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December 14, 2020

Abstract

Following the planet-encircling dust event (PEDE) of Mars Year (MY) 34, MRO/HiRISE has seen many more candidate RSL than in typical Mars years. They were imaged at more than 285 unique locations from August 2018 to August 2019, 157 where RSL had not been seen previously. Of the locations where RSL had been observed in the same season of prior Mars years, 34 sites had more extensive RSL coverage than MY29-33; none had less extensive RSL. 150 active RSL sites were identified in the southern middle latitudes (SMLs) versus the 36/year average during MY28-33. RSL are present on ˜87% of the HiRISE images covering steep, rocky slopes in the SML in southern summer of MY34, rather than ˜40% as in prior years. Post-PEDE RSL are also present over a wider combined range of latitude, slope aspect, and season than in prior years. These RSL sites usually show evidence for recent dust deposition. There are clear dust devil tracks in 54% of post-PEDE images with RSL, and in 73% of such images in the SMLs and L=236°-360° (late southern spring to the end of summer), where and when dust devils are most active. The tracks indicate dust lifting, by several mechanisms. We suggest that dust lifting processes on steep slopes may initiate and sustain RSL formed from flows of dust (perhaps clumped) and/or sand that is destabilized by dust movement. The otherwise puzzling recurrence and year-to-year variability of RSL activity can be at least partly explained by variable yearly dust fallout.

Mars: Abundant Recurring Slope Lineae (RSL) Following the Planet-Encircling Dust Event (PEDE) of 2018

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Key Points:

• The origin of recurring slope lineae on present-day Mars has been controversial, including hypotheses with seeping water or dry granular flows.

• Recurring slope lineae were substantially more abundant following the Mars year 34 planet-encircling dust event in 2018, providing new constraints on their origin.

• Dust lifting processes present multiple possible mechanisms that can trigger downslope movement of dust, with or without sand.

Abstract

Following the planet-encircling dust event (PEDE) of Mars Year (MY) 34, MRO/HiRISE has seen many more candidate RSL than in typical Mars years. They were imaged at more than 285 unique locations from August 2018 to August 2019, 157 where RSL had not been seen previously. Of the locations where RSL had been observed in the same season of prior Mars years, 34 sites had more extensive RSL coverage than MY29-33; none had less extensive RSL. 150 active RSL sites were identified in the southern middle latitudes (SMLs) versus the 36/year average during MY28-33. RSL are present on ~87% of the HiRISE images covering steep, rocky slopes in the SML in southern summer of MY34, rather than ~40% as in prior years. Post-PEDE RSL are also present over a wider combined range of latitude, slope aspect, and season than in prior years. These RSL sites usually show evidence for recent dust deposition. There are clear dust devil tracks in 54% of post-PEDE images with RSL, and in 73% of such images in the SMLs and L_s=236°-360° (late southern spring to the end of summer), where and when dust devils are most active. The tracks indicate dust lifting, by several mechanisms. We suggest that dust lifting processes on steep slopes may initiate and sustain RSL formed from flows of dust (perhaps clumped) and/or sand that is destabilized by dust movement. The otherwise puzzling recurrence and year-to-year variability of RSL activity can be at least partly explained by variable yearly dust fallout.

Plain Language Summary

RSL are puzzling active slope features on Mars that resemble seeping water. Following the great dust storm of 2018, many more candidate RSL were seen than in typical years. These RSL sites usually show evidence for recent dust deposition. There are clear dust devil tracks in 73% of post-PEDE images in the southern middle latitudes in the summer, where and when dust devils are most active. The tracks indicate dust lifting, by several mechanisms. We suggest that dust lifting processes on steep slopes may initiate and sustain RSL formed from flows of dust (perhaps clumped) and/or sand that is destabilized by dust movement. The otherwise puzzling recurrence and year-to-year variability of RSL activity can be explained by variable yearly dust fallout.

1 Introduction:

Recurring Slope Lineae (RSL) are relatively dark linear markings on steep slopes with low albedos (indicating relatively little coverage by bright dust), typically originating at bedrock outcrops (McEwen et al., 2011; 2014). Individual lineae are up to a few meters wide and up to 1.5 km long. RSL recur in multiple Mars years (by definition) over the same slopes and often the exact same locations, but not necessarily every year. The lineae grow incrementally or gradually over a period of several months, usually during the warmest time of year for the particular latitude and slope aspect, then fade (and typically disappear) when inactive. This pattern repeats over multiple years, with varying degrees of interannual variability. They are often associated with pristine small gullies or channels that are otherwise rare on equatorial slopes. Hundreds of individual lineae may be present over a local slope, and thousands in single images captured by the High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007) on Mars Reconnaissance Orbiter (MRO). There were at least 748 confirmed, partially-confirmed, or candidate RSL sites prior to MY34 (Stillman, 2018). A confirmed site (each HiRISE image sequence is considered a site) is one where repeat images show incremental growth and fading, repeated over multiple Mars years. A candidate site has similar-looking features in the same settings and seasons as typical RSL, but there is not sufficient repeat image coverage to document growth, fading, and recurrence. A partially-confirmed site has repeat coverage showing either incremental growth or recurrence, but not both.

RSL are common in (1) the southern middle latitudes (SML; -60° to -30° latitude) where they are most active in southern summer on generally equator-facing (including east- and west-facing) slopes; (2) the equatorial regions where activity is usually timed to when the local slope receives the most insolation; and (3) Acidalia/Chryse Planitia and other northern middle latitudes with activity in northern spring and summer (McEwen et al., 2011; 2014; Stillman et al., 2014, 2016, 2017; Stillman and Grimm, 2018; Stillman, 2018).

