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

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ABSTRACT

Marx 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 ancient 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). Suitcases 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 bedded strata 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-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
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 Mast Camera (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. 3B). 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 lowmost bright sandstone with no ridges and a

Table 2, and examples of Alpha-Particle X-Ray Spectrometer (APXS) targets shown in

Figure 2. Mastcam (sol 1555) and Mars Hand Lens Imager (MAHLI) images of Old Soaker (OS) rock slab, Mars. A: A network of raised ridges forms closed polygons on a red bed on OS. White calcium-sulfate (CaSO₄) veins follow many of the ridges. Ridgeless gray beds underlie the red bed. B: Mosaic of nadir MAHLI images of OS. Arrows point to alpha-particle X-ray spectrometer (APXS) targets shown in Table 2, and examples of dark spots. Illumination from upper left. C: Partly shadowed MAHLI image of Thompson Island. White arrow denotes a sub-millimeter-wide fracture in a polygon. D: MAHLI image shows ridges terminating on a gray patch. Illuminated from left. E: MAHLI image shows a CaSO₄ vein cross-cutting a ridge (arrow). Illuminated from upper left. F: MAHLI image of the gray bed (target Fresh Meadow). Illuminated from upper left. G: 3-D view of the red bed showing ridges tapering off into a depression. Left arrow: CaSO₄ vein on side of ridge; middle arrow: typical polygon-forming ridge; right arrow: CaSO₄ vein.

Figure 3. Distribution of the maximum width of polygons (A) and vertex angles (B) formed by ridges on Old Soaker rock slab, Mars.
The gray bed (target “Fresh Meadow”) is distinctive from the overlying red bed, with relatively enriched K\textsubscript{2}O abundance relative to the Murray bedrock, but is two to three times richer in Cl (2–3 wt%) and Br (1150–1430 ppm). The presence of strong H lines on the red layer indicates the presence of a significant component of hydrous phases absent from the red layer. The dark patches (target “Gilley Field”; Table 1) in the red bed are enriched in FeO (up to 27 wt%) and MnO (0.7 wt%) relative to the surrounding rock. The bright veins are similar to \text{CaSO}_4 veins encountered since the beginning of the mission (Table 1) (Nachon et al., 2017).

**DISCUSSION**

Proposed formation mechanisms for the ridges must account for several observations: (1) ridges form polygonal networks with T-junctions and continuous arcuate shapes; (2) the ridges in the red mudstone beds correspond to fractures that penetrate those beds; (3) the fractures are restricted to the red beds and terminate at the boundary with coarser underlying material; (4) the fractures are filled with very fine-grained sediment; (5) \text{CaSO}_4 veins run along many but not all of the ridges, in some cases cross-cut the ridges, and, unlike the ridges, cut all beds in exposed cross sections; and (6) the ridges are compositionally similar to the underlying gray bed. The most likely fracturing mechanisms include desiccation, syneresis, 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; Young and Chan, 2017), and \text{CaSO}_4-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>SiO\textsubscript{2}</th>
<th>TiO\textsubscript{2}</th>
<th>Al\textsubscript{2}O\textsubscript{3}</th>
<th>FeO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na\textsubscript{2}O</th>
<th>K\textsubscript{2}O</th>
<th>Sum of oxides (wt%)</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>
</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>0.9</td>
<td>0.3</td>
<td>2.3</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>
</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>
</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>
</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>
</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>
</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>
</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>
</tr>
<tr>
<td></td>
<td></td>
<td>Slightly low sum. One Cl line.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></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>88.4</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>
</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>
</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 synaere-
sis cracking or hydraulic fracturing, which in the
latter case would also be expected to cross-cut the
bedding planes (Hubbert and Willis, 1972; Plum-
mer and Gostin, 1981; Young and Chan, 2017).
The 0.5–3.5 cm length scale of the polygon 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 fric-
tion, 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 desiccated 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 composi-
tionally 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. Diagen-
esis associated with later fluids may account for
their current similar compositions. Sulfates and
other salts may have formed during desiccation as
evaporites and/or after the fractures lithified.

After deposition, the Murray formation was bur-
ried under up to several kilometers of sediment
that likely provided sufficient overburden pres-
sure to generate hydraulic fractures (Caswell and
Milliken, 2017; Young and Chan, 2017). These
fractures likely propagated along pathways of
reduced strength produced by the desiccation
cracks, and in some cases cross-cut polygons.
These fracture networks then acted as conduits
for fluid precipitation of CaSO₄ cements.

CONCLUSIONS AND IMPLICATIONS
FOR GALE CRATER PALEOLAKES
Recognition of distinct suites of sedimentary
structures is a powerful tool in interpreting Mars
paleoenvironmental history as it has been for
Earth. The Murray formation is interpreted to
record a transition from long-lived (~10⁷–10⁸ yr)
perennial lacustrine conditions observed in the
basal Murray (Grotzinger et al., 2015; Hurowitz
et al., 2017) to episodically exposed conditions
recorded by the desiccation-cracked surfaces in
the Sutton Island member of the Murray. The

<table>
<thead>
<tr>
<th>Target</th>
<th>Na₂O</th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
<th>P₂O₅</th>
<th>SO₃</th>
<th>K₂O</th>
<th>CaO</th>
<th>TiO₂</th>
<th>Cr₂O₃</th>
<th>MnO</th>
<th>FeO</th>
<th>Ni</th>
<th>Zn</th>
<th>Br</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thompson Island</td>
<td>2.62</td>
<td>5.96</td>
<td>0.13</td>
<td>44.80</td>
<td>1.00</td>
<td>6.28</td>
<td>2.38</td>
<td>0.83</td>
<td>3.75</td>
<td>1.01</td>
<td>0.32</td>
<td>0.16</td>
<td>6.86</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>Error (-)</td>
<td>0.14</td>
<td>0.17</td>
<td>0.19</td>
<td>0.54</td>
<td>0.07</td>
<td>0.08</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.26</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>Fresh Meadow</td>
<td>3.22</td>
<td>5.86</td>
<td>0.75</td>
<td>34.04</td>
<td>0.87</td>
<td>13.34</td>
<td>2.51</td>
<td>2.29</td>
<td>3.95</td>
<td>0.75</td>
<td>0.33</td>
<td>0.20</td>
<td>24.83</td>
<td>477</td>
<td></td>
</tr>
<tr>
<td>Error (-)</td>
<td>0.14</td>
<td>0.17</td>
<td>0.19</td>
<td>0.43</td>
<td>0.05</td>
<td>0.15</td>
<td>0.04</td>
<td>0.07</td>
<td>0.04</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.26</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

Note: Alpha-particle X-ray spectrometer (APXS) oxide wt% or ppm concentrations of two representative measurements on Old Soaker. “Thompson Island” was acquired on the red bed (Sol 1566, SH –41.6 °C, FWHM full width at half maximum 146 eV, duration 8:09:16). Fresh Meadow was acquired on the underlying gray bed (Sol 1570, SH –20.7 °C, FWHM 169 eV, duration 1:26:11).