Granular flows at Recurring Slope Lineae on Mars indicate a limited role for liquid water

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Summary

Recent liquid water flow on Mars has been proposed based on geomorphological features, such as gullies. Recurring Slope Lineae—annually recurring narrow, down-slope flows that are darker than their surroundings and extend during warm seasons—are candidate locations for seeping liquid water on Mars today, but their formation mechanism remains unclear. Topographic analysis shows that the terminal slopes of Recurring Slope Lineae match the stopping angle for granular flows of cohesionless sand in active Martian aeolian dunes. In Eos Chasma, linea lengths vary widely and are longer where there are more extensive angle-of-repose slopes, inconsistent with models for water sources. These observations suggest that Recurring Slope Lineae are granular flows. The preference for warm seasons and detection of hydrated salts are consistent with some role for water in their initiation. However, liquid water volumes may be small or zero, alleviating Planetary Protection concerns about habitable environments.

Mars has widespread H_2O, including polar caps, ground ice, frosts, hydrated minerals, and water vapor. Deliquescence provides a mechanism to generate small amounts of transient liquid[1-4]. However, evidence for larger volumes is ambiguous. Evidence for recent liquid flow near the surface is based on remote sensing. Gullies[5] and Recurring Slope Lineae[6] (RSL) are the leading candidate locations for liquid flow. However, CO_2 frost-related processes are currently forming gully morphologies sometimes attributed to liquid water[7].

RSL are narrow, down-slope trending features, darker than their surroundings, that gradually extend in warm seasons, fade, and recur annually[6, 8-12]. They occur on steep rocky slopes in low-albedo regions, most commonly in southern mid-latitudes[6] and equatorial Valles Marineris[8, 11-12], and at a broad range of elevations[6,8,10-11]. RSL seasonal behavior is consistent with melting brines[13], and lengthening rates are similar to expectations for seepage[10, 14-15]. Liquid H_2O has not been detected spectrally, but surficial liquid should evaporate by the mid-afternoon when high-resolution spectra are acquired[16]. Thus, liquid flow has been the leading hypothesis for their formation, although poorly understood dry processes have not been ruled out[6, 8]. One dry model has been proposed[17] but only examined at one location. Thermal analysis is consistent with no water[18], but ambiguous due to interannual variations and limited temporal coverage[12]. Hydrated salts, likely chlorates or perchlorates, are transiently present in association with some RSL[19], suggesting a role for H_2O, but chloride salts are not observed[20].

Possible sources of water include the atmosphere, shallow ice, and groundwater[6, 8-12]. While Martian pressures and temperatures are occasionally above the H_2O triple point, producing and maintaining liquid on the surface is difficult, a recognized issue for

RSL[6, 21]. For typical Martian conditions, the latent heat flux due to sublimation at sub-melting temperatures is near the maximum possible insolation, so water ice cannot melt unless evaporation or other heat losses are strongly suppressed or the melting point lowered, as in a brine[22]. Atmospheric water vapor is unlikely to condense on warm slopes, while groundwater is unlikely to emerge on all sides of isolated peaks[11]. These challenges suggest that we should consider alternative models for RSL.

Evidence for Granular Flow Processes

We measured the terminal slopes of 151 RSL at ten well-studied sites (Table S1). The results (Fig. 1a) show that in nearly all cases the mean slope near the end of a linea is between 28°–35°. This range matches that of slipfaces for active Martian and terrestrial dunes[23], interpreted as the range of critical angles where granular flows of sand can terminate (often called the dynamic angle of repose), and is similar to earlier measurements of overall RSL slopes[6, 11, 17, 24]. We avoided clear artifacts or interpolated areas (Methods); the few points outside this slope range are likely due to artifacts in the topographic data. RSL slopes (or fans) are straight to slightly concave (Fig. 1b, Fig. S1), consistent with dry granular flows such as sand dune slipfaces, and unlike the strongly concave slope profiles produced by repeated debris flows or fluvial gullies[25]. Figure S2 shows RSL on weakly concave slopes, beginning at >35° and terminating near 30°.