Although multiple hypotheses to explain RSL were considered in most publications, many have favored wet models (e.g., McEwen et al., 2011; 2014; Chevrier and Rivera-Valentin, 2012; Levy, 2012; Ojha et al., 2013; 2014; 2015; Grimm et al., 2014; Stillman et al., 2014; 2016; 2017; Stillman and Grimm, 2018; Stillman, 2018; Wang et al., 2019; Huber et al., 2020). The darkening and gradual growth resembles seeping water, and the fading could be explained by drying. RSL appearance and temporal behavior is similar to that of water tracks in Antarctica (Levy, 2012; Dickson et al., 2013). RSL strongly favor the warmest times and places (although there are exceptions), suggesting but not requiring activity of a volatile. The surface temperatures corresponding to RSL activity are above the freezing points for salty solutions, which can be as low as nearly 200 K (e.g., Hecht et al., 2009; Zorzano et al., 2009; Möhlmann and Thomsen, 2011; Martínez and Renno, 2013). However, explaining the source of sufficient water for seepage is extremely difficult in the present-day Martian environment (Ingersoll, 1970; Haberle et al., 2001; Mellon and Phillips, 2001; Hecht ,2002; Dundas et al., 2017). Evidence for water playing some role in RSL from detection of rare hydrated salts (Ojha et al., 2015) now appears to be a data-processing artifact (Leask et al., 2018; Vincendon et al., 2019). Deep groundwater may persist in Mars, but surface discharge (a spring) requires that the subsurface is unable to transmit water as fast as it is supplied so that the potentiometric surface intersects the land surface. Geological structures and topographic features can thus bring water to the surface (Bryan, 1919), and springs have very specific locations. However, RSL are found over a wide range of elevations and settings, including the tops of isolated peaks and ridges (Chojnacki et al., 2016), not consistent with natural groundwater discharge. Selected locations may be plausible for deep groundwater discharge (Watkins et al., 2014; Abotalib and Heggy, 2019), but this cannot provide a general explanation for RSL. Highly deliquescent salts are known to exist on Mars and may temporarily trap atmospheric water in extremely small quantities, perhaps sufficient to darken the surface (Heinz et al., 2016), but not sufficient for seepage down slopes (Gough et al., 2019a; 2019b). Some workers have speculated that small quantities of water could trigger granular flows (Dundas et al., 2017; McEwen, 2018; Wang et al., 2019). Water would easily boil on most of the Martian surface if present (Haberle et al., 2001) and relatively small quantities of boiling water may trigger granular flows (Massé et al., 2016; Herny et al., 2019), but even these quantities are far more than can be supplied by the Martian atmosphere with a typical water column abundance of 10 precipitable microns (Smith et al., 2008; Leung, 2020). Surface frost (CO_2 and H_2O) forms in only some RSL source regions and will sublimate before RSL typically become active (Schorghofer et al., 2019). Other hypotheses are that mass wasting may occur when damp surface materials dehydrate (Schorghofer et al., 2002; Shoji et al., 2020) or when subsurface brines cause uplift or collapse (Bishop et al., 2019).

Recent papers have favored dry RSL models. Edwards and Piqueux (2016) found that the thermal signature of RSL-bearing slopes at Garni crater was consistent with < 3% water, although Stillman et al. (2017) pointed out that none of the thermal observations were synchronous with observation of sufficient coverage by lineae to enable thermal detection. Schmidt et al. (2017) suggested that RSL could operate via granular flows driven by a Knudsen-pump gas-flow mechanism enhanced by distinct shadowing. However, their model is not consistent with the timing of RSL occurrence on some slopes (Stillman and Grimm, 2018) and some RSL sites lack obvious sources for sharp shadows even with clear atmospheric conditions (Vincendon et al., 2019). Also, we document below that RSL appear to be active during times of high atmospheric opacity when shadows have muted contrast. Dundas et al. (2017) found that RSL terminate on slopes matching the dynamic angle of repose for dry sand, although Stillman et al. (2020) report that some RSL in Garni crater start, stop, and have mean slope angles that are below the expected angle of repose for sand. Stillman et al. (2020) nevertheless concluded that the slopes were consistent with granular flows within errors, and Munaretto et al. (2020) reached the same conclusion about RSL in Hale crater. Schaefer et al. (2019) reported evidence, including relative albedo analysis, that RSL in Tivat crater fade similarly to boulder and dust devil tracks and suggested that this was due to dust removal from the larger region, and proposed that RSL are dry features that mobilize dust. Vincendon et al. (2019) also proposed that RSL are due to dust removal based on relationships between RSL and aeolian activity. Dundas (2020) proposed that RSL are grain flows where sand is seasonally replenished by the uphill migration of ripples, most of which are smaller than the 25-30 cm/pixel scale of HiRISE.

RSL sites have been classified as "unknown" special regions for planetary protection, thus they are treated like special regions where terrestrial microbes might flourish (Rummel et al., 2014; Kminek et al., 2017). The presence of RSL has been used to rule out candidate landing sites for NASA's Mars 2020 (Perseverance) rover (Grant et al., 2018). If RSL are dry or only transiently wet at very cold temperatures, then this restriction on future Mars exploration could be lifted (McEwen, 2018; Rivera-Valentin et al., 2020). However, other work suggests that putative deliquescent RSL sites could be habitable (Maus et al., 2020).

