

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

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20 **Summary**

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

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36 Mars has widespread H₂O, including polar caps, ground ice, frosts, hydrated
37 minerals, and water vapor. Deliquescence provides a mechanism to generate small
38 amounts of transient liquid¹⁻⁴. However, evidence for larger volumes is ambiguous.
39 Evidence for recent liquid flow near the surface is based on remote sensing. Gullies⁵ and
40 Recurring Slope Lineae⁶ (RSL) are the leading candidate locations for liquid flow.
41 However, CO₂ frost-related processes are currently forming gully morphologies
42 sometimes attributed to liquid water⁷.

43 RSL are narrow, down-slope trending features, darker than their surroundings,
44 that gradually extend in warm seasons, fade, and recur annually^{6, 8-12}. They occur on steep
45 rocky slopes in low-albedo regions, most commonly in southern mid-latitudes⁶ and
46 equatorial Valles Marineris^{8, 11-12}, and at a broad range of elevations^{6,8,10-11}. RSL seasonal
47 behavior is consistent with melting brines¹³, and lengthening rates are similar to
48 expectations for seepage^{10, 14-15}. Liquid H₂O has not been detected spectrally, but surficial
49 liquid should evaporate by the mid-afternoon when high-resolution spectra are
50 acquired¹⁶. Thus, liquid flow has been the leading hypothesis for their formation,
51 although poorly understood dry processes have not been ruled out^{6, 8}. One dry model has
52 been proposed¹⁷ but only examined at one location. Thermal analysis is consistent with
53 no water¹⁸, but ambiguous due to interannual variations and limited temporal coverage¹².
54 Hydrated salts, likely chlorates or perchlorates, are transiently present in association with
55 some RSL¹⁹, suggesting a role for H₂O, but chloride salts are not observed²⁰.

56 Possible sources of water include the atmosphere, shallow ice, and groundwater^{6,}
57 ⁸⁻¹². While Martian pressures and temperatures are occasionally above the H₂O triple
58 point, producing and maintaining liquid on the surface is difficult, a recognized issue for

59 RSL^{6, 21}. For typical Martian conditions, the latent heat flux due to sublimation at sub-
60 melting temperatures is near the maximum possible insolation, so water ice cannot melt
61 unless evaporation or other heat losses are strongly suppressed or the melting point
62 lowered, as in a brine²². Atmospheric water vapor is unlikely to condense on warm
63 slopes, while groundwater is unlikely to emerge on all sides of isolated peaks¹¹. These
64 challenges suggest that we should consider alternative models for RSL.

65

66 **Evidence for Granular Flow Processes**

67 We measured the terminal slopes of 151 RSL at ten well-studied sites (Table S1).
68 The results (Fig. 1a) show that in nearly all cases the mean slope near the end of a linea is
69 between 28°–35°. This range matches that of slipfaces for active Martian and terrestrial
70 dunes²³, interpreted as the range of critical angles where granular flows of sand can
71 terminate (often called the dynamic angle of repose), and is similar to earlier
72 measurements of overall RSL slopes^{6, 11, 17, 24}. We avoided clear artifacts or interpolated
73 areas (Methods); the few points outside this slope range are likely due to artifacts in the
74 topographic data. RSL slopes (or fans) are straight to slightly concave (Fig. 1b, Fig. S1),
75 consistent with dry granular flows such as sand dune slipfaces, and unlike the strongly
76 concave slope profiles produced by repeated debris flows or fluvial gullies²⁵. Figure S2
77 shows RSL on weakly concave slopes, beginning at >35° and terminating near 30°.

78 The terminal slopes of RSL, identical to sand dunes, suggest that movement on
79 those slopes is by dry grainflows. Aqueous flows could occur on such slopes and small
80 volumes of liquid might only produce short lineae and prevent runout onto lower slopes.
81 However, it is unlikely that water is only produced near the tops of slopes at these angles

82 or that, if so, it is never able to flow onto lower slopes. RSL at a single site in Eos
83 Chasma with widely varying lengths all terminate on similar slopes (Fig. S2). It is
84 unlikely that liquid volume is the controlling variable—this would require the volume of
85 liquid to correspond to the length of slope available, producing more liquid on longer
86 slopes. (If RSL deposit material they could build their own slopes, but saturated flows
87 should be more mobile than dry sandflows.) We therefore consider the primary
88 mechanism of RSL motion to be dry granular flow.

