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Spectral evidence for hydrated salts in recurring slope lineae on Mars

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Determining whether liquid water exists on the Martian surface is central to understanding the hydrologic cycle and potential for extant life on Mars. Recurring slope lineae, narrow streaks of low reflectance compared to the surrounding terrain, appear and grow incrementally in the downslope direction during warm seasons when temperatures reach about 250–300 K, a pattern consistent with the transient flow of a volatile species[1–3]. Brine flows (or seeps) have been proposed to explain the formation of recurring slope lineae[1–3], yet no direct evidence for either liquid water or hydrated salts has been found[4]. Here we analyse spectral data from the Compact Reconnaissance Imaging Spectrometer for Mars instrument onboard the Mars Reconnaissance Orbiter from four different locations where recurring slope lineae are present. We find evidence for hydrated salts at all four locations in the seasons when recurring slope lineae are most extensive, which suggests that the source of hydration is recurring slope lineae activity. The hydrated salts most consistent with the spectral absorption features we detect are magnesium perchlorate, magnesium chlorate and sodium perchlorate. Our findings strongly support the hypothesis that recurring slope lineae form as a result of contemporary water activity on Mars.

Water is essential to life as we know it. The presence of liquid water on Mars today has astrobiological, geologic and hydrologic implications and may affect future human exploration. Various salts (for example, sulphates, chlorides and perchlorates) have been detected on the surface of Mars from remote and *in situ* investigations[5–7]. These salts can lower the freezing point of water by up to 80 K, lower the evaporation rate of water by an order of magnitude, and can be hygroscopic (that is, able to easily absorb atmospheric moisture), for example, see refs 8–11, thus increasing the possibility of forming and stabilizing liquid water on the surface of present-day Mars[12].

Recurring slope lineae (RSL) are narrow, low-reflectance features forming on present-day Mars that have been suggested to be due to the transient flow of liquid water. RSL extend incrementally downslope on steep, warm slopes, fade when inactive, and reappear annually over multiple Mars years[1–3]. Average RSL range in width from a few metres (<5 m), down to the detection limit for the High Resolution Imaging Science Experiment (HiRISE) camera (~0.25 m pixel^{-1}; ref. 13). The temperatures on slopes where RSL are active typically exceed 250 K and commonly are above 273 K (ref. 2). These characteristics suggest a possible role of salts in lowering the freezing point of water, allowing briny solutions to flow[1–3]. Confirmation of this wet origin hypothesis for RSL would require either detection of liquid water absorptions on the surface, or detection of hydrated salts precipitated from that water.

The mineralogic composition of RSL and their surroundings can be investigated using orbital data acquired by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on the Mars Reconnaissance Orbiter (MRO), which acquires spectral cubes with 544 spectral channels (~0.4 to 3.92 μm; ref. 14). Within the infrared (IR) detector spectral range of CRISM (1–3.92 μm), both liquid water and hydrated salts have diagnostic absorption bands at ~1.4 μm, ~1.9 μm and a broad absorption feature at ~3.0 μm (ref. 15; Fig. 1). In addition, hydrated salts may exhibit combinations or overtones at other wavelengths from 1.7 to 2.4 μm. Given the coarser spatial sampling of CRISM (~18 m pixel^{-1}) compared to HiRISE, few locations exist in which RSL are wide or dense enough to fill even a single CRISM pixel. In this work, we devised a variety of methods to reduce uncertainties from extraction of CRISM spectra from individual pixels (Supplementary Information), allowing examination of pixels mostly filled by RSL.

