Desiccation cracks provide evidence of lake drying on Mars, Sutton Island member, Murray formation, Gale Crater

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ABSTRACT

Mars Science Laboratory (MSL) Curiosity rover data are used to describe the morphology of desiccation cracks observed in ancient lacustrine strata at Gale crater, Mars, and to interpret their paleoenvironmental setting. The desiccation cracks indicate subaerial exposure of lacustrine facies in the Sutton Island member of the Murray formation. In association with ripple cross-stratification and possible eolian cross-bedding, these facies indicate a transition from longer-lived perennial lakes recorded by older strata to younger lakes characterized by intermittent exposure. The transition from perennial to episodically exposed lacustrine environments provides evidence for local to regional climate change that can help constrain Mars climate models.

INTRODUCTION

Reconstructions of ancient habitable environments on Mars increasingly depend on detailed analysis of sedimentary facies recording aqueous environments. Over the past decade, the Mars Exploration Rover Opportunity encountered ancient eolian, fluvial, and lacustrine environments deposited in hypersaline, acidic, sulfate- and hematite-enriched playas formed in interdune depressions at Meridiani Planum (e.g., Grotzinger et al., 2005). This setting contrasts with the clay- and magnetite-bearing, moderate-pH, perennial lacustrine facies in Gale crater (Grotzinger et al., 2014, 2015; Hurowitz et al., 2017). Suites of sedimentary structures, facies associations, and authigenic and diagenetic mineral assemblages were essential to recognize these paleoenvironmental settings. Previously, potential martian desiccation cracks were identified in multiple sedimentary deposits from orbit (e.g., El-Maarry et al., 2014) and in situ by rovers (Grotzinger et al., 2005, 2014).

The kilometers-thick sedimentary succession in Gale crater provides an opportunity to observe changes in surface environments over extended periods in martian history. Studies of basal strata in the informally named Murray formation demonstrated the presence of long-lived perennial lakes in Gale crater at ca. 3.6–3.2 Ga (Grotzinger et al., 2014, 2015; Hurowitz et al., 2017). Recent facies observations at higher stratigraphic levels (Fedo et al., 2017) may record an evolution of the environment over time. Here we present in situ evidence for lithified desiccation cracks in the Murray formation, indicating that the lakes may have partially dried in its younger history.

During Sols 1555–1571, Curiosity investigated a series of distinctive centimeter-scale reticulate ridges on the surfaces of several slabs of rock that expose bedding planes in the Sutton Island member of the Murray formation. Their morphology and composition is characterized to determine if they formed via desiccation and to examine implications for the deposition of associated strata.

GEOLOGIC SETTING

As of Sol 1700, the Curiosity rover has explored more than 200 m of strata consisting of fluvial, deltaic, lacustrine, and eolian sediments (Williams et al., 2013; Grotzinger et al., 2014, 2015; Banham et al., 2016; Edgar et al., 2017) represented by the Bradbury group, the interfingering and overlying Murray formation (Mount Sharp group), and the unconformably overlying Stimson formation (Siccar Point group) (Fig. 1). The first ~25-m-thick Murray interval consists dominantly of finely laminated mudstones with minor siltstones and sandstones of lacustrine origin (Grotzinger et al., 2015). It is overlain by an ~25-m-thick interval with decimeter- to meter-scale cross-stratification that suggests sediment transport as large bedforms or in channels (Fedo et al., 2017), followed by >30 m of finely laminated red/purple-hued mudstone with intervals of very fine sandstone, consistent with sediment accumulation in subaqueous lacustrine environments (Grotzinger et al., 2015; Fedo et
al., 2017). These younger strata, comprising the Sutton Island member of the Murray formation, expose broken and tilted slabs of bedrock, including finely laminated red mudstones, centimeter-scale ripple cross-laminated mudstone, decimeter-scale cross-stratification, and massively bedded intervals of siltstone (Fedo et al. 2017).

OLD SOAKER CAMPAIGN

The focus of the investigation is an ~80-cm-long, 40-cm-wide rock slab called “Old Soaker” (OS) that exposes a bedding plane with a red surface marked by a network of ridges that form polygons (Fig. 2A). The red mudstone is ~1 cm thick and overlies a gray sandstone bed containing bedding-parallel seams of calcium sulfate (CaSO4). OS and a similar nearby slab called “Squid Cove” (SC) were imaged with the Mastcam (Mastcam) and the Mars Hand Lens Imager (MAHLI) to characterize the geometry and fill of the ridges. Their elemental compositions were examined with the rover’s ChemCam Laser Induced Breakdown Spectrometer (LIBS) and Alpha-Particle X-Ray Spectrometer (APXS).

Methods

The geometries of the polygonal ridges were determined using MAHLI images to evaluate whether their shape is consistent with desiccation. Images of ridges and their junctions were traced to calculate vertex angle distributions, widths of ridges and the polygons they form, and ridge surface area. A three-dimensional (3-D) model of OS was generated from 76 MAHLI images processed using photogrammetry software. The grain sizes of the red and gray beds were measured with ~16 µm/pixel MAHLI images.