The terminal slopes of RSL, identical to sand dunes, suggest that movement on those slopes is by dry grainflows. Aqueous flows could occur on such slopes and small volumes of liquid might only produce short lineae and prevent runout onto lower slopes. However, it is unlikely that water is only produced near the tops of slopes at these angles or that, if so, it is never able to flow onto lower slopes. RSL at a single site in Eos Chasma with widely varying lengths all terminate on similar slopes (Fig. S2). It is unlikely that liquid volume is the controlling variable—this would require the volume of liquid to correspond to the length of slope available, producing more liquid on longer slopes. (If RSL deposit material they could build their own slopes, but saturated flows should be more mobile than dry sandflows.) We therefore consider the primary mechanism of RSL motion to be dry granular flow.

Flows on a dune slipface at 27ºN provide a useful comparison (Animation S1). Similar RSL-like features have been noted for Coprates Chasma sand dunes near confirmed RSL[11], sometimes with RSL-like seasonality. Slipface lineae were present and grew more extensive, with some incremental growth, over several months. The lineae then disappeared, only to reappear in the following year. These lineae technically meet the definition of confirmed RSL (incremental growth, fading, and annual recurrence[8]), although the incremental growth is minor and may simply be overprinting by new flows. The dune slipface setting suggests that they are dry grainflows, particularly since they occur when aeolian transport is strongest (perihelion[26]) but northern-hemisphere temperatures are low and northern RSL are inactive[10]. We attribute the visibility of these lineae to the presence of a small amount of dust on the surface, as shown by dust devil tracks. The lineae are initially present at the same time as dust devil tracks, and both fade seasonally although the lineae require longer to fade as the dust is removed or redistributed. These tracks and lineae can fade much faster than crater blast zones or slope streaks[27] because they involve only superficial dust on a low-albedo surface. A few microns of dust can markedly brighten a dark surface[28].

These dunes demonstrate that grainflows on angle-of-repose slopes can sometimes seem to grow incrementally, and appear and disappear seasonally due to changes in surface dust, in contrast with an end-member model in which grainflows are isolated events that might require years to fade. This places many RSL characteristics on a spectrum of behaviors consistent in some ways with apparent grainflows. Diverse Martian lineae with anomalous seasonality, incomplete fading, and/or erratic growth can be explained as part of such a spectrum. However, annual recurrence is easier to explain on dunes with a constant sand supply, which is more challenging at many RSL sites.

A final dune-linea interaction provides additional evidence (Figs. 2, S3). Here a climbing dune encounters an outcrop with apparent RSL. Where the dune material is still free to advance up the slope, the dune has a slipface and no lineae. This suggests that RSL-like granular flows might form in some places where uphill movement of aeolian sand is blocked. The lineae often begin uphill from the fans, which may be due to some granular material higher on the slope; it is more challenging to explain recurrence in such cases.

Difficulties for Liquid Water Models

Subsurface ice or liquid will experience no net loss if the mean water vapor content over the ice is equal to that in the near-surface atmosphere[29-30]. Concentrated brines are more stable because the vapor pressure is reduced by a factor of the water activity, which is 0.4–0.6 for a range of likely salts[1, 31-32]. We used a thermal model[33] to determine temperatures for a 35° NW-facing slope at 40° S with sand-like granular material (a typical mid-latitude setting for RSL) and find that a water content of $\sim 7\times10^{20}$