At Palikir crater, RSL are observed to be longest and widest towards the end of the southern summer. In the HiRISE image acquired at the end of the southern summer of Mars Year (MY) 30, wide RSL were observed on the slopes of Palikir (Fig. 1 and Supplementary Table 1). CRISM spectra from this dense region of RSL were inspected. Six individual CRISM pixels exhibit enhanced hydration absorption features (Fig. 1 and Supplementary Table 1). The CRISM pixels closest to the wide RSL exhibited absorption features at wavelengths near ~1.48, 1.91 (Fig. 1) and ~3 μm (Supplementary Fig. 1), whereas pixels farther away from RSL exhibited absorption features only at ~1.91 and ~3 μm (Supplementary Fig. 1 and Supplementary Table 1). In general, the ~1.4 μm absorption feature generally weakens with dehydration and disappears more rapidly than the ~1.9 and 3 μm absorption bands (for example, see ref. 16). This suggests a higher hydration state in areas closest to the RSL core. The 1.9 μm absorption is also present in the unratioed I/F spectrum, precluding ratio artefacts as the source of the absorption band (Supplementary Fig. 1). We carried out a statistical study to elucidate true signal from noise. The 1.9 μm absorption is consistently well above the noise threshold, and in half of the cases the 1.4 and 2.15 μm absorption features are also above the noise threshold (Supplementary Fig. 2). The wavelength position of the observed 1.4 μm absorption is longer than is typical of perchlorates, suggesting the presence of an additional mineral.

We also analysed CRISM observation of Palikir crater during the middle of MY 30 southern summer, when RSL were shorter and narrower, and found no evidence for absorption features at ~1.4 and/or 1.9 μm anywhere surrounding the RSL (Supplementary Fig. 3

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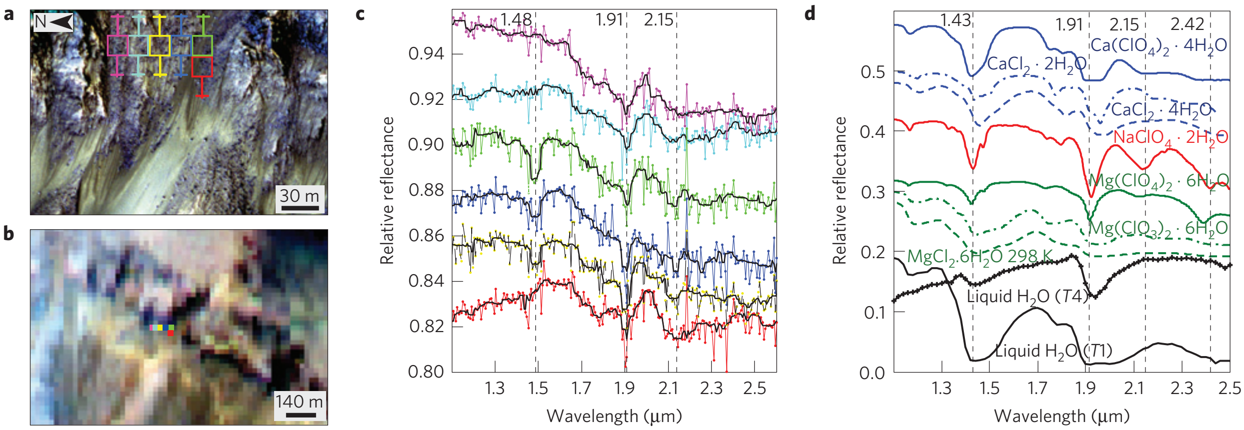

Figure 1 | Palikir crater RSL and spectral detection of hydration features. a, RSL on slope of Palikir crater ESP_024034_1380 (Infrared-Red-Blue/Green (IRB)) (L_S: 359 MY: 30). Coloured boxes show the location of the CRISM pixels with the uncertainty. **b**, Concurrent CRISM observation FRT0002038F (R: 2.53 μm, G: 1.51 μm, B: 1.08 μm) showing the same area as **a**. **c**, Spectra from coloured regions of interest shown in **a** and **b**. The observed data are plotted with coloured lines and the smoothed data in black lines. **d**, Laboratory spectra of various salts[17,28,29] and liquid water ($T1 = 1$ and $T4 = 4$ h into dehydration)[16].

