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Spectral constraints on the formation mechanism of recurring slope lineae

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[1] Recurring slope lineae (RSL) exhibit multiple lines of evidence for a wet origin. In the southern midlatitudes, they form on steep, equator-facing slopes that are warm during southern summer. The formation temperature, seasonality, and other geomorphic characteristics are suggestive of water-related formation, perhaps dense brines. We examined Compact Reconnaissance Imaging Spectrometer for Mars images of all confirmed RSL sites from the southern midlatitudes and the equatorial region to understand the composition of RSL and/or RSL-associated deposits. We did not detect any spectral signature attributable to water; however, a distinct and consistent spectral signature is observed at most sites, indicating enhanced abundances or distinct grain sizes of both ferric and ferrous minerals in RSL-related materials compared to adjacent non-RSL slopes. Like the RSL themselves, the strength of these signatures varies as a function of season. The observed spectral changes may indicate removal of a fine-grained surface component during RSL flow, precipitation of ferric oxides, and/or wetting of the substrate.


1. Introduction

[2] Recurring slope lineae (RSL) are dark, narrow features that extend downslope on steep rocky slopes of Mars (Figure 1a). In the southern midlatitudes, RSL tend to form mostly on the equator-facing slopes [McEwen et al., 2011]. They are also common in Valles Marineris and a few other equatorial locations [McEwen et al., 2013]. The slopes are usually very fresh, lacking any significant aeolian mantle or polygonal landforms that take many years to form. They exhibit progressive growth over time in the downslope direction. They are observed to form and grow during multiple warm seasons and are observed to fade and often completely disappear during colder seasons [McEwen et al., 2011; Ojha et al., 2012]. RSL occur only in relatively low-albedo regions of Mars and have an even lower albedo compared to the surroundings. Although carbon dioxide ice drives many other dynamic activities on Mars [Hansen et al., 2011; Diniega et al., 2010; Dundas et al., 2010], the surface temperature at times and places when RSL are active is too hot for solid CO2 to exist but is ideal for water [McEwen et al., 2011; Ojha et al., 2012]. Freshwater has been suggested based on observed surface temperatures [Stillman et al., 2013], but given a possible subsurface source where temperatures are significantly lower, briny water with a lowered freezing point seems likely [Chevrier and Rivera-Valentin, 2012].

[3] Although geomorphic, visual and temporal data support the liquid hypothesis for RSL, spectroscopic evidence has been lacking. Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) [Murchie et al., 2007] is a visible to near-infrared imaging spectrometer with spectral range of ~0.36 μm to 3.92 μm. It operates with a gimbal mechanism to acquire images at full resolution of 18 m/pixel. The relatively coarse resolution of CRISM makes it challenging to observe RSL, which are a few meters wide at most. A few sites, such as Palikir crater, have dense distributions of RSL, where we expect CRISM to be able to better resolve clusters of RSL, and their inferred deposits. We sought to understand the mineralogical characteristics of RSL slopes and other features associated with RSL using CRISM full-resolution targeted (FRT) and full resolution short images.

2. Methodology

[4] We analyzed CRISM images of the 13 confirmed RSL sites in the southern midlatitudes, and confirmed RSL sites and a few other partially confirmed sites from equatorial latitudes [McEwen et al., 2013], to understand the mineralogy of RSL slopes. Useful IR (1–4 μm) data are only acquired when the CRISM coolers are active, i.e., during ~25% of observing cycles in recent years. We therefore concentrated mostly on the Visible and Near Infrared (VNIR) region (0.4–1 μm) due to its greater availability, although all IR wavelength data were also analyzed where and when available. CRISM TRR3 I/F images were downloaded and preprocessed using ENVI’s (Exelis Visual Information Solutions) CRISM analysis toolkit [Murchie et al., 2007] to reduce atmospheric effects, map project the images, and map parameters indicative of mineralogy [Pelkey et al., 2007]. Atmospheric correction was performed using the standard “volcano scan” technique [Morgan et al., 2011; Murchie et al., 2009].
Spectral plots were produced from observations of slopes with RSL activity. Individual RSL are smaller than the spatial resolution of CRISM (~18 m/pixel), so we averaged data over RSL slopes and their associated relatively bright fans (Figure 1a). The average spectrum from each region of interest (ROI) was divided by an average from a spectrally neutral region in the same scene; this use of “spectral ratios” is a standard CRISM analysis technique [e.g., Ehlmann et al., 2009] to suppress residual artifacts in the data while highlighting spectral variations within a scene. Not all denominators were chosen from the same columns, so detector-dependent noise is not completely erased from our spectra. The ratio of the same