RESULTS

Morphology of the Ridges and Surrounding Beds

The red surfaces of OS and SC are covered by networks of arcuate ridges with up to 5 mm of positive relief that define predominantly four-sided and some five-sided, 0.5–3.5-cm-wide polygons (Figs. 2B and 3A). Red surfaces of adjacent slabs also show raised ridges spanning an area of a few square meters. The ridges range in length from a few centimeters to ~0.3 m and mostly meet orthogonally, forming T-junctions (Fig. 2B). The ridges are made of red-to-gray sediment similar in color to the surrounding bed (Figs. 2B and 2C) and comprise ~20% of OS’s surface. No grains in the ridges or surrounding surface are resolved in MAHLI images (Fig. 2C), indicating a maximum grain size of coarse silt. CaSO4 veins distinct from ridge material follow most, but not all, of the ridges (Figs. 2B and 2C) and in some cases cross-cut the ridges (e.g., Fig. 2E). Sub-millimeter-wide fractures occur within the polygons (Fig. 2C). Gray, semi-circular, millimeter-scale patches dot the red beds on OS and SC. They can show raised relief and in places are cross-cut by veins (Figs. 2B and 2D).

Some very fine sand grains and millimeter-scale concretions or embedded grains are visible in MAHLI images of the gray bed at OS (Fig. 2F). The ridges taper off within millimeter-scale depressions in the red mudstone at OS (Fig. 2G). Fractures associated with the ridges of the SC slab penetrate the red mudstone and terminate at the boundary with the underlying gray sandstone (Fig. 4). The gray beds appear to lack ridges (Figs. 2A and 2F).

Composition Measurements at Old Soaker and Squid Cove

ChemCam analysis of OS identified three distinct bed compositions (Fig. 2A): (1) a lowermost bright sandstone with no ridges and a...
The gray bed (target “Fresh Meadow”) is distinct from the overlying red bed, with comparatively high K2O abundance relative to other Murray mudstones (Table 1) (Mangold et al., 2017). APXS measurements of OS show that the red mudstone bed is similar in composition to the overlying gray bed. The most likely fracturing mechanisms include desiccation, synaeresis, and hydraulic fracturing.

**Origin of the Ridges**

Shrinkage cracks form in response to tensile stresses within sediment that result from contraction due to moisture or heat loss (Shorlin et al., 2000). When stress exceeds local tensile strength, materials fracture and cracks begin to grow orthogonal to the direction of maximum tensile stress, typically resulting in a polygonal pattern (Sletten et al., 2003). In uniform material, new cracks will turn to converge with other cracks orthogonally, resulting in junctions mostly near 90° (Shorlin et al., 2000) as observed at OS and SC (Fig. 3). Abundant T-junctions show that sediments dried to completion, possibly in a single event, rather than undergoing multiple wetting and drying cycles that tend to form 120° junctions (Goehring et al., 2010).

Desiccation cracks form at the sediment-air interface and are preserved in the rock record through sediment infill from overlying strata (Plummer and Gostin, 1981). The compositional and color similarity of the ridges to the average Murray formation, which is predominantly comprised of silt-sized grains or smaller, suggests that the ridges are comprised of sediment. Ridge-forming sediment at OS and SC is indistinguishable from the surrounding bed based on grain size alone, so this observation is not definitive evidence for sediment infill from an overlying bed.

Sulfate-mineralized fractures attributed to hydraulic fracturing are prevalent throughout the Murray formation (Grotzinger et al., 2014, 2015; Caswell and Milliken, 2017), and CaSO4-filled veins also run along most of the OS ridges, so burial-related hydraulic fracturing may be considered a potential mechanism for the origin of the ridges. However, cross-cutting relationships indicate that the ridges and their infilling materials were lithified prior to the formation of sulfate-filled fractures; sulfate-filled fractures cross-cut some ridges and are not visible along all ridges (Figs. 2C and 2E). Moreover, hydraulic fracturing should yield relatively consistent fracture orientations (Hubbert and Willis, 1972), which are not observed at OS or SC. Zones of weakness created by early sediment-filled fractures were likely overprinted by burial-related stresses (Caswell and Milliken, 2017), followed by precipitation of calcium sulfates.