89 Flows on a dune slipface at 27°N provide a useful comparison (Animation S1).
90 Similar RSL-like features have been noted for Coprates Chasma sand dunes near
91 confirmed RSL¹¹, sometimes with RSL-like seasonality. Slipface lineae were present and
92 grew more extensive, with some incremental growth, over several months. The lineae
93 then disappeared, only to reappear in the following year. These lineae technically meet
94 the definition of confirmed RSL (incremental growth, fading, and annual recurrence⁸),
95 although the incremental growth is minor and may simply be overprinting by new flows.
96 The dune slipface setting suggests that they are dry grainflows, particularly since they
97 occur when aeolian transport is strongest (perihelion²⁶) but northern-hemisphere
98 temperatures are low and northern RSL are inactive¹⁰. We attribute the visibility of these
99 lineae to the presence of a small amount of dust on the surface, as shown by dust devil
100 tracks. The lineae are initially present at the same time as dust devil tracks, and both fade
101 seasonally although the lineae require longer to fade as the dust is removed or
102 redistributed. These tracks and lineae can fade much faster than crater blast zones or
103 slope streaks²⁷ because they involve only superficial dust on a low-albedo surface. A few
104 microns of dust can markedly brighten a dark surface²⁸.

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

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

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121 **Difficulties for Liquid Water Models**

122 Subsurface ice or liquid will experience no net loss if the mean water vapor
123 content over the ice is equal to that in the near-surface atmosphere²⁹⁻³⁰. Concentrated
124 brines are more stable because the vapor pressure is reduced by a factor of the water
125 activity, which is 0.4–0.6 for a range of likely salts^{1, 31-32}. We used a thermal model³³ to
126 determine temperatures for a 35° NW-facing slope at 40° S with sand-like granular
127 material (a typical mid-latitude setting for RSL) and find that a water content of $\sim 7 \times 10^{20}$

128 molecules/m³ is required to stabilize ice at the annual-average surface temperature. This
129 is a lower bound on the true amount required for stability in the shallow subsurface since
130 temperature cycles raise the mean vapor pressure²⁹⁻³⁰. This vapor content is sixteen times
131 more than observed by the Phoenix lander³⁴ (4.3×10^{19} molecules/m³), which is likely
132 higher than the annual mean at most RSL sites, since Phoenix landed at a place and time
133 with high water vapor column abundance. Typical brine activities are much too high to
134 lower the vapor pressure by such a factor. The deliquescence relative humidity of calcium
135 perchlorate can be as low as 5%, but only at temperatures >273 K⁴. At typical Martian
136 shallow-subsurface temperatures, it also has an activity near 0.5^{4, 32}. These are minimum
137 requirements for stability of H₂O (i.e., no net loss to evaporation), and much more vapor
138 would be needed to annually resupply water. Thus, although deliquesced liquid is
139 sometimes stable on Mars¹⁻⁴, the volumes are probably limited and transient. A hysteresis
140 effect allows solutions to stay in the liquid phase even when the humidity falls below the
141 deliquescence relative humidity^{1, 2, 4}, but the solution may nevertheless evaporate.

142 H₂O could be stored in hydrated salts with low vapor pressure and annually
143 liquefy³⁵, but the volumes will be limited by the amount of salt available and need for
144 annual recharge. Deliquescence of Mg-perchlorate could occur where and when RSL are
145 observed³⁶, but only within a narrow range of regolith parameters with ice present within
146 a few meters of the surface. It is unlikely that ice is so shallow on warm slopes³⁰.

