Hydrological characteristics of recurrent slope lineae on Mars: Evidence for liquid flow through regolith and comparisons with Antarctic terrestrial analogs

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Abstract. On the basis of their morphology and seasonal thermal characteristics, recurrent slope lineae (RSL) on Mars have been inferred to be a possible result of the flow of a liquid (likely a saline brine) through the upper portions of the martian regolith. In this note, we analyze repeat HiRISE imaging of RSL to show that the downslope growth rate of recurrent slope lineae is well-fit by an elementary groundwater flow model that also describes the downslope propagation of Antarctic water tracks (terrestrial analogs to RSL), and that the apparent permeability of RSL-bearing slopes is consistent with the observed sandy regolith substrate.

1. Introduction.

Recurrent slope lineae (RSL) are narrow (0.5-5 m wide), relatively dark-toned, martian surface features that form on steep (25-40˚), southern-hemisphere slopes, and that appear in early spring, grow longer in the downslope direction during spring and summer, and fade during autumn and winter (McEwen et al., 2011). Several hypotheses have been proposed to account for the formation of RSL, including dry mass wasting (driven by thermal rock cycling, dust devils, etc.), solid-CO_2 sublimation-driven flow, and the shallow percolation and flow of saline brines (McEwen et al., 2011). McEwen *et* al. (2011) favored seasonal regolith textural changes as a mechanism to account for RSL darkening and fading, given a lack of water bands detected in CRISM spectra. However, based on the presence of RSL only on southern hemisphere slopes with warm summer temperatures (>250 K) and also on RSL summer-season growth and winter-season fading, *McEwen et al.* (2011) suggested that an RSL formation mechanism involving the downslope transport of a salt-bearing, water-based fluid that darkens the RSL surface through grain-wetting, and that sublimates/evaporates once flow ceases after the summer thermal optimum, remains a viable hypothesis, pending laboratory results and modeling of CRISM spectra.

A “wet” (water-related) RSL formation model implies a number of characteristics about RSL and the medium in which they form. If RSL form through the downslope flow of saline fluids in the uppermost part of an otherwise frozen or ice-cemented soil column, then the most basic candidate model for describing their growth is unconfined fluid flow through a porous medium (i.e., “Darcy Flow”). This kind of shallow saline groundwater flow is common in terrestrial polar regions, where saline fluids flow downslope within the seasonally thawed active layer through subtle depressions in the ice-cemented portion of the permafrost. Such terrestrial features are referred to as “water tracks” (Levy et al., 2011; McNamara et al., 1999). Darcy flow and surface darkening by grain wetting describe the water transport and surface change characteristics of water tracks—particularly in Antarctica, where a lack of vegetation allows regolith/fluid interactions to dominate water track surface expression (Levy et al., 2011). A similar wetting/darkening process may also be at work in low-permeability bedrock slope streaks in Antarctica (Head et al., 2007; Kreslavsky and Head, 2007).

In this note, the “wet” RSL formation mechanism is tested by using repeat HiRISE image data to determine whether the simplest possible groundwater flow model can be used to explain the spatial patterns of RSL surface darkening. In particular, RSL growth rates are fitted to a simple groundwater flow model by fitting downslope propagation rates to κ, the permeability of the regolith. Permeability is, in part, a function of the grain size in unconsolidated sediments, and is an intrinsic property of porous media (explicitly taking into account changes in flow rate resulting from the viscosity, gravity, and density of the flowing fluid).

Experimental fitting of RSL substrate permeability using HiRISE measurements of RSL growth rates tests the brine flow hypothesis by determining whether the hydrological properties of the RSL substrate are consistent with remote sensing observations of the RSL substrate (sandy, fines-bearing regolith, typical of Mars e.g., Goetz et al., 2010). If κ values for RSL-bearing surfaces are found to be unrealistically low (impermeable), then it suggests that RSL are formed by a mechanism other than seasonal flow (e.g., soil creep). If κ values for RSL-bearing surfaces are found to be unrealistically high (overly permeable, suggesting large voids that would inhibit surface darkening from wetting), then it suggests that some form of mass wasting may be responsible for RSL formation. Finally, if κ values are found to span a reasonable range for sandy regoliths, then the "wet" RSL formation model will have successfully met a critical physical prediction of the brine flow descriptive model.

