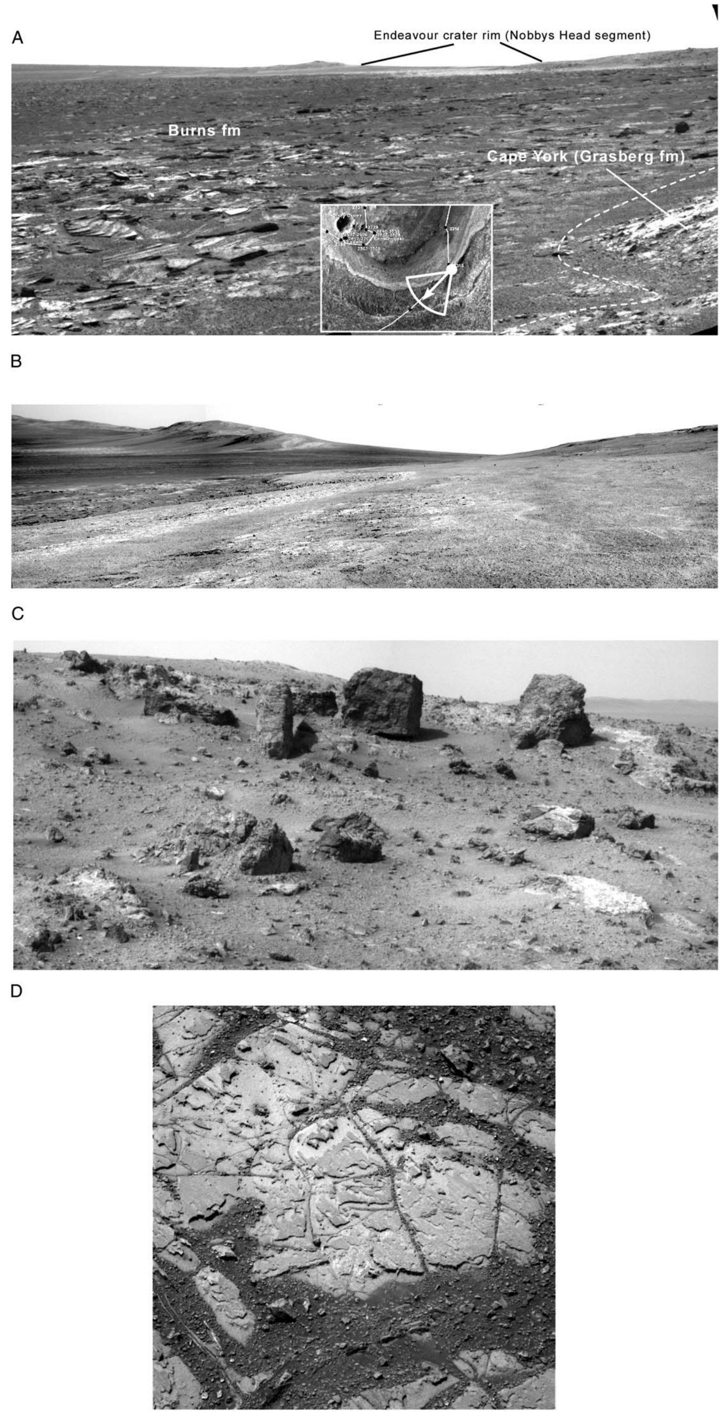

Figure 5. Mesoscopic textures of the four principal lithologic units. (a) Surface of the Burns Formation adjacent to the south margin of Cape York. Note that the surface of the Burns Formation appears as disrupted, laminated sandstone slabs. The view is directed south-southwest toward Nobbys Head, another isolated rim segment to the south, from the position occupied on sol 3315 at the southern margin of Cape York. The contact with the underlying Grasberg Formation is in the lower right. Inset: Direction of view at south end of Cape York. Pancam image 1PP3315EFFBZCYLCUP2368R222C1. Image foreground (bottom) width, ~4 m. (b) View south along the eastern bench of the Grasberg Formation. The contact between dark and rocky Burns Formation and the light-toned, smoother upper Grasberg Formation is on the left. Most of the slope in the foreground is lower Grasberg Formation. Sol3044B_P2388_R2. Image width at base, ~7 m. (c) View north of Shoemaker Formation breccias exposed at the south end of Cape York in the rim of Odyssey Crater (See Figure 2b). The large block at upper right is approximately 1 m high. Sol_2699_P2389_L2. (d) Patchy dark coating on surface of Matijevic Formation at the outcrop Sandcherry. Image is approximately 0.5 m across. Pancam image Sol_ 3136_Sandcherry_P2538_L257.

outcrops of Burns Formation have been recognized inboard of the encircling contacts may be evidence for either incomplete burial of Cape York or is simply the result of erosion. It is possible that small escarpments encircling the interior of Cape York developed during the persistent regime aeolian transport and erosion responsible for the regional sands.

4.4. Upper Grasberg Formation, Unit G_2

In MRO/HiRISE image data the outcrops of this bedrock unit form a light-toned band 2 to 6 m wide outlining the contact between the Burns Formation and Cape York. Inboard of this light-toned band is a darker surface without obvious outcrops and covered uniformly with dark fines. In Navcam and Pancam images, surfaces of the brighter portions of the Grasberg outcrops adjacent to the surrounding plains are uniformly planar and fractured in systematic subpolygonal arrays (Figure 5b). The surface of the Burns Formation by contrast has a wide variation in surface roughness, exhibits nonsystematic jointing angles, is clearly bedded, and displays cross-bedded textures on upturned clasts. Subsequent in situ analysis showed that Grasberg-type outcrops can be distinguished further from the materials of the Cape York interior (*Shoemaker Formation*) and the surrounding plains (*Burns Formation*) based on elemental criteria as well as petrographic distinctions [*Mittlefehldt et al*., 2014].

Viewed along strike, the inboard contact appears to thin or featheredge onto a lower and darker unit forming a broad bench, slope, or apron around the margins of Cape York (Figures 9a and 9b). The result in map perspective is a banded halo wrapping around Cape York. Tonal variations responsible for the banded appearance result from thin layers dipping toward the contact with the Burns Formation and exposed along an angular unconformity. The layers are uniform and dip more steeply than the slope (bench) on which they occur. A simple field explanation of this arrangement is that the banding developed when draping materials of the original Grasberg deposit were graded on a pediment sloping less than the dip of draped bedding planes. Based on the observed outcrop width between the Burns Formation and lower slopes of the Cape York interior and estimates of dip of about 10° from along-strike sighting, we estimate a unit thickness of 1 to 2 m.

Microscopic Imager (MI) data on the RATed surface do not resolve grains [*Herkenhoff et al*., 2013] (Figure 6a) so any grains are smaller than the 32 μm/pixel scale of the MI resolution [*Herkenhoff et al*., 2003] and certainly smaller than the distinctive sand-size [*Squyres et al*., 2004] grains of the Burns formation. Based on a single RAT grind on a Grasberg outcrop (Grasberg, sol 2998, 30 June 2012) the RAT Specific Grind Energy (SGE) 7.6 J/mm^3 indicates that this is one of the stronger rocks at Cape York, even though it is weak compared to typical cliff-forming terrestrial sandstone [*Thomson et al*., 2013]. In contrast, at the outcrop Chester Lake (sols 2707–2735), representative of the Shoemaker Formation, the RAT grind on the target *Salisbury* yielded a SGE of 1.6 J/mm^3, about 5 times weaker than the Grasberg sample. The RAT grind results are representative of only the outer few millimeters of rock surfaces so it is possible that these results represent the strength of weathered rinds or coatings instead of dense unweathered interior rock.

The spectral character of Grasberg formation exposures is distinctive from other rocks of Cape York. Clean surfaces have a purple color in L257 (753, 535, and 432 nm) false color composites and a moderately strong 535 nm band depth with a mean of ~0.35 (Figure 7). They also display a shallow to moderately strong 900 nm absorption band with a 900 nm band depth of ~0.042. The fitted relative reflectance maximum is at ~760 nm. The fitted NIR band minimum is at ~878 nm (Farrand et al., in revision).

The Grasberg Formation is distinguished further by lower Al compared to underlying Endeavour Crater rim rock units and by higher Fe compared with the overlying Burns Formation (Figure 8). Cl, Br, and Zn are notably elevated, yet Mn is low. In fact, the Mn/Al ratio is very low, as is SO_3, compared to that in most rocks analyzed at Cape York. Mobilization and concentration of Br and Zn and preferential flushing of Mn by fluids is one way to accomplish this.

4.5. Lower Grasberg, Unit G_1

Compared with the bright, well-jointed outcrops of the upper Grasberg, this unit is darker, and devoid of distinguishing structure. It is distinguished by its low relief, absence of apparent bedrock exposure, tonal banding paralleling the contact with the plains and the overlying Grasberg unit, and the scattered presence of bright, linear veins 30 to 40 cm long and on the order of a centimeter wide (Figure 9). The contact with the upper Grasberg is defined only by the transition from dark to light exposures and no discernable structure or

 10.1002/2014JE004699

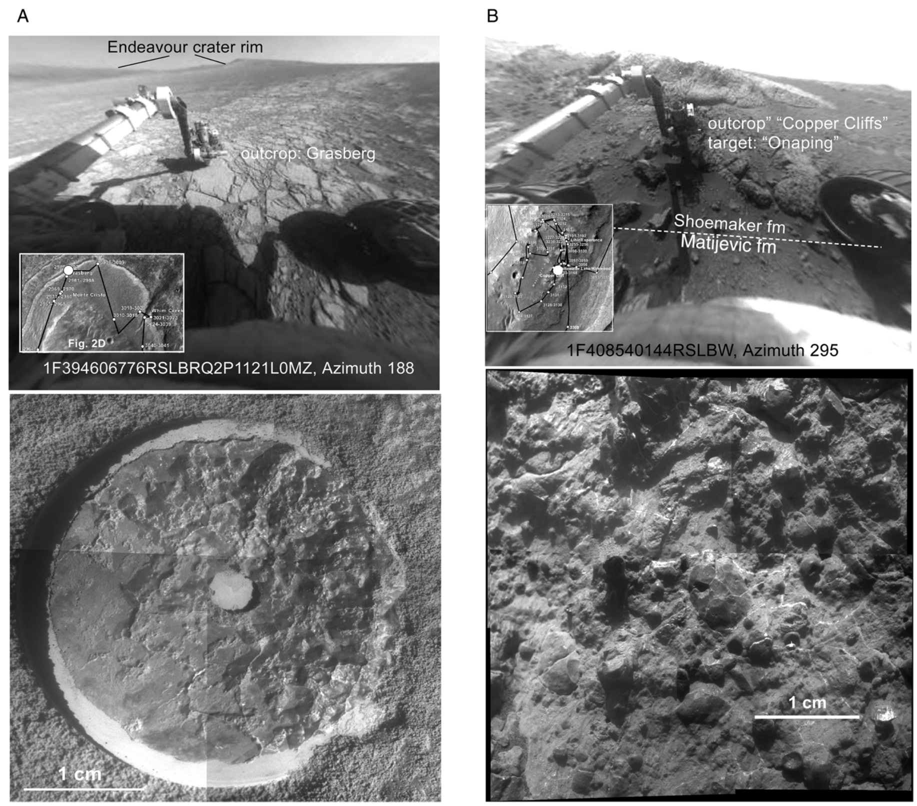

Figure 6. Petrographic characteristics of bedrock units in Microscopic Imager data. (a) Bottom: Grasberg outcrops consist of particles smaller than grain sizes seen in the Burns Formation. RAT hole is about 40 mm across. Top: Southward directed view of outcrop setting from Front Hazard Avoidance Cameras (Hazcams). Inset: Location of observation with respect to north end of Cape York, Figure 2d (postgrind sol 3001, 1MMU01ILFBRPERQ2P2965M222M3). (b) Bottom: Onaping target, lower (Copper Cliffs) member of the Shoemaker Formation. Subangular clasts and spherules are set in a fine-grained matrix. Note small irregular bright veins. Image mosaic of four MI frames is about 56 mm wide (1MMV58ILFBWPER_P2955M222M3). Top: View of outcrop setting from Front Hazcam. This target on the outcrop is within a few centimeters of the contact with the underlying preimpact Matijevic Formation. Inset: Location of observation with respect to central Cape York, Figure 2e at Matijevic Hill. See Figure 11c for another perspective view of location on outcrop. (c) Next page: The MI target Azilda at the outcrop Whitewater Lake, sol 3077 post-RAT brush_2, Matijevic Formation. This is a fine-grained rock bearing infrequent rounded clasts a few millimeters in diameter. Image mosaic of four MI frames is about 56 mm across (1MMU78ILFBWPER00P2906M222M2). Top: Front Hazcam view of outcrop setting. Note the abrupt contact between the Matijevic Formation and unexposed slopes of Cape York (unit cys). (d) Next page: MI mosaic of unbrushed surface, target Ortiz on the outcrop Whitewater Lake, sol 3179, Matijevic Formation. A network of bright veins of $CaSO_4$, each a few millimeters in width, stand in relief against the fine-grained host rock. (1MMV89ILFBWPER_P2906M222M4). Image mosaic of six MI frames is 60 mm wide and 110 mm long. Top: Pancam context image, Ortiz_L257_p2552_sol3187.

relief is obvious. Little is known about the petrography of this unit even though it forms the host rock for the bright veins because it is uniformly mantled with a few centimeters of regolith. The limited elemental data were extracted from the background where APXS integrations were done on bright veins that were narrower than the APXS aperture.

Examples of the veins that characterize this unit were studied at two sites (Homestake, sols 2752–2772, 22 October 2011 to 11 November 2011, and *Monte Cristo*, sols 2971–2980, 3–12 June 2012). The veins consist of hydrated calcium sulfate (gypsum, $CaSO_4$-$2H_2O$) based on APXS major elements results and near-IR spectral properties [*Squyres et al.*, 2012; *Arvidson et al.*, 2014].

