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Polygonal cracks in bedrock on Earth and Mars: Implications for weathering

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Abstract

Polygonal crack systems with domal microrelief imaged by the Mars Exploration Rover (MER) Opportunity show remarkable similarity to terrestrial crack systems developed on outcrop surfaces. Study of Jurassic Navajo Sandstone surfaces show development of crack systems in relatively isotropic host rock as a result of tensile weathering stresses. These terrestrial analogs are utilized to understand potential weathering processes on Mars.

Keywords: Mars, surface; Exobiology; Earth; Geological processes

1. Introduction

Terrestrial analogs are valuable for understanding sedimentary and weathering features imaged by the Mars Exploration Rover (MER) Opportunity. The Jurassic Navajo Sandstone exposed in southern Utah and northern Arizona shares four important characteristics with the Burns formation at Meridiani Planum: (1) presence of eolian cross-bedded sandstone, (2) similar iron oxide concretions related to diagenesis (terrestrial "marbles" and Mars "blueberries"), (3) small (∼0.1 to 1 m scale) polygonal to rectangular cracking of bedrock surfaces and boulders, and (4) small-scale domal relief associated with polygonal crack systems (Fig. 1). Many of the relevant imaged Mars features (e.g., Squyres et al., 2004; Christensen et al., 2004; Grotzinger et al., 2005; McLennan et al., 2005) are comparable to features on Earth. Similarities of hematite concretions in the Burns formation and Navajo Sandstone have been documented in Chan et al. (2004, 2005, 2006) and Ormö et al. (2004), and appear linked to a relatively porous host rock that is broadly homogeneous and isotropic parallel to bedding. Interestingly, small-scale polygonal crack patterns and distinctive surface microrelief of the Burns formation, seen both in outcrop and boulders (including the rock named "Wopmay"; McLennan et al., 2005), are also similar to weathering patterns in the Navajo Sandstone. Although shallow polygonal crack patterns are developed in other terrestrial rocks, such patterns are most common in relatively porous, massive sandstones, found in semi-arid to arid climates where there are large temperature and moisture fluctuations (Williams and Robinson, 1989).

An initial, generalized comparison of Earth–Mars weathering, erosion, and landscape features was presented by Thomas et al. (2005). Weathering features developed in bedrock outcrops and boulders on Mars include flaking along bedding, exfoliation, weathering rinds with local honeycomb patterns, and small-scale rectangular to polygonal ("pachydermal") cracking, interpreted to form by some combination of insolation effects (thermal contraction/expansion), salt weathering, desiccation, surface moisture cycles, and dirt cracking (Oilier, 1965). In addition to small-scale polygonal cracks developed in bedrock (the focus of this paper), larger-scale (∼10 to 100 m) polygons have been observed across some Mars surfaces at middle to high latitudes, and have similar patterns to terrestrial ice-wedge (freeze–thaw) polygons (McGill and Hills, 1992; Yoshikawa, 2003; Mangold, 2005). Giant-scale (km) polygo-

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nal networks have also been described on Earth (James et al., 2006) and Mars (Lane and Christensen, 2000), but their origin(s) remain controversial. Thus, polygonal patterns may form by a variety of processes, each of which creates approximately uniform tension that may exceed the tensile strength of the material.

In this paper, we focus on characteristics of small-scale polygonal and rectangular cracking of bedrock exposures, and implications for processes that generate tensile stresses in the host rock. We compare Navajo Sandstone crack patterns with corresponding features of the Burns formation, noting similarities that are key to interpreting weathering processes on Mars.

1.1. Characteristics of weathering cracks in the Navajo Sandstone

Desert regime weathering of Navajo Sandstone produces distinctive crack systems (Figs. 1A–1C, Fig. 2). Cracks described here form consistently perpendicular to outcrop surfaces and are shallow, with most appearing to propagate <10 to 30 cm downward. This perpendicular relationship is maintained regardless of slope angle and aspect (direction). Sandstone laminations are not offset across cracks, indicating tensile failure, but openings are sufficiently narrow that there is little to no infilling of cracks with foreign material. Such cracks are absent on fresh cliff faces exposed by recent rockfalls. Based on these characteristics, we interpret the cracks to have formed by weathering. These cracks are distinguishable from tectonic joints that cross cut multiple beds and have systematic strikes and near vertical dips, although parts of weathering cracks may coincide with tectonic joints. Weathering cracks are also distinguishable from primary sedimentary structures (e.g., salt polygons, and desiccation/mud cracks) in that they typically cut across strata, rather than forming within a given bed.