2. Methodology

The downslope propagation of RSL was measured using repeat orthorectified HiRISE image data collected at Horowitz crater and Palikir crater (the fresh crater within Newton crater) (32˚S, 140.8˚E and 42.3˚S, 201.8˚E, respectively) acquired from the NASA Planetary Data System (PDS). RSL characterized by McEwen et al. (2011) as "confirmed" (showing multiple warm season recurrences) were selected from an image pair at each site (for Palikir crater, HiRISE images ESP_022689_1380 and ESP_022267_1380; for Horowitz crater, ESP_022256_1475 and ESP_22678_1475). HiRISE images were georeferenced and overlaid, so that changes from one image to the next (showing surface change with time) could be easily detected via inspection. Distances between the downslope termini of the RSL from the earlier image to the subsequent image were measured in ArcMap.

Using the HiRISE image collection metadata and RSL terminus measurements, it is possible to fit a simple groundwater hydrology model (Darcy flow) to the RSL. Displacements between RSL termini at two points in time constitute the distance traveled by putative RSL fluids. Taking the time elapsed between HiRISE images, it is possible to calculate an average downslope velocity, v, for putative RSL fluids (distance divided by time). For a simple unconfined aquifer, groundwater pore velocity is equal to the product of the permeability (κ), the porosity (Φ), the pressure gradient (ρgΔh/l, where ρ is fluid density, g is martian gravitational acceleration, and Δh/l is the tangent of the RSL surface slope), and the inverse of the fluid viscosity (μ, Pa•s):

$$v = (-\kappa \bullet \Phi \bullet \rho g \Delta h)/\mu \quad (1)$$

The pressure gradient is derived from the RSL starting and ending surface slopes reported for each RSL site by McEwen et al. (2011) using HiRISE DTMs. For the results presented below (Table 1), porosity of 0.25 is used as representative value for sedimentary deposits. For fluid properties, pure water ($\rho = 1000$ kg/m^3 and $\mu = 0.001$ Pa•s) and $CaCl_2$ brine ($\rho = 1400$ kg/m^3 and $\mu = 0.009$ Pa•s) (Lide, 2000) are both considered because RSL fluids are thought to be composed of water plus dissolved phases (possibly saturated eutectic brines) (McEwen et al., 2011).

Because average v can be measured through repeat imaging, this leaves κ as the only independent variable. By calculating the range of κ values indicated by the RSL displacement measurements, it is possible to constrain the geological composition of the RSL substrate (e.g., fine sands and silts, well-sorted gravel, etc.) (Bear, 1972). This information can be used to evaluate the “wet” RSL formation mechanism because the thermal inertia of RSL surfaces (~200 to 340 J m^{-2} s$^{-1/2}$ K^{-1}) (McEwen et al., 2011) suggests a surface dominated by typical martian low-albedo sands (Putzig and Mellon, 2007). If the best-fit hydraulic permeability of RSL surfaces greatly exceeds or is less than the permeability of terrestrial sandy deposits, then it is unlikely that percolation of brines through the soil is the best explanation for the formation of RSL.

3. Results.

RSL displacements were measured in Horowitz and Palikir craters (Fig. 1). In Palikir, 37 RSL were measured in a region bounded by 41.539° S, 202.285° E and 41.549° S, 202.291° E. In Horowitz, 40 RSL were measured in a region bounded by 31.978° S, 140.779° E and 32.009° S, 140.803° E. For both locations, the elapsed time between HiRISE image pairs was 33 Earth days. RSL measurements and calculations are summarized in Table 1. Mean RSL terminus displacements were 24 m at Palikir Crater (σ = 10 m, range = 6-45 m) and 37 m at Horowitz crater (σ = 18 m, range = 9-90 m). It should be noted that these displacements do not necessarily represent a cluster about a mean displacement, but rather, may reflect different transport paths generated by different slopes (Levy et al., 2011). Based on the calculations described above, water-based permeability values for Palikir Crater RSL span 2.8×10^{-9} to 1.5×10^{-8} cm^2, with an average 9.2×10^{-9} cm^2 (for brine, the mean permeability is 5.9×10^{-8} cm^2). Water-based permeability values for Horowitz Crater RSL span 3.9×10^{-9} to 3.1×10^{-8} cm^2, with an average of 1.4×10^{-8} cm^2 (for brine, the mean permeability is 9.0×10^{-8} cm^2). These κ values are consistent with fine sand and silt to well-sorted sand and gravel (Bear, 1972), and would be a reasonable estimate for the permeability of loosely packed dark martian sands (Goetz et al., 2010; Shepherd, 1989).