Figure 1. (a) RSL emanating from bedrock exposures at Palikir crater (ESP_023045_1380, 41.6°S, 202.3°E, MY30, Ls: 318). Arrows point to bright, smooth fans at the base of the RSL on equator-facing slopes. (b) CRISM FRT0001E50D (R:BD920, G: R770, B:BD530 from Pelkey et al. [2007]) overlaid on HiRISE PSP_005943_1380 (stretched using standard deviation of the visible scene). The purple/pink color associated with RSL fans implies an enhancement in the 920 and 530 nm bands. (c) Seasonal variability in spectra of Palikir crater RSL and fans. Legend lists CRISM image ID with season Ls in parentheses. Dotted-dashed red line represents band continuum (740 nm) and dotted-dashed black line represents band minimum used to compute band depth [(continuum-minimum)/continuum] for 530 nm (510 nm). Dotted black line represents center of the 950 nm absorption band. (d) Band depth calculated for 530 nm absorption band (blue bars and left axis) for Palikir crater images. Orange line represents the normalized atmospheric optical depth (values on right axis). Bold numbers on top of the bars are the phase angle of the CRISM images. (e) Spectral variation observed on non-RSL slope. Legend same as Figure 1c.
Figure 2. (a) BD530 band of CRISM FRT0001CEEB showing abundance of ferric minerals in Raga crater. (b) Spectra of equator-facing RSL slope of Raga crater (48.1°S, 242.5°E), illustrating seasonal variability. (c) Band depth calculation for 530 nm absorption for Raga crater. Orange line is the normalized optical depth. (d) Seasonal variability of spectra of equator-facing slope of Tivat crater (45.9°S, 9.5°E). (e) Band depth calculated for 530 nm absorption for Tivat crater. Orange line same as Figure 2c. (f) Spectra of equator-facing RSL slope of Asimov crater (46.9°S, 5.1°E), showing the 530 nm and 950 nm absorption along with a broad 2100 nm absorption.
numerator area to the same denominator area was plotted for all CRISM observations available at each site, in order to observe time-dependent behavior in a controlled way.

We calculated band depths for the 530 nm ferric iron absorption band as a function of season for some sites to study any time-dependent behavior. To minimize human bias, we calculated the band depth using consistent local minimum and maximum wavelengths for all the images of a particular site. We also checked the atmospheric opacity and phase angle of few observations to explore whether these correlate with any observed fluctuations in band depth.

3. Results

3.1. Southern Midlatitudes

The dense distribution of RSL along with the wide expanse of bright fans that we observe at Palikir gives us the best opportunity to deduce their mineralogy (Figure 1). We defined an ROI dominated by bright fans (Figure 1a), which are inferred to be deposits from past RSL activity [Ojha et al., 2012]. These fans have a distinct color in images from both CRISM and the High Resolution Imaging Science Experiment (HiRISE) [McEwen et al., 2007], and seem to be composed of homogenous material finer grained than the surrounding area (Figures 1a and 1b). In HiRISE Infrared-Red-Blue/green color images, RSL fans usually have a yellow-green or orange color (Figure 1a), which is consistent with the presence of ferric minerals [Delamere et al., 2010].

In the southern midlatitudes, RSL appear to flow over the bright fans during summer.

