Sedimentary textures formed by aqueous processes, Erebus crater, Meridiani Planum, Mars

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ABSTRACT

New observations at Erebus crater (Olympia outcrop) by the Mars Exploration Rover *Opportunity* between sols 671 and 735 (a sol is a martian day) indicate that a diverse suite of primary and penecontemporaneous sedimentary structures is preserved in sulfate-rich bedrock. Centimeter-scale trough (festoon) cross-lamination is abundant, and is better expressed and thicker than previously described examples. Postdepositional shrinkage cracks in the same outcrop are interpreted to have formed in response to desiccation. Considered collectively, this suite of sedimentary structures provides strong support for the involvement of liquid water during accumulation of sedimentary rocks at Meridiani Planum.

Keywords: Mars, water, cross-lamination, shrinkage cracks, sedimentary structures.

INTRODUCTION

Because of its relevance to habitability, the search for sedimentary rocks formed in aqueous depositional and diagenetic settings is a prime objective of the Mars Exploration Rover Mission. Outcrops at Eagle and Endurance craters investigated by the rover *Opportunity* have provided substantial evidence for involvement of liquid water in the formation and subsequent diagenetic alteration of sedimentary rocks formed in eolian dune and interdune depositional environments (Squyres et al., 2004; Clark et al., 2005; Grotzinger et al., 2005; McLennan et al., 2005). The data have been interpreted to record the formation of sulfate-rich materials during aqueous, acid-sulfate weathering of precursor basalts supplemented by accumulation of salts within playas. Reworking and transport of these materials as sand grains by eolian and fluvial processes to their current site were followed by later alteration via groundwater diagenesis.

Each successive crater encountered by *Opportunity* as it crossed the Meridiani plain provided new bedrock exposures that enable us to test and refine this developing model. *Opportunity's* investigations at Erebus crater provide such a test; the data were collected at a significant distance from Endurance crater (~4 km) and probably at a different stratigraphic level. These new observations indicate an abundance of centimeter-scale trough cross-lamination, intimately associated with other facies characterized by probable desiccation cracking and soft-sediment deformation. The cross-lamination is better expressed here than at Eagle crater, where the original observations of trough cross-lamination were made, and probable sediment desiccation cracks are observed for the first time.

SETTING AND METHODS

Erebus crater is located ~4 km south of Endurance crater (Fig. 1). Both Mars Orbiter Laser Altimeter and stereo Mars Orbiter Camera

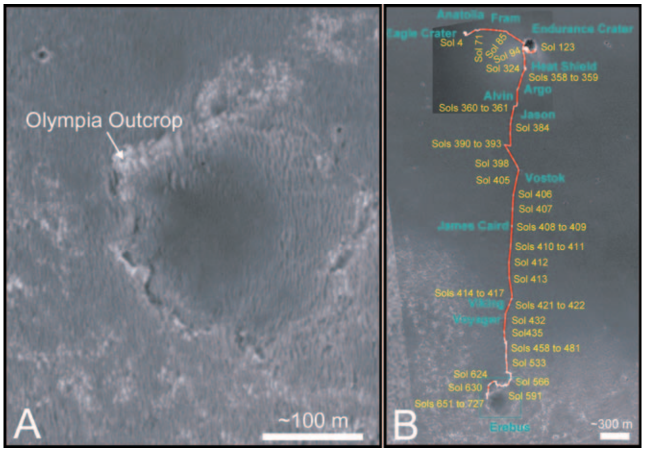

Figure 1. Location of Olympia outcrop. A: Mars Orbiter Camera (MOC) image of Erebus crater. Image is subframe of MOC image S05–00863 and its location is near 2.0°S, 5.8°W. Sunlight illuminates scene from left, scale bar is 100 m, and north is toward top. B: Complete rover traverse path as of sol 727, near end of Olympia campaign. Image credit: NASA/JPL/MSSS/Ohio State University.

Geology; December 2006; v. 34; no. 12; p. 1085–1088; doi: 10.1130/G22985A.1; 5 figures.

(MOC) data suggest that the plains surrounding Erebus are ~10–15 m higher in elevation than those surrounding Endurance. The current investigation at Erebus centered on the northwestern margin of the crater, where an outcrop named Olympia (Fig. 1) was studied comprehensively by *Opportunity* during sols 671–735 (a sol is a martian day).

Noting the elevation gain between Endurance and Erebus, and with the assumption that bedding is approximately horizontal, Erebus should expose a stratigraphic level that is somewhat higher than the uppermost level observed at Endurance. However, imaging of the western rim reveals that the bedrock there has been deformed, suggesting folding and/or faulting, which frustrates detailed correlation with rocks to the north.