147 There is no theoretical difficulty with deep subsurface liquid on Mars, but it has
148 not been detected by sounding radar³⁷, but this non-detection can be explained by
149 attenuation³⁸. RSL are a poor fit for groundwater release: they occur on isolated
150 prominences^{6, 11}, their locations¹¹ show no correlation with trough-bounding faults in

151 Valles Marineris, and the southern highlands are unlikely locations for major
152 groundwater upwelling³⁹. Moreover, we have not observed large salt deposits, which
153 would be expected if RSL are long-term sources of salts. To demonstrate this idea, we
154 consider the implications of a briny-aquifer model. One groundwater model for RSL¹⁰
155 suggests yearly outflow of 1.5–5.6 m³/m headwall and >10 wt% salt. This should deposit
156 a cubic meter of salts for every few years of activity, building deposits similar to
157 terrestrial spring mounds, unless individual sites are only active over a negligible fraction
158 of Martian history. This is unlikely: confirmed RSL occur at 7% of sites with steep,
159 equator-facing, rocky, mid-latitude slopes imaged at high resolution, and candidate or
160 partially-confirmed RSL at an additional 34%²⁴. If individual sites were active for <<1%
161 of Martian history, we should see lineae at <<1% of suitable sites, rather than >7%.
162 Spectral constraints indicate that if chloride salts are involved, the upper limits on
163 production are much lower than in aquifer models²⁰. Therefore, the groundwater model
164 for RSL requires a current, planet-wide burst of activity that is otherwise rare.

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166 **RSL as Granular Flows**

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

171 RSL grainflows could move aeolian sand with an upslope source or a trapped
172 recirculating system, but this does not fully explain the seasonal behavior, as aeolian
173 processes are most active at perihelion²⁶. Although some slope lineae are anomalous,

174 RSL generally show strong seasonality associated with warm slopes, including different
175 timing on opposing slopes at single sites. This suggests some role for a volatile in their
176 activity. Possibilities include hydration and volume changes in salts, or evaporation or
177 boiling⁴⁰ of small amounts of deliquesced liquid, which could affect grain contact
178 cohesion. Both are consistent with the detection of hydrated salts during RSL activity¹⁹.
179 Some dry processes with seasonal dependencies could also trigger grainflows¹⁷, although
180 these do not explain the detection of hydrated salts. One possibility is that desorption of
181 CO₂ (or H₂O) in warm seasons generates overpressure and destabilizes the slope. Viking
182 Lander 1 observed two small summertime slope failures, perhaps initiated by this
183 process⁴¹. Alternatively, pressure gradients generated by thermal creep could generate gas
184 flow¹⁷. This model does not fully explain the seasonal presence and absence of lineae at
185 even the one site considered in detail, but needs further testing. Other possibilities
186 include thermal stresses or ephemeral frost dislodging grains and triggering flows.

187 Grainflows can halt mid-slope if the toe drops below a critical thickness⁴², and
188 repeated incremental flows can occur when grains are supplied too slowly to drive
189 continuous flow⁴³. Therefore, supply-limited grainflows do not necessarily halt
190 immediately upon reaching some final slope value, and can reactivate to extend further
191 down a similar slope. This permits RSL grainflows to occur within a straight or slightly
192 concave slope approximating the angle of repose without reaching the end of the slope,
193 and to grow incrementally and have variable lengths annually. Loss of cohesion could
194 release more material from a grainflow headscarp or the triggering processes noted above
195 could operate repeatedly, and merging lineae could supply added grains. For comparison,

196 the sand of the “Namib” dune slipface in Gale crater has some cohesion⁴⁴, and soils at the
197 Phoenix landing site lost cohesion after excavation⁴⁵ due to loss of H₂O.

198 Grainflows could be dark due to particle size and roughness effects. Surface dust
199 on granular flows will rapidly sink due to kinetic sieving, or be ejected into suspension.
200 Even low-albedo regions like the *Opportunity* rover landing site (which has a bolometric
201 albedo⁴⁶ of 0.12, comparable to RSL sites) experience deposition of a micron of dust
202 every 10–20 sols⁴⁷. Few-micron dust coatings produce strong brightness changes²⁸, so
203 redistribution of such traces may produce contrast in and out of lineae, although it is not
204 clear if this is consistent with RSL colors. Transient detections of hydrated salts¹⁹ may be
205 caused by exposure of subsurface material with stable hydrates³⁵. Annual fading would
206 occur by some combination of dust redistribution, material changes upon exposure to
207 surface conditions (*e.g.*, loss of H₂O from hydrated salts) and reworking by aeolian
208 ripples.