In Palikir crater, a broad absorption edge at 530 nm was observed along with a band centered near 950 nm, with the depth of both bands varying over time (Figure 1c). The absorption bands are weakest prior to the onset of RSL activity (~Ls: 20–250) and strongest at the time when HiRISE started observing peak RSL activity (period when RSL were observed to grow and fade) (Ls: 282–309, in MY30) [Ojha et al., 2012] (Figure 1d); however, they were observed throughout the southern summer. A broad absorption at 2100 nm is also observed in the IR portion of the spectra,
when available (Figure 1c). There seems to be no correlation between observed increase in band depth and phase angle of the images (Figure 1d). Atmospheric opacity data calculated for 900 nm aerosols [Wolff et al., 2009] were also plotted for all the images we examined. In general, we observe greater band depths at times of lower estimated atmospheric opacity, but these do not correlate perfectly. Additionally, non-RSL slopes lack the spectral variation observed on RSL slopes (Figure 1e), so atmospheric opacity cannot be responsible for the observed variation. A possible relationship between atmospheric opacity and band depth has also been observed at other RSL locations in the southern midlatitudes, but generally, the trend is even weaker than that seen at Palikir crater (Figures 2c and 2e).

[9] Similar RSL spectral characteristics have been observed in other locations, including Raga and Tivat craters (Figure 2). However, at these sites, the spatial extents of RSL and the fans are much smaller, so our spectra may include contributions from outside the small features of interest. In Raga crater, the 530 nm absorption is strongly concentrated on the equator-facing slopes of the crater where RSL and their fans are observed (Figure 2a). We observed a similar seasonal pattern of increasing 530 nm band depth with increasing RSL activity (generally southern summer Ls 270–360), although the seasonal pattern for the 950 nm band is less straightforward here (Figures 2b and 2c). In Tivat crater, we observed the 530 nm absorption in all images but again with higher band depths during RSL season (Figure 2d and 2e). Here the 950 nm absorption appears only late in the RSL season (Figure 2d). In Asimov crater, RSL are spread over a wide area. Here too, we observe the 530 nm and 950 nm absorptions, along with the 2100 nm absorption, but none of the RSL regions have more than two CRISM images so the spectral behavior as a function of time is not yet well constrained (Figure 2f).

[10] In Horowitz crater, RSL are observed on all slope aspects of the central uplift complex [McEwen et al., 2011], including on hills that expose hydrous minerals such as chlorite. The VNIR spectra of RSL in Horowitz display the 530 nm absorption, but its seasonal dependence is unclear at this site, and there is no obvious absorption at 950 nm.

[11] We have looked at CRISM data, where available, from all other confirmed RSL sites in the southern midlatitudes of Mars. Our results have been consistent in that we observe the 530 nm and 950 nm absorptions at most RSL sites (see supporting information, Table S1). Band depth fluctuation is observed at sites where we have good temporal coverage. Table S1 presents key spectral highlights from all the sites we examined.

3.2. Equatorial Latitudes

[12] We looked at CRISM observations of all confirmed and several partially confirmed RSL sites from equatorial latitudes (Table S1). We plotted the normalized spectra of one of the RSL slopes from Elorz crater (Figure 3a). Only one image (Ls; 31, when HiRISE observed a few small lineae and darkened fans) shows evidence for absorptions at 530 nm or 950 nm at this site (Figure 3b). Additionally, no 2100 nm absorption is observed in the IR portion of the spectrum (Figure 3b). The RSL at this location are much smaller, so our lack of observation could be simply due to insufficient spatial resolution.

[13] We looked at CRISM images of a crater on the floor of Melas Chasma. This site consists of hundreds of relatively wide confirmed RSL (Figure 3c). Normalized spectra from RSL slopes show evidence for both 530 and 950 nm absorptions (Figure 3d). The activity of RSL at this crater changes from SW facing to NW facing slopes between the two CRISM images, so the spectra correspond to two different slopes where RSL were observed to be active. Due to lack of repeat imaging, the time variability of the spectra from this site is not clear. We also found some locations in Valles Marineris where candidate RSL formed close to known locations of monohydrate sulfates, but the sulfate signatures do not appear especially enhanced nor depleted in the RSL or their fans specifically.

