Anomalous recurring slope lineae on Mars: Implications for formation mechanisms

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ABSTRACT

Recurring slope lineae (RSL) on Mars are dark linear features which lengthen and fade seasonally. The role of water in the processes responsible for their formation remains undetermined. RSL in close proximity (meters to tens of meters apart) are likely to be expressions of the same underlying processes; therefore, differences in behavior between neighbors can provide new constraints on potential mechanisms for initiation, lengthening and fading. We present observations of anomalous RSL, categorized into three types: early faders, collinear RSL, and those which emerge at featureless locations. We conclude that, given currently proposed processes, our observations favor a highly localizable growth mechanism and the possibility of propagation without surface expression. Using the implications of observed anomalous behavior, we evaluate the feasibility of two specific proposed mechanisms: dry granular flow and flow of liquid through porous regolith. Our observations are more immediately compatible with the liquid flow mechanism.

1. Introduction

The presence or absence of liquid water on the surface of present-day Mars has implications for habitability and mission planning as well as for the broader geologic history of Mars (McEwen et al., 2013; Rummel et al., 2014). Recurring slope lineae (RSL) are one type of surface feature where the presence of liquid water is debated; therefore, determination of their governing mechanisms is crucial to assess if and how much liquid water is involved. RSL are dark streaks on steep slopes on the surface of Mars (McEwen et al., 2013; McEwen et al., 2011; Stillman et al., 2014). To be classified as RSL, many streaks in the same site must be observed to incrementally lengthen downslope, fade away, and recur in the same approximate location (McEwen et al., 2013; Ojha et al., 2014; Stillman et al., 2014). Typical RSL behavior varies regionally, e.g. in the number and duration of lengthening periods per year (Stillman et al., 2016; Stillman and Grimm, 2016), and annually, e.g. in overall activity level (McEwen et al., 2013; Ojha et al., 2014; Stillman et al., 2017; Stillman et al., 2014). Despite this variability, typical RSL activity has many common characteristics across all regions and all active seasons. RSL oriented in the same direction at a single site typically all lengthen for a period of time (usually when their host slopes are warmest), then later all gradually fade (McEwen et al., 2013; McEwen et al., 2011; Stillman et al., 2014). Typical RSL are continuous along their extent, following the direction of the topographic gradient (Ojha et al., 2014). RSL usually initiate from rocky areas or bedrock outcrops, especially those associated with faults (Abotalib and Heggy, 2019; McEwen et al., 2011; Schmidt et al., 2017; Watkins et al., 2014).

Many mechanisms have been proposed to drive RSL initiation, growth, and fading. One initial suggestion was that RSL are the surface expression of liquid water or brine percolating through the pore space of the regolith (McEwen et al., 2013; McEwen et al., 2011). The source of the water could be melting cold-trapped ice (Chevrier and Rivera-Valentin, 2012; Head et al., 2007; Levy, 2012), deliquescence (Dickson et al., 2013; Gough et al., 2016; Ojha et al., 2015), or a deep (Abotalib and Heggy, 2019; Watkins et al., 2014) or shallow (Grimm et al., 2014; Stillman et al., 2016; Stillman et al., 2014) aquifer. An alternate hypothesis is that RSL are the result of primarily dry granular flows (Dundas et al., 2017; McEwen et al., 2011; Dundas, 2020). The grains could be destabilized by sublimating frost, volume change of hydrating salts, loss of cohesion due to dehydration, small quantities of deliquescent brines, or overpressure from gas desorption, thermophoresis, or thermal creep (de Beule et al., 2013; Dundas et al., 2017; Schmidt et al., 2017; Wang et al., 2019; Schaefer et al., 2019; Gough et al., 2020). Their fading is linked to deposition of dust (Schmidt et al., 2017; Vincendon et al., 2019), removal of dust (Schaefer et al., 2019), aeolian processes, or exposure to surface conditions (Dundas et al.,

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Other suggested processes for RSL initiation and growth include debris flows (McEwen et al., 2011), mobilization of material by boiling water (Massé et al., 2016), or something similar to wind streaks (Vincendon et al., 2019).

Much attention has been given to determining a mechanism by looking at the typical characteristics of RSL, sometimes taking regional variation into account. Given the importance of understanding RSL formation, novel approaches are needed to assess the feasibility of proposed mechanisms. We address this need by considering RSL which behave atypically, rather than by analyzing typical behavior; we posit that viable mechanisms should be compatible with both characteristic and anomalous behavior.