209 Typical flows on sand dunes are a few cm thick. If RSL are similar, they would
210 not produce topographic changes in HiRISE observations except after years of activity,
211 and the net effect would be negligible if the erasure process transports grains back up the
212 slope. A recirculating system or steady sand supply is required to resupply grainflows
213 annually. Upslope ripple movement has been observed on some RSL fans¹¹ (Animation
214 S2). It has not been demonstrated that this produces an equilibrium with uphill transport
215 balancing grainflows, but where observed the two processes may be balanced. At many
216 sites, ripples are not visible on RSL fans, but Mars has two scales of wind ripples and the
217 smaller are not resolved by HiRISE⁴⁸. A recirculating process could explain why RSL
218 begin at outcrops or the steepest upper slopes, where grains moving upslope will

219 accumulate. Flow separation in the lee of outcrops can create local up-slope winds⁴⁹,
220 allowing upslope saltation on all sides of some hills or craters where RSL are distributed
221 on different aspects.

222 RSL often originate at bedrock, and following them to their source can be
223 challenging. However, lineae are most distinct on smooth fans^{6, 24}, which sometimes
224 transition into wind-blown bedforms, particularly in Valles Marineris⁸ (Fig. 3). This
225 indicates that the grain size is often appropriate for sand flows. Some RSL cross talus
226 slopes¹¹, with a mix of resolvable rocks and finer material, rather than being pure blocky
227 rubble or pure sand; the lineae may disturb the finer-grained component. RSL also appear
228 to cross bedrock in places, although some fine-grained material is likely present.

229 Previous issues with dry hypotheses⁶ can now be addressed. RSL have been found
230 in equatorial and northern latitudes. The reason for rare local concentrations may be the
231 presence of salts, and/or an appropriate local wind regime. The association with rock
232 outcrops may be because outcrops trap grains or concentrate grain movement.

233 A grainflow origin for RSL does have unresolved difficulties demanding further
234 investigation. The most significant is the annual recurrence of RSL. Grainflows should
235 remove sand-sized material from the source area and suppress activity in subsequent
236 years. An active cycle of uphill sand movement can alleviate this issue at some sites¹¹
237 (Animation S2) but many others lack such evidence and would require unresolved sand
238 movement, extending beyond the defined sandy fans. Some RSL appear to change color
239 along-length, matching the colors of the adjacent surface (Fig. 3a). Additionally, RSL
240 commonly have the same color as adjacent slopes, but surficial dust should redden the
241 coarse-grained basaltic materials typical of low-albedo regions on Mars. These issues

242 have not yet been studied broadly. Spectral changes suggest removal of fine-grained
243 material during RSL activity⁵⁰ but were averaged over RSL fans, so the change within the
244 lineae themselves is unclear. Finally, it is unclear whether the topographic effects of
245 grainflows would allow lineae to repeat annually. Most RSL have produced no visible
246 changes to the topography at HiRISE scale (apart from a few locations in Valles
247 Marineris¹¹), and we do not observe significant deposits up- or down-slope from boulders
248 adjacent to RSL. However, we do often observe that RSL follow and closely fit small
249 gullies and fans⁸, so perhaps the recurring grain flows are sometimes from continual
250 erosion. All of these issues point to directions for future study.

251

252 **Importance of Dry RSL**

253 Like gullies, RSL have been considered evidence for significant liquid water on
254 Mars, although this is a major challenge given our understanding of the current climate. If
255 both are essentially dry phenomena, this suggests that recent Mars has not had significant
256 volumes of liquid water, consistent with older models²⁹. Liquid on recent Mars may be
257 limited to traces of deliquesced solutions with low water activity¹⁻⁴ and thin films of
258 water⁵¹⁻⁵², which are not known to be environments that can sustain life⁵³.