In this paper we describe preliminary results from the RSL observation campaign by HiRISE following the MY34 PEDE in 2018, and discuss implications for RSL formation. “Global” dust storms on Mars occur episodically every few Mars years, and each has a unique history. The MY34 storm began at L_s ~186° (June 2, 2018), very early southern spring on Mars, reaching a visible optical depth (τ) of ~5.7 in the Meridiani region on June 8 (L_s=189.8°) (Kass et al., 2019; Kleinbohl et al., 2020). The storm became planet-encircling by June 17, 2018 (L_s=194.9°), which coincides with the peak τ = 8.5 measured from the surface in Gale crater by the Curiosity rover Mastcam at 850 nm (Guzewich et al., 2019). Optical depth in Gale crater then declined nearly linearly with L_s until reaching τ ~1.5 on L_s = 248°. HiRISE began to resolve RSL at L_s = 229°, when Gale crater τ was ~2.6. The zonal mean peak temperature measured by MRO’s Mars Climate Sounder (MCS; Kleinbohl et al., 2020) was on July 7 (L_s = 207°). The storm then began its slow decay, reaching background temperatures by late October 2018 (L_s = 270°-280°). In contrast, the MY28 PEDE started relatively late at L_s ~260° and decayed more rapidly than in MY34 (Wang and Richardson, 2015).

2 Post-PEDE Observations of RSL

Correlations between RSL activity and dust storms have been described previously (McEwen et al., 2011; 2014; Stillman et al., 2016; Chojnacki et al., 2016; McEwen, 2018). In particular there seemed to be more candidate RSL in 2007 following the MY28 PEDE. However, since the unique temporal behavior of RSL had not been recognized in 2007, the HiRISE images were all targeted for other purposes, and we lacked monitoring at these locations in MY28-29. The 2018 PEDE provided the opportunity to more systematically monitor RSL before and after a global dust storm. In addition, HiRISE has an ongoing campaign of imaging gullies for changes (Dundas et al., 2012; 2019), mostly on pole-facing mid-latitude slopes where RSL are not typically found. But in late MY34 we commonly see RSL on the steep east- and west-facing slope facets of pole-facing gullies and alcoves in the SML (Figure 1). We have also seen new RSL in images targeted for reasons other than monitoring slope processes. As a result, we collected a total of at least 432 images containing candidate RSL from 8/12/18 to 8/15/19 (L_s = 229°-66°), in >285 unique locations (Table S1). 298 unique locations are listed in Table S1, but some are questionable as to whether or not they contain candidate RSL due to low contrast. Figure 2 shows the locations of 368 of these images acquired in MY34 (L_s = 229°-360°, late southern spring until the equinox). The greatest number of sites is in the SML (latitudes -60° to -30°). Although the greatest number of RSL are in Valles Marineris (Stillman, 2018), the near-polar orbit of MRO favors greater coverage in the SML. Therefore, post-PEDE repeat imaging within Valles Marineris was limited to particular sites. The potential to identify RSL sites in the low-elevation region of Hellas basin is limited because this region is often hazy in southern spring and summer so few images are attempted in these seasons, and the floor of Hellas basin has few steep slopes.