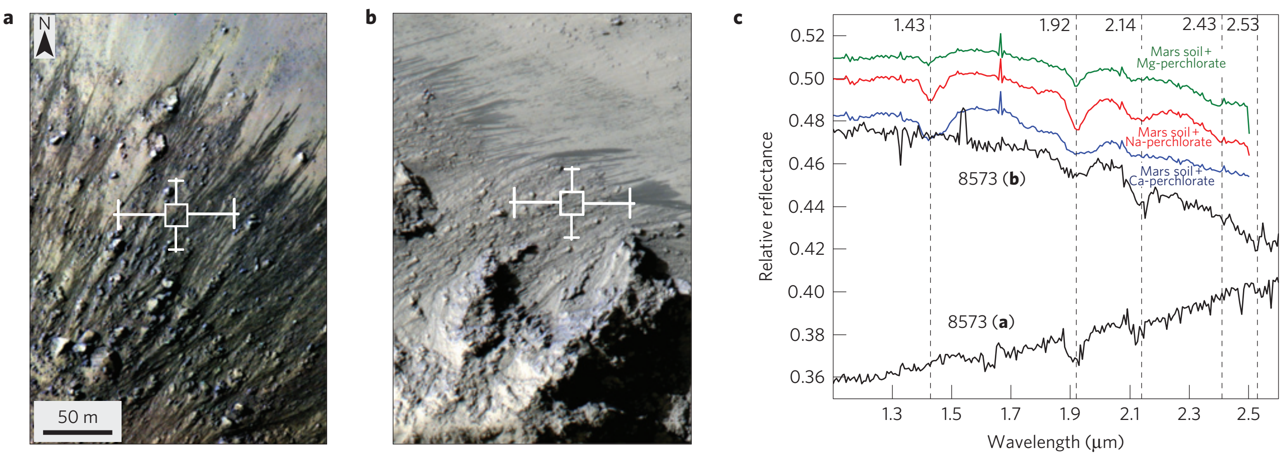

Figure 2 | RSL activity in the central peaks of Horowitz crater and associated CRISM spectra. a, RSL emanating from bedrock exposures at Horowitz crater's central peak. Part of HiRISE image PSP_005787_1475 (IRB) ($L_S = 334°$, MY 28). **b**, A different section of the same HiRISE image as **a**, showing RSL activity at a different peak (scale same as in **a**). In **a** and **b**, the white box with error bars shows the location of the CRISM pixels with the uncertainty. **c**, Black spectra correspond to the area in **a** and **b**, from CRISM observation FRT00008573. Coloured spectra are results from spectral mixing between the Martian soil and a variety of salts (specified in the figure).

and Supplementary Table 1). In MY 31, only the image from the end of the summer (FRT00029F0C) showed 1.9 and 3 μm absorptions (Supplementary Fig. 4). Detections of hydration bands from both MY are only from late-season images where RSL are observed to be the widest, consistent with our hypothesis that the hydration feature is due to the areally extensive presence of RSL.

The absorptions observed in CRISM images of Palikir are too narrow to be explained by liquid water. Instead, they may be consistent with hydrated salts (Fig. 1). The rapid change in hydration state of the minerals imply that at the times and places where RSL form, either the hydration state of the minerals is being increased by the presence of RSL, or hydrated minerals are deposited by RSL and later desiccated. A linear spectral mixture of Martian soil with magnesium perchlorate, chlorate and chloride provides the closest match (Supplementary Fig. 5).

Coordinated HiRISE–CRISM observations of Horowitz crater in MY 29 show large RSL emanating from the central peaks (Fig. 2). At two of the central peaks, we observed absorptions at 1.9, 2.15 and 2.43 μm. A linear spectral mixture of Martian soil and sodium perchlorate[17,18] provided the best match to the observed spectra (Fig. 2 and Supplementary Fig. 7). The spectra reported here lack absorption features above the noise threshold at ~1.4 μm, but they do have broad ~3 μm absorptions consistent with hydration (Supplementary Fig. 8). The 1.9 and 2.15 μm absorptions are also present in the unratioed I/F spectrum (Supplementary Fig. 8).