Two RSL which are in very close proximity and of similar orientation should experience similar environmental conditions, including insolation, air temperature, pressure, humidity, dust cycling, and wind conditions. Then if one RSL behaves differently from another nearby, the same mechanisms must be able to generate both patterns. Therefore, observations of RSL which behave differently from their neighbors, which we term “anomalous RSL”, can provide novel constraints and insight into the processes involved in RSL formation and growth. Some anomalous features, such as specks and line segments that appear downslope in active seasons (Chojnacki et al., 2016; Stillman et al., 2017; Stillman et al., 2014) or RSL which fade as new RSL appear (Stillman et al., 2017; Vincendon et al., 2019) have been noted in previous work. In this paper, we present observations of three types of anomalous RSL and discuss their significance for the processes governing RSL behavior.

2. Methods

We performed a survey to assess the distribution, prevalence, and behavior of anomalous RSL. For our observations, we use exclusively images from the High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007), the only available images that can resolve features as narrow as RSL. The locations surveyed are those which fulfill the following criteria: (1) the location is within 5 km of a candidate or confirmed RSL site (Stillman et al., 2017), (2) a digital terrain model (DTM) for the location has been produced and released by the HiRISE team, and (3) at least three orthorectified images are available which were taken within one martian year. We constrain our locations using the list of 474 candidate and confirmed RSL sites published by Stillman et al. (2017). The more recent update to this catalog (Stillman and Grimm, 2018) did not include any additional sites meeting our criteria. We require a DTM because orthorectified images help us to separate the effects of viewing angle from surface changes. We use the DTMs and orthorectified images released by HiRISE as of June 2019 (DTM production methods are described in Kirk et al., 2008). We require at least three images taken within one martian year because we assess visible changes over the course of a RSL season.

There are 27 locations which meet our criteria (Fig. 2, Supplemental Table 1). Images at each of the selected sites were visually examined. We looked for RSL which behave typically in close proximity to RSL which do not behave typically in some way; the latter were recorded as anomalous and categorized. One additional case of anomalous behavior was noticed incidentally that was near a location included in the survey based on the Stillman et al., 2017 list of RSL sites but was just south of the DTM and orthorectified images; this was included in our analysis as well.

For parts of our analysis, we generated elevation profiles and used these to compute approximate slopes of sections. Elevation profiles were extracted from the DTMs generated by HiRISE using ArcGIS (http://www.esri.com/software/arcgis/); we first generated a set of points evenly spaced along the desired profile, then extracted the DTM value at those locations. The extraction algorithm chooses the elevation of the DTM point nearest to each location. Since the resolution of the DTMs (1 m per pixel) is much smaller than the length of our profiles (27–95 m), we expect this to have little effect on our calculated average slopes. To determine the approximate overall slope of each profile segment of interest, we used a linear least-squares regression in order to find the best fit line to all elevation measurements between the endpoints of the segment. The slope reported is the slope of the best fit line.

3. Observations of anomalous behavior

We observed three types of RSL with anomalous behavior (Fig. 1): (1) early faders, (2) collinear segments, and (3) emergent RSL; each observed case is described in detail in Supplemental Table 2 and illustrated with an animated GIF, also included in the supplementary material. In every observed case, the anomalous RSL are in very close proximity (in most cases <10 m) to “typical” RSL and share the same orientation. Typical RSL greatly outnumbered anomalous RSL at all sites observed. We believe the anomalous cases to be accurately classified as RSL because of their proximity to typical RSL and their similarity in terms of visual appearance and timing of activity. In addition, they individually behave like RSL in that they are observed to do at least two of the following: grow incrementally, recur in exactly the same location, and fade. Lack of image availability is the limiting factor in all cases where all three conditions cannot be confirmed.

Sites or areas within sites where anomalous behavior was not observed or could not be fully confirmed were often similar in nature to sites where anomalous behavior was observed. In some cases, however, despite meeting our basic criteria, the site was unsuitable for detection of one or more types of anomalous behavior. For example, some sites lacked featureless slopes on which emergent RSL might occur; some lacked appropriately timed images to detect or confirm early fading; and at some sites, RSL were often too narrow to conclusively distinguish collinear segments. All sites which met our basic criteria are described in detail in Supplemental Table 1, including any information regarding suitability of the site, the RSL, or the available images for detecting anomalous behavior.

3.1. Early faders

Early-fading RSL (Fig. 1A) fade before their neighbors, even as their neighbors continue to grow. To qualify as an early fader, a sequence of three images must exist over a single active season showing that the RSL in question fades significantly in part or in full without lengthening while neighbor RSL do not fade and do lengthen. Fading is identified by a decrease in contrast in the RSL and its immediate background. To avoid including cases where a RSL only seems to have faded because of reduced image contrast (e.g. due to atmospheric opacity), we look for an obvious decrease in contrast with the background relative to a neighbor (e.g. as illustrated in Fig. 1A).

