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Slope activity in Gale crater, Mars

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ABSTRACT

High-resolution repeat imaging of Aeolis Mons, the central mound in Gale crater, reveals active slope processes within tens of kilometers of the Curiosity rover. At one location near the base of northeastern Aeolis Mons, dozens of transient narrow lineae were observed, resembling features (Recurring Slope Lineae) that are potentially due to liquid water. However, the lineae faded and have not recurred in subsequent Mars years. Other small-scale slope activity is common, but has different spatial and temporal characteristics. We have not identified confirmed RSL, which Rummel et al. (Rummel, J.D. et al. [2014]. Astrobiology 14, 887–968) recommended be treated as potential special regions for planetary protection. Repeat images acquired as Curiosity approaches the base of Aeolis Mons could detect changes due to active slope processes, which could enable the rover to examine recently exposed material.

1. Introduction

The Mars Science Laboratory (MSL) rover Curiosity landed in Gale crater (5°S, 138°E), on August 5, 2012. The most prominent feature of the landing site, and the reason it was selected as the MSL target, is Aeolis Mons (informally called "Mt. Sharp"), a 4 km-high accumulation of layered sedimentary rocks showing spectral signatures of minerals indicating aqueous alteration, including both phyllosilicates and sulfates (e.g., Milliken et al., 2010; Anderson and Bell, 2010). The rover landed on flat terrain away from the mound and at the time of writing has arrived at the base. Unlike previous landing sites, the mound has high relief and many local steep slopes. Combined with recent observations of ongoing mass wasting on Mars, this topography offers the possibility of active slopes in the vicinity of the rover.

Current slope processes on Aeolis Mons would be of importance for several reasons. Mass wasting events could uncover fresh material with a known exposure time and allow it to be inspected by the rover, and might enable tests of the cosmic-ray exposure age estimates of Farley et al. (2014). In situ observations of recent mass movements would also shed light on a key active landscape evolution process on Mars. Most importantly, some types of mass movement could be due to present-day near-surface liquid water. In this case, observations from MSL would be invaluable to understanding the setting of a possible extant habitable environment, but rover operations would need to consider planetary protection issues (e.g., Rummel et al., 2014). Although slope streaks and current gully activity elsewhere on Mars have been suggested to be due to water (e.g., Ferguson and Lucchitta, 1984; Malin et al., 2006), the best candidates for present-day liquid flow are considered (e.g., Rummel et al., 2014) to be Recurring Slope Lineae (RSL; McEwen et al., 2011, 2014). RSL are dark flows that incrementally grow over a period of weeks to months, fade when inactive, and recur annually. They are found on warm (>250 K; >273 K in some regions, Stillman et al., 2014), low-albedo, steep (>25°), rocky slopes, and fade when inactive, especially during cold seasons. RSL were initially discovered in the southern mid-latitudes (McEwen et al., 2011), but have subsequently been found in equatorial sites and the northern mid-latitudes (McEwen et al., 2014). The sources for liquid water in RSL are not known, and a dry origin cannot be ruled out. The seasonality strongly suggests a role for a volatile component. However, the temporal occurrence is inconsistent with CO_2 frost, which is thought to cause other forms of seasonal slope activity (e.g., Dundas et al., 2012). The other likely volatile is water. If liquid water is involved, it is likely to include dissolved salts, although there is not spectral evidence for evaporites associated with RSL slopes. MSL has potentially found perchlorates at Gale crater (Glavin et al., 2013; Leshin et al., 2013; Archer et al., 2014). These salts are associated with substantial freezing point depression, and laboratory work has shown that eutectic brines of calcium perchlorate could be stable at some times of day even in equatorial locations (e.g., Gough et al., 2011; Nuding et al., 2014). Meteorological data from the Curiosity rover indicate that conditions permitting transiently stable brines do occur in Gale crater (Martín-Torres et al., 2015). Here we report on the results of a search for RSL and other active slope processes within Gale crater.

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2. Methods

RSL are typically no more than a few meters wide and thus are difficult to detect by orbital experiments other than the High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007), which has a pixel scale as small as 25 cm. A large volume of HiRISE data was gathered over Gale crater during efforts to characterize the site and certify the landing ellipse. Because layered outcrops are widespread, areal coverage was prioritized and much of the data are single observations or stereo pairs with a small time separation. However, there is also some longer-baseline repeat coverage where such images overlap. Some images have been specifically acquired for change detection, particularly since the discovery of active dunes near the landing ellipse (Silvestro et al., 2013), and the MSL landing and roving site has been heavily imaged.

The criteria defined by McEwen et al. (2014) for "confirmed" RSL are incremental growth of $\geqslant 10$ flows on a slope followed by complete fading and recurrence in a subsequent Mars year. "Partially confirmed" sites have $\geqslant 10$ flows plus either incremental growth or inter-annual recurrence, but not both. "Candidates" are locations with $\geqslant 10$ dark lineations resembling RSL but no available indication of activity. Classification of sites is dependent on the number and temporal distribution of HiRISE observations; a minimum of three HiRISE observations spread over two Mars years is required to fully confirm a site, and many of our sites lack extensive image series. The requirement for $\geqslant 10$ lineae is arbitrary and perhaps should be dropped, since the same (unknown) physical processes could potentially give rise to single flows. For completeness, we inspected sites with <10 possible lineae and/or short time baselines in this paper. We considered changes in any season to be of possible interest. Gale crater is at a latitude similar to Valles Marineris, where RSL on north-facing slopes are generally (but not always) active in northern spring and summer and those on south-facing slopes in southern spring and summer (McEwen et al., 2014).