molecules/m^3 is required to stabilize ice at the annual-average surface temperature. This is a lower bound on the true amount required for stability in the shallow subsurface since temperature cycles raise the mean vapor pressure[29-30]. This vapor content is sixteen times more than observed by the Phoenix lander[34] (4.3×10^{19} molecules/m^3), which is likely higher than the annual mean at most RSL sites, since Phoenix landed at a place and time with high water vapor column abundance. Typical brine activities are much too high to lower the vapor pressure by such a factor. The deliquescence relative humidity of calcium perchlorate can be as low as 5%, but only at temperatures >273 K[4]. At typical Martian shallow-subsurface temperatures, it also has an activity near 0.5[4, 32]. These are minimum requirements for stability of H_2O (i.e., no net loss to evaporation), and much more vapor would be needed to annually resupply water. Thus, although deliquesced liquid is sometimes stable on Mars[1-4], the volumes are probably limited and transient. A hysteresis effect allows solutions to stay in the liquid phase even when the humidity falls below the deliquescence relative humidity[1, 2, 4], but the solution may nevertheless evaporate.

H_2O could be stored in hydrated salts with low vapor pressure and annually liquefy[35], but the volumes will be limited by the amount of salt available and need for annual recharge. Deliquescence of Mg-perchlorate could occur where and when RSL are observed[36], but only within a narrow range of regolith parameters with ice present within a few meters of the surface. It is unlikely that ice is so shallow on warm slopes[30].

There is no theoretical difficulty with deep subsurface liquid on Mars, but it has not been detected by sounding radar[37], but this non-detection can be explained by attenuation[38]. RSL are a poor fit for groundwater release: they occur on isolated prominences[6, 11], their locations[11] show no correlation with trough-bounding faults in

Valles Marineris, and the southern highlands are unlikely locations for major groundwater upwelling[39]. Moreover, we have not observed large salt deposits, which would be expected if RSL are long-term sources of salts. To demonstrate this idea, we consider the implications of a briny-aquifer model. One groundwater model for RSL[10] suggests yearly outflow of 1.5–5.6 m^3/m headwall and >10 wt% salt. This should deposit a cubic meter of salts for every few years of activity, building deposits similar to terrestrial spring mounds, unless individual sites are only active over a negligible fraction of Martian history. This is unlikely: confirmed RSL occur at 7% of sites with steep, equator-facing, rocky, mid-latitude slopes imaged at high resolution, and candidate or partially-confirmed RSL at an additional 34%[24]. If individual sites were active for <<1% of Martian history, we should see lineae at <<1% of suitable sites, rather than >7%. Spectral constraints indicate that if chloride salts are involved, the upper limits on production are much lower than in aquifer models[20]. Therefore, the groundwater model for RSL requires a current, planet-wide burst of activity that is otherwise rare.

RSL as Granular Flows

A granular flow model must explain various characteristics of RSL including seasonality, incremental growth, darkening and fading, resupply of granular material, and the size fit between many RSL and their host gullies and fans. We next consider how these behaviors could occur and then discuss unresolved issues.

RSL grainflows could move aeolian sand with an upslope source or a trapped recirculating system, but this does not fully explain the seasonal behavior, as aeolian processes are most active at perihelion[26]. Although some slope lineae are anomalous, RSL generally show strong seasonality associated with warm slopes, including different timing on opposing slopes at single sites. This suggests some role for a volatile in their activity. Possibilities include hydration and volume changes in salts, or evaporation or boiling[40] of small amounts of deliquesced liquid, which could affect grain contact cohesion. Both are consistent with the detection of hydrated salts during RSL activity[19]. Some dry processes with seasonal dependencies could also trigger grainflows[17], although these do not explain the detection of hydrated salts. One possibility is that desorption of CO_2 (or H_2O) in warm seasons generates overpressure and destabilizes the slope. Viking Lander 1 observed two small summertime slope failures, perhaps initiated by this process[41]. Alternatively, pressure gradients generated by thermal creep could generate gas flow[17]. This model does not fully explain the seasonal presence and absence of lineae at even the one site considered in detail, but needs further testing. Other possibilities include thermal stresses or ephemeral frost dislodging grains and triggering flows.

