Seasonal Flows on Warm Martian Slopes

Alfred S. McEwen,1*, Lujendra Ojha,1 Colin M. Dundas,2 Sarah S. Mattson,1 Shane Byrne,1 James J. Wray,3 Selby C. Cull,4 Scott L. Murchie,5 Nicolas Thomas,6 Virginia C. Gulick7

Water probably flowed across ancient Mars, but whether it ever exists as a liquid on the surface today remains debatable. Recurring slope lineae (RLS) are narrow (0.5–5 m) markings, relatively dark on steep (25° to 40°) slopes; repeat images from the Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment show them to appear and incrementally grow during warm seasons and fade in cold seasons. They extend downslope from bedrock outcrops, often associated with small channels, and hundreds of them form in some rare locations. RSL appear and lengthen in the late southern spring and summer from 48°S to 32°S latitudes favoring equator-facing slopes, which are times and places with peak surface temperatures from ~250 to 300 kelvin. Liquid brines near the surface might explain this activity, but the exact mechanism and source of water are not understood.

Although there is much morphological evidence for water flow on Mars in the past, little definitive evidence exists for surface water today. The chloride and sulfate minerals on Mars are indicative of widespread and abundant brines in Mars geologic history (1–5). Salts can depress the freezing point of water by up to 70 K and reduce the evaporation rate by factors of 10 or more, so brines would be far more stable than pure water at the surface of Mars (6, 7). Most likely, brines would be far more stable than pure water at the surface of Mars (6, 7).

confirmed RSL have been found to date at seven locations (Table 1), often with many separate clusters. There are 12 other likely RSL sites and 20 candidate sites. They extend downslope from bedrock outcrops or rocky areas and are often associated with small channels, and hundreds of them form in some rare locations. RSL appear and lengthen in the late southern spring and summer from 48°S to 32°S latitudes favoring equator-facing slopes, which are times and places with peak surface temperatures from ~250 to 300 kelvin. Liquid brines near the surface might explain this activity, but the exact mechanism and source of water are not understood.

Table 1. RSL types.

<table>
<thead>
<tr>
<th>RSL type</th>
<th>Description and seasonal behaviors</th>
<th>Number of sites</th>
<th>Latitude range</th>
<th>Number of RSL per site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confirmed RSL</td>
<td>Observed to recur in multiple warm seasons and fade in cold seasons</td>
<td>7</td>
<td>48°S to 32°S</td>
<td>10² to 10³</td>
</tr>
<tr>
<td>Likely RSL</td>
<td>Evidence for fading in cold seasons, but not yet observed to recur in multiple years</td>
<td>12</td>
<td>47°S to 34°S</td>
<td>10 to 10³</td>
</tr>
<tr>
<td>Candidate equatorial RSL</td>
<td>Morphology and geologic setting of RSL, changes observed, but seasonality unclear</td>
<td>8</td>
<td>18°S to 19°N</td>
<td>10 to 10²</td>
</tr>
<tr>
<td>Candidate RSL poleward of 30°S</td>
<td>Morphology and geologic setting of RSL, but no repeat imaging</td>
<td>12</td>
<td>52°S to 31°S</td>
<td>10 to 10²</td>
</tr>
</tbody>
</table>

1Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA. 2U.S. Geological Survey, Flagstaff, AZ 86001, USA. 3Department of Astronomy, Cornell University, Ithaca, NY 14853, USA. 4Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130, USA. 5Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA. 6Physikalisches Institut, University of Bern, Bern, Switzerland. 7NASA Ames Research Center and SETI Institute, Moffett Field, CA 94035, USA.

*To whom correspondence should be addressed. E-mail: mcewen@lpl.arizona.edu
The seasonal, latitudinal, and slope aspect distributions show that RSL require relatively warm temperatures. Summertime afternoon brightness temperatures measured from orbit (19) on RSL-covered slopes in the middle to late afternoon range from 250 to 300 K, with daily peak temperatures probably being higher (table S1). Equatorial regions reach temperatures comparable to warm-season temperatures on equator-facing slopes in the southern mid-latitudes. Northern summers are cooler because perihelion occurs shortly before the northern winter solstice. In spite of the equatorial candidates, RSL are clearly most abundant in the southern mid-latitudes.

A range of hypotheses must be considered to explain these observations. Thermal cycling can damage rocks (20) 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 hypotheses explain why RSL are abundant in rare places and absent from most steep rocky slopes; other difficulties are listed in table S5. Nevertheless, all of these hypotheses deserve further consideration.

The latitudinal preference of RSL and their fading in cold seasons suggest some role for a volatile. CO₂ sublimation drives many dynamic phenomena on Mars (18), but CO₂ probably never freezes on these equator-facing slopes and certainly is not present in the summer. Nearly pure H₂O, if present, might drive activity, but (i) the ice would rapidly sublime to dry out these warm slopes, and (ii) some RSL activity occurs below the freezing point for pure water (table S1).

