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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 ⩾10 flows on a slope followed by complete fading and recurrence in a subsequent Mars year. "Partially confirmed" sites have ⩾10 flows plus either incremental growth or inter-annual recurrence, but not both. "Candidates" are locations with ⩾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 ⩾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

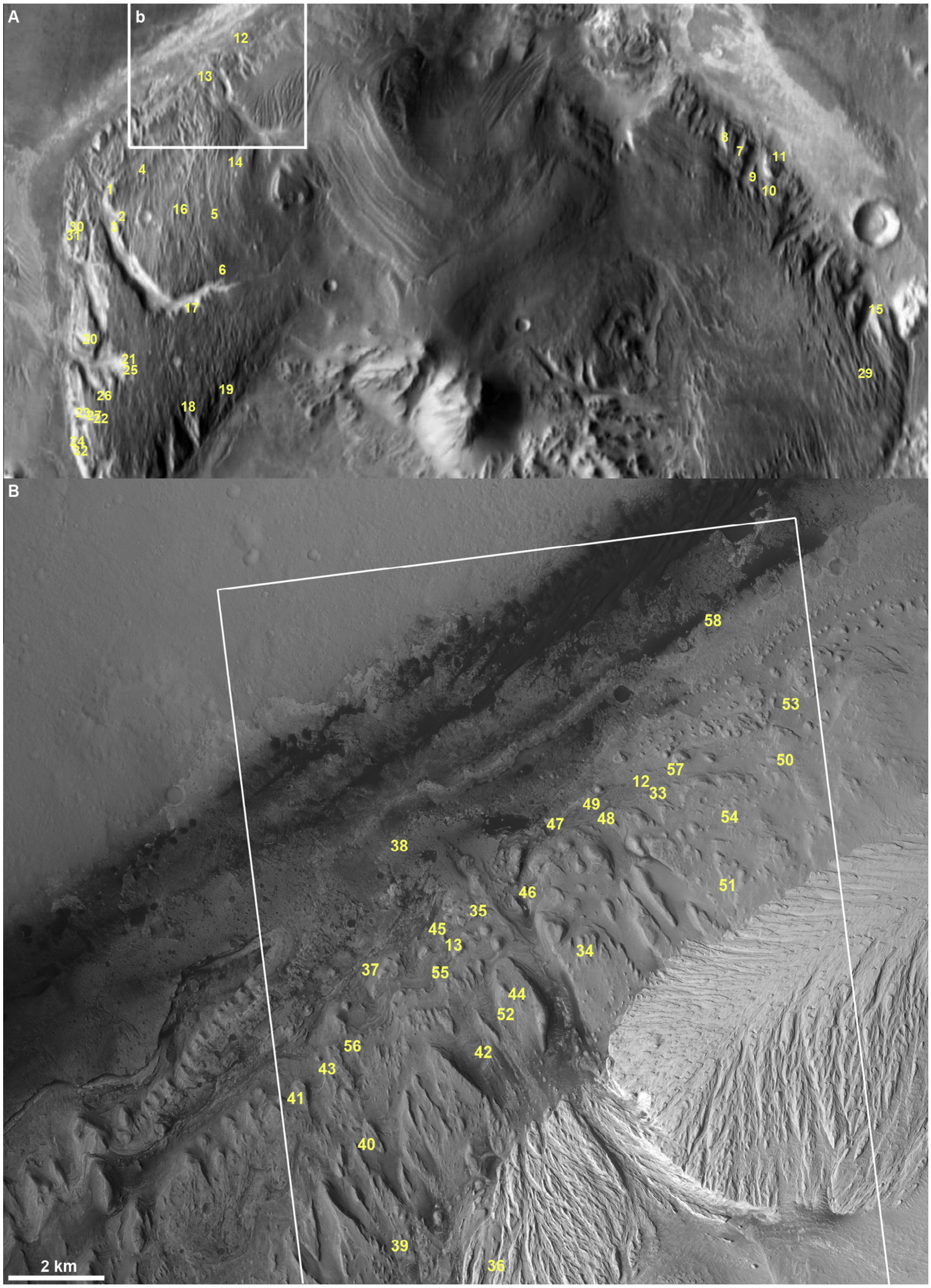

Fig. 1. Map of lineae locations examined in this study. Aeolis Mons ("Mt. Sharp") is the broad hill spanning the image, and rises ~4 km from base to summit. (A) Locations selected from images from the first two Mars years of MRO operations. White box indicates the location of (B). (Background: THEMIS Day IR mosaic, credit NASA/JPL/ASU.) (B) Additional locations from exhaustive survey of the region of likely MSL operations. White box indicates region of comprehensive search. Locations 12 and 13 are shown in both panels, but others are omitted in (A) for readability. Location numbers are arbitrary. (Background: CTX image P06_003453_1752_XI_04S222W, credit NASA/JPL/Malin Space Science Systems.) The figure gives approximate positions; Supplementary Material gives details of the locations of each site. North is up and illumination is from the left in all figures and animations.