Representative MI observations of veins were acquired at Homestake adjacent to the Deadwood background target, and Monte Cristo near the north end of Cape York. The prevailing blanket of dark fines at both sites obscures any identifiable textures in the country rock in these MI mosaics. The Homestake vein is 2 cm wide and 40 cm long and is exposed within the lower Grasberg Formation 1 m from the contact with the upper Grasberg. Striations within the bright vein material at right angles to the walls of the vein are similar to

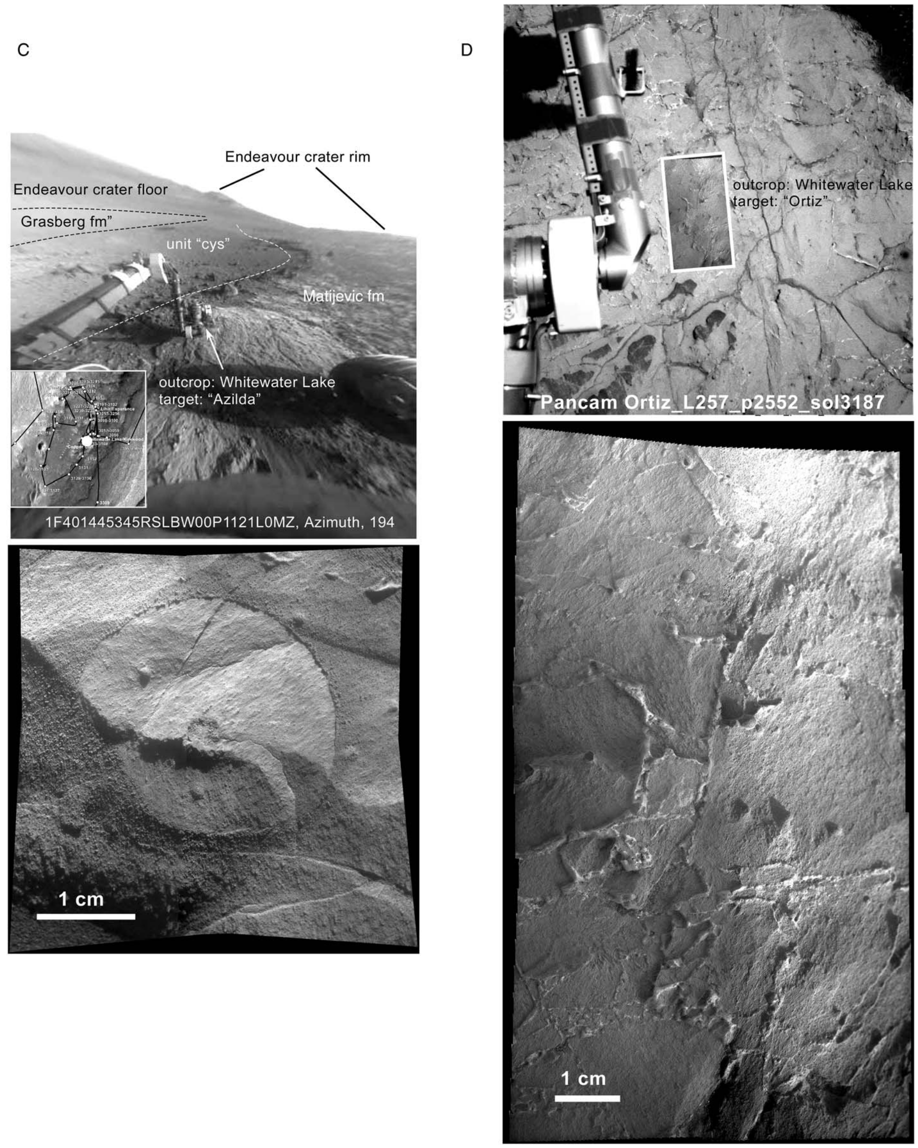

Figure 6. (continued)

striations common in gypsum (selenite) and anhydrite veins, also of similar dimension on Earth. On Earth the striations originate by growth at right angles to the walls as the crack expands [*Machel*, 1985], and crystal growth is accommodated by the additional space. Similar elemental and MI results were obtained at the Monte Cristo vein (sols 2971–2980, 3–12 June 2012) at the north end of Cape York.

The uniform blanket of fines and absence of bedrock exposures discouraged effective multispectral observations of the lower Grasberg. However, the Pancam “hydration filter set” [*Rice et al*., 2010; *Squyres et al*., 2012] was applied to the bright veins. The pronounced negative slope between 934 and 1009 μm is analogous to that in laboratory samples of gypsum [*Farrand et al*., 2013] along with several other spectral signatures of hydration. The strength of the hydration feature increased where the vein was broken by driving over it, supporting the interpretation that the veins consist of a fundamentally hydrated mineralogy. These elemental and spectral results combined with the striated mineral habit and occurrence as veins are sufficiently diagnostic that it is likely that these are hydrated calcium sulfate, i.e., gypsum.

APXS analysis of the bench-forming lower Grasberg at the target Deadwood (sol 2771, 10 November 2011) (Figure 10a) was an unbrushed surface sample. Even though this surface included loose surface fines, the elemental abundances are distinctive from those typical of Burns or Shoemaker Formations.

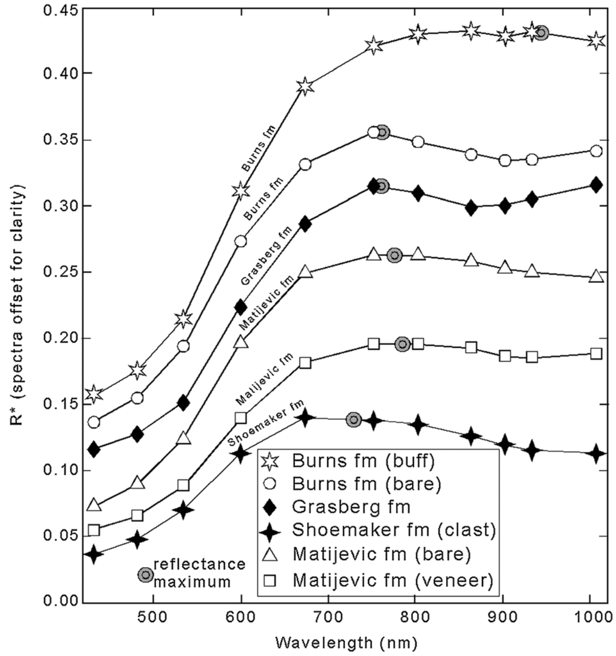

Figure 7. Spectral characteristics of the principal lithologic units observed at Cape York based on Pancam 13 filter observations. Buff refers to typical veneers seen on Burns Formation exposures [*Knoll et al.*, 2008]. Bare refers to RAT brushed exposures. After Farrand, this volume.

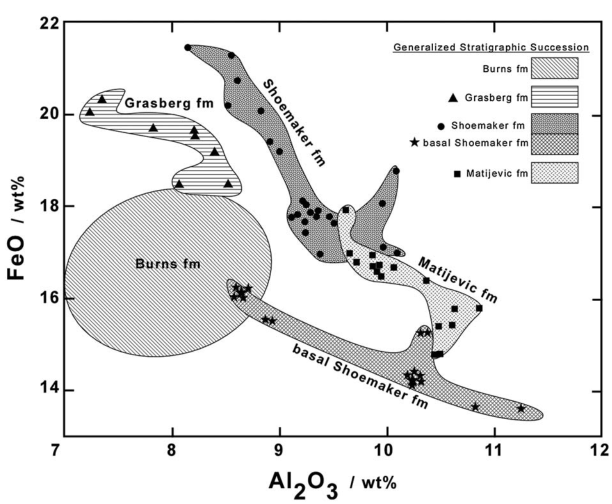

Figure 8. Generalized fields for APXS Fe/Al analyses of the principal lithologic units. Rocks at the lower end of the stratigraphic stack tend toward more aluminous compositions, whereas those at the top are more ferrous. Low Al and plot in restricted but separate areas of the diagram distinguish Grasberg and Burns Formation rocks. Fe and Al are similar in the basal Shoemaker Formation (near the lower contact) and the substrate (Matijevic Formation) compared with the overlying section of the Shoemaker Formation. Either mixing with the substrate may have occurred in the initially deposited ejecta from Endeavour Crater or Fe was selectively leached from the lower Shoemaker Formation following emplacement. After *Mittlefehldt et al.* [2014].

4.5.1. Interpretation and Significance

Outcrops of the Grasberg Formation are distinctive physically, spectrally, and chemically. They are also distinctively jointed, occur as planar outcrop surfaces and have slab-like relief; it unconformably onlaps the Endeavour rim; and elemental abundances are distinctive enough from the Burns Formation or interior Cape York outcrops (Shoemaker and Matijevic Formations) as to be diagnostic. It does not appear related to the deposition of the Meridiani Planum sulfate sandstone, nor is it related to Endeavor crater ejecta or the preimpact substrate because it drapes, and is in unconformable contact with the extremely eroded segments of the Endeavour Crater rim. The uniformly fine-grain size as compared with the sulfate-rich sands of the overlying Burns Formation requires a different transport and deposition mechanism as well.

Laminations in some Grasberg outcrops may be bedding, but exposures are insufficient to establish the deposition mechanism if they are. The thin but uniform character would be consistent with a material deposited uniformly over a large area. An example of such a process would be air fall deposits where local conditions are not a factor in the final texture of the rock. Possible origins include a distal ash deposit from a volcanic eruption or very large and distant impact event. Uniform blankets of deposits consisting of dust-sized material could be a common characteristic of early Mars considering the number of large energetic events over geologic time (impact and volcanic eruptions) and will probably be useful as regional stratigraphic markers in global stratigraphic studies. The key observation for the future will be whether this material appears in a similar stratigraphic position with respect to other areas along the rim of Endeavour Crater and whether it is regional in occurrence or confined to a small part of Meridiani Planum.

The high concentrations of Cl in the Grasberg compared to most APXS samples could be significant. High Cl and Br are also common in the varnish-like coatings on many rocks on Mars [*Haskin et al.*, 2005], so

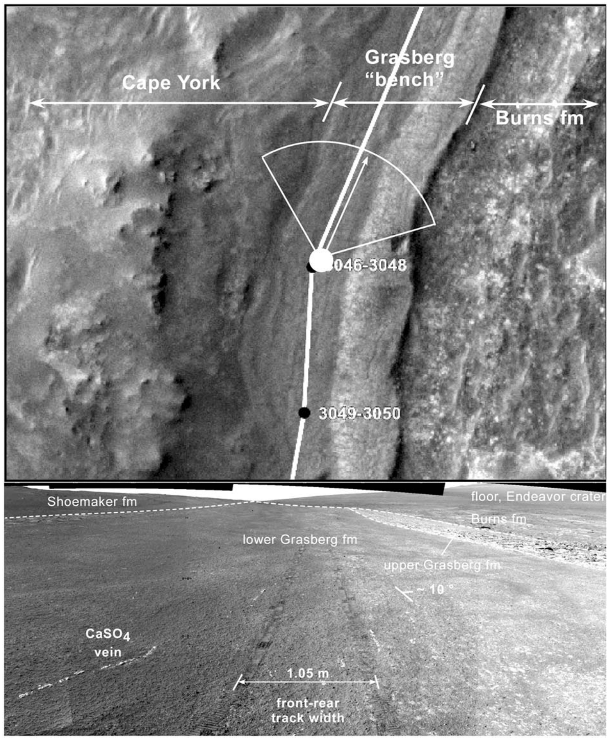

Figure 9. (bottom) View north-northeast along the strike of the planar dark bench surrounding the perimeter of Cape York. The bench surface slopes about 4° toward the plains truncating bedding planes that dip about 10°. The contact between the brighter upper Grasberg and lower Grasberg Formations is visible on the right, and a characteristic light-toned vein is visible in the lower left. The veins are typically from 1 to 2 cm wide and 10 to 40 cm long and commonly strike approximately parallel to the contact with the surrounding plains. The width of the rover tracks is 1.05 m. The interior of Endeavour Crater is in the far upper right. View north on sol 3046–3047 in Navcam panorama 1NNU46ILFBUCYLUSP1863L000M3. (top) Context and direction of view relative to traverse line.

Cl and Br are to some extent ubiquitous. Diagenesis could also play an important part, including processes that uniquely mobilize Cl as suggested for the high chlorine content of rocks in Gusev Crater [*Ming et al*., 2006]. Finally, Cl and Br are known to vary by an order of magnitude over a few meters in Meridiani Planum outcrops [*Squyres et al*., 2004], but the Cl and Br values in the Grasberg outcrops sampled are consistent from site to site. High chlorine is also a characteristic of some rock interiors on Mars, as seen in the rock *Clovis* in Gusev Crater [*Ming et al*., 2006]. Interestingly, the SGE value for Clovis of 8.3 J/mm^3 is similar to Grasberg (7.6 J/mm^3).

While these characteristics could be common among fine air-fall deposits on early Mars, as an alternate explanation, the two samples could be part of a more widespread, perhaps global, unit. The Medussae Fossae Formation [*Bradley et al*., 2002; *Mandt et al*., 2008; *Kerber and Head*, 2010] is an example of an equatorially distributed blanketing deposit with elevated Cl as determined from Odyssey Gamma Ray Spectrometer data [*Keller et al*., 2006]. The similarity between that deposit and the outcrop Clovis at Gusev has been previously made [*Crumpler and Athena Science Team*, 2012] on the basis of their proximity, Cl abundance, and inferred similar stratigraphic positions.