Grainflows can halt mid-slope if the toe drops below a critical thickness[42], and repeated incremental flows can occur when grains are supplied too slowly to drive continuous flow[43]. Therefore, supply-limited grainflows do not necessarily halt immediately upon reaching some final slope value, and can reactivate to extend further down a similar slope. This permits RSL grainflows to occur within a straight or slightly concave slope approximating the angle of repose without reaching the end of the slope, and to grow incrementally and have variable lengths annually. Loss of cohesion could release more material from a grainflow headscarp or the triggering processes noted above could operate repeatedly, and merging lineae could supply added grains. For comparison, the sand of the "Namib" dune slipface in Gale crater has some cohesion[44], and soils at the Phoenix landing site lost cohesion after excavation[45] due to loss of H_2O.

Grainflows could be dark due to particle size and roughness effects. Surface dust on granular flows will rapidly sink due to kinetic sieving, or be ejected into suspension. Even low-albedo regions like the *Opportunity* rover landing site (which has a bolometric albedo[46] of 0.12, comparable to RSL sites) experience deposition of a micron of dust every 10–20 sols[47]. Few-micron dust coatings produce strong brightness changes[28], so redistribution of such traces may produce contrast in and out of lineae, although it is not clear if this is consistent with RSL colors. Transient detections of hydrated salts[19] may be caused by exposure of subsurface material with stable hydrates[35]. Annual fading would occur by some combination of dust redistribution, material changes upon exposure to surface conditions (*e.g.*, loss of H_2O from hydrated salts) and reworking by aeolian ripples.

Typical flows on sand dunes are a few cm thick. If RSL are similar, they would not produce topographic changes in HiRISE observations except after years of activity, and the net effect would be negligible if the erasure process transports grains back up the slope. A recirculating system or steady sand supply is required to resupply grainflows annually. Upslope ripple movement has been observed on some RSL fans[11] (Animation S2). It has not been demonstrated that this produces an equilibrium with uphill transport balancing grainflows, but where observed the two processes may be balanced. At many sites, ripples are not visible on RSL fans, but Mars has two scales of wind ripples and the smaller are not resolved by HiRISE[48]. A recirculating process could explain why RSL begin at outcrops or the steepest upper slopes, where grains moving upslope will accumulate. Flow separation in the lee of outcrops can create local up-slope winds[49], allowing upslope saltation on all sides of some hills or craters where RSL are distributed on different aspects.

RSL often originate at bedrock, and following them to their source can be challenging. However, lineae are most distinct on smooth fans[6, 24], which sometimes transition into wind-blown bedforms, particularly in Valles Marineris[8] (Fig. 3). This indicates that the grain size is often appropriate for sand flows. Some RSL cross talus slopes[11], with a mix of resolvable rocks and finer material, rather than being pure blocky rubble or pure sand; the lineae may disturb the finer-grained component. RSL also appear to cross bedrock in places, although some fine-grained material is likely present.

Previous issues with dry hypotheses[6] can now be addressed. RSL have been found in equatorial and northern latitudes. The reason for rare local concentrations may be the presence of salts, and/or an appropriate local wind regime. The association with rock outcrops may be because outcrops trap grains or concentrate grain movement.

A grainflow origin for RSL does have unresolved difficulties demanding further investigation. The most significant is the annual recurrence of RSL. Grainflows should remove sand-sized material from the source area and suppress activity in subsequent years. An active cycle of uphill sand movement can alleviate this issue at some sites[11] (Animation S2) but many others lack such evidence and would require unresolved sand movement, extending beyond the defined sandy fans. Some RSL appear to change color along-length, matching the colors of the adjacent surface (Fig. 3a). Additionally, RSL commonly have the same color as adjacent slopes, but surficial dust should redden the coarse-grained basaltic materials typical of low-albedo regions on Mars. These issues have not yet been studied broadly. Spectral changes suggest removal of fine-grained material during RSL activity[50] but were averaged over RSL fans, so the change within the lineae themselves is unclear. Finally, it is unclear whether the topographic effects of grainflows would allow lineae to repeat annually. Most RSL have produced no visible changes to the topography at HiRISE scale (apart from a few locations in Valles Marineris[11]), and we do not observe significant deposits up- or down-slope from boulders adjacent to RSL. However, we do often observe that RSL follow and closely fit small gullies and fans[8], so perhaps the recurring grain flows are sometimes from continual erosion. All of these issues point to directions for future study.