To determine whether there are potential RSL in Gale crater, we searched steep slopes in all HiRISE images of the central mound acquired during the first two Mars years of Mars Reconnaissance Orbiter (MRO) observations (mid-MY28 through mid-MY30). These data cover a substantial fraction of the mound and were acquired over a range of seasons. In the vicinity of the MSL landing and operations zone, we examined images from subsequent years as well. A full list of images examined is given in the Supplementary Material. We identified locations with dark lineae resembling RSL. (In this paper, "lineae" refers to any distinct striation oriented approximately down-slope, and does not necessarily imply RSL. We excluded dark parallel features that appeared consistent with eolian ripples.) Fifty-eight lineae sites from the lower mound (Fig. 1) were investigated further, focusing on locations near the MSL operating area. (The sites in Fig. 1b represent a comprehensive survey of lineae in the MSL region, including some faint, poorly defined candidates, while in more distant areas we selected the most promising sites distributed across the mound.) This approach does bias our results towards locations where dark striations form, but such striations were by far the most common distinct slope features. We compiled the full set of HiRISE images of each location and blink-compared the images to look for changes. The "upper mound" and "light-toned yardang" units of Anderson and Bell (2010) were not examined in detail; both are high-albedo materials, and RSL show a strong preference for low-albedo settings (McEwen et al., 2014). We initially used HiRISE red-channel Reduced Data Record (RDR) images for these comparisons; RDRs are map-projected but orthorectified only at large scales based on a smoothed Mars Orbiter Laser Altimeter (MOLA) dataset. Although high-resolution orthorectification substantially improves the registration of images acquired from different viewing angles, it requires a HiRISE Digital Terrain Model (DTM) and pixel resampling via bilinear interpolation that can blur small features (Supplementary Animation 1). The transformation from the camera geometry to a map-projected RDR uses cubic convolution and appears to have less effect (in some cases) on the recognition of small features. The advantage of using RDRs rather than images in the raw camera geometry is that the former are projected with a uniform pixel scale. Non-orthorectified images can only be locally and approximately registered unless the spacecraft viewing angles are very similar, but differences such as lineae growth can be identified as changes that appear incongruent with the shifts of adjacent fixed features in a blink-comparison. Subtle changes like pixel-scale extension may be missed by this method.

We note that apparent small changes between HiRISE images should be regarded with caution. For features which are barely visible, it is difficult to be certain that an apparent difference (such as appearance or growth of a narrow linea) is a real surface change rather than a consequence of some favorable combination of atmospheric opacity and lighting and viewing angles. Because of the potential relevance to Curiosity and the possibility of obtaining higher-resolution ground-truth observations for comparison, we have included such marginal change candidates here. As a result, some of the candidate changes that we describe below are less certain than results from other change-detection studies. The Supplementary Tables note which features are diffuse or poorly defined, characteristics that are not typical of RSL.

3. Results

The most RSL-like features seen in Gale crater were found in the eastern part of the mound in images from MY29 (using the Mars calendar of Clancy et al. (2000); MSL landed at $L_S = 151°$ of MY31), approximately 50 km from the Curiosity landing site. At the most promising location (site 7 in Fig. 1), several dozen small (tens of meters long), dark lineae are visible in both images of a stereo pair, acquired at $L_S = 72°$ and 89° (Fig. 2, Supplementary Animation 2). Most of the lineae showed no change between images, but there are examples of possible new flows or incremental growth. These observations alone would ordinarily place the features in the category of "partially confirmed" RSL (incremental growth or recurrence detected, but not both), although only by a slim margin since incremental growth is at the limit of resolution. Follow-on observations in the same season of MY31–32 have not revealed any unambiguous visible lineae. Failure to recur reduces the likelihood that these are RSL, although there are interannual variations in RSL activity at some locations (Ojha et al., 2014). Regardless of the origin, it is probable that they indicate some form of recent slope activity. Several other sites on the eastern part of the mound behaved similarly, but with only small numbers of lineae.

At most of the localities identified far from MSL, either no changes to lineae have been observed, or the lineae disappeared or faded over time. It is possible that the early part of the MRO mission (MY28–29, the time of acquisition of the images used to identify most of the sites) was particularly favorable for linea formation or detection in Gale crater and elsewhere on Mars (McEwen et al., 2011, 2014; Stillman et al., 2014). There was a planet-encircling dust storm just before southern summer solstice of MY28, and several locations elsewhere on Mars showed apparent RSL only in this year (extending into early MY29). This increased apparent activity may be because (1) a fresh coating of bright dust made activity easier to detect for a considerable time after the storm, and/or (2) the atmospheric dust changed environmental conditions so that they were more favorable for RSL (or other) activity. It is also possible that new lineae have later formed at other locations, not