A vertical section view of the contact between the Grasberg and the Burns Formations does not occur along the traverse, so we have attempted to test the inferred relative sequence indirectly by other field geologic means. For example, the Grasberg unit appears to dip toward the contact with the Burns Formation and thus must underlie it (Figures 10b and 10c). Alternatively, because the exposures of the Grasberg Formation are elevated above the Burns at the contact by a low scarp or slope, the Grasberg could overlie the Burns Formation, it has simply been stripped off mostly and remains only in exposures adjacent to the crater rim. In section 5.3.1 below, we apply a classic field geologic test where there is a simple vertical structural offset of the contact between the two units along a graben (Whim Creek). Agreement between the predicted offset and the observed strongly supports the interpretation that Grasberg is overlain by Burns Formation.

The upper light-toned unit could represent a weathered cap rock rather than a distinct lithologic unit formed at the time of deposition. If exposed to the ambient Mars surface conditions prior to the emplacement of the Burns Formation, leaching with fluids, or cementation by authigenic minerals and subsequent induration in the upper several tens of centimeters of an otherwise thicker homogeneous unit could have resulted in a diagenetically indurated or leached cap rock prior to the emplacement of the Burns Formation. Finally, given the evidence for involvement of aqueous solutions of the Burns Formation overlying of the Grasberg unit, some weathering and corresponding diagenetic alteration at the paleosurface are likely during emplacement of the Burns Formation.

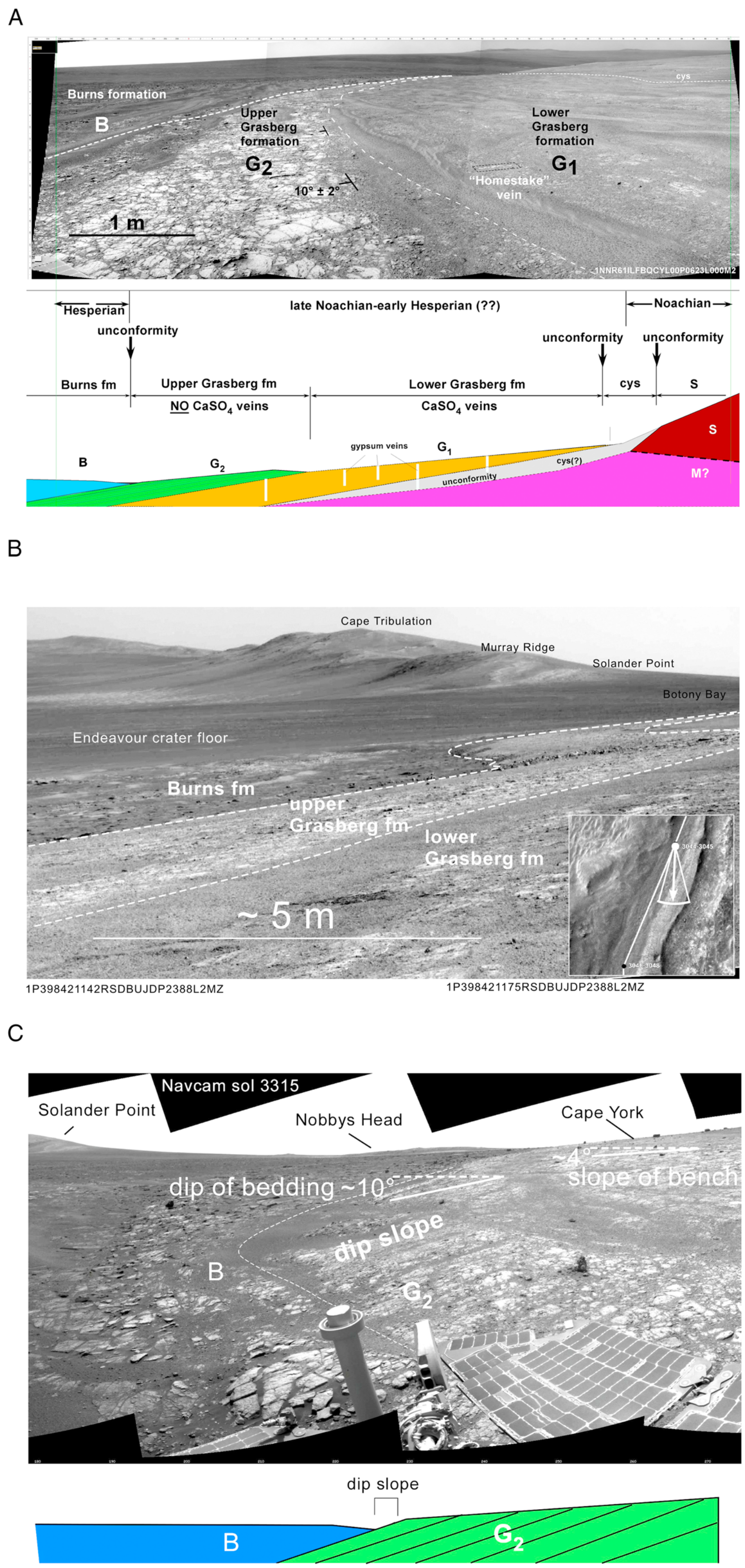

Figure 10. (a) View north around sols 2760–2772 on the west margin of Cape York and along strike at the contact between the Burns Formation, Upper Grasberg Formation (bright, jointed outcrops), and Lower Grasberg (dark-banded unit on right-bearing bright veins). Interpreted geologic cross section is shown below. Navcam mosaic sol 2761. (b) View south across sloping bench on the east side of Cape York. Note the sharp contact between the Burns and Grasberg Formations on the left. (c) Contact between the Burns Formation (left) and Grasberg Formation (right) near the south end of Cape York.

Calcium sulfate ($CaSO_4$) veins common in the lower Grasberg were not observed in the upper Grasberg. Weathering and leaching of the upper layers of the Grasberg unit could account for the absence near the contact with the Burns Formation, particularly if acidic fluids encountered the upper layers of Grasberg during the deposition of the Burns Formation. Alternately, the upper Grasberg may have been deposited in a time postdating vein formation. As there are no exposures of the upper and lower Grasberg contact in section, there is no direct geologic evidence for or against a disconformity between the upper and lower Grasberg units.

There is no evidence (residual outcrops or remnants of veins) that the Grasberg Formation covered more of the interior of Cape York. Either the Grasberg unit featheredged onto the interior of Cape York originally, or it was removed by erosion very early. The dynamic environment at the time of Burns Formation would be sufficient to cause some erosion.

The mean orientations of prominent joint sets and the included veins tend to be parallel to the margins of Cape York [*Crumpler and Athena Science Team*, 2012]. Because orientation is sensitive to far-field stresses at the time of crack formation, the least principal stress is inferred to have been oriented radial to Cape York at the time of fracture formation. The correspondence to the outline of Cape York implies that the shape of Cape York controlled the orientation of tensile strain during opening of the host fractures. A simple mechanism would be compaction of a thick clastic unit over the preexisting relief of Endeavour Crater rim segments and the corresponding development of oriented bending stresses. Compaction during dewatering of sediments could have occurred at the same time as the migration of mineralized fluids responsible for the $CaSO_4$ veins.

In a few locations the veins are not linear, but sinuously trace the contact between the Grasberg unit and the lower slopes of Cape York. So some veins may have been emplaced along bedding planes within the Grasberg.

The absence of gypsum veins in later stratigraphic materials that are more sulfate-rich (Burns Formation) could also be consistent with a transition from a time of moderate-pH fluids to a time of more acidic fluids. Leaching of the upper Grasberg with acidic fluids at the time of Burns Formation deposition would result in widespread diagenesis in the upper layers of the Grasberg formation, possibly accounting for the cap-like character of the upper Grasberg. There is insufficient information to establish whether the $CaSO_4$-rich fluids responsible for the veins moved upward from a groundwater source or downward from the surface, so models of fluid sources during vein formation remain relatively unconstrained.

4.6. Shoemaker Formation, Unit S

Outcrops along the crest of Cape York are lithic breccias containing centimeter-sized angular to subrounded dark clasts enclosed in a lighter-toned fine-grained matrix material [*Squyres et al*., 2012; *Arvidson et al*., 2014] (Figure 5c). Important stops where this rock type was examined include Tisdale, Greeley Haven, Chester Lake, and *Copper Cliffs*. The latter three are representative of three distinctive textures in the observed stratigraphic section and give rise to informal formation members, divided from top to bottom into the *Greely Haven member*, the *Chester Lake member*, and the *Copper Cliffs member*.

An exposure on the northerly sloping outcrop Greeley Haven (Figure 11a), where Opportunity spent its fifth winter (sols 2778–2945), is characteristic of the upper part of the Shoemaker Formation (Greeley Haven member). This outcrop was well characterized by five separate APXS measurements during a prolonged outcrop transect campaign [*Squyres et al*., 2012] *that also* included a 2 by 12 frame (approximate) MI transect mosaic across the outcrop target *Amboy*.

Outcrops on the southeast flanks of Cape York (Chester Lake outcrop, sols 2774) are typical of much of the crater-interior exposures and consist of slab-like exposures and mixed dark clast-rich breccias supported in a lighter-toned (welded? altered glassy?) matrix (Chester Lake member) (Figure 11b). The outcrops also display prominent lineation consisting mostly of trains of clasts. The lineations are oriented radial to the crater interior.

Exposures of the Shoemaker Formation near its lower contact with the underlying Matijevic Formation were examined at Copper Cliffs (sols 3158–3177, 12–31 December 2012) (Figure 11c) and are transitional in texture, consisting of coarse breccias as well as 1 to 2 mm round clasts [*Arvidson et al*., 2014] (Copper Cliffs member). The basal contact is planar, and the transition is abrupt from the underlying Matijevic Formation upward into darker, coarsely textured, and poorly jointed Shoemaker Formation. This is a disconformity and is a surface buried by ejecta in Noachian times during the formation of the Endeavour Crater.

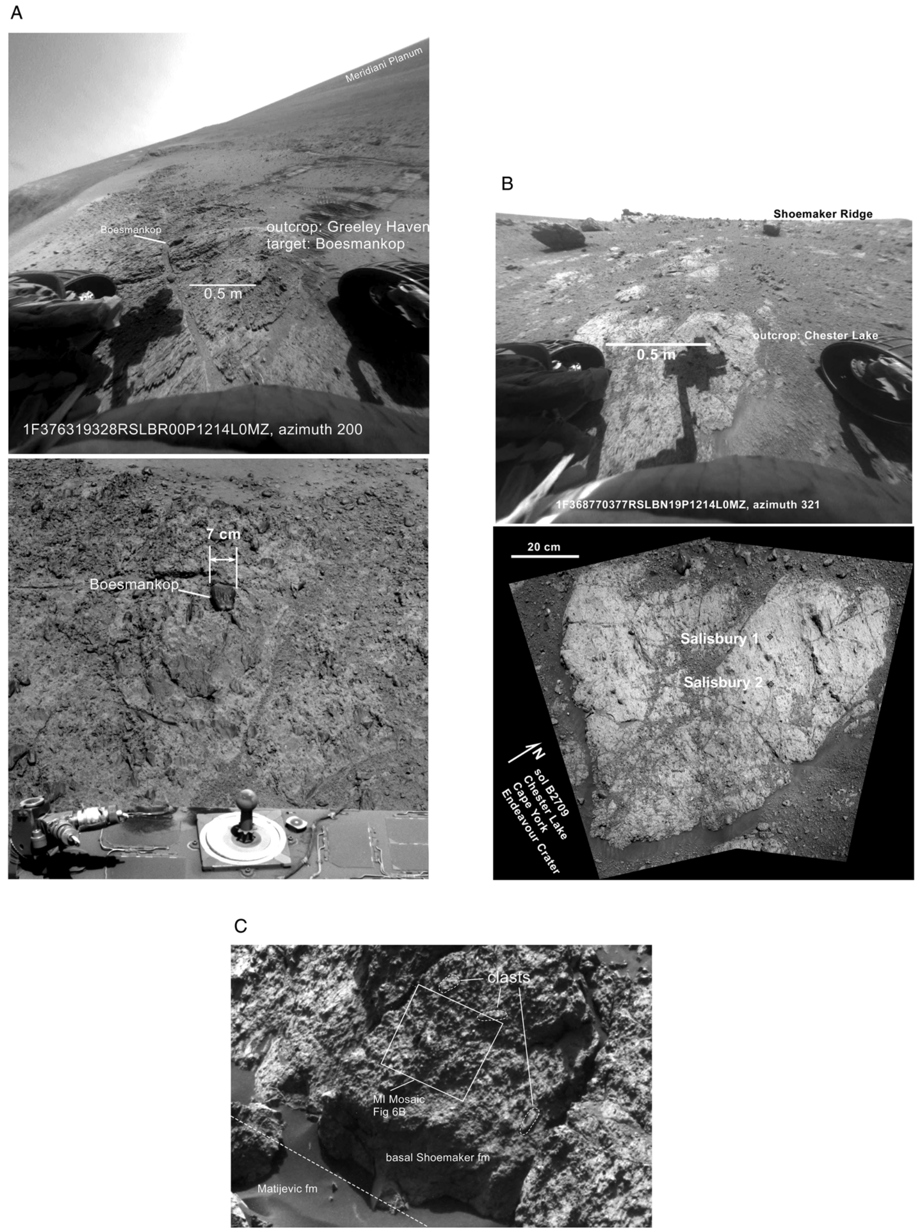

Figure 11. Shoemaker Formation outcrops. (a) Bottom: Greeley Haven, outcrop target "Boesmankop," a large clast is about 7 cm across. Pancam sol2795B_P2588_L257. Top: Front Hazcam context of outcrop. The view is directed south along the crest of Cape York. (b) Bottom: The outcrop Chester Lake, Pancam sol2709_Chester Lake_L257 mosaic showing location of targets Salisbury 1, 2. Top: Front Hazcam view of outcrop context. Large rocks in upper right are ejecta from Odyssey Crater. (c) Basal Shoemaker Formation at the outcrop Copper Cliff, outcrop target, Onaping. Approximate area and location of MI frame in Figure 6b shown as boxed area. Image is about 30 cm across. Pancam mosaic sol3155_P2545_257.