Importance of Dry RSL

Like gullies, RSL have been considered evidence for significant liquid water on Mars, although this is a major challenge given our understanding of the current climate. If both are essentially dry phenomena, this suggests that recent Mars has not had significant volumes of liquid water, consistent with older models[29]. Liquid on recent Mars may be limited to traces of deliquesced solutions with low water activity[1-4] and thin films of water[51-52], which are not known to be environments that can sustain life[53].

Flowing liquid water in the current Martian climate has always been an extraordinary claim. The observations and interpretations presented here suggest that RSL are no longer extraordinary evidence. There are major difficulties with all proposed sources of volumetrically significant water, the topography of RSL indicates a grainflow mechanism, and grainflows with some of the necessary characteristics occur on Martian dunes. Although some additional process is likely needed to explain all RSL characteristics, this suggests that they are essentially dry granular flow features. Additional processes could be related to deliquescence[35] or hydration, or to gas processes like thermal creep[17] or desorption, but any liquid water involved is likely to be low-volume with low activity, inhospitable to known terrestrial life, alleviating Planetary Protection concerns.

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Author Contributions

A.S.M., C.M.D., and M.C. planned many of the HiRISE observations to locate and study RSL. C.M.D. designed the study and gathered the slope data. A.O. and M.C. made observations of uphill ripple movement. M.C. assisted with DTM production. All authors contributed to discussion, interpretation, and writing.

Competing Financial Interests

The authors declare no competing financial interests.

Supplementary Materials

Supplementary information is available in the online version of the paper. Supplementary material for this paper includes supplementary text, Table S1, Figures S1–S4, and Supplementary Animations 1–2.