3.2. Collinear RSL

Collinear RSL (Fig. 1B) are segments approximately aligned along a slope, with the gap between them often occurring at a location where surface texture changes. To be considered in this category, a set of collinear segments must behave in the following way: downslope segments do not appear before upslope segments and upslope segments do not lengthen considerably once downslope segments appear. Furthermore, the segments must be approximately collinear; that is, taking into account the typical tortuosity of RSL at the site and the possibility that irregular topography or a change in soil column properties might slightly alter the path of a RSL, the segments must reasonably be aligned along the same RSL footprint. To attempt to exclude cases where the visual discontinuity is due to narrowing of the RSL below image resolution rather than due to a genuine lack of surface expression of RSL, we only include cases where RSL are at least several pixels wide. We also exclude cases where the gap between collinear segments is associated with large boulders and shadows which may obscure rather than
interrupt the surface. We additionally confirm RSL-like behavior of the patch of collinear RSL itself (fading, recurrence, incremental lengthening).

3.3. Emergent RSL

Emergent RSL (Fig. 1c) initiate and grow from a location with no obvious surface feature or visible connection to the nearby bedrock outcrop or rocky areas from which their typical neighbors appear to be sourced. The seasonality of the activity of emergent RSL aligns with the activity of their neighbors; that is, temporally sequential image pairs usually show similar activity (appearance, growth, stagnation, or fading) or lack thereof for both the emergent RSL and their typical neighbors.

3.4. Previous observations of similar features

Behavior similar to that which we define above has been observed previously (Chojnacki et al., 2016; Stillman et al., 2014; Stillman et al., 2017; Stillman et al., 2014; Tebolt et al., 2019; Tebolt et al., 2020). All sites at which such behavior was described in the cited works were included in our survey, and we observed and considered each case.

Unusual fading activity was described in Garni Crater (Stillman et al., 2019; Tebolt et al., 2020). The observations described are usually specks or short lines that appear on RSL slopes. We observed the segments described by Chojnacki et al. (2016) to appear later than upslope RSL activity, whereas we observed the segments described by Stillman et al. (2014) and Tebolt et al. (2020) to appear downslope of growing RSL, in alignment with the observations of those authors. These authors suggested that the segments may be a discontinuous surface expression of the process causing growth of the upslope RSL. These authors did not describe observations of recurrence, though we note that the segments are sometimes associated with unusually active seasons and so a lack of observed recurrence may not indicate that they are not part of an inherently recurrent process. These authors also did not describe observations of gradual lengthening of these segments, though in one case (Stillman et al., 2014) only a single image is available from the season.
observed. We also do not observe recurrence or incremental lengthening of these segments and so we do not include these candidates in the emergent or collinear categories. However, if these features are indeed discontinuous surface expressions of the process causing the RSL activity elsewhere on the slope, they carry similar implications to collinear segments and emergent RSL.

3.5. Survey results

We observed 4 occurrences, distributed among 3 sites, of early fading; 4 occurrences, distributed among 3 sites, of collinear RSL; and 3 occurrences, distributed among 2 sites, of emergent RSL. Multiple instances of anomalous behavior in close proximity (in the same cluster of RSL within a site) are considered a single occurrence. The locations of these as well as the 27 sites considered and all 474 RSL sites published by Stillman et al. (2017) as well as the additional 43 sites published by Stillman and Grimm (2018) are mapped in Fig. 2. Details of all observed cases are documented in Supplemental Table 2.

Anomalous RSL were identified in all broad geographic regions in which RSL have been observed: the southern and northern mid-latitudes, Valles Marineris, and the rest of the equatorial region. At some sites, more than one type is present. For example, collinear segments are present approximately 2 km from early faders in Coprates Chasma in Valles Marineris. Emergent RSL are present approximately 1.5 km from early faders in Horowitz crater in the southern mid-latitudes. In both cases, the two types of anomalous RSL are active at the same time.

We observe early faders at three sites; at some, multiple RSL fade early. Time-series images showing examples of early fading are given in Fig. 3. No major changes such as rockfalls are observed at the initiation points or along the length of the RSL. In the sequences of three images used to confirm early faders, we observe neighboring RSL which lengthen between all three, RSL which lengthen between the first two but fade between the second two, and RSL which also fade early, fading between all three images. Early faders are initially similar in darkness to their typical neighbors; they then may either fade through a decrease in contrast between streak and background that is consistent along the length of the streak, or they may retreat; the figures given as supplementary material illustrate examples of both. The neighbors that continue to grow usually exhibit consistency in darkness along their full length (that is, they do not develop gaps). The neighbors that also begin to fade early mostly do so consistently along their full length, though we have observed cases of retreat. The distance between early faders and their closest typical neighbors is generally much smaller than the length of the early faders at their maximum extent. Therefore, they generally have similar orientation and slope. In a single image, viewing geometry and lighting conditions should also be nearly identical, so the fading we observe is likely a genuine surface change rather than a viewing effect.