Tisdale 2, a tabular ejecta block from the 20 m diameter crater *Odyssey*, is unlike the other rocks of Cape York both texturally, in terms of its visible and near-infrared (VNIR) reflectance, and in elemental abundances. It is either a fundamentally different lithologic unit excavated at Odyssey Crater from deeper in the section, or it is relatively fresh sample from the substrate of the Shoemaker Formation preserving characteristics of a more widely occurring texture and alteration history. APXS detection of high concentrations of Zn (~6300 $\mu g\, g^{-1}$) and Ni (~2030 $\mu g\, g^{-1}$) [*Squyres et al.*, 2012] and some P enrichment are interesting because they may be ascribable to trace metal mobility in the presence of hydrothermal fluids [*Squyres et al.*, 2012]. The formation of impact craters the size of Endeavour and larger releases energy on a scale sufficient to drive a substantial and short-lived hydrothermal system [*Newsom et al*., 1986], an environment in which enrichments in mobile metals and other secondary minerals can easily occur.

RAT SGE values compared with other Meridiani Planum rocks show that Shoemaker Formation rocks are as weak as most of the sandstones of the Burns Formation. A RAT grind on the target Salisbury on the outcrop Chester Lake yielded an SGE of 1.6 J/mm^3. Relative to other values of SGE, in Meridiani Planum and at Gusev Crater [*Thomson et al*., 2013], this is among the weakest of any materials abraded and weaker than any of the other rocks at Cape York.

Shoemaker Formation rocks are coarse, unbedded, or massively bedded breccias. Lineations consisting of trains of clasts and parallel alignments of elongated clasts are common, particularly in the Chester Lake member. Although laminations may be absent at the outcrop scale, the mapped extent of Shoemaker breccias itself defines a tabular cap at Cape York sloping toward the interior of Endeavour Crater as discussed later (section 5.3.2).

The basal contact of the Shoemaker Formation with the underlying Matijevic Formation at Copper Cliffs is distinctly defined and planar, resting disconformably on exposed and horizontally truncated joints within the underlying Matijevic Formation. If Endeavour Crater formed in Noachian times, then this planed surface is a plaeosurface buried in Noachian time and now exposed in outcrop.

MI data at the target *Onaping* (Figure 11c) in the Copper Cliff member near the lower contact are noteworthy. In the lower 30 cm the breccia texture is visible at the scale of MI image frames together with small spherules and irregular bright veins a few millimeters long and 1 or 2 mm wide.

The reflectance values of clasts and matrix in the breccias (Figure 7) are generally similar and fairly distinctive compared with other lithologies in Meridiani Planum. Overall relative reflectances of wind-abraded or RAT-brushed surfaces are generally less than 0.2 with a fitted reflectance maximum of ~720 nm. Some Shoemaker Formation spectra show a uniform decrease in reflectance from the reflectance maximum to 1009 nm, whereas spectra of other units show an upturn in reflectance from the 934 to the 1009 nm band. Clean surfaces show a very low 535 nm band depth with a mean of ~0.13 [*Farrand et al*., 2013].

APXS analyses were done on targets representative of upper, middle, and lower members of the Shoemaker Formation (Figure 8) and also distributed across the crest and slopes of Cape York laterally. All of the Endeavour Crater rim breccias examined are fundamentally basaltic and have Fe and Mn ratios like those of Martian meteorites. But variable Fe and Mn suggest that aqueous processes have been influential in fractionation of Fe and Mn [*Mittlefehldt et al*., 2014]. At Greeley Haven (sols 2795–2946, 5 December 2011 to 8 May 2012) APXS analysis of the targets *Transvaal*, *Boesmanskop*, and *Komati* are all basaltic, similar to typical Martian basaltic meteorites and close to the composition of the typical Meridiani Planum basaltic sands [*Clark et al*., 2005; *Mittlefehldt et al*., 2014]. At Chester Lake (Figure 11b), APXS analysis of the target *Salisbury_1 and Salisbury_2* on the Shoemaker formation outcrop Chester Lake yielded similar results.

The elemental composition of the Copper Cliffs breccias at the bottom of the section is distinct (Figure 8) from the upper and middle (Greeley Haven and Chester Lake) members of the Shoemaker Formation. The Copper Cliffs (target Onaping) has higher Al and lower Fe than other Cape York breccias [*Arvidson et al*., 2014]. Other samples that lie stratigraphically above Onaping (*Vermillion Cliffs*, *Vermillion Lake*, *Maley*) appear to transition in composition between these lower outcrops and the composition of outcrops along the crest of Cape York. All of the outcrop targets in the lower member also have high Ni compared with other Cape York breccias. Aside from the higher Ni, they are similar in elemental abundances to the underlying Matijevic Formation rocks and to the dark veneers on Matijevic Formation outcrops.

Another unusual petrography possibly related to the Shoemaker formation occurs in fin-like dark outcrop, Kirkwood, on the lower slope of Matijevic Hill. These exposures contain concentrations ranging from ~1 to >40 vol % of small spherules, 2–3 mm in diameter, with a maximum size of ~5 mm [*Squyres et al*., 2012]. Erosion has sectioned some of the spherules revealing a concentric structure, with an erosionally resistant outer shell, a less resistant interior that is visually similar to the surrounding matrix, and some irregular resistant internal structure. These spherule-rich materials are more resistant to abrasion by the RAT than the boxwork "veins" in the underlying Matijevic Formation. The densest spherule accumulation at the outcrop Kirkwood occurs as a dark north-south oriented fin-like mass 40 cm wide and discontinuously exposed for ~10 m. The Kirkwood outcrop is relatively linear. Although it appears as a vertical fin, it is unclear whether the

Kirkwood outcrop cuts across the local stratigraphy or it is simply a discontinuous layer within the Shoemaker Formation that here overlies the Matijevic Formation as a localized residual outcrop. No outcrops of bedrock material are exposed east of the Kirkwood outcrop, so it is also possible that it is the margin of a vertical discontinuity in the section. If so the restricted occurrence of Kirkwood-type outcrop could be a result of differential erosion along an abutting, disconformable contact of the Shoemaker Formation and the Matijevic Formation. A fault scarp formed during the initial terracing of the crater walls is a possible example of a relatively sharply defined vertical discontinuity that could result in this sort of contact.

.Spherules in the Kirkwood outcrop are mostly matrix supported, although some are in contact with one another. Kirkwood lacks laminar bedding, although roughly horizontal partings accentuated by erosion are weakly expressed. The RAT specific grind energy of Kirkwood is ~23 J/mm^3, ~8 times higher than that of spherule-poor materials of the underlying Matijevic Formation. So it is not surprising that the Kirkwood outcrop stands out in positive relief and appears more resistant to erosion relative to bedrock exposures around it.

4.6.1. Interpretation and Significance

The Shoemaker Formation is interpreted to be an impactite of basaltic composition emplaced as ejecta from Endeavour Crater. Some of the outcrops consist of unsorted and coarse clasts bearing plastic deformation characteristics similar to proximal ballistic volcanic agglomerate deposits. The lineated texture of many outcrops and the sub-MI resolution interclast groundmass that appears to support larger angular clasts are consistent with melt or altered glass analogous to terrestrial suevite. Outcrops consist of sub-rounded clasts supported in a fine-grained matrix similar to that in suevite occurrences exposed at terrestrial impact structures. The presence of seuvite-like materials supports the suggestion [*Newsom et al*., 1986] that suevite-type deposits should be present, and possibly common, on Mars. The basaltic composition and the embedded clasts probably reflect the composition of the preimpact target material as suevite does on Earth. Variations in petrography, particularly the prevalence of spherules near the basal contact and gradational abundances of glass observed up section at Matijevic Hill are not entirely understood. Complex textures and localized structures are known to occur in deposits associated with large impact craters. We suggest that many of the trends and most of the scatter in elemental abundances of the breccias at Chester Lake and Greely Haven could easily result from differences in postimpact alteration, including that associated with localized thermal fluid circulation.

4.7. Matijevic Formation, Unit M

The Matijevic Formation occurs as a series of low relief bedrock exposures on the lower east slopes of Cape York (Figures 5d and 12). These outcrops are a candidate site for the presence of Fe^{+3} smectites based on MRO/CRISM data [*Arvidson et al*., 2014]. Initial results are discussed in detail by *Squyres et al*. [2012] some of which is summarized below.

Outcrops of the Matijevic Formation are light-toned, fine-grained ($<$30 μm) and somewhat systematically jointed. The outcrops range from planar surfaces with discontinuous, erosionally resistant darker veneers to erosion-resistant, fin-like ridges in polygonal to suborthogonal lattice or boxwork arrays. The dark coatings occur commonly on tabular surface laminations resulting in a scaly appearance on the larger outcrop exposures on the lower east slope of Matijevic Hill [*Arvidson et al*., 2014]. The area of Fe^{+3} smectite detection corresponds to the east slopes of Matijevic Hill where these dark-coated surfaces occur.

The outcrop surfaces are characterized by veins, wide joint-plane alteration zones arranged in rectilinear or boxwork patterns, and an absence of large clasts, and planar outcrops. In a few locations, apparent bedding exposed in cross section is expressed as millimeter- to centimeter-scale planar lamination. The energy required to grind a typical Matijevic Formation exposure at the target *Azilda* on the outcrop *Whitewater Lake* (sol 3085) is ~2.8 J/mm^3 [*Thomson et al*., 2013]. This is similar to soft sulfate-rich sandstones of the Burns formation.

The RAT target *Esperance* (sol 3301 and 3305) on one the boxwork features yielded an SGE of 5.6 J/mm^3 making the boxwork features the toughest rocks in the Cape York area. The apparent greater resistance to erosion accounts for the relief of boxwork features that tend to stand as resistant fins against the background of more easily eroded Matijevic Formation bedrock.

Two types of surfaces are characteristic of the Matijevic Formation outcrops: light-toned exposures with a poorly laminated, fine-grained matrix (Figure 6c) and surfaces bearing patchy, dark, veneers, or varnish-like

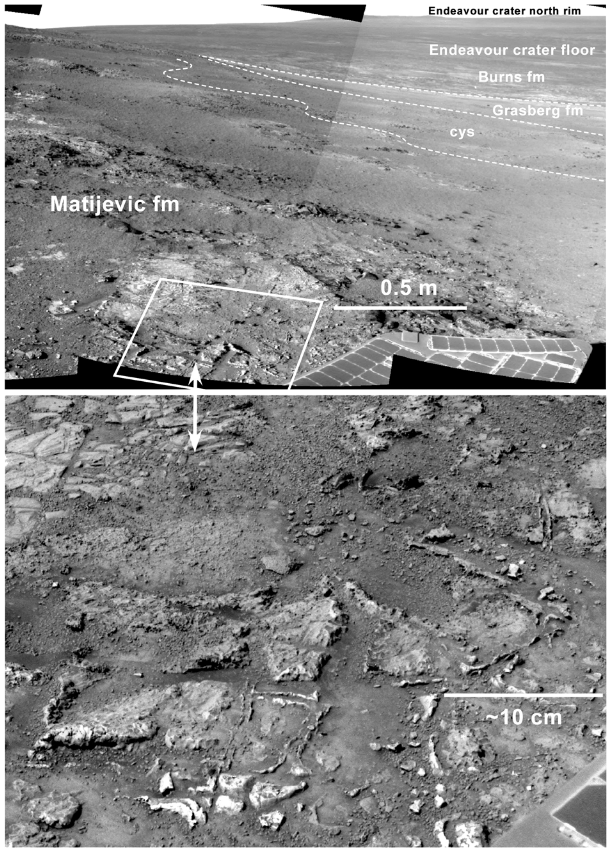

Figure 12. (bottom) Lattice or boxwork of alteration zones along fractures exposed on an outcrop surface in the Matijevic Formation, the oldest rocks examined by Opportunity. Image is approximately 50 cm across. Pancam image sol3103B_P2411_L257, Boxwork. (top) Navcam mosaic view of outcrop context. View is north-northeast across lower east slopes of Cape York. This is the easternmost edge of the Matijevic Formation exposures that abruptly terminate at the scarp sloping steeping down to the Grasberg bench.

coatings on raised tabular surfaces (Figure 5d). Spectral characteristics are distinctive for these two types of exposure. Bare surfaces of the matrix are characterized by a shallow negative slope from 754 to 1009 nm and a fitted relative reflectance maximum of 770 nm (Figure 7). Dark coatings, such as that at the Whitewater Lake and *Sandcherry* outcrops have fitted reflectance peaks that are shifted to approximately 778 nm. They also exhibit a shallow NIR absorption feature (band depth of ~0.03) with a fitted reflectance minimum of 947 nm. Both the matrix and the dark coatings display intermediate levels of oxidation as gauged by the depth of the inflection at 535 nm that is on the order of 0.2 for both types of surfaces (*Farrand et al*., this volume).

Elemental abundances using the APXS were determined at several sites within the Matijevic Formation, including analysis of veins, alteration zones along fractures, and the pervasive dark veneers (Figure 5c). The Matijevic Formation is similar in composition to average Martian soil, to average Martian upper crust on an S- and Cl-free bases, and slightly higher in Si and Al and lower in Fe than the impact breccias that make up most of Cape York. The darker veneers are richer in S, Cl, Br, and Mg than the underlying rock. Analysis of the interior of one of the boxwork veins identified the lowest values of Fe and Ca and highest Si of any rock at Cape York [*Arvidson et al*., 2014].