captured by our survey of the first two Mars years; the fading of many observed lineae suggests that slope activity of some form is common, but the typical lifetime could be several years. Several small-scale changes have been observed at the existing sites. For example, several lineae may have extended at site 31 on the western edge of Aeolis Mons, although the lineae were initially not well-defined, making growth hard to quantify. Another location near the base of the upper mound unit (site 36) shows incremental changes in some lineae, while others are unchanged. This is not uncommon at RSL sites, but since the time separation is two Mars years, this behavior is not necessarily like the seasonal advance and fading of RSL. Some lineae appear to

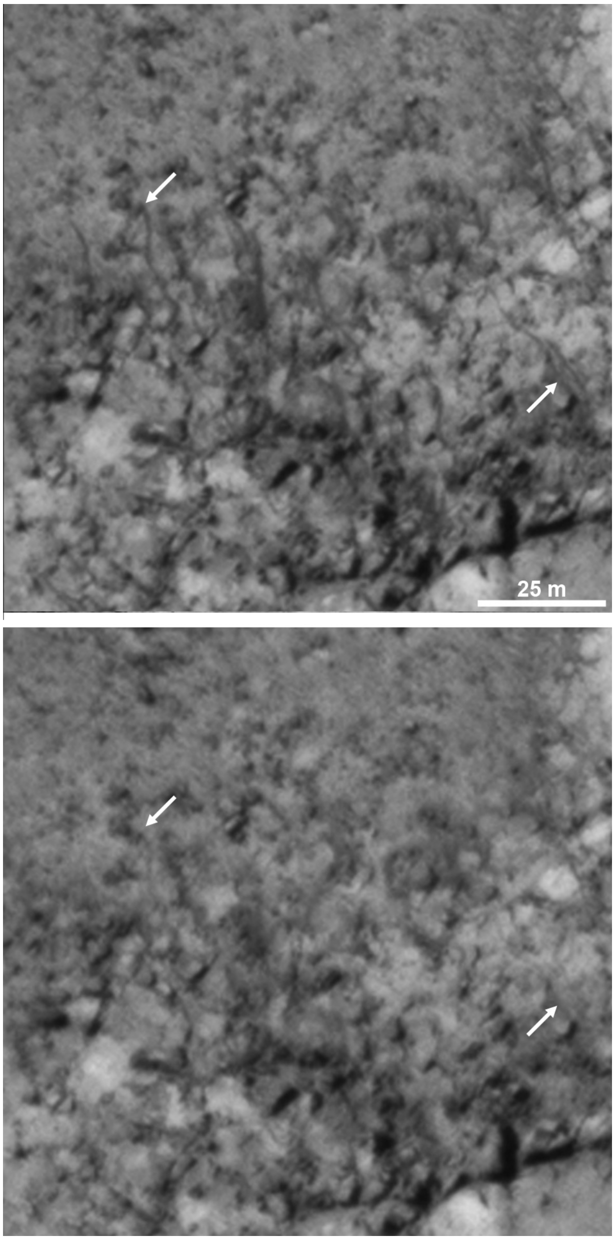

Fig. 2. Changes in lineae seen at site 7. Top panel shows many lineae present in HiRISE image PSP_008437_1750 ($L_S = 72°$, MY29). Arrows indicate examples. The lineae are absent in the bottom panel (ESP_026291_1750, $L_S = 79°$, MY31). Supplementary Animation 2 shows a comparison of the same location. Images have been stretched to enhance contrast; original images are available via the Planetary Data System. All HiRISE images credit NASA/JPL/University of Arizona.

partially fade and re-darken without any indication of growth, but such changes are difficult to separate from the effects of variable atmospheric opacity and changing lighting conditions and we do not regard diffuse changes in relative contrast as evidence for surface change. In other cases (e.g., site 18), distinct lineae were unchanged or subtly faded over a period of more than two Mars years, a behavior very unlike that of RSL.

Over twenty locations with lineae were identified within a few km of the likely Curiosity working area (Fig. 1b). (We emphasize that "lineae" does not necessarily imply RSL, and for completeness our analysis of this area includes poorly defined features with limited resemblance to RSL.) Two of these exhibit possible extension of very small, narrow lineae, consistent with advance of existing flows (Supplementary Animations 3–4). However, the lineae in question are at the limit of HiRISE resolution, so we are not confident that we have seen true incremental growth. Furthermore, the possible examples have so far shown only one incremental advance, which could simply reflect overprinting of an older flow. Some of the lineae in question also persist or partially persist from year to year, unlike most RSL. This behavior most resembles certain features in Aram Chaos noted by McEwen et al. (2014), which have not been characterized sufficiently to constitute a well-defined class. (They were considered "partially confirmed" in that paper, but subsequent images showed inter-annual persistence, which is not typical of RSL (Rummel et al., 2014).) Multiple other likely mass movements are seen in the area (Fig. 3, Supplementary Animations 5–8). Several of these are sufficiently well-resolved for us to be confident that they indicate slope activity, but they appear to be one-off or episodic events. Apparent fading of lineae is also seen, but many persist from year to year. Most events have poorly constrained timing, so there is no clear evidence for seasonality.