4. Comparison with Terrestrial Analogs.

In order to verify that an elementary unconfined aquifer flow model can be used to effectively to describe RSL-like systems, an identical analytical procedure is employed here to calculate the permeability of water tracks (permafrost groundwater features that form as water/brines flow through the shallow subsurface over an impermeable ice layer) in Antarctica (Levy et al., 2011). Water tracks flow through sandy haplorthels (>70% sand by mass), with variable fractions of pebbles, silt and clay, that are surfaced by a desert pavement of pebbles, cobbles, and boulders (Levy et al., 2011). Water tracks share many morphological and seasonal characteristics with RSL, including downslope propagation of linear or branching patterns of surface darkening, growth during spring/summer seasons, and fading during winter (Levy et al., 2011). Water tracks are typically ~3 m wide but can expand to widths of several 10s of meters on low slope surfaces or where multiple tracks coalesce, and range in length from 100s of meters to ~2 km (Levy et al., 2011). Martian RSL are generally straighter than terrestrial water tracks, although short, straight water tracks do form on uniform slopes in Antarctica. The limited branching and low sinuosity of RSL may reflect minimal thermal erosion of RSL into the martian permafrost, in contrast to terrestrial water tracks, which form broad channels in the ice table that serve as preferred flowpaths over interannual timescales.

Saline fluids associated with water track flow are sourced by snowmelt, shallow ground ice melt, and the direct conversion of atmospheric water vapor into brines through high-elevation salt deliquescence (this latter process is inferred based on the excess of Cl, Mg, and Ca ions in water track fluids—concentrations greater than can be explained by the weathering of calcite or gypsum for the Ca, or of marine aerosols for the Cl and Mg) (Levy et al., 2011). This lattermost process is a candidate for RSL fluid generation on Mars.

Repeat Quickbird satellite images were collected in the Goldman Glacier basin of Taylor Valley, Antarctica, (77.7˚S 162.8˚E) between 19 December, 2010 and 22 December, 2010 (Fig. 2). Apparent, average propagation rates of ten water tracks flowing downslope during this period range from 2.5×10^{-4} to 7.9×10^{-4} m/s, with an average of 4.8×10^{-4} m/s. Slopes in the basin range from 3˚ to 27˚, with an average of 15˚, based on slope calculations from USGS 30 m/pixel topographic data. Using equation (1), and assuming that these water track fluids are relatively-dilute saline solutions (Levy et al., 2011) with a density and viscosity similar to pure water, the soil permeability for the Goldman basin was calculated to range from 1.2×10^{-6} to 4.0×10^{-7} cm^2, with an average of 4.5×10^{-7} cm^2.

These calculated permeability values can be used to compute the apparent hydraulic conductivity of the Goldman basin sediments, which can then be compared to field measurements of soil hydraulic conductivity to determine whether the elementary Darcy flow model accurately reproduces groundwater flow behavior. The hydraulic conductivity of a porous medium is the product of permeability, fluid density, gravitational acceleration, and the inverse of fluid viscosity. Calculated hydraulic conductivity values using the imaging-derived permeability estimates span 0.04 to 0.12 cm/s, with an average of 0.05 cm/s. Soils in Taylor Valley have an average hydraulic conductivity of 0.02 cm/s (range: 0.002 to 0.06 cm/s) based on infiltrometer measurements (Levy et al., 2011). Accordingly, these results suggest that remote determination of substrate permeability from orbital flow observations may be accurate to within an order of magnitude—resolution sufficient to distinguish a range of hydrogeological regimes.

5. Discussion.

The calculations presented above suggest that, in the simplest hydrological paradigm possible, average RSL spatial growth is consistent with flow of fluids through a porous regolith with hydrological properties similar to the sands, pebbles, and fines that dominate terrestrial water track environments. The above calculations constitute a best-case scenario for water-track-like flow, because they assume constant flow at non-freezing (or non-cryotic/brine-freezing (Yershov, 1998)) temperatures, over which temperature-dependence of fluid viscosity is less than a factor of ~5. Accordingly, it is important to evaluate the role of temperature in RSL formation.