We observed the sites of early faders both with and without contrast stretching; some previous work (Schafer et al., 2019) has suggested that RSL fading may actually be due to albedo change of the background rather than of the streaks. While in some cases we observe an increase in overall image brightness in later images relative to earlier, this is not the case in all early fader locations and trends to affect not only the RSL but also their background slope as well as other areas in the image. In all images, background albedo does not vary noticeably between one RSL and its immediate neighbors. However, we note that visual inspection may be insufficient to detect the subtle changes quantified in Schafer et al. (2019); we do not draw conclusions about the mechanism of contrast reduction.

In the two cases (from the same site) where sufficient images during later active seasons exist, RSL are observed to occur in exactly the same place as the early fader in later active seasons; in the other cases, such images are not available. Among the two cases with sufficient images, one has a later image suggesting recurrence of early fading, though a three-image sequence showing continued simultaneous growth and fading (as we required for initial anomalous behavior detection) to fully confirm recurrence of early fading behavior does not exist. In no case does an image series with sufficient time resolution exist at the end of the regular RSL season to determine exactly how early the early faders fade in comparison to their typical neighbors.

We identify four examples at three sites where RSL exist in multiple collinear segments such that downslope segments never appear before upslope segments, only the lowest segment is ever observed to lengthen significantly, and segments fade at the same time. In all of the observed cases, we can confirm that the line or patch of collinear RSL itself fades, recurs, and incrementally lengthens. A site may have a single line of collinear segments or many (Fig. 4). In the case of distinct individual RSL, downslope segments are sometimes slightly wider at the point where they emerge, but otherwise have approximately the same width as upslope segments; additionally, downslope segments which are shorter than, longer than, and similar in length to the corresponding upslope segments are all observed. Where RSL are especially dense, e.g. in parts of the location shown in Fig. 4C, the precise correspondence between upslope and downslope RSL can become ambiguous; our overall observations are the same when limited only to segments which can be unambiguously correlated.

In the gap between collinear segments, there is usually a change in surface texture from smooth to rough, with no clear associated change in colour or albedo. Examination of shadows suggests that the interrupting area between segments has raised topography; elevation profiles from DTM s, when available, support this claim, though the topographic perturbation is not always clearly greater in magnitude than variability (possibly noise) in the profile along the rest of the slope.

In the one case where early season images are available, we observe that the upslope segment appears before the downslope segment fades in comparison to their typical neighbors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
(Fig. 4A, B). In all other cases we observe, images are not available to determine the relative timing of growth of upslope and downslope collinear segments; all but the lowermost segments are already emplaced in the first image of the active season.

We note two sites where RSL occur which initiate from a point with no other resolvable surface feature (Fig. 5A). At both sites, the RSL are in areas where other RSL grow from bedrock outcrops or rocky patches. In Horowitz crater, available images show that the emergent RSL lengthen gradually. In Juventae Chasma, we observe a patch of emergent RSL which recur and fade several times with timing matching the activity of other RSL in the region. Unlike other RSL at the site, only a few of the emergent RSL here are observed to lengthen gradually. Of all detected anomalous RSL, this is where they are most distant from typical RSL; the patch (which is 450 m wide) is 150 m from the other RSL. There is a bright streak approximately aligned with the top of the patch; however, based on its linearity and similarity to other streaks at regular intervals in the image, we believe it to be an image artifact (Fig. 5A).

We generated elevation profiles aligned with two example emergent RSL in Horowitz crater and with one emergent RSL in the patch in Juventae Chasma and used these to measure approximate slopes (Fig. 5B). Of the two profiles in Horowitz, one indicated nearly no change in slope (a steepening of ~1°) at the initiation point of the RSL and one indicated a shallowing in slope (~10°; note that the resulting slope of 20° is unusually shallow for RSL (Dundas et al., 2017, Tebolt et al., 2020)). The profile of the RSL in Juventae Chasma indicated a slight steepening in slope (~3°) near the top of the patch but no additional change in slope associated with the initiation point of the emergent RSL. In each case, we generated a single profile, which was sufficient to conclude that there is no obvious trend in the angle of slope around the initiation point of the three examples.

4. Discussion

In each of the 12 cases we observed, the anomalous RSL are close enough in proximity and timing of activity to their typical neighbors that we infer that the same mechanisms are responsible for both. Therefore, a proposed process for one must also be compatible with the other. This allows us to use anomalous RSL to provide constraints on the processes at work at their locations, though because anomalous RSL are rare relative to typical RSL, conditions permitting their formation may be similarly rare.