Figures and Captions

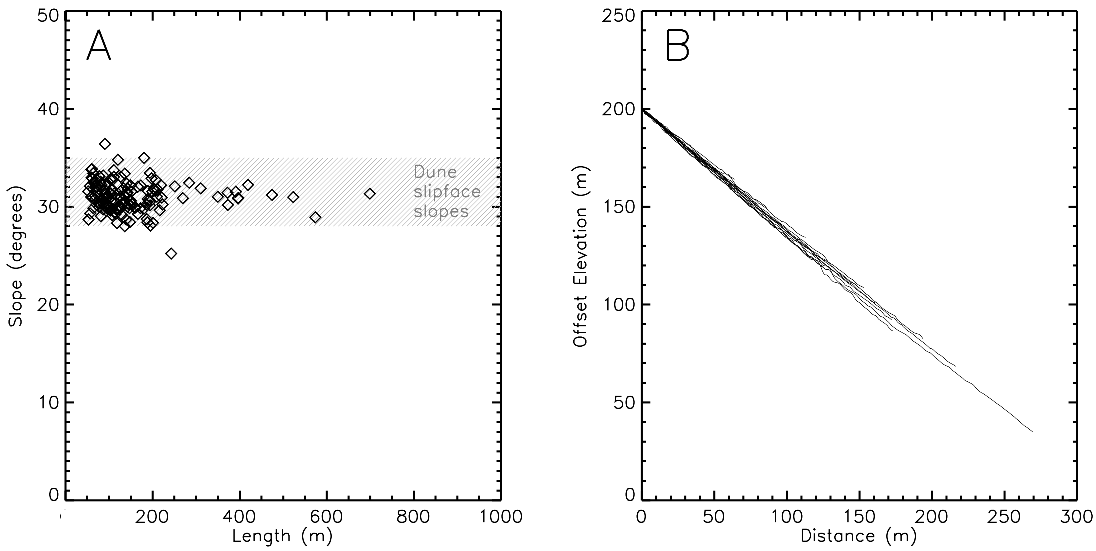

Figure 1 | RSL slopes and profiles. a, Along-linea slopes from near RSL termini (Supplementary Table 1). Slipface slope range (shaded area) is for dune slopes up to a few tens of meters long[23]. Lengths are plan-view, not slope-corrected. **b,** RSL profiles from Raga crater, arbitrarily offset to a constant starting elevation for comparison.

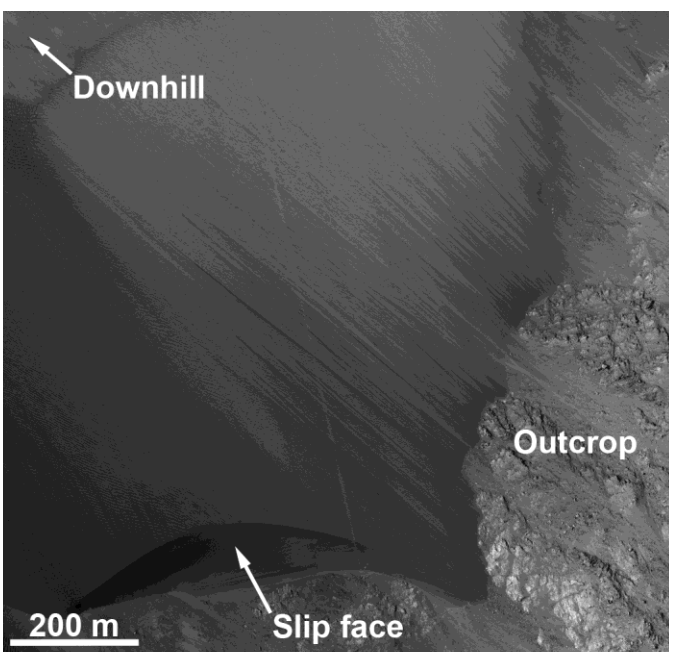

Figure 2 | Merger of a climbing dune and slope lineae. The dune is advancing up-slope with a slipface at lower left. Lineae due to return grainflow begin where the sand is prevented from advancing up-slope by a steep outcrop. See also ref. 11 and Fig. S3. (HiRISE image ESP_046619_1665, credit: NASA/JPL/University of Arizona.)