Outcrops at Olympia were imaged under conditions of late afternoon lighting to enhance surface relief, using Pancam's (panoramic camera) L7 and R1 (blue) filters, and employing lossless compression for maximum resolution. Several targets were also imaged using superresolution sequences as described in Bell et al. (2006). In addition, one rock (Overgaard) was selected for study using the microscopic imager (MI).

The exposed surfaces of all rocks analyzed here are flat, due to relatively recent eolian abrasion. In contrast, the structural dips of these rocks are moderately steep, ~15°–30°. These dips were likely acquired during impact-generated deformation of the crater rim and differential rotation of breccia blocks. Nevertheless, key structures and laminae can be traced from rock to rock in many cases, and stratigraphic facing directions are provided by crosscutting relations indicated by stratal truncations and onlap.

TROUGH CROSS-LAMINATION

When subjected to shear stresses created by shallow, subaqueous flows with moderate current velocities, fine- to medium-grained sand will spontaneously form highly sinuous-crested ripples with amplitudes of as much as a few centimeters (Southard, 1973; Southard and Boguchwal, 1990). The diagnostic attribute of such ripples is exposed in cuts transverse to flow, where laminae have a trough-shaped or festoon geometry (Rubin, 1987a). Cross-lamination of this type and scale is not known to develop in eolian flows and, to our knowledge, has not been observed in deposits resulting from volcanic- or impact-generated base surges. The recent suggestion that the Meridiani deposits may result from base surge processes (McCollom and Hynek, 2005; Knauth et al., 2005) is inconsistent with both textural and geochemical data (Squyres et al., 2006). Very likely, small (centimeter) scale, sinuous-crested ripples are not stable under the conditions of high particle sedimentation rates and rapidly decelerating current velocities that are characteristic of base surge flows. For these reasons, the presence of trough cross-lamination in the Burns formation at Eagle and Endurance craters is regarded as compelling evidence for overland water flow across the ancient surface of Mars (Squyres et al., 2004; Grotzinger et al., 2005; Squyres et al., 2006). This conclusion is independent of the difference in gravity between Mars and Earth, which affects only the transitions between bedforms and not their existence; for constant grain size and flow depth, a given transition will occur at a lower flow velocity on Mars as compared to Earth, by a factor of 0.74 (Grotzinger et al., 2005).

Recent observations at Olympia confirm these earlier interpretations and suggest that water flow was more extensive across the ancient Meridiani surface than is evident from Eagle and Endurance craters alone. The Overgaard locality consists of two rocks studied during sols 708–723: upper Overgaard and lower Overgaard. The bedding sequence in upper Overgaard contains three units: a lower cross-stratified unit, a middle planar-laminated unit, and an upper unit with centimeter-scale trough cross-lamination (Fig. 2A). Laminae that define the middle planar-stratified unit onlap a scour surface from right to left. Note that five laminae define the middle unit on the right part of the rock (yellow bar); however, due to onlap, these decrease in number to one or two laminae at the left part of the rock. Trough cross-laminae of the upper unit scour down into the middle unit, from left to right. Note additional, stratigraphically higher, planar laminae in the middle unit at the far left (green arrows), where the scour surface rises up through the section. All units are affected in a small way by what is interpreted as soft-sediment deformation, but this is not discussed further here.

Trough cross-stratification in the upper unit forms a bed set with at least 3–4 cm of apparent thickness. Blue arrows in Figure 2A point to three distinct troughs, as indicated by basal truncation and concave-upward geometry. Several superimposed sets show basal scouring and backfilling by concave-upward to occasionally convex-upward cross-laminae (red arrows). Truncation surfaces and backfilling of subjacent sets are well expressed in the left-center part of the upper unit, where scalloped cross-lamination (Rubin, 1987b) is developed; each trough-shaped subset truncates (scallops) the subset to its left and shows a small angle of climb from left to right. Two processes, fluctuating flow and superimposed bedforms, can form scalloped cross-lamination. Unfortunately, it is not possible to distinguish between the two in this case due to a lack of bedding-parallel exposures.

