

RECURRING SLOPE LINEAE: WARM-SEASON INCREMENTAL FLOWS IN THE MIDDLE SOUTHERN LATITUDES OF MARS.

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Introduction: Mid-latitude processes today may be polar processes in different obliquities, and processes involving volatiles are relevant to polar science. Recurring slope lineae (RSL) are relatively low-albedo features that extend downslope from bedrock outcrops, often associated with small channels, and hundreds of them may form in rare locations [1]. RSL appear and lengthen in the late southern spring/summer from 52°S to 32°S latitudes, favoring equator-facing slopes--times and places with peak surface temperatures from ~250-300 K. Liquid brines near the surface might explain this activity, but the mechanism and source of water are not understood.

Observations: MRO's High Resolution Imaging Science Experiment (HiRISE) [2] provides the primary dataset for these meter-scale features. RSL are narrow (0.5-5 m) markings, up to ~40% darker than their surroundings, on steep slopes (>25°; Figure 1); they are recurring—forming and growing in the warm season (late spring to early fall) and fading or vanishing in cold seasons. There may be significant interannual variations in the abundances, lengths, and exact locations of the RSL. Confirmed RSL have been found to date at 9 locations (Table 1), often with many separate clusters. There are 12 other likely RSL sites and 20 candidate sites. RSL have lengths up to hundreds of meters, and more than 10³ lineae may be present in a HiRISE observation.

Our survey of steep slopes has identified confirmed and likely RSL only from 32°S to 52°S latitudes, favoring equator-facing slopes. There are also 8 candidate RSL sites in equatorial regions (18°S to 19°N), but they are few in number at each site and the seasonal recurrence has not been confirmed. Where repeat imaging within a Mars year is available, RSL are observed to form and grow from late southern spring to early fall (Ls ~245-360 and 0-20), and to fade or disappear in other seasons (Ls 20-245). Since they terminate on steep slopes, RSL lengths must be controlled by a limited volume of mobile material. There are up to 8 images per season for confirmed RSL sites, which show that they grow incrementally but not concurrently at uniform rates. Measured growth rates range from 0 to 20 m/day on average.

RSL occur in the classical dark regions of Mars, which have moderate thermal inertias. Determining the composition of RSL from orbit is challenging, as they are much smaller than the ~18 m pixel scale of

MRO's Compact Reconnaissance Imaging Spectrometer for Mars, CRISM [3]. RSL cover a substantial fraction of resolvable slopes in some areas, but no distinctive spectral features have been identified, including the strong absorption features expected from even small quantities of water. Hydrated minerals are associated with bedrock at several RSL sites, but there is no known correlation between RSL regions and particular minerals.

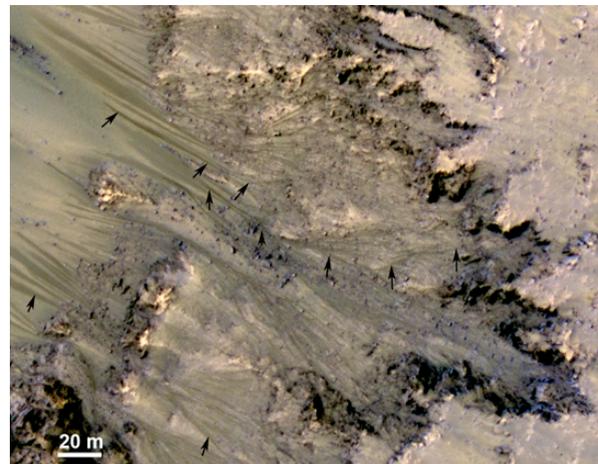


Figure 1. RSL (arrows point to a few examples) emanating from bedrock layers in the wall of a crater at 41.6°S, 202.3°E; ESP_022834_1380.

Table 1: RSL Types

RSL Type	Description and Seasonality	# Sites	Latitude Range
Confirmed RSL	Observed to recur in multiple warm seasons and fade in cold seasons	9	52°S to 32°S
Likely RSL	Evidence for fading in cold seasons, but not yet observed to recur in multiple years	12	47°S to 34°S
Candidate equatorial RSL	Morphology of RSL, changes observed, but seasonality unclear	8	18°S to 19°N
Candidate mid-latitude RSL	Morphology of RSL, but no repeat imaging	12	49°S to 31°S

Other Martian slope features may appear similar to RSL. The seasonal, latitude, and slope aspect distribution of RSL and their occurrence in regions with low dust index distinguishes them from streaks on dust-mantled slopes. Small slope lineaments are also seen

on high-latitude dunes during late winter and spring, as the seasonal CO₂ cover is sublimating. The hypothesis that these are sand flows initiated by CO₂ sublimation has been confirmed by the appearance of new dune gullies [4]. Grain flows removing thin dust covers may resemble RSL, but lack seasonality and create a color contrast not seen in RSL.