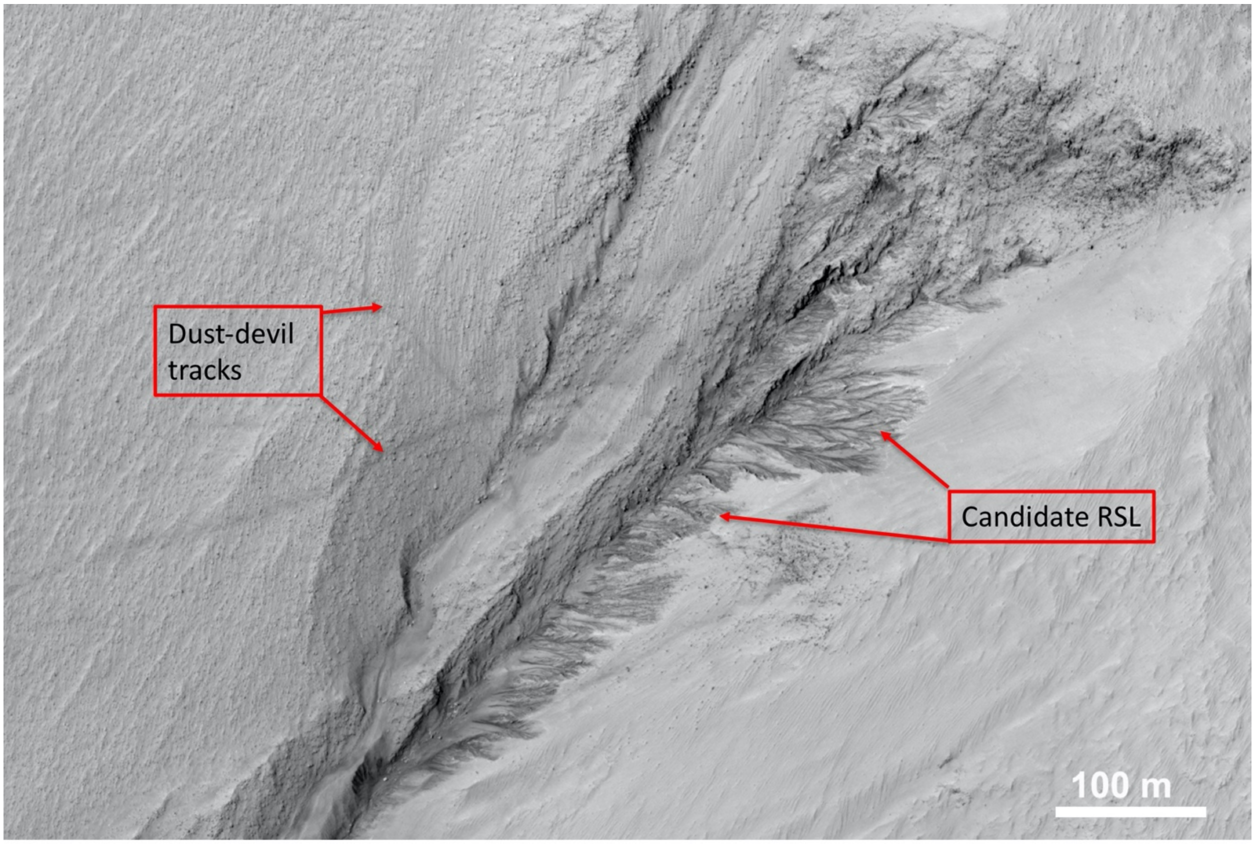

Fig. 1. Gullies on pole (south-southwest)-facing slopes with candidate RSL in west-facing slope facets, plus dust devil tracks. ESP_057951_1400 acquired December 7, 2018, MY34, L_s 302º, post-PEDE. All images in this paper are map-projected with north up and illumination from the left (west). Full-resolution and un-cropped versions of these and other images shown in this paper are available at https://uahirise.org.

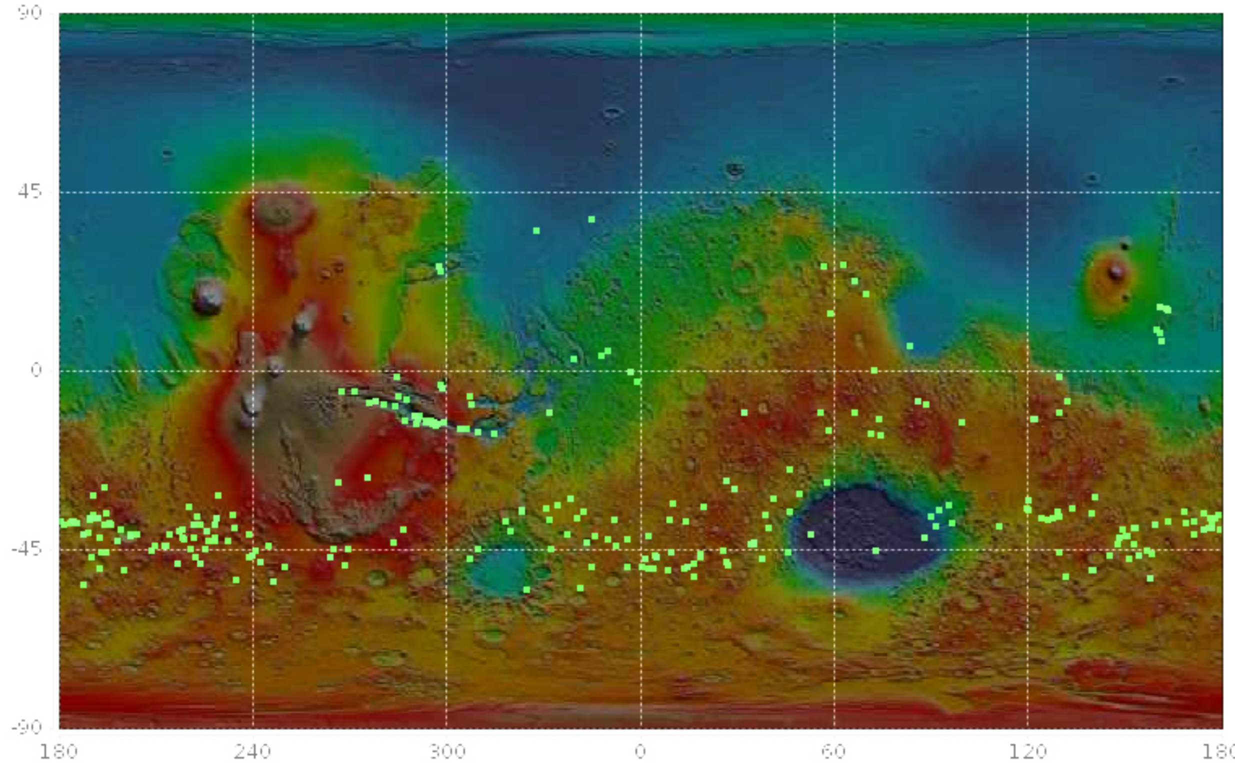

Fig. 2: Map of post-PEDE image locations with candidate RSL acquired in MY34, L_s 229-360° (8/2018 to 3/2019).

The first HiRISE images resolving RSL as the PEDE decayed were acquired in August 2018 (L_s = 229°) when the PEDE was well into its decay phase, but dust opacities remained quite high with visible optical opacity ~2.5 (Guzewich et al., 2019; Kleinbohl et al., 2020). We did identify some apparently active RSL during this decay phase (Figure 3), which provided an important hypothesis test. In a series of experiments, Wurm and Krause (2006) first showed that illumination can cause dust to erupt at low atmospheric pressures. For this mechanism to work on Mars, an area must be strongly insolated for some time and then rapidly shadowed, inducing a strong transient temperature profile in the subsurface (Kocifaj et al., 2011). Schmidt et al. (2017) extended this analysis to sand flows by assuming that the tiny forces would be sufficient to destabilize grains at the limit of stability (i.e., the static angle of repose). However, this mechanism would be much weaker during times of high atmospheric opacity, when shadows are only slightly darker than illuminated areas. The presence of active RSL during the PEDE decay phase is a challenge for this mechanism. At 10° latitude separation from the subsolar latitude, compared to optical depth (τ) = 0.1, τ = 2.0 allows ~8.8% of the solar radiation to reach the surface (Levine et al., 1977). An image in Coprates Chasma acquired at L_s = 229° (~10° latitude separation from the subsolar latitude) is barely clear enough to see small features (consistent with τ ~2 to 3), and shows well-developed RSL that were not present in the prior image from before the PEDE (Figure 3). The next image (L_s = 242.7°) reveals growth at the tips of some of the lineae (Figure S1). Thus RSL were active between L_s = 229° and 242.7° with $\tau > 2$ such that less than 10% of the top-of-atmosphere illumination reached the surface. RSL were seen at 12 other sites before L_s = 270° (Table S1), during the PEDE decay phase, and were often well-developed, suggesting activity during high τ.