In terrestrial permafrost environments, freezing of water in rock and sediment pores can dramatically reduce the porosity of geological materials, reducing the apparent permeability of the substrate (Kleinberg and Griffin, 2005). If frozen water exists in the pores of RSL-bearing sediments, then these calculated κ values may represent a minimum value, with the potential permeability of the sediments (if fully unfrozen) being higher when pores are free of ice. Pore-filling ice can reduce the permeability of frozen soils by up to two orders of magnitude (Kleinberg and Griffin, 2005). If RSL-bearing soils are thoroughly ice-filled, then the actually permeability of the RSL sediments would be ~10^{-7} to 10^{-4}, which, although large, are not so great as to preclude sands and fines as the primary constituent of the RSL-bearing medium, so long as ice-cemented pebbles were a significant component of the sedimentary matrix (Bear, 1972).

Phase changes associated with RSL flow may also have an effect on the runout distance of RSL on Mars (and possibly water tracks on Earth) (Conway et al., 2011). As RSL/water track fluids flow through the saturated portion of the active layer (likely only several cm thick on Mars) (McEwen et al., 2011) and 1-20 cm thick on Earth (Levy et al., 2011), freezing of fluids at the top of the flow path may provide latent heat contributions to the flowing (unfrozen) fluids, and may also insulate fluids flowing beneath the frozen shell against evaporative loss (Carr, 1983). Accordingly, surficial freezing may enhance the duration of RSL flow processes.

As noted in the results section, the differences in inferred permeability for RSL sediments varies by only ~1 order of magnitude whether pure water or hypersaline brines are moving through the sediment pores. This observation suggests that a range of brine compositions and origins could account for the flow of liquids through RSL at the martian surface (Burt et al., 2008; Chevrier et al., 2009).

Finally, it is important to note that the permeability of regoliths calculated in this manuscript for both Earth and Mars are average permeabilities, calculated using an assumption that downslope propagation of RSL/water tracks occurs continuously between point measurements of feature length, through a homogenous substrate, with a uniform (slope-dependent) pressure gradient, with no overland transport (terrestrial water tracks flow primarily through the subsurface, discharging only occasionally as seep-like springs with 10s of cm of overland flow). Because both HiRISE and Quickbird make measurements at discrete times, neither instrument can determine whether flow is primarily continuous or episodic. McEwen et al. (2011) showed that RSL growth is episodic to some degree, but may also have continuous (daily) motion within each propagation episode (e.g., flow during the warm parts of unusually warm days). A similar flow regime exists for water tracks in Antarctica, which flow primarily during the warm parts of the warmest summer days (Levy et al., 2011). The accuracy of the remote method for determining permeability of Earth soils (approximately an order of magnitude) would still suggest brine-like flow for martian RSL, even if the daily duration of flow were only a few hours every sol.

6. Conclusions.

Repeat HiRISE images of recurrent slope lineae (RSL) at Palikir and Horowitz craters were analyzed to document the downslope growth rate of RSL as a function of time during one martian spring. On the basis of the measured average growth rates, RSL-bearing surfaces were found to have a permeability consistent with sandy unconsolidated sediments—a hydrological prediction consistent with the morphology of the RSL site, as well as with the thermal inertia characteristics of the RSL surfaces. The remote determination of substrate permeability based on satellite observations of near-surface fluid flow were found to be accurate to within an order of magnitude for RSL terrestrial - analog water tracks in Antarctica. These results support the *McEwen et al.* (2011) hypothesis that RSL form through the downslope flow of liquids (likely saline brines) at the martian surface under current climate conditions.

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9. Figure Captions.

Fig. 1. RSL downslope growth from early-season (a) to late-season (b) at Palikir Crater. White lines b left image show measured downslope growth. Portions of HiRISE images ESP_022267_1380 (a) and ESP_022689_1380 (b). North to image top, downslope to image left. RSL downslope growth from early-season (c) to late-season (d) at Horowitz crater. White lines in d show downslope growth. (c) is a portion of ESP_022256_1475 and (d) is a portion of ESP_22678_1475. North to image top.

Fig. 2. Downslope growth of water tracks in the Goldman Glacier basin, McMurdo Dry Valleys, Antarctica. White lines in right image (December 22) show downslope growth from left image (December 19). Portions of Quickbird images orthowv02_10dec192055054-p1bs-1030010008a27200_u08ns4326 (left) and orthowv02_10dec222046120-p1bs-103001000825e900_u08ns4326 (right). Downslope to image bottom.

Table 1. RSL downslope growth measurements and derived substrate permeability, assuming pure water and $CaCl_2$ brine compositions. Mean indicates the average of the measured and calculated values and minimum and maximum give the range of measured and calculated values.