259 Flowing liquid water in the current Martian climate has always been an
260 extraordinary claim. The observations and interpretations presented here suggest that
261 RSL are no longer extraordinary evidence. There are major difficulties with all proposed
262 sources of volumetrically significant water, the topography of RSL indicates a grainflow
263 mechanism, and grainflows with some of the necessary characteristics occur on Martian
264 dunes. Although some additional process is likely needed to explain all RSL

265 characteristics, this suggests that they are essentially dry granular flow features.
266 Additional processes could be related to deliquescence³⁵ or hydration, or to gas processes
267 like thermal creep¹⁷ or desorption, but any liquid water involved is likely to be low-
268 volume with low activity, inhospitable to known terrestrial life, alleviating Planetary
269 Protection concerns.

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402

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410

411 **Author Contributions**

412 A.S.M., C.M.D., and M.C. planned many of the HiRISE observations to locate and study

413 RSL. C.M.D. designed the study and gathered the slope data. A.O. and M.C. made

414 observations of uphill ripple movement. M.C. assisted with DTM production. All authors

415 contributed to discussion, interpretation, and writing.

416

417 **Competing Financial Interests**

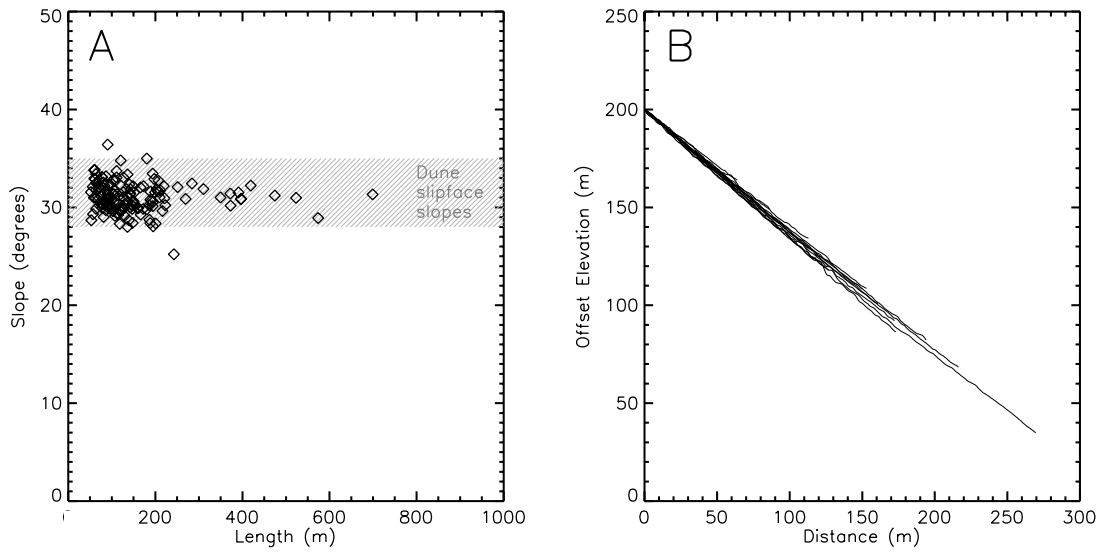
418 The authors declare no competing financial interests.

419

420 **Supplementary Materials**

421 Supplementary information is available in the online version of the paper. Supplementary
422 material for this paper includes supplementary text, Table S1, Figures S1–S4, and
423 Supplementary Animations 1–2.
424

