Cracks and fins in sulfate sand: Evidence for recent mineral-atmospheric water cycling in Meridiani Planum outcrops?

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ABSTRACT

Gypsum dunes at White Sands National Monument, New Mexico, provide an excellent analog to sulfate-rich eolian outcrops on Meridiani Planum, Mars, as characterized by the Rover *Opportunity*. Numerous outcrops imaged by *Opportunity* contain polygonal cracks that crosscut bedding and extend across most surfaces of boulders. Some of these cracks are associated with millimeter-thick platy fins that protrude as much as a few centimeters above outcrops. Similar cracks crosscut bedding at White Sands on erosional stoss slopes and in pedestals of cemented dune sand. The cracks at White Sands form in response to cementation of damp gypsum sand followed by contraction due to dehydration. During warm seasons, cracked sand is dry and cracks rarely grow, although some may form after rainstorms. Two types of fins form along cracks and differentially eroded laminae. White fins represent subsurface differential cementation along cracks followed by differential erosion. Tan fins form due to cementation of crack edges and laminae on exposed dune surfaces. Wind-blown sediment adheres to damp tan fins. Similar processes may be important for crack and fin formation in Meridiani Planum outcrops, implying recent water cycling between sulfate outcrops and the Martian atmosphere.

Keywords: sulfates, Mars, eolian environment, desiccation, cracks, differential weathering.

INTRODUCTION

Searching for life elsewhere in the universe is fundamental to our cultural heritage and is a major motivation for space exploration. Planetary missions like the Mars Exploration Rovers provide insights into the distribution of habitable environments in space and time. The Rover *Opportunity* provided evidence for water-rock interactions and suggestions of surface water flow during deposition of sedimentary rocks now exposed on Meridiani Planum (Arvidson et al., 2005; Christensen and Ruff, 2004; Christensen et al., 2004; Grotzinger et al., 2005; Hynek, 2004; Klingelhofer et al., 2004; Squyres et al., 2004; Squyres and Knoll, 2005). These outcrops consist of layered sedimentary bedrock composed of ~30%–50% siliciclastic minerals, ~20%–30% magnesium and calcium hydrous sulfates, ~15%–25% other silica-containing minerals possibly including amorphous silica, 10% jarosite, and 6% hematite (Clark et al., 2005; McLennan et al., 2005). Outcrops contain sedimentary structures indicating deposition from predominantly eolian processes with rare subaqueous ripple cross lamination (Grotzinger et al., 2005). Spherules, interpreted as concretions, and vugs, interpreted as displacive evaporite pseudomorphs, represent postdepositional aqueous alteration of sediments (McLennan et al., 2005; Squyres et al., 2004). The cross-stratification styles, composition of the rocks, and evaporite pseudomorphs indicate a dune field to playa environment (Squyres et al., 2004; Grotzinger et al., 2005). The hydrous sulfate minerals and frost observed by *Opportunity* (National Aeronautics and Space Administration, 2004) demonstrate that water is still present, although not observed in liquid form.

Two additional features may imply recent water cycling between outcrops and the atmosphere on Mars. Contractional cracks in many outcrops define centimeter- to decimeter-scale polygons that are perpendicular to outcrop surfaces (McLennan et al., 2005). Cracks crosscut stratification in the rocks, and some extend across most of the irregular exposed rock surfaces (Fig. 1). Thus, the geometry of cracks appears to be inconsistent with synsedimentary contraction (McLennan et al., 2005). We propose that they represent post-exposure water loss. Preferentially cemented fins that are <1 cm thick protrude as much as a few centimeters above the edges of some cracks. Their geometry is consistent with differential cementation along cracks, followed by differential weathering (McLennan et al., 2005), although if cracks formed near the surface, fin cementation must also be a near-surface phenomenon.