With the small sample of detected examples, it is difficult to draw statistically supported conclusions about the distribution of each type or areas of absence, but our observations do not support regional concentration or clustering. Furthermore, anomalous RSL are found in every major region where RSL have been documented and in a variety of geologic settings, and we see no obvious differences between sites (or regions within sites) which host anomalous RSL and those which do not. Therefore, we infer that any constraints derived from atypical behavior in one location are likely to apply to RSL mechanisms globally. That is, while rare or localized processes or peculiarities may be triggering anomalous behavior, it is unlikely that the underlying mechanisms which are responding to these triggers are varying fundamentally in nature between sites with and without anomalous RSL.

4.1. Interpretations

We interpret our observations of RSL which appear to fade as their
neighbors appear to lengthen across multiple images to indicate that some RSL fade gradually at the same time as others are lengthening gradually. This gradual lengthening may take the form of constant lengthening or multiple episodes of lengthening as long as the episodes are sufficiently common to be statistically compatible with our observations that many neighbors lengthen between each image pair. While it is possible that the observed behavior could be produced by rapid successive episodes of appearance/growth and fading, we find this interpretation to be unlikely given the consistency in location of the RSL population from image to image, our observations of gradual lengthening of many RSL over at least three images, and the lack of reappearance of previously faded RSL. We would expect this pattern of growth to produce behavior much more like that observed in Garni Crater (Stillman et al., 2020), where we observe that between any two consecutive images, many RSL appear and disappear, while gradual lengthening is unusual. We note that although RSL in Garni Crater are not included in our survey results, our observations of early faders strengthen the conclusion of Stillman et al. (2020) that neighboring RSL can lengthen and fade contemporaneously and give several examples of this phenomenon outside Garni Crater, including one outside Valles Marineris.

Since early-fading RSL and their typical neighbors have similar slope and orientation and because observations of fading are made across sequences of three images, we find it unlikely that observed fading is simply due to differences in viewing or lighting geometry between the two. We also find it unlikely that early faders are not changing and instead both the background and all neighboring typical RSL are darkening since we do not observe consistent and coordinated late-season darkening of slopes and RSL in unstretched images; however, we note that fading due to darkening slopes still implies simultaneous growth and fading.

We interpret collinear segments to be the discontinuous surface expression of single RSL. The RSL grows from upslope; when it encounters the surface disturbance associated with the gap between segments, it continues without surface expression, reappearing below the disturbance and growing from there. This aligns with our observations that upslope segments appear before downslope segments and do not grow after downslope segments appear. We note that in only one case do we have early-season images to suggest a dependent order of appearance. We do observe a lack of growth of upslope segments after appearance of downslope segments in each of the many individual instances.

We consider also an alternative interpretation that collinear segments are independent RSL which occur collinearly due to external factors, e.g., topographic forcing related to the small channels often observed on RSL slopes (McEwen et al., 2011; Ojha et al., 2014). In this case, we would expect the timing of their appearance and lengthening to be similar. We would therefore expect to see upper and lower segments lengthen throughout the season. Instead, we observe lengthening of only the current lowermost segment, even when in a few cases it is shorter than upslope segments (implying in these cases that either the upper linea began growing earlier or grew faster than the downslope linea). We note that the growth of upper segments may be limited by availability of hillside conducive to propagation, in which case it is possible that downward propagation of the upper RSL is stopped sooner than that of the lower RSL due to physical obstruction. If there is variability in timing of appearance, we would expect to sometimes see lower segments appear before upper ones. In the one case where early-season images are available, we observe appearance of the upper segment before the appearance of the lower.

Therefore, we find the most consistent and simplest explanation to be that segments which are collinear belong to the same RSL. Additional observations which capture the timing of appearance of upslope and downslope segments in these locations could refute or more strongly support our interpretation. Images with high temporal resolution captured at the beginning of the RSL active season in the locations of

Fig. 4. Examples of collinear RSL, both in Valles Marineris: (A, B) near Juventae Chasma and (C) in Coprates Chasma. (A, B) Sequence of images demonstrating that RSL segment (indicated by yellow arrow; typical RSL are indicated by red arrows) appears above discontinuity at Ls 171° (MY 31) before segment appearing below at Ls 206°. (C) Area with many collinear RSL with a few continuous RSL interspersed; examples are outlined in inset. Image taken at Ls 84° (MY 32). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
collinear segments are the key to obtaining such observations, even given the limitations on temporal resolution due to the orbital restrictions of HiRISE (e.g. to one image every 16 sols at Garni crater (Stillman et al., 2020)). We note, however, that observation through repeated imaging cannot prove a relationship between segments; this must be inferred statistically from the absence of observations suggesting their independence.