The ridges are restricted to the red surfaces and their associated fractures terminate at the boundary with the underlying sandstone, consistent with desiccation of a thin mud layer. This

**TABLE 1. CHEMCAM MEASUREMENTS ON AND AROUND OLD SOAKER ROCK SLAB, MARS**

<table>
<thead>
<tr>
<th>Target</th>
<th>No. Points or Targets</th>
<th>SiO2</th>
<th>TiO2</th>
<th>Al2O3</th>
<th>FeO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na2O</th>
<th>K2O</th>
<th>Sum of oxides (wt%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murray mudstones</td>
<td>88 targets</td>
<td>52.4</td>
<td>9.8</td>
<td>12.3</td>
<td>19.0</td>
<td>5.5</td>
<td>2.7</td>
<td>2.7</td>
<td>1.2</td>
<td>96.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>2.1</td>
<td>0.05</td>
<td>1.4</td>
<td>1.0</td>
<td>1.1</td>
<td>0.9</td>
<td>0.4</td>
<td>0.3</td>
<td>2.3</td>
<td>Sol 1410–1520</td>
</tr>
<tr>
<td>Red layer (3)</td>
<td>70 points</td>
<td>51.6</td>
<td>9.5</td>
<td>13.9</td>
<td>19.0</td>
<td>5.9</td>
<td>1.8</td>
<td>3.0</td>
<td>0.9</td>
<td>97.0</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>1.6</td>
<td>0.07</td>
<td>1.5</td>
<td>1.5</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Gray layer (2)</td>
<td>12 points</td>
<td>49.8</td>
<td>9.3</td>
<td>11.7</td>
<td>19.1</td>
<td>5.8</td>
<td>1.4</td>
<td>2.8</td>
<td>2.2</td>
<td>93.9</td>
<td>Slightly low sum. One Cl line.</td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>1.4</td>
<td>0.15</td>
<td>1.7</td>
<td>0.9</td>
<td>0.7</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>Bright layer (1)</td>
<td>12 points</td>
<td>39.8</td>
<td>8.6</td>
<td>8.8</td>
<td>12.5</td>
<td>3.0</td>
<td>17.1</td>
<td>1.5</td>
<td>0.4</td>
<td>84.0</td>
<td>Slightly low sum. Local F, Low sum.</td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>5.2</td>
<td>0.30</td>
<td>1.8</td>
<td>2.2</td>
<td>0.6</td>
<td>3.4</td>
<td>0.4</td>
<td>0.3</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>Dark ridges</td>
<td>13 points</td>
<td>47.6</td>
<td>9.4</td>
<td>11.3</td>
<td>19.3</td>
<td>4.8</td>
<td>1.6</td>
<td>2.4</td>
<td>1.8</td>
<td>89.9</td>
<td>Low total. High H line.</td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>2.4</td>
<td>0.19</td>
<td>0.9</td>
<td>0.7</td>
<td>0.7</td>
<td>0.9</td>
<td>0.3</td>
<td>0.5</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Gilley Field Dark Spot</td>
<td>3 points</td>
<td>44.1</td>
<td>8.6</td>
<td>10.4</td>
<td>24.6</td>
<td>4.4</td>
<td>1.2</td>
<td>2.6</td>
<td>0.4</td>
<td>86.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>std. dev.</td>
<td>2.0</td>
<td>0.01</td>
<td>0.7</td>
<td>4.0</td>
<td>0.6</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td>Light vein</td>
<td>1 point</td>
<td>2.5</td>
<td>0.20</td>
<td>0.7</td>
<td>5.6</td>
<td>2.7</td>
<td>31.2</td>
<td>0.5</td>
<td>0.0</td>
<td>43.5</td>
<td>Multiple S lines.</td>
</tr>
</tbody>
</table>

*Note: Targets consist of multiple points. Points on each feature are obtained at various locations and averaged to give a mean chemistry close to bulk chemistry. The quantification is obtained from comparison with laboratory data on Earth. Volatiles difficult to identify with laser ablation techniques (S, Cl, P) are not quantified. Oxide wt% sums are not normalized, such that low totals highlight the presence of volatiles. Standard deviations are calculated from the number of points of each category to display the variability inside each category.*
style of termination is inconsistent with synaeresis cracking or hydraulic fracturing, which in the latter case would also be expected to cross-cut the beddings planes (Hubbert and Willis, 1972; Plummer and Gostin, 1981; Young and Chan, 2017). The 0.5–3.5 cm length scale of the polygons on OS and SC is consistent with a millimeter- to centimeter-thick deformable layer, similar to the observed thickness of the red mudstone bed and analogous to terrestrial experiments (e.g. Shorlin et al., 2000). Variation in polygon size across slabs may be due to changes in basal friction, bed thickness, or impurities. The cracks are parallel-sided (do not taper downward) in profile (Fig. 4), which can occur if the coupling between the descissated and underlying beds is low enough to not affect the fractures (Shorlin et al., 2000).

**Lithification of Ridges**

The ridges likely formed via desiccation of a surficial mud layer and filling by sediment sourced from an overlying bed. Although the ridges and underlying gray bed are compositionally similar, the occurrence of interstratified gray and red beds suggests that a gray mudstone originally covered the cracked red mudstone and acted as a source of fracture fill material. Diagenesis associated with later fluids may account for their current similar compositions. Sulfates and other salts may have formed during desiccation-cracked or hydraulic fracturing, which in the desiccated and underlying beds is low enough to not affect the fractures (Shorlin et al., 2000).

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