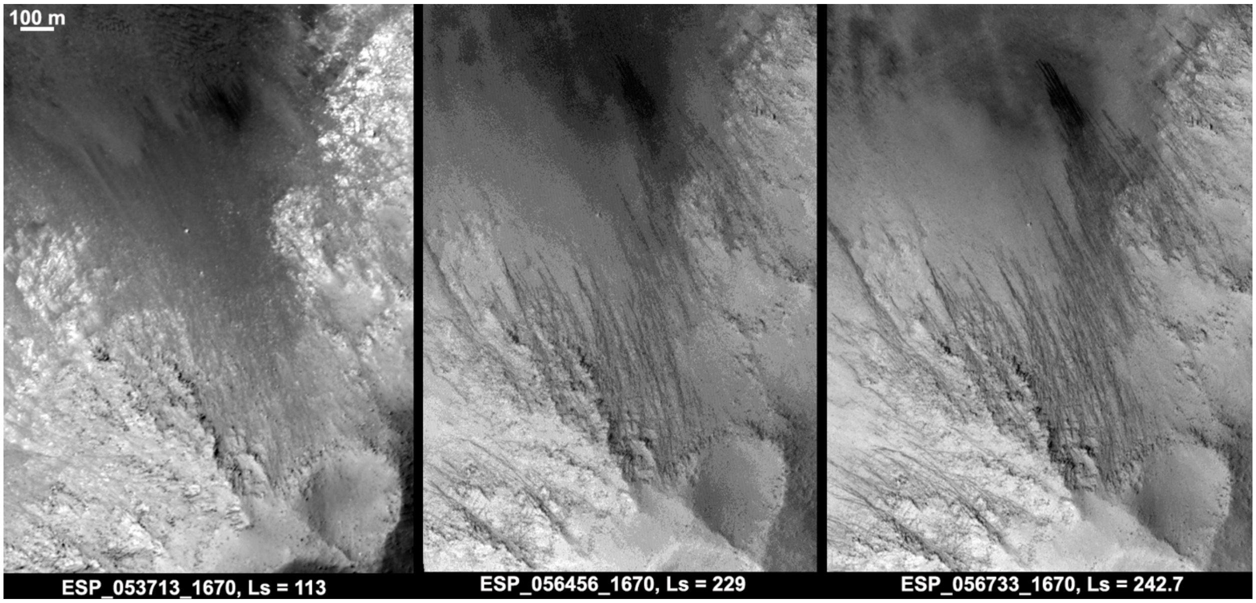

Fig. 3: RSL started forming during the decay phase of the PEDE, when optical depths were high enough to block >90% of the light from reaching the surface. Here we see a small portion of large images covering a ridge in Coprates Chasma, first before the MY34 PEDE (left), then during the decay phase (middle and right). Full-resolution and un-cropped versions of these and other images shown in this paper are available at https://uahirise.org. An animated gif of these images is available as supplementary Figure S1.

About half (157) of the 285 unique locations with distinct post-PEDE RSL are at locations where RSL have not been seen previously (e.g., Figure 4). For 76 sites where RSL had been seen in prior Mars years and in the same season (Table S1), 34 have no or far fewer RSL in prior years and no site had distinctly more RSL in prior years, except in MY28 following that year's PEDE. Other sites seem to have about the same RSL abundances as in prior years or are ambiguous due to poor atmospheric conditions or pixel binning or other issues. One key site, the central peaks of Horowitz crater, had extensive RSL on east-, west-, and south-facing slopes following the MY28 PEDE (PSP_005787_1475, L_s = 334°). Horowitz images in MY29-33 have fewer/shorter RSL on west- and south-facing slopes, but comparable RSL on east-facing slopes. The MY34 image (ESP_057174_1475, L_s = 264°) is similar to MY29-33 images acquired in southern summer. Dust devil tracks are common in all of the summer images at Horowitz. We could not acquire a late summer image in Horowitz in MY34 for comparison to the RSL extent in MY28 due to restrictions on MRO pointing for relay operations for the Curiosity rover.

Candidate RSL appear to be present on most steep, rocky slopes in the SML in southern summer of MY34, rather than the ~40% reported previously. Ojha et al. (2014) examined all HiRISE images of steep low-albedo slopes in the SML (28°-60° S) acquired from L_s = 250° to 10° in MY30-31, and found 82 out of 200 (41%) sites with candidate RSL. This was puzzling: why were RSL present on some such slopes and absent on others that appeared otherwise identical? This result suggested that some unknown variable such as availability of water or salt made the difference. We examined all MY34 images acquired from L_s = 280°-300° (to limit the data volume; this is peak RSL season) over steep rocky slopes in the SML, and found 76/87 (87%) with candidate RSL, significantly more than in MY30-31.