Some of the most intense RSL activity in the southern mid-latitudes occurs on the central peak structures of Hale crater (Fig. 3). A HiRISE–CRISM coordinated observation was acquired during the late RSL season (Fig. 3 and Supplementary Table 1). Analysis of the CRISM data shows strong ~1.48 and 1.9 μm absorption features in the location where dense RSL activity is observed in the HiRISE image (Fig. 3). Similar to Palikir, the presence of narrow 1.48 and 1.9 μm absorption bands is consistent with a linear spectral mixture of magnesium perchlorate and Martian soil.

In Coprates Chasma, RSL are abundant and in some cases entire fans associated with RSL are observed to change their reflectance[2] (Fig. 4). Spectra of RSL fans in Coprates Chasma were analysed, and we found multiple places in the CRISM images with 1.9 μm absorptions (Fig. 4). Without detection of other absorptions, assignment to a particular salt mineralogy is not possible. The 1.9 μm absorption on the RSL slope suggests precipitation of salts and resulting modification of grain sizes as a viable mechanism

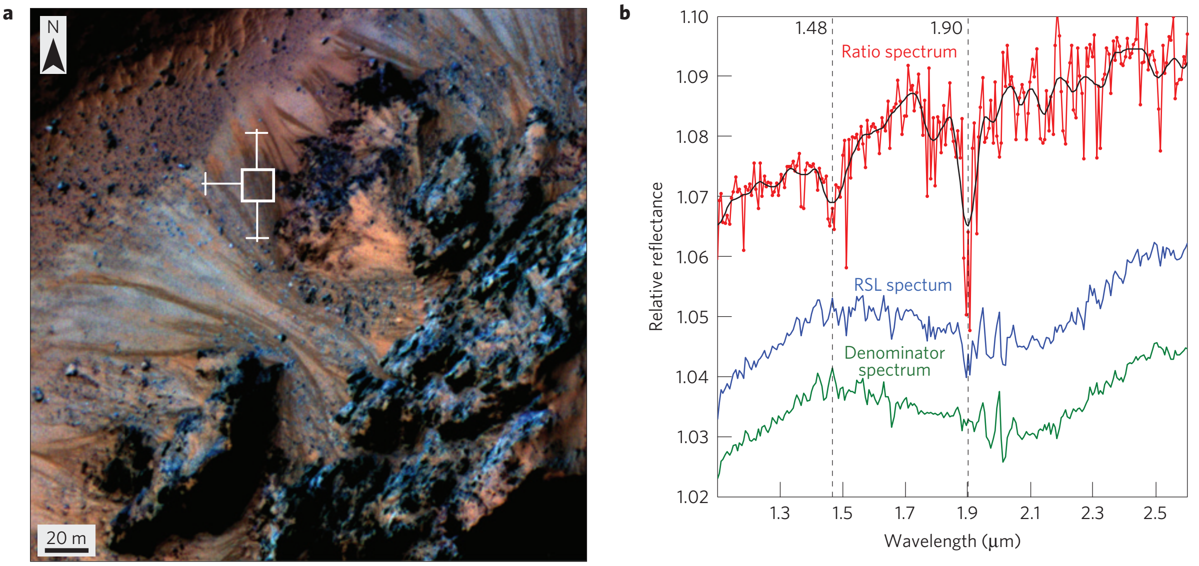

Figure 3 | RSL emanating from a central peak in Hale crater and associated CRISM spectrum. a, RSL on a central peak of Hale crater. Section of HiRISE image ESP_032416_1440 (IRB) (L_s = 342, MY 31): north is up and light is from the left. White box with error bars shows the location of the CRISM pixels with the uncertainty. **b**, IR spectrum from the RSL seen in the HiRISE image. The symbols and the smoothing functions used are the same as in Figs 1 and 2.

