PATTERN AND DISTRIBUTION OF SHRINKAGE FRACTURES AT MERIDIANI PLANUM

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Ubiquitous fractures at Meridiani Planum provide clues to the role of water in the formation and modification of landing site materials. Fractures of at least three kinds occur at the Opportunity landing site: (a) fractures associated with impacts that formed at a wide range of scales; (b) large-scale fractures that exhibit regional alignments; and (c) smaller hierarchical and polygonal fractures formed by shrinkage. Impact fractures (a) are associated with impact craters or collections of dark cobbles of meteoritic origin [1]. The large-scale fractures (b) exhibit alignments over hundreds of meters to kilometers and occur locally as conjugate sets [2] and were therefore likely influenced by regional tectonic stresses. These fractures are also the widest, ranging up to 10-20 cm in width and up to tens of meters long. Fractures formed by shrinkage (c) are ubiquitous at Meridiani Planum and occur in two patterns.

Shrinkage fracture patterns. Fractures several mm to several cm wide are separated by 10 cm to 1 m and usually exhibit a hierarchical pattern: i.e., the order of fracture formation can be established from a hierarchy of T-shaped junctions (i.e., fractures that form the basal stem of a T-shaped junction were formed *later*). This hierarchy is also expressed in the distribution of fracture widths. That later fractures are narrower implies that fracturing occurred in stages that were separated in time: trunks of the fracture pattern are widest and deepest because they formed earliest. As stresses increased with more shrinkage, subsequent generations of fractures were formed in a sequence. Where best preserved, the patterns exhibit five to seven generations or "orders" of shrinkage fractures. The last generation of fractures are < 1 mm wide and up to 3 cm apart, and often occur in a hexagonal ("columnar" or "polygonal") pattern, typical of rapid and simultaneous shrinkage that is not hierarchical. The fractures in both hierarchical and hexagonal patterns exhibit random orientations.

The hierarchical patterns exhibit fractal scaling that is consistent across the broad geographical area visited by the Opportunity rover (> 20 km). Fracture spacing W varies with fracture width d as $W \sim d^{\,n}$ for $n = 0.75$ across 3.5 orders of magnitude in d and 3 orders in W. This relationship is probably determined by a wide range of factors including the rate of shrinkage and mechanical properties of the shrinking stratum. The broad geographical extent and uniformity of this relationship at least suggests that shrinkage occurred under similar conditions across the Meridiani plains. Maximum shrinkage in the upper centimeters can be estimated from orthographically projected images of the Meridiani bedrock in locations where sand has been excavated from between fractures by wind. Assuming isotropic contraction, estimates yield a total shrinkage of between 20-30% at the surface, which exceeds the volume change expected from dehydration of epsomite to anhydrous magnesium sulfate if this comprises 40% [3] of the Meridiani sandstones (< 20% volume change). Preliminary results from numerical spring-block models imply that hierarchical fracturing occurs when the shrinking medium stiffens significantly during shrinkage, akin to the drying of mud rather than cooling or mineral dehydration of solid rock. These observations favor shrinkage via loss of water from interstices rather than solely from dehydration of minerals.

Shrinkage fracture distribution. Shrinkage fractures occur in a variety of settings and, significantly, are absent in others where they might be expected. First, shrinkage fractures are ubiquitous on the flat inter-crater plains where they propagate vertically downward (Fig. 1D). These can be seen in vertical cross-section in the walls of Victoria crater (D ~ 800m) where columns widen with depth in a fashion typical of mud cracks and columnar basalts. Fractures of a given width and spacing propagate downward roughly two to three times their horizontal separation. These vertical cross-sections occur beneath the pre-impact surface (below Victoria's ejecta), implying shrinkage *before* the crater formed (Fig. 1B). Second, shrinkage fractures also formed on the eroded ejecta from Victoria crater (Fig. 1A). These formed *following* the formation of the crater, implying at least one additional shrinkage event after the crater formed and after the ejecta were mostly destroyed by wind-mediated sand abrasion. Shrinkage fractures do not occur on the flanks or walls of smaller, better-preserved craters like Santa Maria (D ~ 100m).

Third, shrinkage fractures occur on rotated blocks and boulders inside Beagle Crater (D ~ 25 m) and Endurance Crater (D ~ 150 m) but not inside Victoria or Santa Maria craters (Fig. 1C). These fractures are often oblique with respect to bedding planes and occur on all faces of some boulders derived from upper rim materials. This implies a shrinkage event that occurred since the formation of Endurance crater. The presence of extensive post-crater shrinkage fractures in Victoria crater, limited post-crater shrinkage fractures in Endurance crater but not Santa Maria and younger craters suggests that shrinkage fracturing can be limited in regional extent and has happened in the recent past. Counting of craters < 250 m in diameter at Meridiani has revealed a young surface age that is of order 10 Ma [4] which Endurance crater post-dates.

Fracture modification. Polygonal tiles separating shrinkage fractures have been modified by aeolian sand abrasion, tending to a produce a domical shape. Beneath the sand, fracture walls are nearly vertical in the upper ~10 cm (i.e., apparent in locations where sand has been excavated by wind). Columns have also rotated and tilted, and some isolated polygonal tiles have been displaced onto the surrounding plains.

Terrestrial analogues. Several proposed terrestrial analogues for the Meridiani shrinkage fractures have been investigated, including polygonal fractures in hydrous sulfate sand dunes [5,6] and via weathering-induced stresses in the Navajo sandstone [7]. We present preliminary results of a study of hierarchical fractures in the Mesquite Planum inter-dune playas of Death Valley National Park, CA, USA. At this locale, lithified playas consisting of quartz sand cemented with calcite desiccated to form hierarchical fractures that in some cases exhibit the Meridiani pattern (e.g., identical fracture width-separation scaling) and similar amounts of contraction to the Meridiani fractures. These have also been modified in similar ways. At Mesquite Flat, shrinkage fractures that formed in different desiccation events exhibit markedly different patterns.

References: [1] Schröder et al. *Geophys*. Res. Lett. 2010. [2] Watters et al. *Icarus* 2011; [3] McLennan et al., *EPSL* 2005; [4] Lane et al., *Geophys Res. Lett.* 2003; [5] Chavdarian & Sumner, *Sedimentology* 2011; [6] Chavdarian & Sumner, *Geology* 2006; [7] Chan et al., *Icarus* 2008;

Fig. 1: (A) Hierarchical fracturing in ejecta blocks on the rim of Victoria crater (sol 1176; arrows span ~30 cm); (B) vertical cross-section through probable shrinkage fractures in the heavily-eroded walls of Victoria crater (sol 1603; arrows span ~ 40 cm); (C) Boulder inside Endurance crater with shrinkage fractures covering surface (sol 250; arrows span 80 cm); (D) Typical shrinkage fractures on inter-crater plains (sol 1709; arrows span ~ 20 cm)