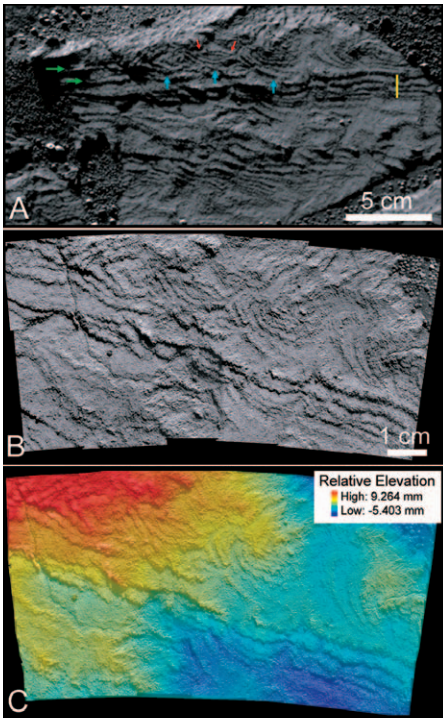

Figure 2. Trough (or festoon) cross-lamination in upper Overgaard. A: Note cross-stratified lower unit, overlain by planar-laminated middle unit (indicated by yellow bar), and trough cross-laminated upper unit. See text for discussion. Image of Overgaard is one of several taken at different lighting geometries using Pancam's (panoramic camera) 432 and 436 nm filters. Low-angle light image was acquired on sol 716, sequence id p2593, 432 nm filter. B: Microscope imager (MI) mosaic of middle and upper units. Note generally granular texture and excellent sorting, right-to-left pinch out of middle unit, and stratal truncation and downlap of cross-laminae in upper unit (cf. A, red arrows). Mosaic was constructed from images obtained on sols 721 and 723. C: Digital elevation model (DEM) of MI mosaic. Note lack of correlation between topography and bedding in left-central part of upper unit, indicating primary origin of stratal (lamina) geometries. DEM was created by first holding fixed position and angles for image 1M192204573IFF64KWP2956M2F1 (sol 721) and then adjusting positions and angles for all other images (from sols 721 and 723) to fit first image. DEMs were created for each stereo pair and merged together. Image processing on merged DEM removed seams, and DEM was overlain transparently on image mosaic.

A mosaic of MI images was constructed to coincide with the middle and upper units of upper Overgaard; this provides additional supporting detail of the grain-scale variability in primary lamination (Fig. 2B). Furthermore, the MI mosaic was used to construct a digital elevation model (DEM) of the outcrop topography (Fig. 2C); the rock surface is flat at the relevant scale across the left-center region where the upper unit is exposed, and other-

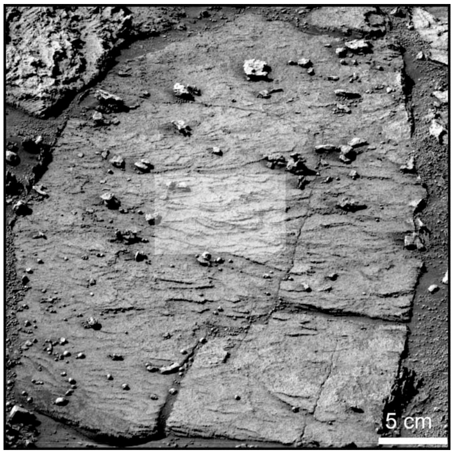

Figure 3. Centimeter-scale, trough (or festoon) cross-lamination is abundant in Cornville. Center part is highlighted and approximates area of Figure 4A. Exposed surface is largely transverse to flow, with small component of climb from right to left. Note abundant scour surfaces that truncate underlying concave-up laminae, overlain by downlapping cross-laminae of next set. Rock is ~30 cm wide and 50 cm long. Note moderately steep dips of laminae exposed along left side of crack at center part of lower boundary of rock. These indicate that true thickness of this cross-laminated unit must be less than apparent thickness, which equals long dimension of rock (~50 cm); correcting for dip (~30°), true thickness of centimeter-scale cross-lamination is likely still to be several tens of centimeters, thickest observed so far at Meridiani. Superresolution image of Cornville acquired sol 705 using Pancam's (panoramic camera) 482 nm filter (sequence id p2576).

wise bedding shows no systematic relationship with respect to the minor local slopes. This demonstrates that the cross-lamination is a primary attribute of the rock rather than an artifact of erosion.

Trough cross-lamination is also well displayed at a rock named Cornville (Fig. 3). Cornville is ~1 m from Overgaard and has a moderate dip toward the upper part of the rock. The entire rock is cross-laminated (Fig. 3), representing a true stratigraphic thickness of ~20–30 cm. Centimeter-scale trough cross-lamination is well developed near the center of the rock. The geometry and scale of these cross-laminae sets are nearly indistinguishable from terrestrial analogs formed in subaqueous flows (Fig. 4). Cornville trough cross-laminae sets are as thick as 1–2 cm and as wide as 2–3 cm in sections that are most likely transverse to flow. The rock surface exposes a cut that is largely transverse to flow, with a small component of climb from right to left. The scale and geometry of this cross-lamination are critically different from the structures formed in base surge deposits, as illustrated by McCollom and Hynek (2005) and Knauth et al. (2005).