Similar cracks and fins are episodically present in gypsum dunes at White Sands Na-

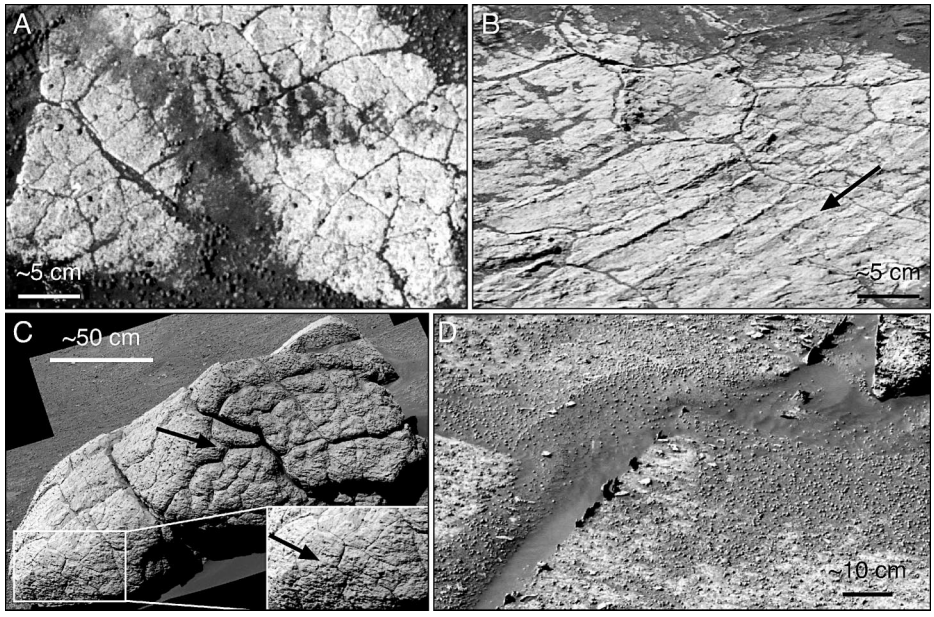

Figure 1. Images from *Opportunity* (courtesy of NASA/JPL-Caltech; ~5-mm-diameter spherules for scale). A: Cracks in outcrop in Endurance Crater (after 1p146650570eff35b8p2565r5c1.GIF). B: Cracks in "Escher" showing raised rims along cracks and along sedimentary layers (arrow) demonstrating differential cementation (after 07-SS2-02-Escher-B251R1.jpg). C: Cracks in "Wopmay" extend across all visible surfaces and crosscut bedding (arrows) (after 08-SS-01-Wopmay-B278R1.jpg). D: Fins on "Razorback" extend above outcrop surface along fractures (after 1p142569702eff3221p2387l2c1.27663.GIF).

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Figure 2. Images from White Sands National Monument. A: Cross-stratification on stoss side of dune. Fins grew on high-relief laminae (arrows). Pen for scale. B: Cracks and tan fins in dune sand. Wind shadows demonstrate that fins face upwind. C: Cracks and tan fins that stand millimeters above sand and are very thin. Arrow indicates depositional laminae. D: White fins along cracks buried in loose sand. E: Cracks on all exposed surfaces of erosional pedestal. Cracks crosscut laminae. Cemented surfaces similar to white fins project out from sand (arrow).

tional Monument, New Mexico, which provides a prime analog site to Meridiani Planum outcrops. White Sands contains sulfate dunes deposited in evaporitic and eolian environments similar to those interpreted for Meridiani Planum outcrops. Constraints on processes forming cracks and fins at White Sands provide insights into processes that may produce similar features on Mars.

Geological Background

At White Sands National Monument, gypsum sand erodes from playa lakebeds and is transported northeast to form the >400 km^2 dune field (Langford, 2003). Sedimentary structures associated with the dunes include contorted bedding, ripple laminae, festoon bedding, and large-scale cross-stratification (McKee, 1966). Dune grain sizes range from fine to very coarse, but medium sand is dominant. White Sands dunes are mostly gypsum with <10% calcite and <10% siliciclastic sand (Chavdarian, 2005).