Like RSL, the lineae described in this paper have a marked tendency to face west. However, in both cases there is a strong possibility that this reflects an observational bias common to all HiRISE images (McEwen et al., 2011). The local time beneath the MRO orbit is always near 3 PM on the day side, and west-facing slopes are always better-illuminated in the afternoon, making it easier to see small albedo features and distinguish them from topographic shading.

Our observations include uncertain examples of possible changes—this is a predictable result of attempting to provide a comprehensive summary of activity. Image-by-image observations for each site are summarized in the Supplementary Material, including notations about ambiguous candidates. Such cases are worthwhile targets for further investigation but definitive answers may not be possible with HiRISE data alone, and we caution that it is *expected* that some fraction do not represent real surface change.

4. Discussion

Evidence for active processes on the slopes of Aeolis Mons appears definitive at several sites. Aspects of this activity resemble RSL in some instances, but no location has so far exhibited the full set of characteristics of confirmed RSL, and most have some trait that is at least partially inconsistent with such a classification. Accordingly, it is likely that multi-meter-scale slope changes occur frequently, but at present there is no compelling evidence that RSL occur in Gale crater. However, some sites warrant additional monitoring. The location shown in Fig. 2 had features that strongly resembled RSL and could be an intermittently active site, with favorable conditions in MY28–29. Other locations also had RSL-like lineae that subsequently faded, and several do not have image coverage sufficient to fully test the RSL hypothesis.

If not RSL, what is the nature of the slope activity? The overall pattern of behavior for many events is most like that of slope streaks (single events leaving markings that remain visible for years (e.g., Bergonio et al., 2013)), although at particularly small scale. However, slope streaks are likely to be dry granular avalanches (e.g., Sullivan et al., 2001) and are associated with thick, steep dust deposits (e.g., Schorghofer et al., 2002), which are not seen near the base of Aeolis Mons. Several of the changes involve dark material, likely sand, which appears to be banked against local steep slopes. The most likely explanation for this sort of event is slumping of sand, perhaps erased by eolian processes. This is consistent with observations of sand movement nearby (Silvestro et al., 2013), but it is then puzzling why some lineae persist unchanged for multiple years. One possibility is that steep rocky slopes add a coarser-grained component that is not as easily