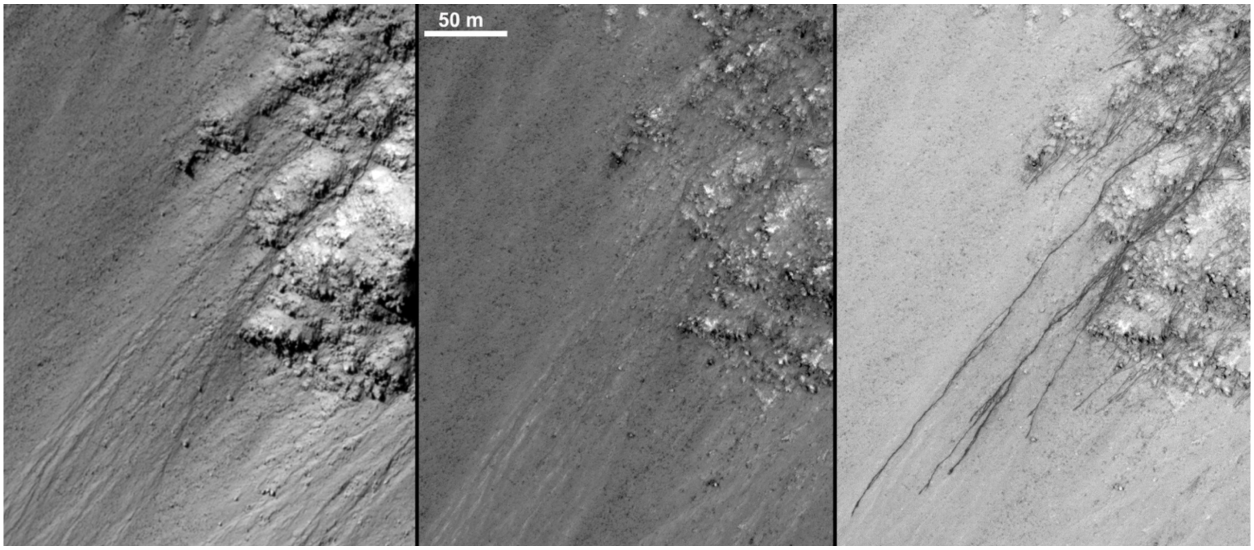

Fig. 4: Candidate RSL present in Coprates Chasma after MY34 PEDE (right, ESP_057419_1685, MY34, $L_s = 276°$) but not visible in a prior Mars year at about the same season and illumination angles (middle, ESP_031204_1685, MY 31, $L_s = 288°$). The surface here is also mostly brighter and redder in the post-PEDE image. Image on left (PSP_008616_1685) was acquired in MY 29 at $L_s = 78°$ with low illumination that accentuates topography, showing small channels that the RSL appear to follow.

3 Post-PEDE Surface Dust

There is evidence for fresh dust deposition over most of the southern mid-latitudes after the MY34 PEDE, as indicated by the overall color, brightness, and surface contrast of the images, and by the presence of dust devil tracks. Given complications with lighting angles, atmospheric opacity, and sparse color coverage, the presence or absence of dust devil tracks is the easiest way to quantify evidence for surface dust (Table S1). There are 3 types of dust devil tracks on Mars (Reiss et al., 2016): dark continuous, dark cycloidal, and bright. Nearly all are dark continuous over the set of SML images that follow the MY34 PEDE. These dark tracks most likely form when surficial dust is removed to expose larger-grained (rougher) substrate materials, which changes the photometric properties of the surface, but there may also be compositional differences. For example, basaltic-dominated dark dunes commonly showed extensive dust devil tracks and brighter lower slopes in post PEDE images (e.g., ESP_057312_1390, $L_s = 264°$). The removal of just ~1 μm dust thickness is sufficient to explain the lower albedo (Wells et al., 1984). Bright dust devil tracks, based on a terrestrial analog study (Reiss et al., 2011), result from the disturbance of aggregates of dust, silt and sand by dust devils, producing smooth surfaces in contrast to the undisturbed rough (darker) surfaces.

From the full set of post-PEDE RSL images (Table S1), 233/432 (53.9%) have clear dust devil tracks. When confined to images in the SML acquired L_s = 236°-360°, 177/243 (73%) have dust devil tracks. For comparison, a global survey of all HiRISE images acquired over almost two Mars years identified dust devil tracks in 5.8% of the images, and within that subset, 71% of the images were in the southern hemisphere (Hausmann et al., 2019). Note that nearly every HiRISE image contains markings that might be dust devil tracks, but here we noted linear or curving albedo markings of nearly constant width that cross topography rather than only extend downhill (because mass wasting features can appear similar to dust devil tracks). See Reiss et al. (2016) for other characteristics used to distinguish dust devil tracks from wind streaks or other Martian features. Dust devil tracks are found at all elevations and in all regions of Mars except on the permanent polar caps (Reiss et al., 2016), and maximum areal densities occur during spring and summer in both hemispheres due to maximum insolation. Dust devil track densities vary spatially, likely controlled by changes in dust cover thicknesses and substrate materials as well as the frequency of atmospheric vortices. Cantor et al. (2006) estimated that only 14% of dust devils leave tracks visible in Mars Orbital Camera images; Verba et al. (2010) found less than 1% of the dust devils observed at ground level produced tracks. Tamppari et al. (2020) found that dust devil tracks near the Phoenix lander (68° N latitude) created tracks when winds exceeded 8 m/s. The InSight lander has recorded up to 40 pressure drops per sol soon after landing in late MY34 (Banfield et al., 2020), and Perrin et al. (2020) report dust devil tracks near the InSight lander forming as often as 0.68 track/sol/km^2. And inferr4d that such tracks require wind speeds >6 m/s. Renno et al. (2004) suggested that dust devils form preferentially on slopes, where convection cells are common. In summary, the presence of abundant dust devil tracks associated with post-PEDE RSL is consistent with the expected higher dust fallout rates and wind velocities associated with large dust storms.