4.2. Implications

The existence of early-fading RSL suggests that one or both of the following is true: (1) the efficiency of the fading mechanism can be variable on a scale of meters across a slope while still allowing the early fader to grow in the first place; (2) fading is active simultaneously and consistently over neighbor RSL, but some aspect of the growth mechanism is variable locally, with effective growth or fading resulting from a variability in the balance between two competing processes over short distances. Furthermore, since some RSL remain dark along their full extent as they lengthen despite the fading of their neighbors, the mechanism by which RSL darken and grow must be active along the full length of RSL on a shorter timescale than that of fading. That is, even if RSL are darkened intermittently, the typical time between episodes of darkening must be short enough that fading during that interval is unlikely, and the mechanism of darkening must act on all parts of the streak which are susceptible to fading (rather than e.g. only the downslope end of it). The variable growth rates observed by Schaefer et al. (2019) also suggest local variability in the growth mechanism.

The implications of collinear and emergent RSL are similar, so we will discuss them together. If we accept the causality suggested by the temporal dependence of growth observed between upslope and downslope collinear segments and therefore the interpretation that collinear RSL are the discontinuous expression of a single process, discontinuities in the surface expression of RSL indicate either that the process of RSL growth does not operate strictly at the surface of Mars (i.e., the force driving propagation of RSL can travel either over or under these discontinuities) or that it operates at the surface but may have no visible surface expression over part of the extent. Alternatively, it may also be that the surface expression disappears rapidly and is not captured by

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Fig. 5. (A) Three locations of emergent RSL, the leftmost one in Juventae Chasma and the rightmost two in Horowitz Crater. Example emergent RSL are highlighted in boxes. Note that in Juventae Chasma, there is a patch of emergent RSL; the top of the patch is indicated with a purple dashed line in (A) and a square marker in (B). (B) Elevation profiles along each highlighted emergent RSL, beginning above the initiation point and continuing below. The initiation point of each RSL along the profile is marked with a circle. The location of the top of the emergent patch in Juventae Chasma is marked separately with a square. Approximate slope of each segment is given. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
successive images. In the case of emergent RSL, either the initiation point of the underlying process is at the upslope tip of the streak, in which case it must be possible (but unusual, since these are rare) for RSL to initiate somewhere with no obvious surface feature, or else the surface expression of the RSL does not connect to its initiation point. In the latter case, the implications are the same as those of discontinuous RSL; it must be possible for RSL to propagate with no surface expression that is observable in HiRISE images and then resume observable surface expression. The implications of independent collinear segments are similar to the former case; it must be possible for RSL to initiate from a very small region.

Many processes have been proposed to drive RSL initiation, growth, and fading; our observations of anomalous RSL behavior have implications for all of these processes, as well as any future proposed process. As an example of evaluation of these implications, we focus here on two frequently discussed mechanisms: continuous wet seeps sourced from melting ice, deliquescence, or an aquifer which fade due to evaporation, and slow or intermittent (but frequent) grain flows which fade due to a change in dust cover.

### 4.3. Liquid flows

RSL may be the result of water or brine seeping through the subsurface over an impermeable layer; the surface darkens where liquid wicks up. In this model, the extent of a flow is determined by the balance between liquid production rate, the rate of transport (controlled by the soil hydraulic conductivity and the slope), and evaporation rate, whereas its visible footprint within that extent is determined by the capillary properties of the soil column (Grimm et al., 2014; Huber et al., 2020). The flows would grow early in the season when liquid production rate outstrips evaporation rate, reach a steady-state, and then fade when liquid production slows or stops, and evaporation begins to dominate. This is the same mechanism which is observed to produce the dark streaks called ‘water tracks’ in the McMurdo Dry Valleys in Antarctica, described in detail by Dickson et al. (2013), Head et al. (2007), and Levy et al. (2011); these streaks have previously been compared to RSL (Dickson et al., 2013; Levy, 2012).

Because the extent of RSL depends on three primary factors, fading must be triggered by a change in one of the three: liquid production rate, evaporation rate, and soil column properties. While seasonal RSL fading can result from a widespread change (e.g. lower temperatures leading to a reduced liquid production rate), early fading must be due to a change localized to the single RSL which fades early. Here we evaluate the plausibility of a local mid-season change in each of the three factors.