The high solubility of gypsum leads to synsedimentary cementation of sulfate sand near dune surfaces and within dunes, resulting in good exposures of cross-stratification on almost all stoss sides of White Sands dunes (Fig. 2A; Chavdarian, 2005; Schenk and Fryberger, 1988). Pedestals of cemented sand also demonstrate sufficient subsurface cementation to form wind-resistant structures. Many pedestals are associated with plants, whose roots may promote cementation by cycling water (Schenk and Fryberger, 1988). Gypsum sand grains have collision-damaged rims, providing highly soluble crystal fragments that dissolve in percolating rainwater, dew, and frost; cements form as water evaporates (Schenk and Fryberger, 1988). Temperature changes may also promote cementation in the presence of thin films of water. In aqueous solutions, the gypsum-anhydrite transition occurs within the temperature range of 42–60 °C, but depends critically on the activity of water (see discussion in Freyer and Voigt, 2003). Specifically, solutions with high ionic strengths, such as evaporating thin films, have lower transition temperatures, e.g., 18 °C for solutions saturated with halite (Freyer and Voigt, 2003). Temperature changes during warm summer months, when thunderstorms are also common, probably promote gypsum-anhydrite transitions as temperature and the ionic strength of thin water films cycle through gypsum and anhydrite stability fields. Thus, water and temperature changes both promote active cementation of gypsum sand at White Sands.

CRACKS AND FINS IN GYPSUM SAND

Contractional cracks and upward-projecting fins were identified in White Sands dunes (Chavdarian, 2005). Cracks form oblique to bedding in the gypsum sand, and fins protrude as much as several centimeters above dune slopes, providing excellent analogs to similar features observed at Meridiani Planum. Field work at White Sands in 2005 demonstrated that atmospheric water and temperature strongly influence crack and fin formation. During a 5 day field season in January, temperatures ranged from <−5 °C to 14 °C, with little wind, no rain, and abundant frost. During 5 days in March, rain showers wet dune sand once, and the wind blew at ~25 km/h with gusts to 50 km/h for 3 days. In June, showers wet the sand once during 5 days, and temperatures ranged from 14 °C to 40 °C.

Cracks

Polygonal cracks at White Sands form in interdune sediments, at interdune-dune boundaries, on stoss slopes and tops of dunes, and in pedestals of cemented dune sand (Fig. 2). These cracks form perpendicular to most erosional surfaces that obliquely cut bedding in dunes. Cracks in interdune sand and at interdune-dune boundaries extend downward from depositional surfaces; cracks are absent from other depositional surfaces. Cracks define five- to six-sided polygons similar to mudcracks, although clay minerals are absent. Polygons between cracks range from 15 to >40 cm in diameter. Cracks are straight to wavy and extend downward a minimum of 1–5 cm. Cracks can also be observed cutting through erosional pedestals of cemented sand at various angles, including both horizontally and vertically (Fig. 2E). Poorly cemented cracks define polygons on erosional surfaces, whereas well-cemented cracks often form through-going features extending for more than 40 cm (Fig. 2E).

In January, cracks were ubiquitous along interdune-dune boundaries and across erosional surfaces on dune slopes. The cracked sand was moist and cohesive, consistent with active crack growth. In contrast, cracked sand on dune slopes in March and June was dry and not cohesive, and cracks were filled with loose sand, implying that cracks were not actively forming. Cracks were abundant; all exposures of cemented sand on stoss surfaces showed cracks once surficial sand was removed. Moist, actively forming cracks were present along the interdune-dune boundaries in March, but were absent in June when sand was dry. In June, ~10% of stoss dune surfaces contained sharply defined, unfilled cracks in poorly cemented sand; a substantial rainstorm immediately before the start of June observations and high evaporation rates may have formed these cracks.

Fins

Fins at White Sands are thin, platy, preferentially cemented features that protrude out of the dune sand (Figs. 2B–2D). They are commonly associated with cracks, but can also form along differentially eroded ripple cross lamination or thin bedding with centimeter-scale relief. Fins can be either supported on one side by gypsum sand or protrude out of the ground unsupported. Most fins are tan, and <5% are white. Tan fins extend as much as several centimeters above the dune surface and are as thick as 3 mm. They dip 50–90 degrees, and fin surfaces always face into the wind. Though tan fins have relief, they are typically soft and cohesive rather than firmly cemented. Some react with dilute HCl, demonstrating the presence of minor $CaCO_3$ cement. Their tan color may be due to siliciclastic dust or the presence of sufficient water to darken them. On average, tan fins have a finer grain size than surrounding sediment, consistent with adhesion of wind-blown sediment. Tan fins were only present in January when dune sand was moist, suggesting that water plays an essential role in their formation.