Thin, irregular veins at the outcrop *Ortiz* occurring within the lower parts of the Shoemaker Formation breccias consist mostly of calcium sulfate [*Arvidson et al*., 2014]. VNIR multispectral and elemental differences between the veins in the Grasberg Formation and the veins in the Matijevic Formation, such as that at Ortiz, suggest that the veins either formed at different times by fluids of different composition or simply record local differences in the source of soluble minerals.

4.7.1. Interpretation and Significance

The above results highlight some of the interesting ways in which the Matijevic Formation appears unusual compared with most rocks at Cape York. But the geologic origin of the Matijevic Formation remains unresolved, primarily because the outcrop exposures of the Matijevic Formation are limited to a small area ($<$400 m^2) on the lower east flank of Cape York and a very short vertical section ($<$2 m). This is also a fine-grained clastic rock bearing only a few subhorizontal laminations that may or may not represent bedding or deposition planes, so information from the internal geometry of exposures about the mode of deposition is not available. Because there are no distinctive structures or textures in the outcrops, there is no visible evidence for the processes associated with its mode of deposition. Nor is the composition as determined by APXS diagnostic because it is not distinguished from the composition of average Martian basaltic soil. Its homogeneity, at least over the area, in which it is observed, would be consistent with a well-mixed and widely dispersed material. It could be a widespread deposit of air fall fines such as that associated with a regional event, including a distal impact or ash from a distal volcanic eruption. Observation of additional outcrops over a larger area will be necessary to conclude anything about its lateral variability. The presence of a few small spherules and dark clasts locally suggest a more complex origin, possibly as a local or regional deposit from distal ejecta, or origination as a second generation deposit through the remobilizing an original crustal target material bearing spherules.

The dark veneers on outcrops are similar in appearance to varnish-like deposits seen elsewhere at both Spirit and Opportunity sites, some of which include elevated Cl and Br [*Haskin et al*., 2005; *Knoll et al*., 2008], but the higher Si and Mg are distinctive. Alternatively, they could be the results of mineralization along bedding plane fractures. The orbital detection from CRISM data of Fe^{+3}-rich smectites corresponds to the areas where dark coatings were identified in outcrop by Opportunity [*Arvidson et al*., 2014], so the dark coatings may be the repository of the smectites. The formation process of the dark coatings is unknown, but the outcrops are at or near the unconformity with the overlying Shoemaker Formation impactites. The dark coatings could be the result of weathering on a paleosurface, now mostly buried by the ejecta from Endeavour.

Veins in both Whitewater Lake (Figure 6d) and Copper Cliff (Figure 6b) outcrops formed when mineral-rich fluids filled narrow fractures. Unlike veins within the lower Grasberg, which were linear and 1 to 2 cm thick, calcium sulfate veins within the Matijevic Formation are less than a few millimeters thick and irregular to roughly rectilinear. Within the overlying Shoemaker Formation, small veins also occur but are irregularly shaped. This distinction in vein morphology would be consistent with the inability of fractures to propagate linearly within a nonhomogeneous material such as the Shoemaker Formation breccias while being free to open along a single and easily propagated planar fracture within more homogeneous rock masses such as the Grasberg Formation. Smaller veins in the Shoemaker Formation could also mean that there was simply less water circulated within the breccias compared with the Grasberg Formation or that the Shoemaker Formation may have had a greater intergranular permeability than the Grasberg Formation and that fluid transport within the Grasberg Formation was primarily along established fractures.

Regardless of origin, the deposit was compacted, indurated, and subsequently fractured by a systematic array of joints after deposition. Aqueous solutions flowing through the fractures were either chemically active enough, or present for sufficient time, that substantial leaching of mobile elements occurred in the wall rocks, leaving an Al- and Si-enriched and more indurated aureole about each fracture [*Arvidson et al*., 2014]. Subsequent erosion has resulted in exposure of a boxwork or lattice-shaped pattern in outcrop surfaces of Matijevic Hill. The country rock hosting the fractures could have been saturated with the same fluids and diagenetically altered at this time. Other fluids moving through more pervasive and smaller fractures deposited gypsum. We are unable to resolve whether the boxwork features and gypsum veins in the Matijevic Formation are related to the same aqueous circulation environment or occurred at different times. The widespread occurrence of gypsum veins in postimpact Endeavour erosional time within the lower Grasberg Formation allows for the possibility that mineralization of the Matijevic Formation took place in several events over an expanded period of geologic time.

5. Geologic Map From In Situ Observations

The traverse around Cape York is the first field study of the rim of a large complex crater on Mars and the first test of some long-held notions about complex crater structure. On Earth there are no morphologically preserved examples of complex craters and little is known about the origin and emplacement of complex crater rims, structure of the terraced walls, and details of the stratigraphy, particularly that related to early and late ejecta emplacement and modification. In the following we briefly review some of the methods used to resolve fundamental questions about stratigraphy, structure, and exposures.

5.1. Matijevic Hill

The contact between the Matijevic and Shoemaker Formations was established at multiple locations on the hill slope along the looping traverse of Matijevic Hill (the interior of Cape York) between sols 3057 and 3108. Knowing the locations and attitudes of contacts with respect to a topographic profile across Matijevic Hill from MRO/HiRISE DTMs (checked locally with in situ Navcam ranging measurements) allowed construction of an interpretive geologic section (Figure 13). From the intercept of the contact at the surface along different elevations along the side of Matijevic Hill, the dip of the contact plane is estimated at less than 11° east. The apparent attitude of bedding planes was also noted at each stop from along-strike viewing, which generally

10.1002/2014JE004699

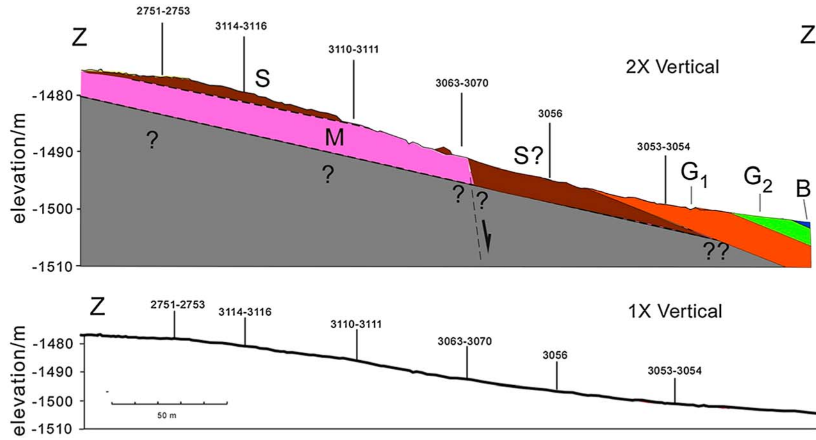

Figure 13. Interpreted geologic section across Matijevic Hill part of central Cape York, Endeavour Crater rim along line Z-Z′ of Figure 13e. The relief profile was established from the HiRISE-based DTM and confirmed in situ Navcam ranging from multiple positions occupied during the closed traverse. The sol numbers indicated refer to the positions occupied by Opportunity and the corresponding in situ observations of lithologic contacts and attitude of units. Vertical scale is 2 times horizontal. Below is the unexaggerated profile of Cape York for comparison.

indicated an eastward dip between 4 and 12°. The geologic section at Cape York consisting of a preimpact material (Matijevic Formation) and the breccia unit deposited by the Endeavour impact (Shoemaker Formation) dips toward the interior of Endeavour Crater.

The Shoemaker Formation section at Cape York is estimated at approximately 3 m thick based on observed relief, the known upper and lower elevations, and approximate attitude of the basal contact with the Matijevic Formation. This must be a minimum thickness reflecting the advanced state of erosion of Endeavour Crater. For example, the measured ejecta thickness at the similarly sized and uneroded, 29 km diameter Tooting Crater [*Mouginis-Mark and Garbeil*, 2007] ranges from tens of meters to several hundred meters. These initial observations simply highlight the fact that we are seeing examples of the lithologic and structural complexities for the first time with in situ mapping on a complex crater.

5.2. Copper Cliff

The sequence of geologic units described above was determined mostly on the basis of embayment, apparent overlapping, and geometric (structural) arguments. Direct exposure of the stratigraphic sequence occurs at an outcrop near the east base of Matijevic Hill (Copper Cliffs) (sols 3152–3181, 6 December 2012 to 4 January 2013) (Figure 14). At the base of the Copper Cliffs outcrop, a planar unconformity truncates lattice or boxwork alteration zones developed within the jointed blocks of the fine-grained Matijevic Formation. A breccia unit rests directly on this erosion surface that is laterally contiguous with outcrops of Shoemaker Formation farther west and consists mostly of basaltic clasts and spherules a few millimeters in diameter (*Onaping*, sol 3155–3164, 9–18 December 2012). The boxwork features are the result of hardening or induration of the walls of vertical planar fractures in the host rock through mineralization or leaching in proximity to the fluid pathways. Fluid circulation between planar fractures for periods of time long enough to result in chemical alteration of the fracture walls typically occurs below the vadose zone, a depth that can vary according to the amount of weathering and disintegration that has occurred near the surface of a rock mass. Fracture spacing typically approximates fracture depth for most outcrops with prominent jointing. The exposure of boxwork patterns of mineralized veins or fractures on a horizontal surface at Matijevic Hill requires erosion of a meter or more.

5.3. The Unconformity Between the Burns and Grasberg Formations

Along-strike views of the inclination of the planar surfaces (Figure 10a) from the position occupied at the contact between the Burns and Grasberg Formations (sols 2760–2762 and sol 3415, 30 October 2011 to 1 November 2011 and 2 September 2013) show that the Grasberg Formation dips several degrees away from Cape York. Down-dip projection predicts that the Burns Formation therefore overlies the Grasberg Formation. Most of the observations appear to support a sequence with Burns Formation postdating Grasberg. Yet a sectional view of the contact between the Burns Formation and Endeavour Crater rim that

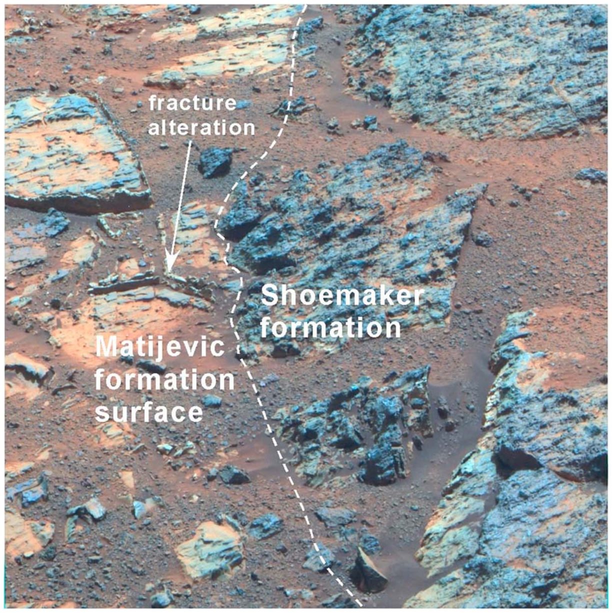

Figure 14. Unconformity between the basal Shoemaker Formation outcrops at Cooper Cliffs and weathered surface of Matijevic Formation. Alteration or vein deposition in the Matijevic Formation along planar fractures resulted in more resistant "fins" following erosion that planed the outcrop horizontally. After planation and exposure to the Martian ambient environment, this erosion surface and exposed veins were then buried and preserved by impact ejecta (the Shoemaker Formation). False color Pancam image Sol3156B_P2438_L257. Image width is 1 m.

would confirm this is not exposed along the traverse. An alternative interpretation that the Grasberg overlies the Burns and that the Grasberg Formation has been striped back to a residual position on the lower slopes of Cape York that it now occupies, although geologically more complicated, nonetheless requires testing. Two tests are described in the following.

5.3.1. Whim Creek

The *Whim Creek* fracture is a 1 to 10 m wide and approximately 100 m long trough a few centimeters deep bounded by two N28E trending, nearly parallel scarps. Geometrically, it appears to be a simple graben that has displaced the surface across the between Burns and Grasberg Formations at the northern tip of Cape York contact (Figures 2c and 16a). Knowing the type of structural displacement and attitude of bedding being displaced (Figure 16b) allows a simple field test of two alternative models of the stratigraphic sequence (Burns over Grasberg or Grasberg over Burns?) based on the predicted interaction of the contact with the fracture for the two scenarios. On both sides of Whim Creek, bedding planes dip 10° striking approximately parallel to the perimeter of Cape York. The slope of the bench (4°) grading away from Cape York in the vicinity of Whim Creek is much lower than the dip of the bedding planes resulting in unconformable erosion across the dip of bedding, which is consistent with the banded appearance likely associated several units "featheredging" onto Cape York. At the Whim Creek fracture, if the Burns Formation is stratigraphically higher than the Grasberg, an offset along a graben-like trough (Whim Creek) followed by erosion on a dipping plane (the bench) (Figure 16c) would result in Burns Formation rocks in the floor of the trough and Grasberg rocks on the margins, and offset of the contact between the Burns Formation and Grasberg Formation up dip (southwest) along the floor of the trough.

The lithologic units within and on the margins of the trough were identified using APXS measurements that were then compared with previous APXS results on the two lithologies. The rocks outside the trough were found to be comparable to the upper Grasberg Formation (*Mons Cupri*, sols 3021–3023), whereas the rocks of the trough floor (Rushall, sol 3027) were comparable to Burns Formation analyses. Additionally, tracing the contact from the rover perspective, the contact between these two units is abruptly offset to the south between the two parallel fractures by about 10 m, generally as predicted from the model shown in Figure 16c. The geometry of the contact and how it deflects across the floor of the Whim Creek fracture is therefore consistent with that predicted only if the Burns Formation overlies the Grasberg Formation. From the estimated dip of the Grasberg unit (10°) and the bench slopes (4°), simply geometry shows that the observed offset of the contact (approximately 10 m southwest) implies a vertical displacement of at least 1 m along the axial trough of the Whim Creek fracture. For this offset pattern to be visible in the current surface of the bench, at least a meter of vertical erosion must have occurred across the bench since the emplacement of the Burns Formation.