All dust devil tracks previously reported to be coincident with and approximately contemporaneous to RSL have been dark (e.g., Schaefer et al., 2019). However, a late 2019 HiRISE image revealed bright dust devil tracks over candidate RSL (Fig. 5). Outside the RSL, these dust devil tracks are not detectable, and where they cross the RSL, they express as bright tracks but are not brighter than the background slope. If the RSL are dark due to water, then perhaps the passing dust devil served to dehydrate the RSL, although it is not clear how the typically brief passage of a vortex could do this. If RSL are dry features, then this suggests they may be dark due to roughness, and the roughness elements are easily destroyed by a passing vortex. One speculative idea (see below) is that electrification in dust storms produces dust clumps that may be weak and easily broken down into finer grains, producing a smoother, brighter surface.

Figure 5. Bright dust devil tracks (black arrows) over candidate RSL in Eos Chasma, observed post-MY34 PEDE (ESP_062917_1640, MY35 Ls 127º).

The MY34 PEDE provided another hypothesis test. The increased RSL presence after the MY28 PEDE could be explained either as an effect of dust deposition on the ground, or from the environmental effects of the dusty air (i.e., colder days and warmer nights). Fresh surface dust also increases RSL contrast, perhaps making smaller RSL visible, but we clearly see more large and longer RSL after the PEDE, so contrast alone does not explain the apparent increase in RSL activity. There was no systematic monitoring of RSL sites until MY30 when their significance was appreciated, plus the SML RSL faded as the dust storm decayed in MY28. From more systematic monitoring of selected sites before and after the MY34 PEDE, we did see some activity while dust opacity was still high as described above (Fig. 3). However, the great majority of RSL seen to lengthen did so after atmospheric dust levels were close to typical seasonal levels, L_s = ~270°-280° (Kleinbohl et al., 2020). The fact that the MY34 dust storm decayed early, before SML RSL typically fade, helped to separate effects. While not ruling out an environmental effect on RSL from dusty air, this shows that simply having more fresh dust on the surface under typical atmospheric conditions corresponds to greater RSL activity.

4 Discussion

Our results suggest that RSL formation and growth are strongly favored during the aftermath of dust storms. Dust may directly cause RSL formation, or dust storms may correlate with some other factor, such as sand transport, that facilitates RSL activity (Dundas, 2020). In either case, the presence of thin dust deposits over steep, warm, and (usually) low-albedo slopes could facilitate or enhance RSL formation. Also, the dust could be preferentially trapped within the rocky areas in which RSL are seen to originate. How could dust deposition lead to greater RSL activity? If RSL are wet seeps, then a dust coating could slow evaporation (Grimm et al., 2014), but the source of sufficient water for seepage is problematic. Additionally, dust lags must be millimeters thick to significantly slow evaporation or sublimation (Schorghofer, 2020), and this is greater than the expected dust deposition in regions that retain a low albedo. Perhaps dust deposition provides salts that aid deliquescence as the driver of RSL growth, but the source for sufficient water to cause downhill flow is still problematic (Gough et al., 2019a; Leung, 2020).

We suggest that RSL are dry flows of dust and/or sand on steep slopes, and dust lifting enhances RSL activity. Dust lifting certainly occurs on Mars to keep the atmosphere dusty, and one major mechanism of dust lifting is by dust devils, which are common over sites with active RSL. Dust lifting must occur in the low-albedo regions of Mars where RSL occur in order for them to maintain their low albedo. Dust devils are most active over the warmest times and places, similar to RSL seasonality, and closely correlate with RSL occurrence at Tivat crater (Schaefer et al., 2019). However, it may not be plausible for every incremental RSL movement to require direct passage of a dust devil. For example, there are thousands of individual flows in Palikir crater, yet the many (49) HiRISE images here do not show dust devil tracks in the MY28-33 timeframe except after the MY28 PEDE (e.g., PSP_005943_1380). There were more extensive RSL in Palikir following the MY34 PEDE than in 5 previous MYs, but no dust devil tracks in the 4 post-PEDE images (L_s = 278.5°, 305°, 327°, 26°). Although most dust devils do not create visible tracks (e.g., Verba et al., 2010), the presence of many tracks in Palikir crater after the MY28 PEDE suggests that the surface properties do not preclude dust devil track formation.

Rather than triggering of RSL growth by direct passage of a dust devil, we hypothesize that conditions are nevertheless optimal for dust lifting, which could help initiate surface flow of sand or dust. As reviewed by Neakrase et al. (2016), there are four important dust lifting processes in dust devils:

(1) Wind entrainment aided by formation of dust aggregates.
(2) Thermo-luminescent lifting, important at low atmospheric pressures (i.e., not effective on Earth). Kelling et al. (2011) and Kocifaj et al. (2010) also demonstrated that up to 100 times more particles could be released after the light source was suddenly shut off, perhaps by local airborne dust.
(3) Pressure drop in the core of a vortex (the delta-P effect).
(4) Electrodynamics, as the electric forces produced by atmospheric turbulence can be the same order of magnitude as gravitational forces (Schmidt et al., 1998; Zheng et al., 2003).

Of these four processes, only #3, the delta-P effect, requires passage of a dust devil directly over the site of dust lifting. However, wind entrainment (including via slope winds), thermo-luminescent lifting, and electrical forces can operate over the entire slope. These forces can work together, as thermo-luminescence and electrodynamics reduce the friction velocity necessary to initiate saltation and dust lifting.