Hypotheses and Discussion: The seasonal, latitudinal, and slope aspect distributions show that RSL require relatively warm temperatures. Summertime afternoon brightness temperatures measured by THEMIS on Mars Odyssey of RSL-covered slopes in the middle to late afternoon range from 250-300 K, with daily-peak temperatures likely higher.

Thermal cycling can damage rocks and might eventually trigger rock falls and dry granular flows, but is a very slow process. Another hypothesis is that adsorbed water, which makes grains sticky, is released at high temperatures, allowing dry mass wasting, but the association with bedrock and rocky slopes is left unexplained. Triggering by seasonally high winds or dust devils is possible, but doesn't explain the absence of RSL in the northern hemisphere or the orientation preference of the mid-latitude features. None of these "dry" hypotheses explain why RSL are abundant in rare places and absent on most steep rocky slopes. Nevertheless, all of these hypotheses deserve further consideration.

The temperature, latitude, and seasonal relations suggest a role for volatiles in RSL behavior. The definite association between RSL and temperatures greater than 250 K points to brines as the most relevant volatile. Chlorides (Mg, Na, or Ca) or Fe sulfates have eutectic temperatures (T_e) from 205-250 K [5-6]. Brines could trigger RSL from seeps or thin flows. The formation mechanism could resemble that of [7] for putative "wet" slope streaks, in which the warm-season temperature exceeds T_e at depths of a few cm, brines percolate and refreeze at depth to form an impermeable layer, and downslope percolation occurs at the interface between liquid and frozen brine. Alternatively, a thin debris flow might be mobilized at the liquid-ice interface. This model should be more effective over surfaces with moderate to high thermal inertias, warming a thicker layer above T_e . Given the lack of water absorption bands in CRISM spectra we assume that RSL are usually dry at the surface, perhaps wet only in the subsurface and perhaps small surface areas while moving.

The origin of the water to form RSL could be absorption of water vapor by hygroscopic salts (deliquescence) or subsurface seeps. Deliquescence from the atmosphere, most likely in polar regions where relative humidity is higher, is marginally possible in the middle latitudes [6]. Deliquescence might also result from

sublimation of relict subsurface ice and diffusion of water vapor towards the surface. It is unclear if sufficient water can be trapped each year from either source.

To produce brine seeps from groundwater there must be sufficient liquid to fill the pore spaces between particles, and a hydraulic head. Although many RSL occur in favorable topographic locations for groundwater, some do not. Another difficulty is that the RSL-bearing slopes are too warm to preserve shallow ground ice in equilibrium with the atmosphere. RSL formation, if driven by groundwater seeps, must be a non-equilibrium process.

Modeling by [8] shows that groundwater discharge on Martian slopes in the present-day environment requires either (1) high permeability and ample (pure) water, (2) geothermally heated water, or (3) brines with a depressed freezing point. The presence of brines is the most realistic scenario, requiring modest quantities of water and no geothermal heat. Furthermore, the brine model exhibits a dependence of discharge on season and favors equator-facing slopes in the middle to high latitudes [8], much like the RSL.

Conclusions: The origin of RSL is a fine mystery. The action of brines in some manner seems the best hypothesis, but we can't explain the exact mechanisms such as why the RSL fade in cold seasons and there is no direct evidence for water. HiRISE is continuing intensive monitoring of key sites to better understand the detailed formation timing and relations to topography and seasons, and sampling of other sites to better understand the global distribution. CRISM is acquiring observations in super-resolution mode and at multiple seasons. Laboratory experiments [e.g., 9] or a landed mission may be needed to finally explain these observations.

References: [1] McEwen, A.S. et al. (2011) *Science*, in press. [2] McEwen, A.S. et al. (2007) *JGR 112*, E05S02. [3] Murchie, S. et al. (2007) *JGR 112*, E05S03. [4] Hansen, C. et al. (2011) *Science 331*, 283-295. [5] Brass, G.W. (1980) *Icarus 42*, 20-28. [6] Mohlmann, D., K. Thomsen (2011) *Icarus 212*, 123-1301. [7] Kreslavsky, M., J.W. Head (2009) *Icarus 201*, 517-527, 2009. [8] Goldspiel, J.M., S.W. Squyres (2011) *Icarus 211*, 238-258. [9] Wang, A., Z.C. Ling (2011) *JGR 116*, E00F17.