Less common white fins are harder than tan fins; they are sufficiently cemented to deform brittlely. They protrude as much as 8 cm above the dune surface and are similar to cemented crack surfaces observed in erosional pedestals (Fig. 2D). Where differentially eroded along laminae and cracks, white fins always face upwind, but on pedestals they can face any direction. White fins react with dilute HCl, demonstrating the presence of trace calcite cement. Their white color suggests that they are composed of nearly pure gypsum and calcite. White fins were present but rare in all three months.

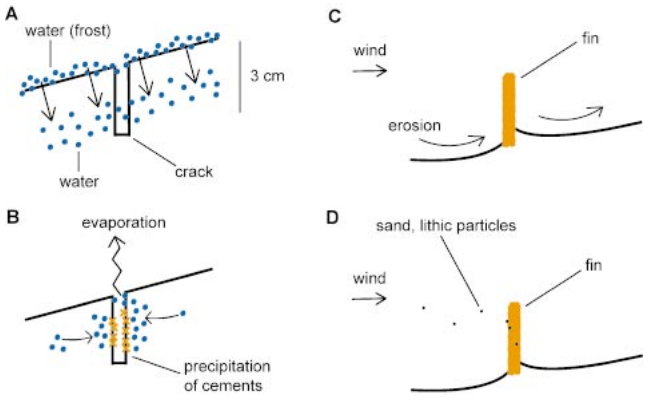

Figure 3. Tan fin formation. A: Water from frost percolates into dune sand. B: Increased airflow in cracks speeds evaporation, cements precipitate, and capillary flow provides moisture to cracks. C: Dune surfaces erode, leaving slightly cemented crack faces. D: Adhesion of fine particles and continued cementation strengthen fins.

Adhesion Structures

Wind adhesion structures form throughout damp interdune areas and on some dunes. Adhesion structures range in size from a couple of millimeters to a few centimeters in height. They project directly upwind from objects that protrude above the sediment surface such as cemented sand flakes and grass stems. They are recognized as adhesion structures based on their upwind growth and the incorporation of finer grains than the surrounding sand. Adhesion structures only form in damp areas, suggesting that the cohesiveness provided by thin films of water allows them to form.

DISCUSSION

Hypotheses for Crack Formation

Fresh cracks were only observed in damp sand or sand that had recently dried. These cracks extend centimeters to perhaps decimeters into the subsurface, demonstrating that they are associated with exposure surfaces. Evaporation of water, cementation of sand, and shrinking of sand volume promote crack formation. It is possible that very small volumes of gypsum dissolve and reprecipitate almost daily due to highly reactive damaged grain rims and cycling between gypsum and anhydrite stability fields. This cementation, plus the presence of thin films of water, may provide the cohesiveness necessary for crack formation in sand-sized sediment. Water cycling between the sediment and the atmosphere appears to be critical for crack formation.

Some through-going cracks on pedestals may form within the interiors of dunes. These decimeter- to multimeter-long cracks tend to define aligned planes rather than polygons or columns, which are typical of contraction (e.g., Jagla, 2002). Thus, through-going fractures are probably due to burial stresses in cemented dune interiors rather than to contraction.

