A GRANULAR FLOW MODEL FOR RECURRING SLOPE LINEAE ON MARS. C. M. Dundas[1], A. S. McEwen[2], M. Chojnacki[2], M. P. Milazzo[1], S. Byrne[2], [1]U.S. Geological Survey, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001, USA (cdundas@usgs.gov), [2]The University of Arizona, Lunar and Planetary Laboratory, 1541 E. University Blvd., Tucson, AZ 85721, USA.

Introduction: Recurring Slope Lineae (RSL; Fig. 1) are considered candidate locations for present-day near-surface liquid water on Mars [1-6], which makes them of high importance for understanding Martian geology, chemistry, climate, and habitability. RSL are surface flows, darker than their surroundings, that gradually move down steep slopes during warm seasons—behavior suggestive of seeping water, as in some terrestrial analogs [e.g., 7]. However, hypotheses invoking liquid water on Mars today must reckon with the extremely cold, arid climate. In light of this challenge, we consider the possibility that RSL involve little or no liquid water.

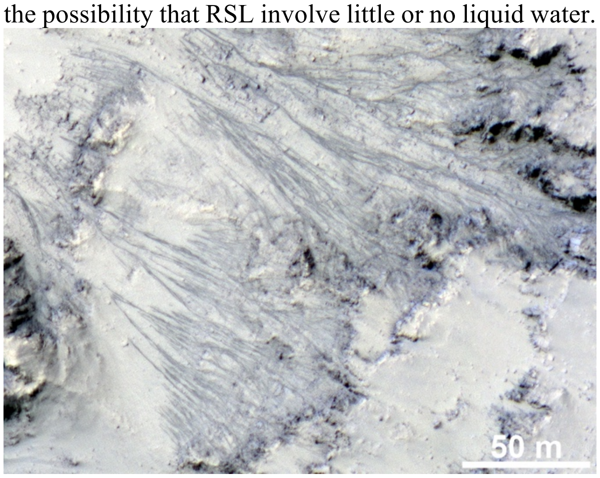

Figure 1: RSL in Palikir crater. Downhill to upper left. (HiRISE PSP_005943_1380, light from left, north up).

Observations: We used high-resolution (1 m/post) Digital Terrain Models (DTMs) generated from High Resolution Imaging Science Experiment (HiRISE) data to examine the longitudinal profiles of RSL at nine sites at a range of latitudes. Previous studies have noted that the overall average slopes of RSL are quite steep [1,3,8] and that at one site RSL have near-linear longitudinal profiles [9]. Here we focus on the terminal slopes, on which RSL incrementally grow and eventually halt. We examined 20-m-baseline slopes in order to reduce the effects of DTM noise, and avoided locations with obvious artifacts. RSL were examined late in the growth season, when near full length. At locations with extremely large numbers of RSL, we selected only a subset for measurement in order to avoid over-weighting those locations in our data.

The results indicate that RSL terminate almost exclusively on slopes of 28–35°, regardless of location. This range of slopes matches the slipfaces of active Martian dunes measured by Atwood-Stone and McEwen [10], which must be at the dynamic angle of repose for unconsolidated sand. The full profiles range from linear to slightly concave, similar to observations by Schaefer et al. [9]. The terminal slope is independent of the length of the linea, both in general and at specific sites. Linea lengths ranged from roughly 50–700 m. RSL in general can be over 1 km long.

Discussion: These slope observations suggest that RSL are granular flows similar to those that form on sand dunes. It is unlikely that liquid water would only be able to form and flow on angle-of-repose slopes, across a range of latitudes and seasons. Further, RSL of different lengths have identical terminal slopes, but it is unlikely that liquid-generating processes would produce variable volumes that always terminate on such slopes. At one measurement site in Eos Chasma, RSL have similar terminal slopes despite over an order of magnitude difference in length, and their lengths appear controlled by the availability of suitable steep slopes.

A granular flow mechanism resolves the fundamental gap between RSL processes and our understanding of current Martian surface and atmospheric conditions. However, several characteristics of RSL suggested seeping liquid and do not match our expectations for granular flows. How can this be reconciled?

One option is that a small amount of H_2O is involved in RSL, triggering effectively-dry granular flows. Some possible explanations include volume or cohesion changes associated with hydration and dehydration of salts, or deliquescence and loss of traces of brine. Consistent with these possibilities, hydrated salts transiently appear at some RSL sites [11]. An H_2O-free model in which aeolian processes reset RSL slopes is possible, and upslope ripple movement has been observed on an RSL apron [8]. However, RSL favor warm seasons, sometimes switching slopes seasonally [2], placing some activity in the low-atmospheric-pressure season (when aeolian activity is low [12]), so some additional factor is required for an H_2O-free model. One possibility is insolation effects [cf. 13] but those should be most effective on very fine dust. Thermal cycling or displacement by non-melting frost are also possible [see 14].

Incremental growth of granular flows on near-constant angle-of-repose slopes is also puzzling. However, grainflows on sand dune slopes can halt partway down a slipface [15], and experiments indicate that flows can halt if the toe thins [16]. Growth can be explained if flows are reactivated by a fresh supply of grains from above. This could occur if the grains in the source region lose cohesion when exposed to the atmosphere, as observed in scooped soils at the Phoenix landing site [17].

Dark granular flows with some of the required properties occur on some Martian dunes (Fig. 2) [8, 18]. These grainflows appear to grow incrementally in some cases (likely due to overprinting by fresh flows) and are seasonally visible. This seasonality is due to the presence of surface dust (as shown by the variable presence of dust devil tracks), which provides contrast when removed by sandflows. These dune lineae are not classic RSL, but demonstrate that dune grainflows can have several of their characteristics.