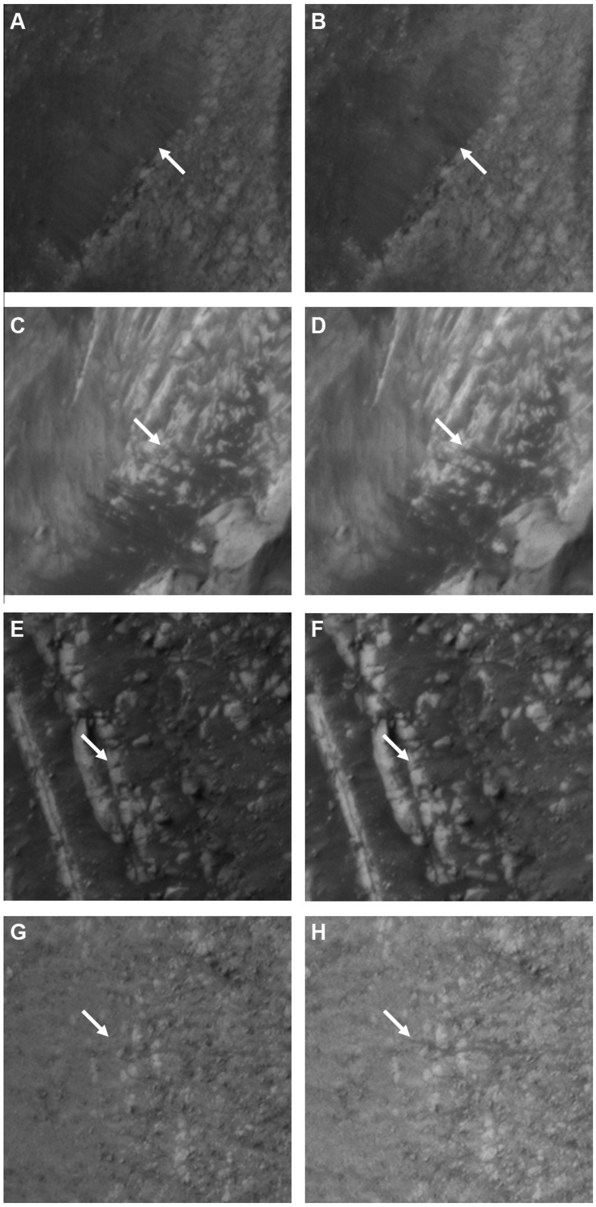

Fig. 3. Likely changes seen in the vicinity of the MSL operations region. (A and B) Site 33, HiRISE images PSP_009294_1750 and ESP_025935_1750. (C and D) Site 36, HiRISE images PSP_009294_1750 and ESP_026924_1750. (E and F) Site 46, HiRISE images PSP_009149_1750 and ESP_027834_1755. (G and H) Site 56, HiRISE images ESP_026924_1750 and ESP_033649_1750. Arrows indicate locations of inferred changes. Images used for this figure were selected for similar geometry and lighting and do not necessarily indicate the tightest constraints on timing of activity. Animations of these comparisons are available in the Supplementary Material, and show the subtle changes better than side-by-side images. Images have been stretched to enhance contrast; original images are available via the Planetary Data System.

modified by the wind. Slope streaks are generally not thought to grow incrementally, but the evidence for incremental growth is ambiguous and, if real, could simply reflect overprinting by successive events rather than true incremental advance. The episodic formation style also resembles the formation of boulder tracks and some lineae could be due to small (unresolved) rocks falling or rolling down slopes. Locations with large numbers of fresh lineae (e.g., site 7) are unlike simple slope streaks or rockfalls but could have been triggered by weather events like high winds or dust storms. Although these hypotheses appear consistent with many observed changes, there could be multiple mass movement processes active in Gale crater, and the observed lineae are diverse.

Many of the possible changes we see are near the limit of HiRISE resolution, and it will always be difficult to separate true small changes from the effects of differences in lighting and atmospheric conditions. Curiosity should be able to provide observations to better understand the nature of current slope activity. At present, there is no indication of topographic changes in Gale crater resolvable at HiRISE scale nor of any effects extending beyond the base of steep slopes, so the hazard from falling material appears to be very small, unless the rover itself triggers larger mass movements. The MSL Mastcam and the Chemcam Remote Micro-Imager can provide resolution superior to HiRISE at distances of 3.6 and 14 km, respectively (Bridges et al., 2014). Accordingly, systematic observation of steep slopes from moderate distances has the potential to produce new insights into the nature of slope activity in Gale crater. Moreover, while there is currently no strong evidence for RSL in the vicinity of the MSL operating area, continued monitoring will more thoroughly test this possibility. We note that although RSL are considered potential Special Regions (Rummel et al., 2014) and the origin is unknown, there is no evidence that liquid water ever reaches beyond the local steep slopes.

A lack of RSL in Gale crater would provide little information on their nature, because the controls on their formation are not well-understood—many seemingly suitable sites lack RSL (Ojha et al., 2014). If any of the activity that we have observed is eventually confirmed as RSL-like, data from Curiosity would provide valuable clues to the origin of RSL. Presuming that they are indeed caused by water, the source of the liquid remains unknown. Although Aeolis Mons is an isolated topographic high, it is predicted to be a location of groundwater upwelling (Andrews-Hanna et al., 2012) and a subsurface origin for RSL could be considered. Compositional data, meteorological data and observations of any ephemeral frost at an RSL location would be valuable for testing models of atmospheric recharge. Regardless of the nature of current activity, comparison of the barely-resolved features in HiRISE with better detail from Curiosity would improve interpretations of mass movements elsewhere on Mars and shed light on the processes driving current activity in Gale crater.

The observation of currently active slope processes on Aeolis Mons also has some significance for interpretations of the current geomorphology. The activity that we have seen to date involves loose material rather than bedrock, but evolution of the cover layer must ultimately affect the landscape. An assessment of this interaction would be essential to interpreting cosmic-ray exposure ages of slope materials (Farley et al., 2014). Moreover, while we have been unable to observe any volumetric changes with HiRISE, co-analysis of HiRISE results and in situ MSL measurements (in combination with an understanding of the role of mantling deposits) might enable measurement of the rate of current slope evolution, placing a valuable constraint on the Amazonian history of Aeolis Mons.

5. Conclusions

Present-day activity is observed on local steep slopes near the base of Aeolis Mons in Gale crater. Some of the observed slope features have characteristics similar to Recurring Slope Lineae, but none is confirmed to be RSL and most have some characteristics suggesting other origins. Continued monitoring of sites with some RSL-like properties would provide more insight. The frequency of activity suggests that it should be considered in analyzing cosmic-ray exposure ages and interpreting the Amazonian geomorphology of the site.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.icarus.2015.04.002.

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