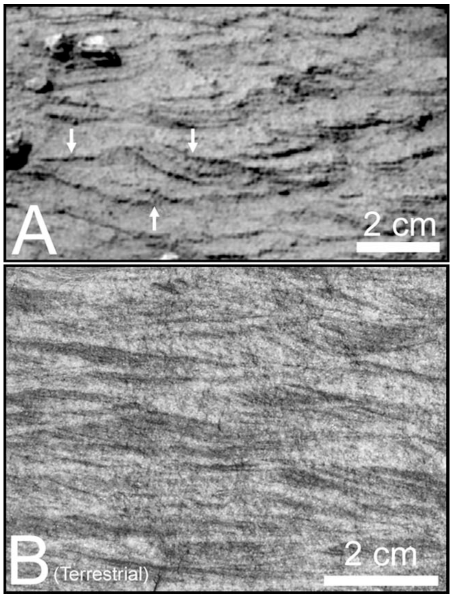

Figure 4. Enlargement of center part of Figure 3. A: Well-developed trough cross-lamination. In left center of image, set has classic concave-up lower bounding surface (up arrow), and upper boundaries are marked by two intersecting concave-up surfaces (down arrows). Internal cross-laminae are truncated by upper bounding surface on right, and that bounding surface is then downlapped by cross-laminae of superjacent set. Cross-laminae show small angle of climb from right to left. B: Terrestrial trough cross-lamination (Cretaceous Mesa Verde Group) shows strong geometric similarity with that preserved in Cornville (cf. A). Note similar (centimeter) scale of cross-lamination. However, these cross-laminae differ from those in A in that they show small angle of climb from left to right (rather than right to left) and cut is more parallel to flow direction.

SHRINKAGE CRACKS

Olympia outcrops expose distinct cracks that developed during or shortly after deposition of sandy sediment. The cracks are present in several rocks, including lower Overgaard and Skull Valley (Fig. 5). Cracks are oriented perpendicular to bedding and typically extend to depths of >10 laminae (~5 cm or more). Crack width generally does not exceed 1 mm, and remains approximately constant for the length of the crack. Crack spacing typically is several centimeters. Truncated laminae commonly are deformed along crack margins; edges typically are rotated upward, forming curl-up structures (see Allen, 1982, Figs. 13–25). In some cases, cracks splay upward into zones of massive or convolute bedding, but then are capped abruptly by succeeding undeformed laminae.

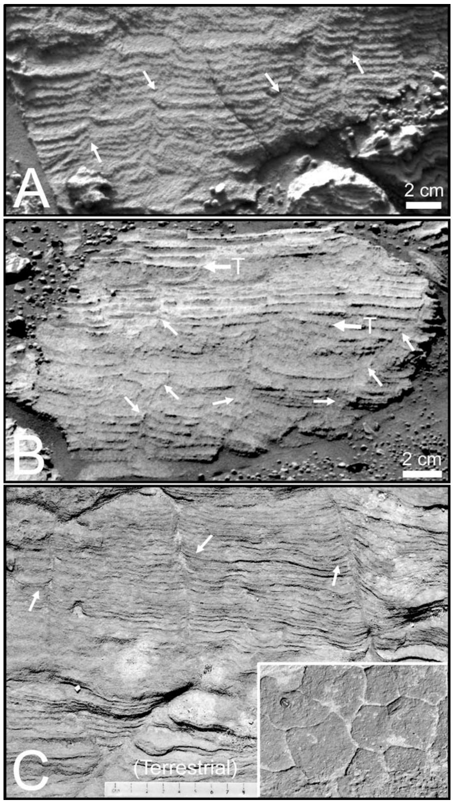

Figure 5. Penecontemporaneous cracks typically are narrow and cut across lamination for more than 5 cm. A: Lower Overgaard. Note that truncated laminae adjacent to cracks (small arrows) are deflected upward along crack margins, and cracks have lateral spacing of several centimeters. This superresolution image was acquired on sol 698 using Pancam's (panoramic camera) 482 nm filter, sequence id p2572. B: Skull Valley. Numerous penecontemporaneous cracks (small arrows) crosscut lamination, some oblique to bedding. Note characteristic upward-deflected laminae along crack margins; termination of prominent crack in center of rock at discrete bedding plane; and truncation of upward-deflected laminae along discrete bedding planes in center and upper parts of rock (large arrows with T). This superresolution image was acquired on sol 713 at 13:48:35 using Pancam's 482 nm filter, sequence id p2589. C: Prism cracks formed in terrestrial eolian interdune depression, Jurassic Navajo Sandstone, Tuba City, Arizona. In cross section, cracks are expressed as narrow lines, with spacing of several centimeters. Note upward deflection of laminae adjacent to cracks (arrows), similar to what is seen in Overgaard and Skull Valley at Erebus crater. Ruler is subdivided in centimeters. Inset shows polygonal pattern in plan view; coin is 18 mm in diameter.