5.3.2. West and South Contact—Interpreted Cross Section of Contact

Panoramas acquired of the contact between the Burns and Grasberg Formations during the drive southward on the west slopes of Cape York reveal trough-like relief at the contact (Figure 10b). The Grasberg bench terminates as a low escarpment. A better view of the relief across the contact was observed on sol 3316 at the last stop in the traverse before leaving Cape York and returning to the plains (Figure 10c). The light- and dark-toned bands in the Grasberg outcrops paralleling the contact with the margins of the Cape York interior rock are interpreted to be the trace of southeasterly dipping bedding planes. Because the 10° dip of the bedding planes is greater than the 4° slope of the bench, the Grasberg dip slope is overlapped by the Burns Formation. The simplest model, and the one consistent with most of the observations, is that the Burns Formation postdates the emplacement of the Grasberg Formation.

The Grasberg Formation is in contact with the eroded slopes of Cape York, so it was deposited after most of the erosion of Endeavour Crater and before the emplacement of the Burns Formation. We interpret all of the field relations described above to mean that the bedding within the Grasberg originally draped, at a repose angle of 10° over the interior mass of Cape York. After the deposition of the Burns Formation, the slopes of Cape York were eroded on a grade to the surrounding plains obliquely grading or beveling the draped units resulting in the banded appearance currently visible along the apron around Cape York.

5.4. Summary and Implications of Stratigraphy and Structure

In situ geologic observations of outcrops on the Cape York rim segment of Endeavour Crater documented approximately 10 m of mappable stratigraphic section and identification of at least two major geologic unconformities. From this we can construct a generalized columnar stratigraphic section (Figure 17). The stratigraphic sequence at Cape York consists of four bedrock units. Two of these, the Burns and Grasberg Formations, postdate the extensive period of erosion of Endeavour Crater. One of these, the Shoemaker Formation, is an impact breccia that was likely emplaced during the formation of Endeavour Crater. The weathered preimpact substrate, the Matijevic Formation, is the oldest bedrock unit examined by Opportunity. Judging from the apparent great age of Endeavour Crater, and its similarity to craters and terrains within the ancient Martian highlands to the south, the Matijevic Formation likely dates from the Noachian. Much of the preimpact stratigraphy, the Matijevic Formation and unexposed stratigraphically lower rocks, remains unknown and neither the thickness nor mode of emplacement of the Matijevic Formation is well determined. The incomplete understanding of its origin is not surprising given that the exposures are limited less than 400 m^2 on the east slopes of Cape York.

The unconformable contacts between the Burns Formation and the Grasberg Formation and between the Grasberg and the Shoemaker Formations separate rocks formed at different times and different environments on Mars. The differences in the rocks across these unconformities preserve evidence for that water was much more prevalent and erosion much more energetic during formation of the rocks of Cape York compared with later rocks of the Shoemaker Formation. The unconformity between the Burns Formation and Endeavour Crater is a direct record from the rock record of change in environment on Mars over geologic time.

At the exposure of the contact between Shoemaker and Matijevic Formations at Copper Cliffs, these joint planes are abruptly planed horizontally along surfaces that section joint blocks along with their marginal alteration zones. This latter characteristic is taken to imply substantial erosion of the jointed bedrock prior to deposition of the impact breccias. The uniformly fine-grained matrix and absence of any breccia-like characteristics together with the abrupt and planar contact with the overlying breccias is consistent with erosion that predated the impact and ejecta deposition. Substantial mineralization along fractures in this lowest stratigraphic unit is evidence for abundant water in the surface and near-surface rocks of Mars at some time prior to the formation of Endeavour Crater. Valley networks occur widely within the area of the highlands immediately to the south of Meridiani Planum as they do in some of the oldest terrains on Mars [*Tanaka et al*., 1992; *Hynek and Phillips*, 2001]. These results are consistent with early infiltration of water into the upper crust during the time period over which these valleys were forming. If these conditions were present within the cratered Noachian highlands in general, then hydrothermal circulation associated with impact craters [*Newsom et al*., 1986], hydrothermal alteration of local bedrock, metal concentrations, and secondary mineralization driven by high-pH fluids and fluids at higher than ambient temperatures could be a common characteristic. The unusual trace metal concentrations of the sample Tisdale at the south end of Cape York are consistent with trace metal mobility within simple and short-lived hydrothermal circulation systems [cf. *Butler*, 1956].

Craters the size of Endeavour are in the size range morphologically defined as “complex craters” on Mars, a size range in which the crater undergoes transient crater collapse during development [*Melosh and Ivanov*,

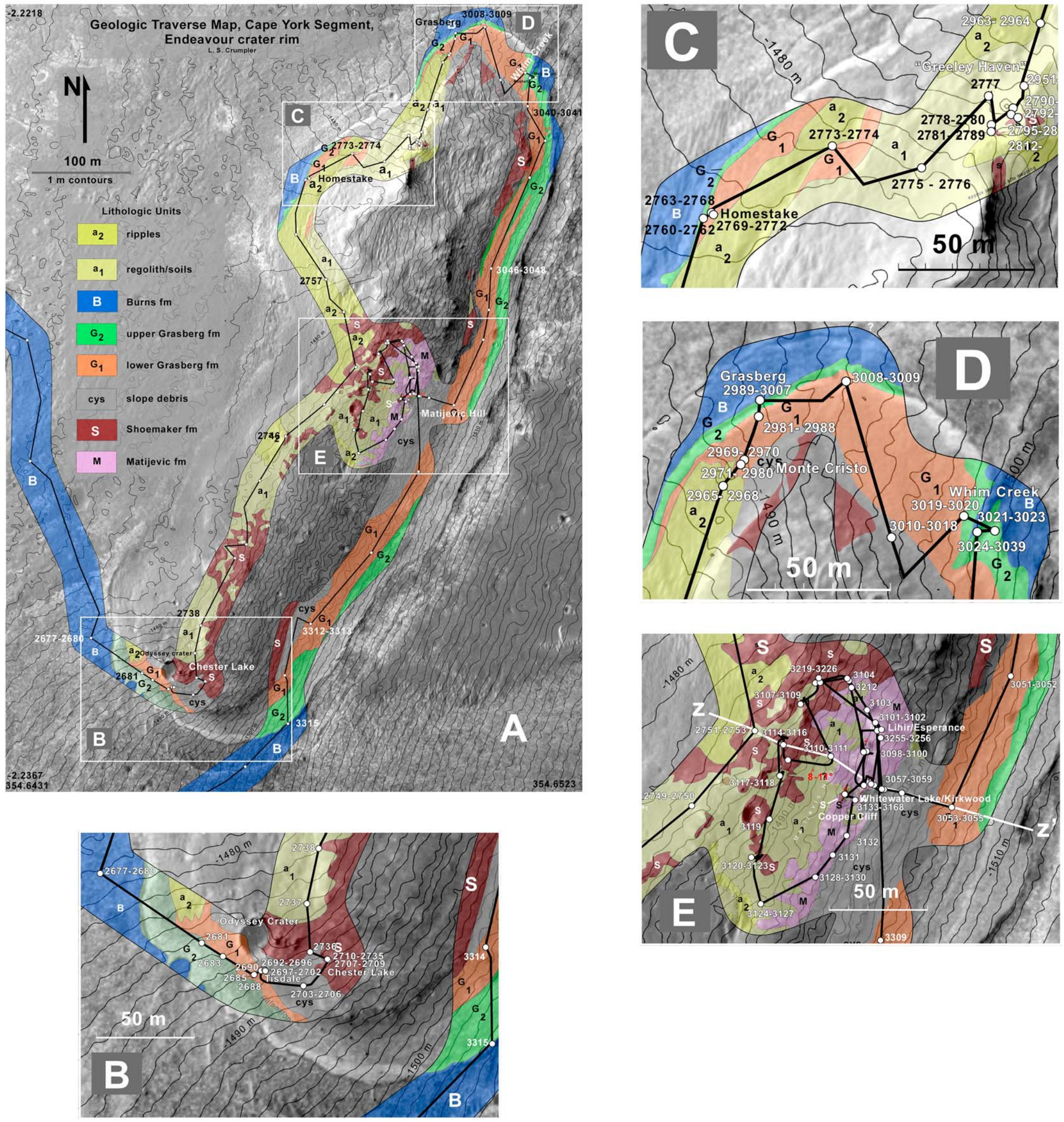

Figure 15. Rover-based geologic strip map of Cape York and condensed explanation of lithologic units. Differences in lithologic units were determined from in situ examination of outcrops at multiple stations along the traverse around Cape York. (b–e) Boxed areas correspond to areas shown in Figure 2b–2e. (b) Southern end of Cape York showing contact between Burns Formation, Grasberg Formation, debris covered lower slopes of Cape York, and interior Shoemaker Formation exposures. (c) Left, northwest contact between Burns Formation and Grasberg Formation. See Figure 10a. Right, site of fourth winter work location, Greeley Haven. (d) Contact between Burns Formation, Grasberg Formation, and lower slopes of Cape York and Shoemaker Formation near the north tip of Cape York. The fracture labeled Whim Creek is a graben 2 m wide and southward closing walls striking across the contact between the Burns and Grasberg Formations. (e) Mapped location of Matijevic Formation outcrops (M), overlain by Shoemaker Formation, on the eastern slope of Cape York. Line Z-Z′ identifies the interpreted section shown in Figure 14.

1999] and structural modification immediately following the impact event. Multiple slump blocks on the inner crater slopes, central uplift peaks, and broad flat floors distinguish complex craters. In contrast to the uplifted and outward dipping layers of smaller impact craters, the craterward dip of layers observed at Cape York may emphasize the role of a variety of postimpact slumping and crustal readjustments.

Results at Cape York show that bedding along the rim may dip either into or away from the crater interior. Offsets and attitudes of the resulting fault blocks along the east margin of Cape York appear to have exposed the preimpact substrate, the Matijevic Formation. Because it is exposed by backwasting of the overlying Shoemaker Formation ejecta unit, the exposed surface of that unconformity (Figure 16) is a paleosurface

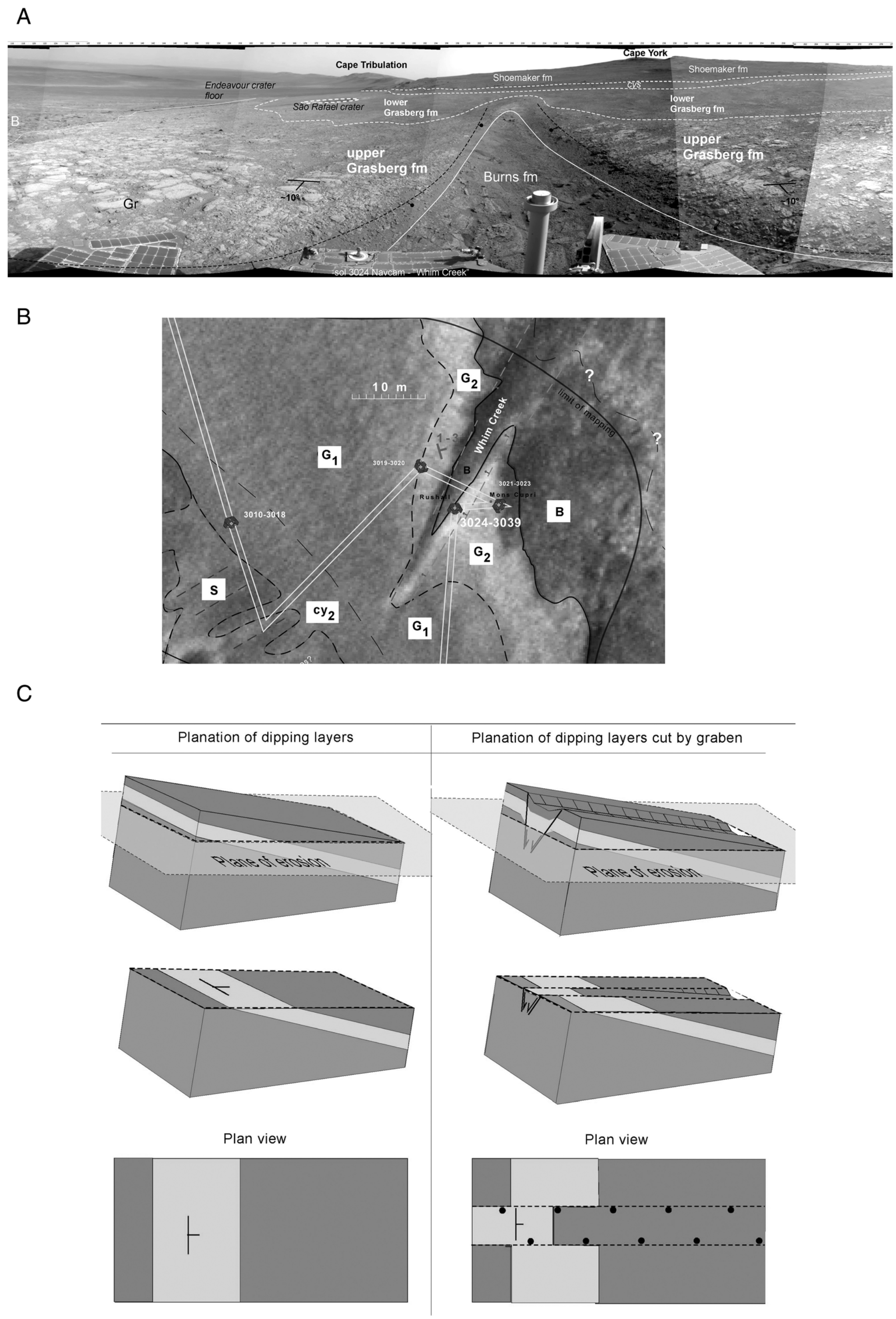

Figure 16. Contact relationships between the Burns and Grasberg Formations at Whim Creek, a graben-like fracture trending across the northern end of the apron or bench surrounding Cape York. (a) South-southwest directed view down the axis of the Whim Creek fracture. Note that the lower-upper Grasberg contact is deflected south around the far tip of the graben. (b) Geologic map perspective of contact geometry shown in Figure 16a looking down the floor of the graben-like fracture. (c) Model showing stratigraphic sequence required to generate observed geometry of contact offset along a graben similar to the Whim Creek fracture. The graben axis strikes across the azimuth of dip in layers shown. The model assumes that the dip of layering is steeper than the eroded surface and that a simple graben displaces the section at right angles to the strike of the slope.