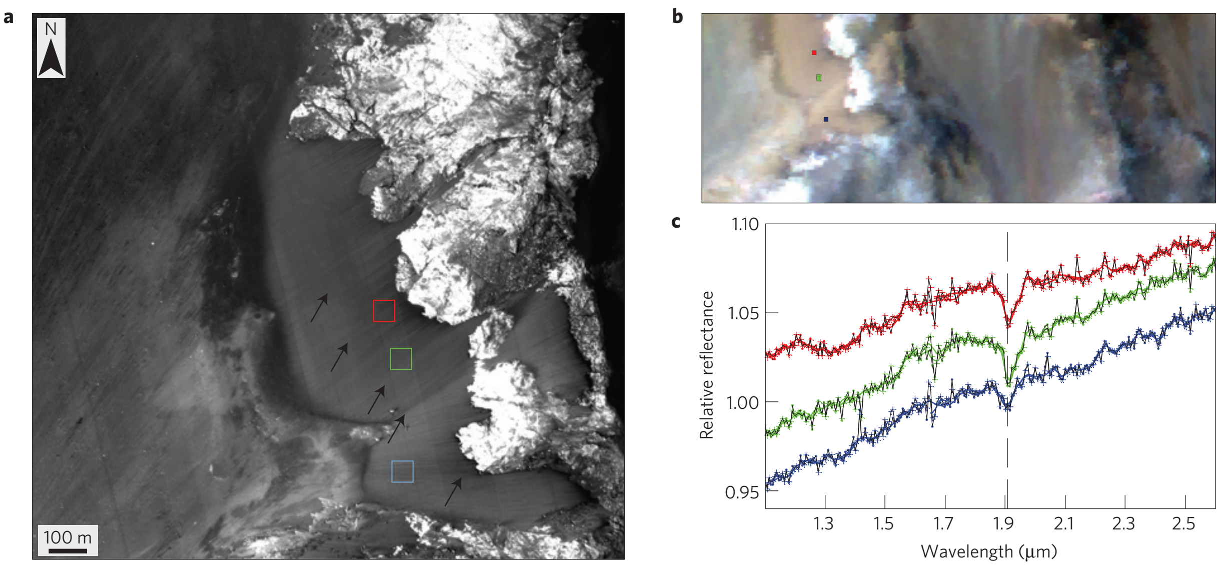

Figure 4 | RSL and associated dark fans observed in Coprates Chasma and associated CRISM spectra. a, RSL emanating from bedrock exposures at Coprates Chasma. Dark fans associated with RSL are indicated by arrows. Various coloured boxes show the approximate location of CRISM pixels shown in **b**. Section of HiRISE image ESP_031019_1650 (L_s = 279° , MY 31). **b**, Areas analysed in concurrent CRISM observation FRS00028E0A. Same RGB channels are used as in Fig. 1b. **c**, Spectra from the three coloured pixels in **b** are shown ratioed to nearby non-RSL material.

for the change in albedo of the fans, and may also explain spectral changes previously reported on RSL fans[4].

MRO's mid-afternoon (~3 p.m.) observations occur at the time of the day with lowest relative humidity[19], which minimizes the probability of detecting liquid brines that emplaced hydrated salts, and may even facilitate dehydration of salts. In all sites discussed here, we observe H_2O-related absorption features at 1.9 and 3 μm, but the OH-related ~1.4 μm feature is observed only in Palikir and Hale crater. On the basis of the widths and the band centres of the absorptions at 1.4 and 1.9 μm, a magnesium perchlorate, magnesium chlorate and magnesium chloride mixture was found to be the best match from our spectral mixture model (Supplementary Fig. 5). On the basis of spectral mixing models and absorption features at 2.15 and 2.43 μm, sodium perchlorate was found to be the best match at Horowitz (Fig. 2). We also performed similar spectral mixing models with various sulphates, but found no good match (Supplementary Fig. 6).