**Liquid production rate** If the rate of fluid production generating a single RSL were to suddenly drop close enough to zero, the RSL would be expected to evaporate and disappear. This could happen and result in early fading if the source of one RSL were depleted before the sources of neighbor RSL, or if one RSL became disconnected from its source. Here we consider RSL sourced from deliquescence, melting ice, or an aquifer. Liquid sourced from deliquescence might cease to flow if salt reservoirs are distinct and one is exhausted. Melting water from smaller ice patches might similarly result in early faders if patches of different sizes or subjected to different melting rates (which might reasonably result from locally variable factors such as soil structure above the ice, depth to the ice, and differences in aspect or local shadowing) could be exhausted at different times. Melting ground ice or an aquifer might cease to flow if some reservoir is more difficult to explain, though not impossible. In general, early faders are compatible with all liquid sources discussed.

A wet seep mechanism is also compatible with observations of discontinuous and emergent RSL. Discontinuous RSL could result from along-slope variation in capillary properties of the soil or thickness of the porous layer; liquid would continue to flow in the subsurface, but its surface expression would only exist where the overlying layer supports wicking of liquid all the way to the surface. This is similar to the processes suggested by others for discontinuous segments downslope of active RSL (e.g. Stillman et al., 2017), and is supported by the observation of coarser texture of the regions of interruption. Discontinuities could also result without subsurface flow if surface soil conditions at the discontinuities promote such rapid evaporation that the flow quickly fades. Similarly, the liquid feeding emergent RSL could have traveled underground from a distant source, springing up where regolith conditions (capillary radius of the porous regolith) or thickness allow wicking to reach the surface. Unfortunately our observations of steepening vs. shallowing do not permit us to make any conclusions about what change in the soil column properties (e.g. steepening leading to a thinner active layer, or shallowing leading to a change in grain size distribution) may be causing these. Similar behavior is observed in the McMurdo Dry Valleys (Head et al., 2007), where in one case a seep arises approximately 50 cm downslope of a small boulder; in this case the boulder affected the soil column in its downslope lee such that the saturated column in the water track intersected the surface downslope of the boulder (Levy et al., 2011). The patch of emergent RSL in Juventae Chasma is the most puzzling in the wet paradigm since if these RSL share a source with the typical RSL nearby, liquid would need to flow quite far beneath the surface. However, this is still possible to explain with subsurface flow; for example, a fracture in the bedrock underneath the sand could route liquid to the emergent patch.
4.4. Dry granular currents

RSL may be the visible manifestation of granular flows; the surface darkens as grain sorting and suspension occur and fades as dust is deposited, lifted, or redistributed (Dundas et al., 2017; Schmidt et al., 2017; Vincendon et al., 2019; Schaefer et al., 2019; Dundas, 2020).

In the context of early fading, seasonal dust redistribution should not vary significantly between one RSL and its neighbors, so it is more reasonable to consider variation in growth mechanism. Note that while we do not analyze aeolian reworking or exposure to surface conditions as fading mechanisms here, similar arguments should apply since neither should vary significantly between neighboring RSL. Mechanisms involving a sustained (or intermittent but frequent) flow of grains could be consistent with early faders if the activity that triggers the flow is locally variable. Then despite continuous deposition of dust, the active flow remains dark as the moving grains resuspend or sieve any deposited dust whereas the flow which is no longer active fades due to dust accumulation. It is difficult to explain early fading if RSL formation is primarily controlled by the wind; wind activity should be fairly similar between neighbors, but for fading and lengthening to occur simultaneously, wind activity must be sufficiently consistent near one RSL to cause the appearance of lengthening while being sufficiently low near its neighbor to allow fading mechanisms to take over. Exuastion of the repository of loose grains is a possibility, though as with an exhausted water or salt source, a frequent recharge mechanism would be required to explain early faders which recur. Sublimating frost, gas desorption, or loss of cohesion due to dehydration as destabilization mechanisms are compatible with early faders, since one area of frost or adsorbed gas may be exhausted before the end of the active season. The Knudsen pump destabilization mechanism suggested by Schmidt et al. (2017) is also compatible, as seasonally changing shadowing of the surface could potentially affect the force destabilizing grains feeding one RSL differently from its neighbor based on very local differences in surface topography.

It is difficult to reconcile a granular flow with the existence of discontinuous RSL. If a flow is halted by an obstacle associated with the discontinuity, the observed gap in surface expression requires explanation of how the RSL process would begin again downslope of the discontinuity. If the downslope segments are independent, both their collinearity and the timing of growth of upslope and downslope segments must be explained in a way that is consistent with both individual and clustered instances. For example, downslope winds might provide a super-surface force driving grain flows past an obstacle. If a flow has sufficient momentum to continue past the obstacle, the lack of visible surface expression must be explained. One possibility is that the continued surface expression is simply not visible in images, e.g. because in one area the material removed or deposited by the granular flow looks the same as the material underneath. However, this would need to be true despite the blocky texture often associated with the gaps between segments and the lack of distinct colour change of the surface where the gaps are. Another possibility is that the fading mechanism is for some reason intensely active in the location of the gap; however, this requires local variation in fading that is not consistent with seasonal dust deposition or lifting.