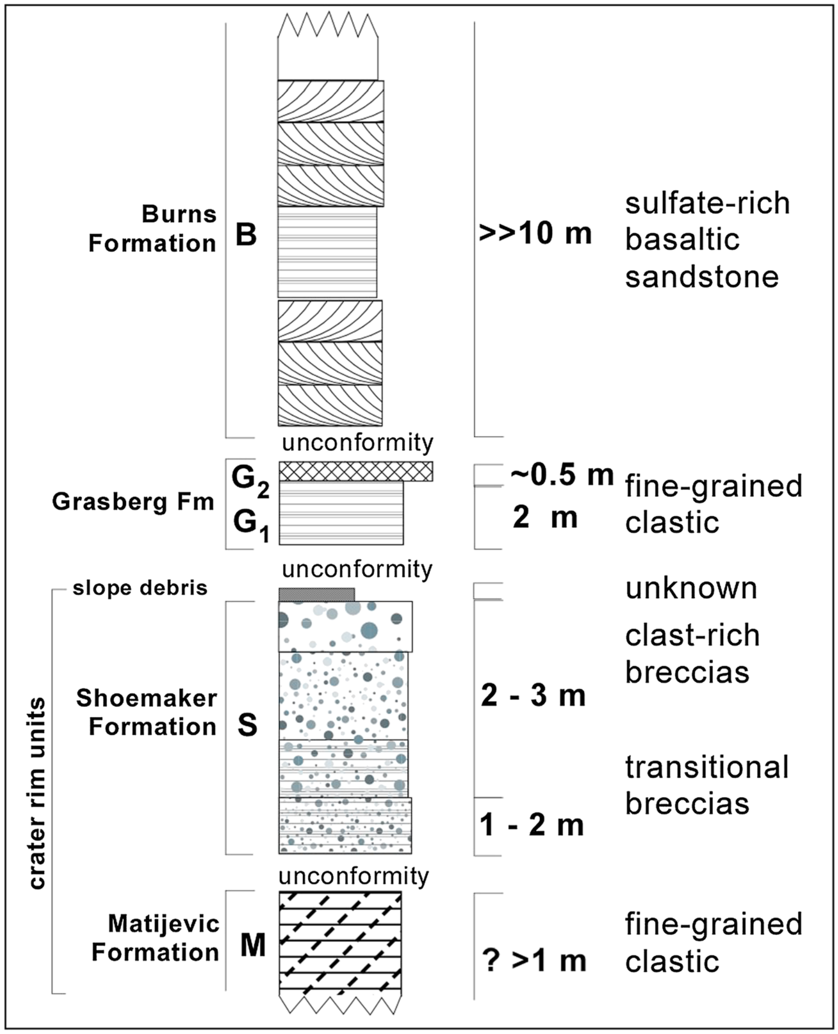

Figure 17. Unit thicknesses and stratigraphic sequence based on lithologic and structural geologic mapping along Opportunity's traverse at the Cape York segment of the Endeavour Crater rim. Relative erosion resistances (unit widths) shown are based in part on relative differences from measured RAT SGE values.

dating from the Noachian. It is a surface that was exposed to the environment of that time and has been preserved by burial beneath impact ejecta. In addition to burial by fluvial deposition, this shows that impact crater proximal ejecta and regional air-fall deposits are another important means whereby past environment indicators and structures may be preserved on Mars.

Geochemical measurements up and down the section contain subtle differences reflect a generally basaltic composition and the influences of subsequent alteration processes. Certain trends that correlate with stratigraphy are persistent (Figure 8) and could reflect the excavation of different bedrock lithologies bearing differences in Si- and Al-enrichment dating from the time of aqueous activity during the Noachian and the sequential deposition of materials representative of those differences as ejecta during the formation of Endeavour Crater.

The widespread, fine-grained material of the Grasberg Formation is physically and chemically unlike the older units beneath it or the later sandstones overlying it. We suspect that it originated as a homogeneous and widely dispersed deposit, possibility even analogous to other deposits elsewhere in the equatorial region. For example, Grasberg is comparable in many characteristics to the outcrop Clovis in the Columbia Hills at Gusev Crater in terms of the fine-grained character, cap-rock characteristic, similarity of SGE values, similarity of relative stratigraphic position with respect to ancient terrains, and some chemical affinities to a

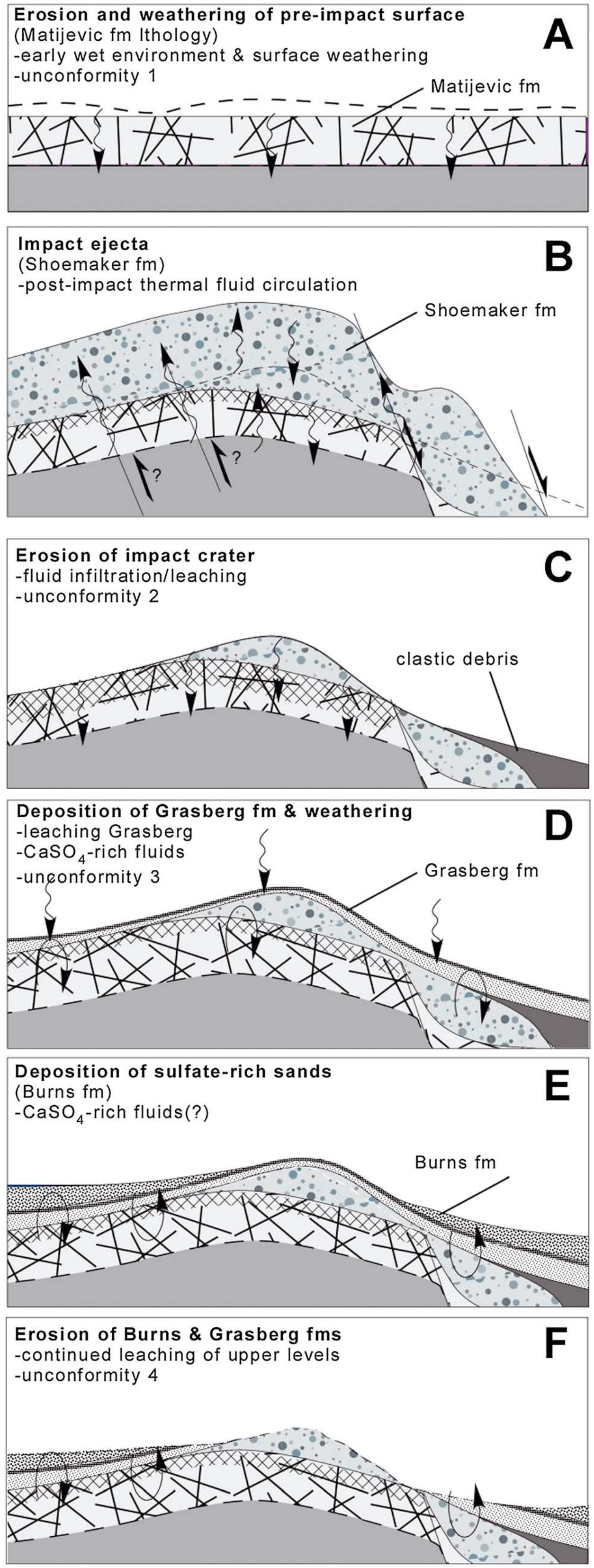
Erosion and weathering of pre-impact surface
(Matijevic fm lthology)
-early wet environment & surface weathering
-unconformity 1
A
Matijevic fm
Impact ejecta
(Shoemaker fm)
-post-impact thermal fluid circulation
B
Shoemaker fm
?
?
Erosion of impact crater
-fluid infiltration/leaching
-unconformity 2
C
clastic debris
Deposition of Grasberg fm & weathering
-leaching Grasberg
-CaSO4-rich fluids
-unconformity 3
D
Grasberg fm
Deposition of sulfate-rich sands
(Burns fm)
-CaSO4-rich fluids(?)
E
Burns fm
Erosion of Burns & Grasberg fms
-continued leaching of upper levels
-unconformity 4
F

Figure 18

known widespread equatorial deposit (Medussae Fossae Formation), particularly Cl abundance. Regional units with well-defined petrologic character may be expected as a result of specific large geologic events (for example, impact basin formation and large volcanic eruptions) distributing a single-source rock over regional and global distance scales. Distinctive regional, and in a few instances, global deposits may be more common than on Earth and raise the possibility that they will provide important global stratigraphic control as "marker beds" as more sites are visited and studied in situ on Mars in the future.

6. Summary of Geologic Sequences and Processes

The methodology of field geologic mapping from a rover on a planetary surface is established in this work. The techniques are comparable to that used on Earth because the dimensions of lithologic units are at the human scale (meters) of observation, a consequence of the geologic complexity resulting from the long geologic history, deposition of distinctive lithologic units, cycles of deposition and erosion, changes in environment, and exposures by widespread erosion. While the mapping process is much slower, and the observations and the field tests are more limited, the fundamental methods remain the same. The results are restricted to small map areas, but they establish some of the first ground truth observations of Martian geologic history. We are able to identify rock types, their contacts, their relative overlapping relations, and their correlations from site to site along Opportunity's traverse at the rim of Endeavor Crater based on documentation of outcrops by using the in situ Athena instrument package (the RAT, MI, and APXS) and remote sensing cameras (Navigation Camera and Panoramic Camera).

The result is a geologic map (Figure 15) and a measured stratigraphic section (Figures 16 and 17) that outline aqueous events (Figure 18) before and long after the formation of Endeavour Crater. If the Matijevic Formation exposed beneath the Endeavour Crater rim breccias is representative of the Noachian substrate, then fluids infiltrated the surface along fractures and were present in the substrate for time sufficient enough to alter basaltic materials to smectite-rich phyllosilicates long prior to the Endeavour Crater formation event. These deep mineral-filled fractures were planned off by regional erosion (Figure 18a) prior to being buried by a sheet of impact breccias in the form of the Shoemaker Formation (Figure 18b). Alteration of the matrix material in the later impact breccias includes some evidence for aqueous circulation within the breccias sufficient to mobilize metals such as zinc. In some outcrops there are microfractures filled with calcium sulfate either deposited during early hydrothermal circulation as well or later during the same time that the calcium sulfate veins formed within the Grasberg formation.

The rim of Endeavour Crater was eroded, the relief softened, and the segmentation of rim relief enhanced (Figure 18c) long before the later geologic units (Grasberg and Burns Formations) were emplaced. The Grasberg Formation was deposited after this early deep erosion of the crater rim, possibly completely draping over the eroded rim segments. The more resistant capping light-toned upper member of the Grasberg may have developed at this time or much later from weathering and leaching of the upper surface of the widespread Grasberg deposit (Figure 18d). Prior to deposition of the Burns formation fluid-filled fractures developed in response to an active groundwater system, resulting in deposition of calcium sulfate in veins. An unconformity developed on the Grasberg Formation and crater rim material as substantial sheets of wind-blown sand [*Grotzinger et al*., 2005] energetically eroded the Grasberg Formation and crater rim. Regional sand deposition engulfed and surrounded the Endeavor Crater rim segments (Figure 18e) and

Figure 18. Interpretive section of Cape York geologic history. Section is approximately west to east across central Cape York. (a) The initial surface consisted of a weathered and graded exposure of the Matijevic Formation. Before erosion, deep fractures enabled infiltration of fluids and substantial alteration along fracture walls. These altered fractures were exposed by planation and lightly weathered in the ambient Noachian environment. (b) Uplift, impact ejecta deposition (Shoemaker Formation), and postimpact deformation. Local postimpact epithermal energy and hydrothermal circulation mobilized and concentrated many elements such as Mg and trace metals such as Zn, particularly along bedding planes and small shallow fractures. (c) Erosion of the original sequence of Shoemaker Formation overlying Matijevic Formation lowers the Endeavour Crater rim profile and creates the subdued form of the crater similar to that present today. (d) The Grasberg Formation blankets the region and featheredges onto the eroded rim topography of Endeavour Crater. Weathering of the upper surface probably established the distinction between the light toned (leached?) upper and lower Grasberg members. Calcium sulfate veins precipitate from sulfate-rich solution pervading fractures. (e) Deposition of the Burns Formation on the unconformity and continued infiltration of aqueous solutions. (f) Unconformable erosion across the Burns and Grasberg Formations to form the encircling the bench, and continued erosion of the Cape York impact breccias (Shoemaker Formation). Compare with cross section in Figure 14.

sulfate-rich groundwater resulted in light cementation of the sand grains and development of the Burns Formation as sandstone. During a subsequent period of erosion (Figure 18f), the lower flanks of Cape York were exhumed along an unconformable erosion surface resulting in the banded bench now surrounding Cape York. The erosion and grading of this sloping apron around Cape York resulted in exhumation of the calcium sulfate veins that formed much earlier within the Grasberg Formation.