The definite association between RSL and temperatures greater than 250 K points to brines as the most relevant volatile. The Spirit landing site in Gusev Crater (14.6°S) reaches temperatures similar to those of the RSL slopes (table S1); the subsurface temperature at the hottest times should exceed 250 K down to at least 2 cm depth (21). Many brines expected on Mars have eutectic temperatures (Tₑ) below 250 K, except most sulfates (2, 10); RSL have not been found near the extensive sulfate deposits mapped from orbit (4). The most likely brine compositions relevant to RSL are chlorides (Mg, Na, or Ca) or Fe sulfates, with Tₑ from 205 to 250 K.

Brines could lead to RSL from seeps or thin flows. The formation mechanism could resemble that of (22) for putative “wet” slope streaks, in which the warm-season temperature exceeds Tₑ at depths of a few centimeters, 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 the brine eutectic. For either seeping or debris flow, sufficient water to fill pore spaces is needed; interfacial water (23) is probably not sufficient. 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 in small surface areas while moving.

The origin of the water to form RSL could be the absorption of water vapor by hygroscopic salts (deliquescence) or subsurface seeps. Deliquescence from the atmosphere, most likely in the polar regions where relative humidity is higher, might occur in the middle latitudes (10), although it is unclear whether sufficient water can be trapped each year. Deliquescence might also result from sublimation of relic subsurface ice and the diffusion of water vapor toward the surface (SOM). RSL formation would be localized by concentrations of hygroscopic salts and water vapor, in addition to other factors. Salt concentrations at RSL sites have not been identified from CRISM data, but anhydrous chlorides lack distinctive absorption bands (24).

To produce brine seeps from groundwater, there must be sufficient liquid to fill the pore space between particles and create a hydraulic gradient to initiate and maintain water flow to the surface. Although many RSL occur in favorable topographic locations for groundwater (Fig. 2 and figs. S3 and S4), some do not (Fig. 1). Another difficulty is that the RSL-bearing slopes are too warm to preserve shallow ground ice in equilibrium with the atmosphere (25). RSL formation, if driven by groundwater seeps, must be a nonequilibrium process, requiring ground-

![Fig. 1. RSL on the central structure of Horowitz Crater (32°S, 140.8°E), MRO Primary Science Phase (PSP) image PSP_005787_1475 (Δ = 334: late summer). Altimetry map (A) locates the full 5.1-km-wide HiRISE image (B), with the white box indicating the color enlargement (C). Yellow arrows in (B) show some concentrations of RSL within the central peaks and pits. Colors in (C) have been strongly enhanced to show the subtle differences, including light orange streaks (black arrows) in the upper right that may mark faded RSL. North is up on all images in this paper except fig. S4.](image-url)
water migration or active surface processes to expose subsurface brines. Modeling by (26) shows that groundwater discharge on Martian slopes in the present-day environment requires either (i) high permeability and ample (pure) water, (ii) geothermally heated water, or (iii) brines with a depressed freezing point. The presence of brines is the most realistic scenario for Mars, 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 (26), much like the RSL.

The mechanisms of darkening and fading of RSL are uncertain. Wetting of particulate materials causes optical darkening by a combination of processes (27), and drying or freezing would explain the fading in cold seasons, but this model is inconsistent with the lack of water absorption bands in CRISM data. Alternatively, the RSL could darken by an increase in grain size or roughness from seeping or flows, but the fading in cold seasons still needs an explanation. The gradual settling of atmospheric dust is not a likely mechanism for the fading, based on the longer fading time scale (years, not months) of other relatively dark transient features such as slope streaks and new impact markings. Also, removal of dust during RSL formation would cause a strong color change that is not observed (SOM). RSL surface structure might change in cold seasons by a mechanism not currently understood.

We have not found any candidate RSL in the northern mid-latitudes. This may be explained by the current seasonal asymmetry, by differences in bedrock geology, or both. The putative chloride deposits, hypothesized to result from the ponding of surface runoff or groundwater upwelling, are strongly concentrated in low-albedo regions of the southern hemisphere (24), similar to the distribution of RSL. Brines forming the chloride deposits might infiltrate or remain underground and could be stable over geologic time in the middle latitudes in a liquid or frozen state, until new craters or troughs expose the brines on warm slopes. This could explain the association of RSL with bedrock layers, either because they control the subsurface migration of fluids or water vapor or because they contain hygroscopic salt-rich lenses such as buried chloride deposits.