Within the framework of dry flows, the source of grains of emergent RSL (or of collinear segments, if they are independent) is likely at the visible initiation point of the RSL. Since the Knudsen pump mechanism relies on shadows it is an unlikely destabilization force where there is no visible object to cast a shadow over the observed initiation point. RSL triggered by wind or wind-borne grain deposition are potentially compatible with the observation of emergent RSL; a subtle change in slope, which is observed in two of three cases, could allow for seasonal accumulation and destabilization of grains.

In summary, for mechanisms which rely on flows of grains triggered from a reservoir for darkening and growth, early faders can be explained by grain source exhaustion but a recharge mechanism is required, and emergent RSL require that the grain reservoir and any features required to trigger flow not always be visible in HiRISE images. Mechanisms which instead rely on gradual accumulation and destabilization of wind-borne grains require an explanation for early faders but are potentially consistent with RSL emergence at a featureless location. Discontinuous RSL are difficult to reconcile with any grainflow-based mechanism; the absence of darkening between segments (or else collinearity and dependent order of growth and appearance) must be explained. Therefore, taking the implications of all types of anomalous RSL together, the dry granular current model for RSL requires additional explanation on multiple fronts to reconcile the model with our observations.

4.5. Exhaustivity of survey

Our survey is not exhaustive or without bias in geographic distribution. Our observations are made where images are available; HiRISE images are collected and DTMs are made preferentially in places of known scientific interest. Furthermore, site characteristics and the regional behavioral patterns of typical RSL affect the detectability of anomalous RSL. For example, it is more difficult to detect and conclusively identify a RSL that begins fading early in a location where fading occurs over many months. As another example, in locations where the width of RSL approaches what is detectable given the resolution of the images, a visual discontinuity in the RSL is more simply explained as narrowing below the detection threshold than as a definitive interruption of the surface expression of the RSL.

4.6. Further work

It is important to continue to search for examples of anomalous RSL behavior. It is especially important to confirm the behavior of collinear segments, which have potentially very significant implications but are difficult to interpret conclusively with available images. The previous observations of specks and line segments downslope of active RSL indicate that discontinuous and emergent RSL may be more widespread than found here, and that unusually active RSL seasons (e.g. following dust storms) may offer ideal opportunities to look for these types of anomalies. Targeting the capture of additional HiRISE image series with high temporal resolution in the early RSL growth season would allow further progress in detecting and confirming anomalous RSL behavior, especially in establishing the sequence of events in the collinear cases; this is not possible with currently available data in most instances.

5. Conclusions

We present observations of 11 occurrences of RSL which behave anomalously. The anomalous RSL are categorized into RSL which fade early, collinear segments which we interpret as RSL with a discontinuous surface expression, and RSL that initiate from locations with no visible surface features. We conclude because of the proximity of these RSL to others which behave typically that the processes driving RSL initiation, growth, and fading are very likely to be identical for both normal and anomalous activity. Therefore, observations of anomalous RSL provide new constraints on the mechanisms controlling the formation and occurrence of RSL.

We infer from our observations that (1) given that all proposed fading mechanisms should be locally consistent, the growth process must be highly localizable and (2) the process driving the growth of RSL can operate without detectable, long-lived surface expression. We evaluate two frequently proposed paradigms: aqueous fluid seeps which fade due to evaporation, and slow/intermittent grain flows which fade due to settling dust. Of these, seeping liquid is compatible with our observations of anomalous RSL, though the behavior of early faders carries different implications for each potential fluid source. The dry current mechanism, while potentially compatible with early fading, requires additional explanation to accommodate other anomalous RSL.
behavior. Further imaging, especially with high temporal resolution captured in the early RSL growth season of known sites of collinear segments, would assist in confirming the nature of these anomalies and would therefore help to constrain potential mechanisms for RSL formation. Supplementary data to this article can be found online at https://doi.org/10.1016/j.icarus.2020.114129.

Data availability

Data supporting the conclusions in this paper can be found in the supplemental tables and figures. Supplemental Table 1 gives information about the DTMs used for our survey. Supplemental Table 2 gives notes, precise locations, and relevant images for each occurrence of anomalous RSL behavior observed. The list of RSL sites used to determine survey locations can be found in the supplementary material of (Stillman et al., 2017; Stillman and Grimm, 2018). The supplemental figures illustrate each example of anomalous behavior.

Declaration of Competing Interest
None.

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