7. Note on Names and Naming Conventions

Informal names have been used to identify large outcrop features and the targets of specific instruments (Pancam, APXS, or MI) within those features (for example, Table 1). Names are chosen from "themes." In the case of Cape York, themes were frequently selected that had geological connotations such as greenstone belts and gold mines, to name a few examples. Themes used throughout the mission include ships of exploration for craters and places visited during the voyages of these ships for prominent physiographic features.

Some important sites and relief features are also named in honor individuals who are widely known to have made important contributions to the success of the mission or to an understanding of the science of Mars. The Burns Formation was named in honor of Roger Burns [*Squyres and Knoll*, 2005] who predicted the prevalence of ferric sulfates on the surface of Mars based on early Viking Lander data. The site of the fifth winter traverse stop was named in honor of Ron Greeley, a pioneer in planetary exploration and strong advocate of Mars exploration beginning from the early days of planetary missions. The assemblage of impactites along the rim of Endeavour Crater was informally named the *Shoemaker Formation* in honor of Gene Shoemaker and his pioneering field studies of impact craters [*Levy*, 2002]. Exposures of the oldest unit which also contain evidence for aqueous alteration are named the *Matijevic Formation* in honor of Jake Matijevic whose engineering expertise was an important reason that the mission was able to successfully arrive at, identify, and study that unusual and important lithologic unit preserving evidence of the early aqueous history of Mars.

Acknowledgments
This work was supported by the Mars Exploration Rover mission project through contracts with the Jet Propulsion Laboratory, California Institute of Technology, sponsored by NASA. The Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment (HiRISE) is supported by the Mars Reconnaissance Orbiter project through the NASA contract to the Jet Propulsion Laboratory, California Institute of Technology. Data are available from the NASA Planetary Data System (https://pds.jpl.nasa.gov/).

References

Arvidson, R., et al. (2006), Nature and origin of the hematite-bearing plains of Terra Meridiani based on analyses of orbital and Mars Exploration rover data sets, *J. Geophys. Res.*, *111*, E12S08, doi:10.1029/2006JE002728.

Arvidson, R., et.al. (2014), Ancient aqueous environments at Endeavour Crater, Mars, *Science*, *343*, 6169, doi:10.1126/science.1248097.

Bagnold, R. A. (1941), *The Physics of Blown Sand and Desert Dunes*, 265 pp., Methuen, London.

Bell, J., III, et al. (2003), The Mars exploration rover Athena Panoramic camera (Pancam) investigation, *J. Geophys. Res.*, *108*(E12), 8063, doi:10.1029/2003JE002070.

Bibring, J., et al. (2006), Global mineralogical and aqueous Mars history derived from OMEGA/Mars express data, *Science*, *312*, 400–404.

Bradley, B., S. Sakimoto, H. Frey, and J. Zimbelman (2002), Medusae Fossae Formation: New perspectives from Mars global surveyor, *J. Geophys. Res.*, *107*(E8), doi:10.1029/2001JE001537.

Butler, B. S. (1956), Mineralizing solutions that carry and deposit iron and sulfur, *Am. Inst. Min. Eng. Trans.*, *205*, 1012–1017.

Calvin, W., et al. (2008), Hematite spherules at Meridiani: Results from MI, Mini-TES, and Pancam, *J. Geophys. Res.*, *113*, E12S37, doi:10.1029/2007JE003048.

Clark, B., et al. (2005), Chemistry and mineralogy of outcrops at Meridiani Planum, *Earth Planet. Sci. Lett.*, special issue on Meridiani Planum, *240*, 73–94.

Crumpler, L., and Athena Science Team (2012), Field Geologic Context of Gypsum veins and impactites on the rim of Endeavour Crater, Cape York, MER Opportunity rover, *Proc. Lunar Planet Sci. Conf. 43rd*, Abstract 1258.

Crumpler, L., et al. (2011), Field reconnaissance geologic mapping of the Columbia Hills, Mars, based on Mars Exploration Rover Spirit and MRO HiRISE observations, *J. Geophys. Res.*, *116*, E00F24, doi:10.1029/2010JE003749.

Farrand, W., J. Bell III, J. Johnson, S. Squyres, J. Soderblom, and D. Ming (2006), Spectral variability among rocks in visible and near-infrared multispectral Pancam data collected at Gusev Crater: Examinations using spectral mixture analysis and related techniques, *J. Geophys. Res.*, *111*, E02S15, doi:10.1029/2005JE002495.

Farrand, W., et al. (2007), Visible and near-infrared multispectral analysis of rocks at Meridiani Planum, Mars, by the Mars Exploration Rover Opportunity, *J. Geophys. Res.*, *112*, E06S02, doi:10.1029/2006JE002773.

Farrand, W., J. Bell III, J. Johnson, R. Arvidson, L. Crumpler, J. Hurowitz, and C. Schröder (2008), Rock spectral classes observed by the Spirit Rover's Pancam on the Gusev Crater Plains and in the Columbia Hills, *J. Geophys. Res.*, *113*, E12S38, doi:10.1029/2008JE003237.

Farrand, W., J. Bell III, J. Johnson, M. Rice, and J. Hurowitz (2013), VNIR multispectral observations of rocks at Cape York, Endeavour Crater, Mars by the Opportunity rover's Pancam, *Icarus*, *225*, 709–725.

Golombek, M., K. Robinson, A. McEwen, N. Bridges, B. Ivanov, L. Tornabene, and R. Sullivan (2010), Constraints on ripple migration at Meridiani Planum from Opportunity and HiRISE observations of fresh craters, *J. Geophys. Res.*, *115*, E00F08, doi:10.1029/2010JE003628.

Greeley, R., and J. Guest (1987), Geologic map of the eastern equatorial region of Mars, 1:15,000,000, U.S. Geological Survey Map I-1802-B.

Greeley, R., et al. (2006), Gusev Crater: Wind-related features and processes observed by the Mars Exploration Rover Spirit, *J. Geophys. Res.*, *111*, E02S09, doi:10.1029/2005JE002491.

Grotzinger, J., et al. (2005), Stratigraphy and sedimentology of a dry to wet eolian depositional system, Burns Formation, Meridiani Planum, Mars, *Earth Planet. Sci. Lett.*, *240*, 11–72.

Haskin, L., et al. (2005), Water alteration of rocks and soils from the Spirit Rover Site, Gusev Crater Mars, *Nature*, *436*, 66–69, 2004.

Herkenhoff, K., et al. (2003), Athena microscopic imager investigation, *J. Geophys. Res.*, *108*(E12), 8065, doi:10.1029/2003JE002076.

Herkenhoff, K., et al. (2004), Evidence from opportunity's microscopic imager for water on Meridiani Planum, *Science*, *306*, 1727–1730.

Herkenhoff, K., R. Arvidson, B. Jolliff, C. Weitz, and The Athena Science Team (2013), Recent results from Opportunity microscopic imager, *Proc. Lunar Planet. Sci. Conf. 45th*.

Hynek, B., and R. Phillips (2001), Evidence for extensive denudation of the Martian highlands, *Geology*, *29*, 407–410.

Jerolmack, D., D. Mohrig, J. Grotzinger, D. Fike, and W. Watters (2006), Spatial grain size sorting in eolian ripples and estimation of wind conditions on planetary surfaces: Application to Meridiani Planum, Mars, *J. Geophys. Res.*, *111*, E12S02, doi:10.1029/2005JE002544.

Keller, J., et al. (2006), Equatorial and midlatitude distribution of chlorine measured by Mars Odyssey GRS, *J. Geophys. Res.*, *111*, E03S08, doi:10.1029/2006JE002679.

Kerber, L., and J. Head III (2010), The age of the Medusae Fossae Formation: Evidence of Hesperian emplacement from crater morphology, stratigraphy, and ancient lava contacts, *Icarus*, *206*, 669–684.

Knoll, A., et al. (2008), Veneers, rinds, and fracture fills: Relatively late alteration of sedimentary rocks at Meridiani Planum, Mars, *J. Geophys. Res.*, *113*, E06S16, doi:10.1029/2007JE002949.

Krumbein, W., and S. Sloss (1963), *Stratigraphy and Sedimentation*, 660 pp., Freeman and Company, San Francisco, Calif.

Levy, D. (2002), *Shoemaker: The Man Who Made and Impact*, 320 pp., Princeton Univ. Press, Princeton, N. J.

Machel, H. (1985), Fibrous gypsum and anhydrite in veins, *Sedimentology*, *32*, 443–454.

Mandt, K., S. de Silva, J. Zimbelman, and D. Crown (2008), Origin of the Medusae Fossae Formation, Mars: Insights from a synoptic approach, *J. Geophys. Res.*, *113*, E12011, doi:10.1029/2008JE003076.

McLennan, S., et al. (2005), Provenance and diagenesis of the evaporite-bearing Burns Formation Meridiani Planum, *Mars, Earth Planet. Sci. Lett.*, *240*, 95–121.

Melosh, J., and B. Ivanov (1999), Impact crater collapse, *Ann. Rev Earth Planet. Sci*, *27*, 385–415.

Ming, D., et al. (2006), Geochemical and mineralogical indicators for aqueous processes in the Columbia Hills of Gusev Crater, Mars, *J. Geophys. Res.*, *111*, E02S12, doi:10.1029/2005JE002560.

Mittlefehldt, D., R. Gellert, R. Arvidson, J. Bell III, and W. Farrand (2014), Noachian impact breccias on the rim of Endeavour Crater, Mars: Opportunity APXS results, *Proc. Lunar Planet. Sci. Conf. 45th*, Abstract 1640.

Mouginis-Mark, P., and H. Garbeil (2007), Crater geometry and ejecta thickness of the Martian impact crater Tooting, *Meteorit. Planet. Sci.*, *42*, 1615–1626.

Newsom, H., G. Graup, T. Sewards, and K. Keil (1986), Fluidization and hydrothermal alteration of the Suevite deposit at the Ries Crater, west Germany, and implications for Mars, *J. Geophys. Res.*, *91*, E239–E251, doi:10.1029/JB091iB13p0E239.

Rice, M., J. Bell III, E. Cloutis, A. Wang, S. Ruff, M. Craig, D. Baily, J. Johnson, P. de Souza Jr., and W. Farrand (2010), Silica-rich deposits and hydrated minerals at Gusev Crater, Mars: Vis-NIR spectral characterization and regional mapping, *Icarus*, *205*, 375–395.

Rieder, R., et al. (2004), Chemistry of rocks and soils at Meridiani Planum from the Alpha Particle X-ray Spectrometer, *Science*, *306*, 1746–1749.

Scott, D., and M. H. Carr (1978), Geologic map of Mars, 1:25,000,000, *U.S. Geological Survey Map* I-1083.

Scott, D., and K. Tanaka (1986), Geologic map of the western equatorial region of Mars, *U.S. Geol. Surv. Open File Rep.*

Sharp, R. (1963), Wind ripples, *J. Geol.*, *71*, 617–636.

Sharp, R., and M. Malin (1984), Surface geology from Viking landers on Mars: A second look, *Geol. Soc. Am. Bull.*, *95*, 1398–1412.

Soderblom, L., et al. (2004), Soils of eagle crater and Meridiani Planum at the Opportunity rover landing site, *Science*, *306*, 1223–1227.

Squyres, S., and A. Knoll (2005), Sedimentary rocks at Meridiani Planum: Origin, diagenesis, and implications for life on Mars, *Earth Planet. Sci. Lett.*, *240*, 1–10.

Squyres, S., et al. (2003), The Athena Mars rover science investigation, *J. Geophys. Res.*, *108*(E12), 8062, doi:10.1029/2003JE002121.

Squyres, S., et al. (2004), The Opportunity rover's Athena science investigation at Meridiani Planum, *Science*, *306*, 1698–1703.

Squyres, S., et al. (2006), Overview of the opportunity Mars exploration rover mission to Meridiani Planum: Eagle Crater to purgatory ripple, *J. Geophys. Res.*, *111*, E12S12, doi:10.1029/2006JE002771.

Squyres, S., et al. (2012), ancient impact and aqueous processes at Endeavour Crater, Mars, *Science*, *336*, 570–576, doi:10.1126/science.1220476.

Sullivan, R., et al. (2005), Aeolian processes at the Mars exploration rover Meridiani Planum landing site, *Nature*, *436*, 58–61.

Sullivan, R., et al. (2008), Wind-driven particle mobility on Mars: Insights from MER observations at "El Dorado" and surroundings at Gusev Crater, *J. Geophys. Res.*, *113*, E06S07, doi:10.1029/2008JE003101.

Tanaka, K., and W. Hartmann (2008), The planetary time scale, in *The Concise Geologic Time Scale*, edited by J. Ogg, G. Ogg, and F. Gradstein, 177 pp., Cambridge Univ. press, New York.

Tanaka, K., D. Scott, and R. Greeley (1992), Global stratigraphy, in *Mars*, edited by H. Keiffer et al., pp. 345–382, Univ. of Arizona Press, Tucson.

Thomson, B., N. Bridges, J. Cohen, J. Hurowitz, A. Lennon, G. Paulsen, and K. Zacny (2013), Estimating rock compressive strength from Rock Abrasion Tool (RAT) grinds, *J. Geophys. Res. Planets*, *118*, 1233–1244, doi:10.1002/jgre.20061.

Weitz, C., R. Anderson, J. Bell, W. Farrand, K. Herkenhoff, J. Johnson, B. Jolliff, R. Morris, S. Squyres, and R. Sullivan (2006), Soil grain analyses at Meridiani Planum, Mars, *J. Geophys. Res.*, *111*, E12S04, doi:10.1029/2005JE002541.