Hypotheses for Fin Growth

Two models for fin growth explain observations at White Sands. Cements can preferentially precipitate on sides of some cracks due to enhanced evaporation along highly permeable cracks, probably when cracks are buried within dunes in the vadose zone. When these cemented crack walls are exposed at the surface, differential erosion removes surrounding sand and the cemented crack edges protrude above dune surfaces, producing white fins. Softer tan fins do not fit this growth model because they only face upwind and are not associated with well-cemented crack walls. Because tan fins were only present during January when nighttime temperatures were sufficiently low to form a heavy frost, we hypothesize that as the frost melts, water percolates into the dune sand and cracks (Fig. 3). Cracks have increased airflow due to their high permeability, speeding evaporation of water, which causes cements to precipitate along crack edges, particularly where they are exposed at the surface. Capillary action pulls water to the cracks, where it evaporates, precipitating more cement. The crack edges become more resistant to erosion with increased cementation. As sediment between cracks is eroded by wind, the more resistant crack edges are left protruding out of the ground, forming fins. The fins are now exposed to wind, and are further strengthened by adhering fine particles. Moisture from surrounding sand can also wick into fins, enhancing adhesion of fine grains and cementation. Tan fins are thus interpreted as near-surface differential cementation combined with adhesion. Their absence in the warmer but wet months can be explained by rapid evaporation across the entire exposed surface of the sand due to very high temperatures, which do not allow localization of evaporation along cracks. An overall paucity of moisture in the vadose zone reduces the importance of near-surface capillary migration of water, possibly also limiting tan fin growth.

Implications for Mars

Cracks. Contractional cracks with geometries similar to those at White Sands are abundant in many Meridiani Planum outcrops.

They define centimeter- to decimeter-scale polygons on outcrop surfaces that are oblique to stratification in the rocks (Figs. 1A–1C). Cracks on some rocks do not correlate with ancient depositional surfaces because they extend across most of the exposed rock surface (Fig. 1C). Thus, the geometry of many cracks appears to require crack growth after exposure of current surfaces, similar to those at White Sands. Dehydration of outcrops could have caused contraction and crack formation. If pore water or thin films of water were present when the outcrops were first exposed, evaporation of this water may have provided a sufficient volume change to produce cracks, similar to those at White Sands. Meridiani Planum outcrops contain gypsum, but hydrous Mg-sulfates are likely more abundant (Arvidson et al., 2005; Bell et al., 2004; Christensen et al., 2004; Clark et al., 2005; Gendrin et al., 2005). Hydrous Mg-sulfates can decompose into water plus less-hydrous Mg-sulfates at temperatures near and slightly below 0 °C (Hogenboom et al., 1995), temperatures frequently reached on Martian surfaces exposed to sunlight. Much lower night temperatures and low humidity make it likely that released water evaporates or sublimates rapidly, leading to volume loss in the rock. However, contributions of water via frost could lead to rehydration of Mg-sulfates, creating a water cycle that is similar to that in gypsum dunes at White Sands. Differential cementation is expected during this water cycling and will be strongly affected by sites of preferential evaporation.

Fins. Preferentially cemented fins that are <1 cm thick protrude as much as a few centimeters above the edges of some cracks in Meridiani Planum (Fig. 1D; McLennan et al., 2005). Their geometry is consistent with differential cementation along cracks, followed by differential weathering, similar to white fin formation at White Sands. However, this model for fin formation requires crack growth in the subsurface, which may be consistent with some crack geometries, but not all of them. Alternative models for fin growth include cementation due to evaporation and sublimation along fractures and adhesion of fine dust on slightly raised crack surfaces, similar to White Sands tan fins. Several of the cracking models predict moisture associated with cracks after exposure, which suggests that adhesion and postexposure cementation could cause fin growth.

CONCLUSIONS

Gypsum dunes at White Sands National Monument provide an excellent analog to eolian outcrops on Meridiani Planum, as characterized by the Rover *Opportunity*. Both White Sands and Meridiani sulfate-rich rocks contain polygonal cracks that crosscut bedding and extend across most surfaces of sand pedestals and loose boulders. Some cracks at both sites are associated with fins. Cracks and fins at White Sands can be attributed to atmospheric water-sulfate mineral interactions. Cracks form in response to evaporation of water leading to cementation of gypsum sand followed by contraction due to drying and mineral dehydration. White fins form from preferential cementation along crack surfaces in the subsurface, and tan fins form due to evaporation and cementation along crack edges on exposed dune surfaces. Sediment also adheres to damp fins, and adhesion may play a critical role in tan fin growth. Similar processes may be important for crack and fin formation in Meridiani Planum outcrops, providing evidence for recent water cycling between sulfate outcrops and the Martian atmosphere.

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