The cracks form systems that commonly range from: (1) well-developed polygonal networks in areas with massive sandstone (Figs. 1A and 1B), to (2) rectangular networks with cracks perpendicular and parallel to bedding that form along steeper outcrop faces in well-bedded lithologies (Fig. 1C, at *Checkerboard Mesa* in Zion National Park). Both polygonal and rectangular patterns are examples of weathering that have been called pachydermal (e.g., Thomas et al., 2005), turtleback or tortoise weathering (e.g., Williams and Robinson, 1989), and are generally attributed to expansion and contraction of the rock (e.g., Eves, 2005) or to differential weathering and erosion due to moisture retention along cracks (Netoff, 1971). The main controls of rectangular versus polygonal systems are: (1) host rock characteristics (whether anisotropic or isotropic; Fig. 2) and (2) slope angle relative to bedding.

1.1.1. Polygonal weathering cracks

Polygonal crack systems (Figs. 1A and 1B) typically have 5- and 6-sided forms and develop where sandstone is relatively massive (isotropic), and along some gentle outcrop surfaces subparallel to bedding. Massive sandstone is typically a result of syndepositional soft-sediment deformation or intense bioturbation that destroyed original lamination. Individual polygons have interior angles typically close to 120° (Table 1). In areas where cracking is particularly well developed, small polygons are present within larger polygons. At locality 3 (Fig. 1A, inset), large polygons have sides up to ∼2 m in length, with smaller nested polygons that have sides ∼10 cm in length. Crack depth is typically less than polygon diameter and varies between nested sets. Both large and small polygons differentially weather to form ‘turtlebacks’ with local domal relief of a few to a few tens of centimeters. Polygonal crack patterns locally change into rectangular systems where eolian laminations become better developed, even in areas with the same slope (Figs. 2A and 2B).

Table 1
Comparative measured polygon angles

Polygon angles	Jn-A	Jn-B	Wopmay
Mean	123.6°	126.8°	118.0°
Std. dev.	1.9°	2.3°	2.0°
Min	103°	71°	45°
Max	150°	174°	153°
N	41	116	100

Note. Jn = Jurassic Navajo Sandstone (locality 3 of Fig. 1), where A = small polygons (<1 m diameter) and B = large polygons (>1 m diameter). Mars Wopmay angles (Fig. 1D, uncorrected for distortions) measured from remote images.

1.1.2. Rectangular weathering cracks

Observations of widespread crack patterns in the Navajo Sandstone and other sandstone units (Netoff, 1971) indicate that rectangular systems develop in areas with distinct bedding anisotropy, mostly controlled by variations in grain size, sorting, and clay content. A dominant crack set forms perpendicular to both bedding and weathering surfaces across varying slope aspect and angle (Fig. 1C). Cracks curve in order to maintain orthogonality to cross bedding that systematically changes dip. At locality 1 (Fig. 1, inset), measurements of angles between cracks and eolian laminations from the toe to top of dune sets show consistent orthogonality (average angle $= 87° \pm 5.3°$, $n = 90$). Average crack spacing here is 62 cm, with a relatively small standard deviation of 13.1 cm, indicating an organized network. The high-angle cracks locally terminate against bed-parallel cracks and fine-grained beds that lack visible cracking but are more deeply weathered. Cross bedding typically weathers to a small-scale topographic expression of a ribbed slope, due to differences in the internal eolian lamination structure (grain size or textural differences of wind-ripple versus grain flow laminae; after Hunter, 1977).

1.2. Characteristics of cracks in the Burns formation

Small-scale (∼0.1 m) polygonal to rectangular crack systems are also developed on many outcrops of the Burns formation exposed along rims of Eagle, Endurance, and Erobus craters and in ablated areas, as well as on some exposed boulders (e.g., Wopmay rock; Figs. 1D and 1E). The cracks cross cut multiple beds and remain perpendicular to outcrop surfaces of various orientations along crater rims. These relations indicate that small-scale cracks post-date sandstone deposition