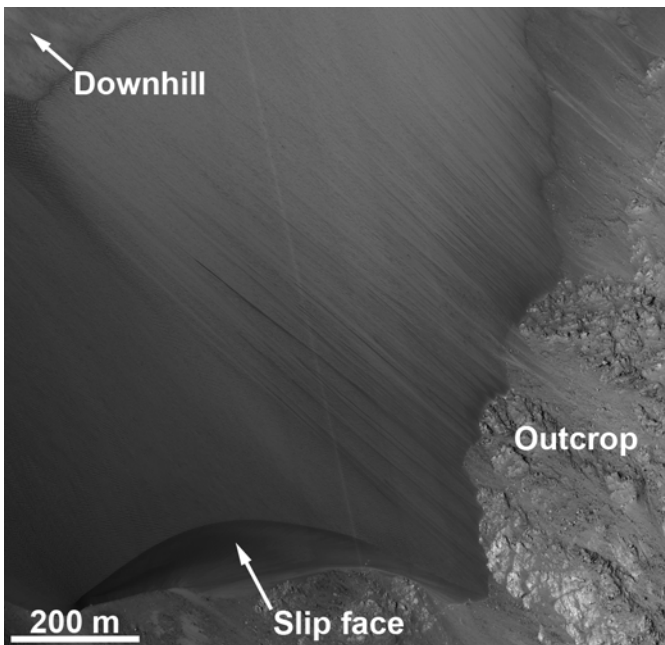
425 **Figures and Captions**



426

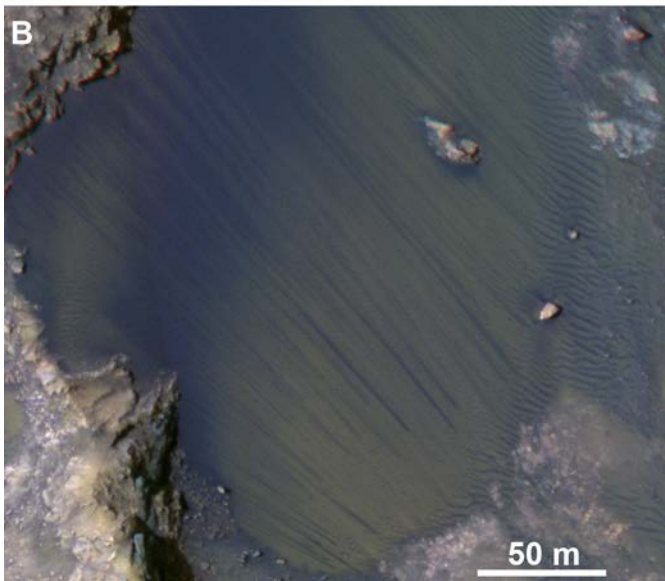
427 **Figure 1 | RSL slopes and profiles. a**, Along-linea slopes from near RSL termini
428 (Supplementary Table 1). Slipface slope range (shaded area) is for dune slopes up to a
429 few tens of meters long²³. Lengths are plan-view, not slope-corrected. **b**, RSL profiles
430 from Raga crater, arbitrarily offset to a constant starting elevation for comparison.

431



432

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



437
438 **Figure 3 | RSL fans transitioning downhill into aeolian bedforms.** **a**, RSL in Coprates
439 Chasma with along-length color transitions. Downhill towards upper left. **b**, RSL with
440 color similar to nearby sand. Lineae become indistinct in a mid-slope section with
441 relatively-blue color similar to sand. Downhill towards lower right. (A:

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

444

445 **Methods**

446 We used 1 m/post Digital Terrain Models (DTMs) derived from High Resolution
447 Imaging Science Experiment (HiRISE) images⁵⁴⁻⁵⁵ to examine along-linea profiles and
448 terminal slopes of 151 RSL at ten sites (Supplementary Table 1), similar to Schaefer et
449 al.⁵⁶. These sites include many of the best-studied RSL on Mars, at diverse geographic
450 locations and a range of scales. Linea paths were traced using orthorectified images, and
451 we avoided obvious artifacts and interpolated regions in the DTMs by comparing with
452 shaded-relief images. Minor artifacts may account for some of the scatter in the data.
453 When RSL were densely packed, we chose only a few of the best-defined lineae from
454 each cluster. This could introduce some bias, but the RSL from dense and sparse sites
455 show the same slope behavior. To study lineae that were near their full length for the
456 year, we used images from late in an active season for each site. Lengths vary somewhat
457 from year to year. In order to understand the slopes over which RSL grow incrementally,
458 we examined the terminal (lower) segments of the lineae. Upper slopes may be slightly
459 steeper, but the mean slopes of the upper half of individual lineae never exceeded 38.5°.
460 As precautions against small-scale noise and artifacts, we examined twenty meter-
461 baseline slopes, and took the median of five separate twenty-meter segments from within
462 the final thirty meters of the linea. Lineae were between 50–700 m long, and profiles
463 range from linear to slightly concave (Fig. 1b). In a few cases, the tips of long lineae were

464 excluded when they intersected significant DTM artifacts but were otherwise suitable for
465 measurement, in effect moving the measurement slightly up-slope.

466

467 **Data Availability**

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

470

471 **Methods References**

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