4. Discussion and Conclusions

[14] The 950 nm absorption band from the VNIR data combined with a broad, shallow band centered around 2.1 μm could be attributed to pyroxene [Adams, 1974] with small amounts of a ferric oxide such as red hematite. The red hematite would account for the observed absorption at 530 nm, the ~700 nm shoulder, and a ~1000 nm pyroxene absorption shifted to a slightly shorter wavelength than expected [Morris et al., 2000]. The inferred enhancement and possible fluctuation in pyroxene signature on RSL slopes (relative to the surrounding terrain) at sites like Palikir and Raga craters seem most readily explained as due to grain size sorting within the fans, in which a fine component is removed, leaving a coarser-grained residue with stronger spectral signatures of pyroxene [e.g., Pieters, 1983] and red hematite in the coarse component. The enhanced 530 nm band could also originate from an additional ferric component that changes in abundance over the RSL season, as previously suggested for other relatively dark slope features on bright regions of Mars [Mushkin et al., 2010]. Although, wet processes can cause grain size sorting, we did not find any water-related absorptions on RSL slopes. Many other dry processes including saltation, dust deposition, Brazilian nut effect can be the cause of grain size sorting within the RSL fans. We also did not find evidence of phase angle or atmospheric opacity playing a role in the observed spectral fluctuation. The lack of water-related absorptions also rules out hydrous ferric salts as a spectrally dominant phase on the RSL slopes, despite hypothesized evidence for their presence in the subsurface throughout the southern midlatitude soils of Mars [Karunatillake et al., 2013].

[15] In principle, seasonal fluctuation in spectral properties of RSL sites could also be due to wetting of the substrate, which would lower the overall reflectance and deepen the overall band depths of any absorbing minerals that are present [Balsam et al., 1998]. At Palikir crater, the deepest band depths and the lowest reflectance occur during RSL season (Figures 1c and 1d). If RSL are formed by brines or pure water, then it is possible that the wetness of the substrate is responsible for lowering the overall reflectance and deepening the band depths. Atmospheric opacity may also have an effect, based on our inference of deeper band depths coinciding with lower estimated 900 nm aerosol opacities. However, southern summer (when RSL are most active) is generally the dustier season on Mars, so the 900 nm aerosols may not fully represent the atmospheric behavior, and the increasing band depths observed at these sites during RSL seasons (Figures 2c and 2e) likely have a nonatmospheric component. This is further
supported by several instances where the band depth increases even when opacity has also increased. Wetting of the substrate or grain size sorting that increases during the RSL season may therefore play a role in the observed temporal variations, and regardless, atmospheric opacity cannot explain the spectral differences between RSL slopes and adjacent non-RSL slopes (Figure 1e).

[16] The lack of water-related IR absorptions (e.g., at ~1.4 and 1.9 μm) seemingly precludes hydrous ferric salts as a spectrally dominant phase on the RSL slopes; however, several laboratory spectroscopy studies of ferric sulfates have shown that the water-related features reduce considerably under exposure to Martian conditions [Cloutis et al., 2008; Rice et al., 2011; Wang and Ling, 2011]. These absorptions would also be expected for a wet surface, but when exposed to desiccating conditions they vanish rapidly, even while the surface still retains its darkened albedo [Massé et al., 2012]. In water tracks (a proposed terrestrial analog for RSL), the volumetric water content (VWC) increases with depth [Levy et al., 2011]. Since IR spectrometers are only sensitive to microns depth, the absence of hydration-related spectral features may be explained by low VWC on the surface. However, we do observe distinct spectral absorptions, fluctuations in band depth, and in relative reflectance that can be attributed to wetting of the substrate or grain size sorting. Additionally, H2O and S chemical maps (sensitive to decimeter depths) support sulfate-driven hydration of bulk soil in the Southern Hemisphere [Karunatillake et al., 2013], including a consistency with hydrous Fe3+ sulfates in the latitudinal band of RSL.

[17] Future laboratory modeling that recreates RSL-like morphology with both dry and wet mechanisms, coupled with spectral documentation, will be crucial towards our understanding of RSL. A comparison of VNIR spectra we observe with sulfate-driven hydration of bulk soil in the Southern Hemisphere [Karunatillake et al., 2013], including a consistency with hydrous Fe3+ sulfates in the latitudinal band of RSL.

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