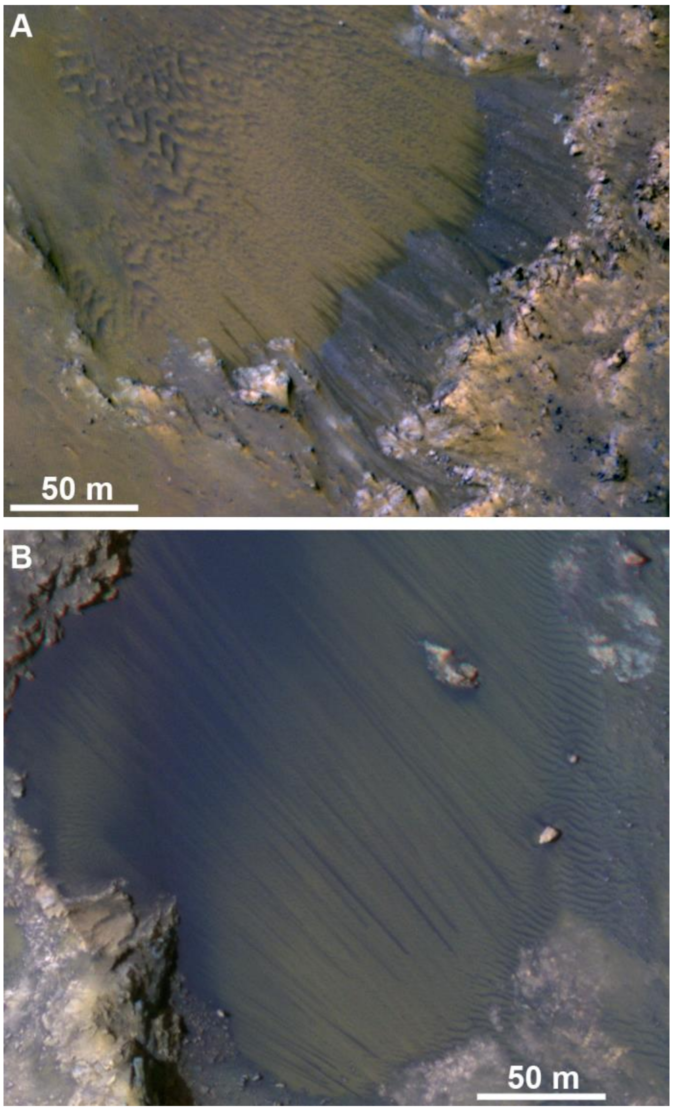

Figure 3 | RSL fans transitioning downhill into aeolian bedforms. a, RSL in Coprates Chasma with along-length color transitions. Downhill towards upper left. **b,** RSL with color similar to nearby sand. Lineae become indistinct in a mid-slope section with relatively-blue color similar to sand. Downhill towards lower right. (A:

ESP_027815_1670. B: ESP_032298_1650. HiRISE enhanced-color images, stretched for contrast, credit: NASA/JPL/University of Arizona.)

Methods

We used 1 m/post Digital Terrain Models (DTMs) derived from High Resolution Imaging Science Experiment (HiRISE) images[54-55] to examine along-linea profiles and terminal slopes of 151 RSL at ten sites (Supplementary Table 1), similar to Schaefer et al.[56]. These sites include many of the best-studied RSL on Mars, at diverse geographic locations and a range of scales. Linea paths were traced using orthorectified images, and we avoided obvious artifacts and interpolated regions in the DTMs by comparing with shaded-relief images. Minor artifacts may account for some of the scatter in the data. When RSL were densely packed, we chose only a few of the best-defined lineae from each cluster. This could introduce some bias, but the RSL from dense and sparse sites show the same slope behavior. To study lineae that were near their full length for the year, we used images from late in an active season for each site. Lengths vary somewhat from year to year. In order to understand the slopes over which RSL grow incrementally, we examined the terminal (lower) segments of the lineae. Upper slopes may be slightly steeper, but the mean slopes of the upper half of individual lineae never exceeded 38.5°. As precautions against small-scale noise and artifacts, we examined twenty meter-baseline slopes, and took the median of five separate twenty-meter segments from within the final thirty meters of the linea. Lineae were between 50–700 m long, and profiles range from linear to slightly concave (Fig. 1b). In a few cases, the tips of long lineae were excluded when they intersected significant DTM artifacts but were otherwise suitable for measurement, in effect moving the measurement slightly up-slope.

Data Availability

All HiRISE images and DTMs used in this study are available via the Planetary Data System and at www.hirise.lpl.arizona.edu.

Methods References

54. Kirk, R. L., et al. Ultrahigh resolution topographic mapping of Mars with MRO HiRISE stereo images: Meter-scale slopes of candidate Phoenix landing sites. *J. Geophys. Res.*, 113, E00A24, doi:10.1029/2007JE003000 (2008).
55. McEwen, A. S., et al. Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE). *J. Geophys. Res.*, 112, doi:10.1029/2005JE002605 (2007).
56. Schaefer, E. I., McEwen, A. S., Mattson, S., Ojha, L. Quantifying the behavior of Recurring Slope Lineae (RSL). Lunar Planet. Sci. Conf. 46, abstract #2930 (2015).