One possible interpretation of the cracks is that they are related to the Erebus crater-forming impact, which might be expected to include swarms of small-scale fractures, in addition to related faults. Textures that result from the impact process include crush zones, small-scale thrust faults, and the authigenic breccia described by Shoemaker and Kieffer (1974). However, these impact-related textures postdate and overprint the features described here, which are instead bounded and truncated by younger laminae, and are associated with zones of soft-sediment deformation, including the curl-up structures that show clear evidence for plastic deformation.

The cracks described here are interpreted as shrinkage cracks formed during desiccation of damp sediments. They have direct analogs in terrestrial environments where intermittent wetting and drying of laminated sediments result in development of narrow but deep cracks (Chavdarian and Sumner, 2006; Demicco and Hardie, 1994; Kocurek and Hunter, 1986). In plan view these cracks form well-developed polygons, with widths of several centimeters to several decimeters. Because the cracks extend to significant depths, the crack-bounded sediment volumes have shapes similar to prisms, and thus these cracks are commonly referred to as prism cracks (Fischer, 1964). In terms of process, prism cracks differ from ordinary desiccation cracks in that they involve multiple desiccation events, as frequently as after deposition of each lamina or after deposition of a few laminae (Chavdarian and Sumner, 2006; Demicco and Hardie, 1994; Kocurek and Hunter, 1986). Prism cracks are developed in a broad range of environments, ranging from tidal flats to interdune depressions.

The terrestrial shrinkage cracks shown in Figure 5C are developed along an interdune bounding surface in the Jurassic Navajo Sandstone and form discrete prisms 10–15 cm wide extending to depths as great as 11 cm. These prism cracks formed by wetting and drying of a truncation surface that separates sets of eolian strata. Such surfaces are regarded to have formed during hiatuses in sedimentation, followed by deflation to the water table (Kocurek and Hunter, 1986). By analogy, Martian strata in lower Overgaard and Skull Valley are interpreted to have become intermittently wet so that prism cracks could form along discrete surfaces. Minor oscillations of the water table would have been sufficient to accomplish this. The upward deflection of laminae to form curl-up structures is developed because a desiccating layer undergoes more evaporation than the underside of the same layer, leading to differentially greater shortening, and thus curling, of the upper surface.

Curl-up structures are a well-known, almost diagnostic, feature of desiccated terrestrial sediments (see Demicco and Hardie, 1994, their Fig. 46). Fine laminae may have been formed by migrating wind ripples across a damp, prism-cracked interdune surface. Capillary wicking of moisture through freshly deposited, millimeter thick sediment layers would have resulted in their wetting. Subsequent drying would have encouraged new cracks to exploit zones of weakness inherited from antecedent cracks; these older cracks would then extend upward through the sediment veneer. In this manner the cracks are able to maintain their narrow width, yet cut across bedding for many laminae. In terrestrial analogs, precipitation of salts is a key part of the process, and results in the addition of fresh material to the crack void space (Kocurek and Hunter, 1986). Once cracked, and filled with sediments and/or precipitated salts, thermal stresses may cause the crack to close. However, because the addition of fresh material reduces the crack volume, the margins may be subjected to compressive forces that can lead to buckling of adjacent laminae.

CONCLUSIONS

Rocks exposed at the Olympia outcrop, Erebus crater, show a distinct set of primary stratification geometries and shrinkage cracks that are consistent with deposition and subsequent modification under aqueous conditions. Trough cross-lamination is distributed on a regional basis, at least across the $\sim$4 km traverse examined by *Opportunity*, and this suggests that overland aqueous flows were widespread. Prism cracks provide strong evidence for iterative shrinkage and expansion of sediments during desiccation. This may have occurred whenever the capillary fringe of the groundwater table rose to intersect the surface. Subsequent drying would have induced cracking, as commonly happens in playa lake or sabkha-type environments. Intermittent wetting and transient flooding of interdune depressions during groundwater migration provide a simple model that is consistent with observations from all three craters (and several intervening outcrops) examined to date.

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