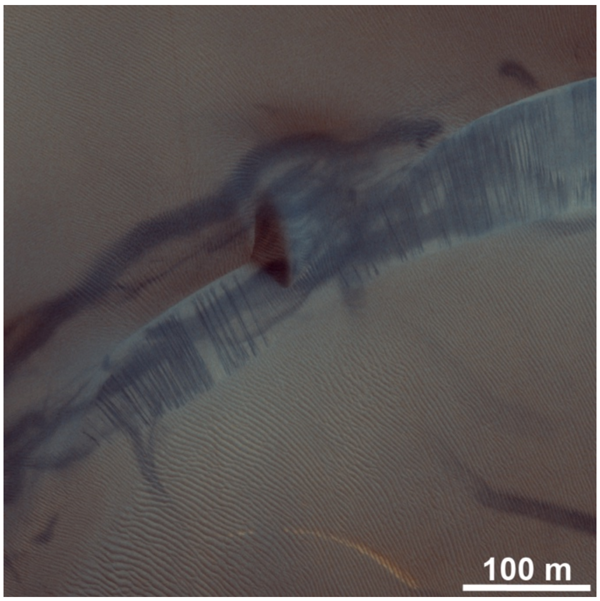

Figure 2: Dark lineae on sand dunes. At this site, the lineae are most distinct when there is a small amount of dust present on the dunes, as shown by the dust devil tracks. (HiRISE ESP_023327_2065, light from left, north up.)

The granular flow model for RSL is consistent with the low upper limits on water abundance derived using THEMIS thermal data [19] and the lack of spectral detections of liquid. It is also consistent with the profusion of RSL immediately after the major 2007 dust storm [1,4], which could have moved enough material to destabilize the surface, and/or provided a fresh coat of dust for contrast. RSL fans in Valles Marineris commonly blend into aeolian ripples (Fig. 3), demonstrating that the material is sand-sized.

There are some open questions remaining within the grainflow model. Some RSL appear to change color along-length, particularly at transitions between substrates; this might reflect sub-pixel mixing or changes in the grainflow but requires further investigation. The aeolian processes needed to restore the system each year are also not fully understood, as many RSL are not associated with obvious climbing dunes or ripples.

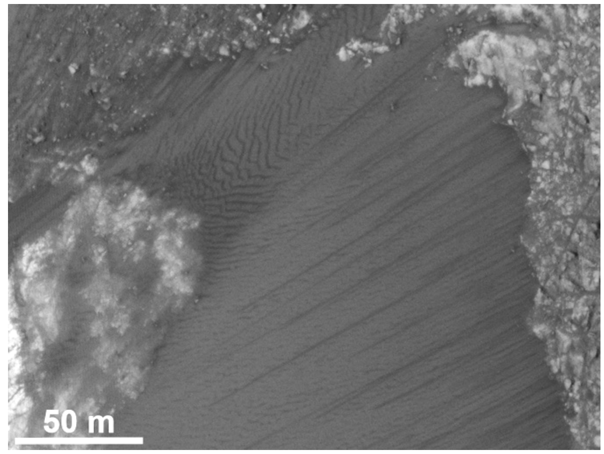

Figure 3: RSL fan merging into aeolian ripples. (HiRISE image ESP_031876_1650, light from left, north up.)

Conclusions: Slope measurements suggest that RSL are granular flows, although small amounts of H_2O may be involved in their initiation. This is consistent with our understanding of the current Martian climate and suggests dry conditions at present and likely in the geologically recent past. Dry or nearly-dry RSL would be inhospitable to terrestrial life and would likely not be favorable habitats for putative Martian biota.

Acknowledgments: We thank Mars Data Analysis Program NNX13AK01G and MRO/HiRISE for funding.

References: [1] McEwen A. S. et al. (2011) *Science*, 333, 2330-2335. [2] McEwen A. S. et al. (2014) *Nature Geosci*., 7, 53-58. [3] Ojha L. et al. (2014) *Icarus*, 231, 365-376. [4] Stillman D. E. et al. (2014) *Icarus*, 233, 328-341. [5] Stillman D. E. et al. (2016) *Icarus*, 265, 125-138. [6] Rummel J. D. et al. (2014) *Astrobiology*, 14, 887-968. [7] Levy J. (2012) *Icarus*, 219, 1-4. [8] Chojnacki M. et al. (2016) *J. Geophys. Res.*, 121, doi:10.1002/2015JE004991. [9] Schaefer E. I. et al. (2015) *LPSC* 46, abstract #2930. [10] Atwood-Stone C. and McEwen A. S. (2013) *Geophys. Res. Lett.*, 40, 2929-2934. [11] Ojha L. et al. (2015) *Nature Geosci.*, 8, 829-833. [12] Ayoub F. et al. (2014) *Nature Comms*., 5, doi:10.1038/ncomms6096. [13] de Beule C. et al. (2014) *Icarus*, 260, 23-28. [14] Bridges N. T. et al. (2017), this meeting. [15] Pelletier J. D. et al. (2015) *J. Geophys. Res. Earth Surf.*, 120, 1911-1934. [16] McDonald R. R. and Anderson R. S. (1996) *J. Sediment. Res.*, 66, 642-653. [17] Hecht M. H. et al. (2009) *Science*, 325, 64-67. [18] Fenton L. K. (2006) *Geophys. Res. Lett.*, 33, doi:10.1029/2006GL027133. [19] Edwards C. S. and Piqueux S. (2016) *Geophys. Res. Lett.*, 43, doi:10.1002/2016GL070179.