How does dust lifting create RSL? One concept is that small ballistic fountains of dust on a steep slope will deposit much more material downslope than upslope (Schaefer et al., 2019). If there is daily fountaining within the downslope deposit, then the net dust migration downslope would leave a dust-depleted, and hence dark, track in its wake that could grow downhill over weeks. However, if this system were closed, we would expect thicker and hence brighter dust deposits near RSL termini and possibly along their margins, but bright fringes have only been reported for one site (Stillman et al., 2014). Alternatively, as speculated by Schaefer et al. (2019), aeolian deflation may prevent the accumulation of thick downslope deposits. In their conceptual model, RSL growth is possible because dust fountaining is preferentially concentrated near RSL termini, where the disaggregation of dust grains (as observed in dust fountaining experiments; Wurm and Krauss, 2006) enhances the underlying physical processes. However, if the surface dust layer is very thin, consistent with the low albedos, then this process might simply loft dust into suspension without creating any surface flow.

Another dust-RSL concept involves grain flows of dust aggregates, with or without sand. Dust is very cohesive, but loses cohesion with the surface when lifted. Atmospheric transport and suspension of dust frequently brings electrification, which may be substantial (Harrison et al., 2016). Experiments to entrain dust with electrostatic and fluid-dynamic forces result in particulate clouds of aggregates rather than individual dust grains (Marshall et al., 2011). In other words, the dust sticks to other dust particles in clumps that have less contact with the surface. Freshly-deposited dust on Mars may tend to be in aggregates that provide sufficient surface area for entrainment by modest winds. Such aggregates may behave like grains, flowing for a short distance on sufficiently steep slopes once motion has been initiated, and perhaps entraining sand grains. Sand on steep slopes may also be mobilized simply by lifting and removing dust that created cohesion between sand grains. Fractures have been observed on the slipfaces of active Martian sand dunes, indicating cohesion (Ewing et al., 2017). Furthermore, the dust-lifting conditions persist through the warm season.

A sand-driven dry granular flow model for RSL (Dundas et al., 2017) avoided the problem of explaining the origin of significant water, but the incremental or gradual growth, rapid fading, and yearly recurrence remained challenges. The annual recurrence of RSL has been difficult to explain in most RSL models, as the activity is depleting something, either water, salt, or small grains, which must be replenished for recurrence. Dundas (2020) proposed replenishment of sand by uphill saltation. Dark ripples spaced a few meters apart, ubiquitous over sandy regions imaged with HiRISE, have been directly observed to migrate up angle-of-repose fans (Chojnacki et al., 2016; Dundas et al., 2017; Urso et al., 2017). Such sand motion has not been detected in the higher and steeper RSL initiation regions, but there may be smaller ripples common to landing sites not resolved by HiRISE (Lapotre et al., 2016). Such sand-dominated RSL could be particularly active after a PEDE either because the storm helps replenish sand at the RSL source regions or because the thin dust coating enables dust-lifting processes to trigger sand movement.

If RSL are flows of recently deposited dust, then dust fallout from the atmosphere replenishes at least some of the flowing material. Notably, gullies from which RSL head in Tivat crater have been observed to change color during years with high RSL activity, consistent with the broad mobilization of dust; when local RSL fade, and in subsequent years with lower RSL activity, these gullies lack distinct coloration (Schaefer et al., 2019). However, dust thicknesses in the low-albedo regions of Mars where RSL occur are thought to be very thin (the typical dust thickness must not be great enough to obscure the underlying surface albedo) or patchy, which is a challenge for models where dust is the only flowing material. Additionally, it would be difficult for dust clumps to erode small gullies, if RSL activity creates these gullies. If dust lifting initiates flow of higher-density sand grains, then erosion of small gullies over many years is at least more plausible than erosion by dust or fluffy dust aggregates.

One objection to the sand-flow model is reported evidence that some RSL flow onto slopes below the dynamic angle of repose for sand dunes (Stillman et al., 2020; Tebolt et al., 2020). However, Stillman et al. (2020) concluded that their low-slope observations were consistent with statistical noise, and some of the measurement points of Tebolt et al. (2020) do not appear to correspond to RSL (Dundas, 2020). While these observations may need greater scrutiny, we note that Martian slope streaks on heavily dust-mantled slopes, believed by some workers to be dry dust avalanches (Sullivan et al., 2001; Baratoux et al., 2006), form on slopes as low as 10° (Brusnikin et al., 2016). Perhaps dust-sand flows can transition into flows that are like small dust avalanches in some cases. Dust flows may be able to continue over lower slopes like the dilute upper regions of snow avalanches on Earth (Schaerer and Salway, 1980; Köhler et al., 2017).

5 Summary and Conclusions

• RSL were substantially more abundant following the MY34 planet-encircling dust event than in typical years.

• RSL can be active even when dust opacity is high and direct insolation is low (~10% of normal), challenging purely insolation-driven models.

• A dust devil track that is bright only where it crosses RSL suggests that in some cases RSL may be dark due to particle aggregation, based on terrestrial analogs.

• Dust lifting processes present multiple possible mechanisms that can trigger downslope movement of dust, with or without sand. These mechanisms should be further investigated as candidates for RSL formation and initiation.

Our results suggest that the presence of freshly-deposited dust causes or enhances RSL formation. This result may resolve the mystery of why RSL occur on some slopes but not others that are largely similar (steep, rocky, warm). Rather than requiring some unseen variable such as groundwater or salt or ripples, the activity may in part be a function of whether or not sufficient dust is deposited over a slope in each year.

Acknowledgements: We thank the MRO project and HiRISE team for returning amazing images and funding this work. Constructive review comments were provided by Ryan Anderson (USGS) and TBD. All HiRISE images used in this study are publicly available via the Planetary Data System and at https://uahirise.org.

Supplementary Materials: Table S1 (spreadsheet) and Figure S1 (an animated GIF of cutouts in Figure 3).

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