Liquid water on Mars today would be of great interest for astrobiology. Its presence has been suggested previously. Water flow is one hypothesis for the formation of the active mid-latitude gullies (28), although recent observations show that gullies are active in the winter and in places where seasonal CO$_2$ is present and water is least likely (29, 30). Briny flows have been suggested (17) for high-latitude dune streaks that appear during CO$_2$ defrosting, but CO$_2$ is the more likely driving volatile (18). Brines have been suggested for slope streaks (22), but there is no
Reduced Interannual Rainfall Variability in East Africa During the Last Ice Age

Christian Wolff,1,2,3 Gerald H. Haug,3,4* Axel Timmermann,5 Jaap S. Sinninghe Damsté,6,7 Achim Brauer,4 Daniel M. Sigman,9 Mark A. Cane,9 Dirk Verschuren10

Interannual rainfall variations in equatorial East Africa are tightly linked to the El Niño Southern Oscillation (ENSO), with more rain and flooding during El Niño and droughts in La Niña years, both having severe impacts on human habitation and food security. Here we report evidence from an annually laminated lake sediment record from southeastern Kenya for interannual to centennial-scale changes in ENSO-related rainfall variability during the last three millennia and for reductions in both the mean rate and the variability of rainfall in East Africa during the Last Glacial period. Climate model simulations support forward extrapolation from these lake sediment data that future warming will intensify the interannual variability of East Africa’s rainfall.

In the tropics, changes in rainfall patterns have severe consequences for millions of people. East Africa, in particular, has in recent years experienced both extreme flooding and severe droughts, with serious impacts on developing economies and wildlife throughout the region (1). Seasonality in East African climate is controlled primarily by the biannual migration of the Intertropical Convergence Zone (ITCZ) across the region (2) (fig. S1). As a result, equatorial East Africa experiences two climatological rainy seasons (3). Dry seasons are windy because of the trade winds that straddle the ITCZ. All original data reported in this paper are tabulated in the SOM and archived by NASA’s Planetary Data System.

References and Notes
12. 0 is the true anomaly of Mars in its orbit around the Sun, measured from the vernal equinox, used as a measure of the season on Mars. is 0 corresponds to the beginning of northern spring; 180 is the beginning of southern spring. The numbering of Mars years (MRY) was defined to facilitate comparison of data sets across decades and multiple Mars missions; year 1 started on 11 April 1955.
13. Time sequences in animated GIF format are posted at http://hirise.lpl.arizona.edu/xmls. These are stacked cutsouts from orthorectified HiRISE images (archived to be archived within 1 year) in the Planetary Data System.
17. A. Kreuz et al., Icarus 207, 149 (2010).
34. All original data reported in this paper are tabulated in the SOM and archived by NASA’s Planetary Data System.

Supporting Online Material
www.sciencemag.org/cgi/content/full/333/6043/740/DC1
SOM Text
Figs. S1 to S6
Tables S1 to S5
References (34–40)
25 February 2011; accepted 17 June 2011
10.1126/science.1204816

Table 2. Slope streaks versus RSL.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Slope streaks</th>
<th>RSL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope albedo</td>
<td>High (&gt;0.25)</td>
<td>Low (&lt;0.2)</td>
</tr>
<tr>
<td>Contrast</td>
<td>~10% darker</td>
<td>Up to 40% darker</td>
</tr>
<tr>
<td>Dust index*</td>
<td>High (e &lt; 0.95)</td>
<td>Low (e &gt; 0.96)</td>
</tr>
<tr>
<td>Thermal inertia</td>
<td>Low (&lt;100)</td>
<td>180 to 340</td>
</tr>
<tr>
<td>Width</td>
<td>Up to 200 m</td>
<td>Up to 5 m</td>
</tr>
<tr>
<td>Slope aspect preferences</td>
<td>Varies with regional wind flow</td>
<td>Equator-facing in middle latitudes</td>
</tr>
<tr>
<td>Latitudes; longitudes</td>
<td>Corresponds to dust distribution</td>
<td>32°S to 48°S; all longitudes</td>
</tr>
<tr>
<td>Formation Ls</td>
<td>All seasons (J1)</td>
<td>Ls = 240 to 20 Months</td>
</tr>
<tr>
<td>Fading time scale</td>
<td>Years to decades</td>
<td>No</td>
</tr>
<tr>
<td>Associated with rocks</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Associated with channels</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Abundance on a slope</td>
<td>Up to tens</td>
<td>Up to thousands</td>
</tr>
<tr>
<td>Regional mineralogy</td>
<td>Mars dust</td>
<td>Variable</td>
</tr>
<tr>
<td>Formation events</td>
<td>One event per streak or streaks</td>
<td>Incremental growth of each feature</td>
</tr>
<tr>
<td>Yearly recurrence</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*1350 to 1400 cm⁻² emissivity (e) (SOM).