The presence of perchlorates on the surface of Mars has been confirmed at Gale crater by Mars Science Laboratory (MSL), the northern plains by the Phoenix mission, and is suspected at the Viking landing sites[6,20,21] (Supplementary Fig. 9). At Gale crater, hydrated calcium perchlorate is interpreted to be the best matching oxychlorine compound[6]. Magnesium perchlorate and calcium perchlorate were proposed as the most likely cation species of perchlorate at the Phoenix landing site[6,20,22]. Furthermore, thin films of water were suggested to have dissolved perchlorate from the surface to the subsurface and to have created concentrated patches at the Phoenix landing site[5,20]. Re-interpretation of the Viking data also found magnesium perchlorate to be the most likely perchlorate species[21]. These *in situ* perchlorate detections are consistent with our observation at RSL sites. Perchlorate and chlorate species have also been found in a Martian meteorite[23].

The origin of water forming the RSL is not understood[1–3]. Water could form by the surface/subsurface melting of ice, but the presence of near-surface ice at equatorial latitudes is highly unlikely[24]. RSL could form alternatively through deliquescence, but it is unclear whether the Martian atmosphere can supply sufficient water vapour every year to create RSL (ref. 2). Another hypothesis is seasonal discharge of a local aquifer, but lineae extending to the tops of local peaks[2] are difficult to explain. It is conceivable that RSL are forming in different parts of Mars through different formation mechanisms.

In all the sites reported here, we find evidence for hydrated salts on the RSL-containing slopes, supporting a genetic connection between the two. Sodium perchlorate can lower the freezing point of water by up to 40 K, whereas magnesium perchlorate and magnesium chlorate can depress the freezing point even more, by up to 70 K (refs 9,10,19). Magnesium chlorate, magnesium perchlorate and sodium perchlorate monohydrate are also predicted to be the most likely salts to concentrate from evaporation of brine at the Phoenix landing site[22]. Our observation of perchlorate could be due to liquid water in RSL dissolving perchlorates present in the soil and re-precipitating them in higher concentrations. Regardless, the spectral absorption of hydration bands at times and places when we observe maximum RSL activity implicates RSL as the source of hydrated salts.

These results strongly support the hypothesis that seasonal warm slopes are forming liquid water on contemporary Mars. The spectral identification of perchlorate in association with RSL also suggests that the water is briny rather than pure. Terrestrially, in the hyper-arid core of the Atacama Desert, deliquescence of hygroscopic salts offers the only known refuge for active microbial communities[25,26] and halophylic prokaryotes[27]. If RSL are indeed formed as a result of deliquescence of perchlorate salts, they might provide transiently wet conditions near surface on Mars, although the water activity in perchlorate solutions may be too low to support known terrestrial life[19]. The detection described here warrants further astrobiological characterization and exploration of these unique regions on Mars. This enhanced evidence for water flow also provides new clues as to the nature of the current Martian hydrologic cycle.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

The methodology was conceived and designed by L.O. All data analysis was done by L.O. with significant feedback from S.L.M., J.J.W., A.S.M. and M.B.W. J.J.W., M.B.W., J.H. and M.M. provided all the laboratory spectra used in this paper. A.S.M., M.C. and S.L.M. planned many of the HiRISE–CRISM coordinated observations of the RSL sites. All authors contributed to discussion, interpretation and writing.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to L.O.

Competing financial interests

The authors declare no competing financial interests.

Methods

Previous work[4] inspected only averages of many CRISM pixels, such that absorptions present over smaller areas would have been significantly weakened as a result of areal mixing. We extracted spectra from areas that had the widest RSL and normalized them using reference spectra from the same detector columns to avoid instrument artefacts (Supplementary Table 1). We also used multiple variants of the standard 'volcano-scan' approach to normalizing atmospheric absorptions to rule out inadvertent introduction of processing artefacts. Spectral mixing models used a spectrum from a spectrally neutral area within the same scene and column ('Martian soil'), combined with laboratory spectra of various salts, to find the best matching mixture of soil and a salt to the RSL spectra observed in CRISM data. A flow chart outlining how we separated signal from noise for the band detection algorithm routine is provided in Supplementary Fig. 10.