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# Implications for the origin and evolution of Martian recurring slope lineae at Hale crater from CaSSIS observations

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## Abstract

Recurring Slope Lineae (RSL) are narrow, dark features that typically source from rocky outcrops, incrementally lengthen down Martian steep slopes in warm seasons, fade in cold seasons and recur annually. In this study we report the first observations of RSL at Hale crater, Mars, during late southern summer by the Colour and Surface Science Imaging System (CaSSIS) on board ESA’s ExoMars Trace Gas Orbiter (TGO). For the first time, we analyze images of RSL acquired during morning solar local times and compare them with High Resolution Imaging Science Experiment (HiRISE) observations taken in the afternoon. We find that RSL activity is correlated with the presence of steep slopes. Our thermal analysis establishes that local temperatures are high enough to allow either the melting of brines or deliquescence

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of salts during the observation period, but the slope and aspect distributions of RSL activity predicted by these processes are not consistent with our observations. We do not find any significant relative albedo difference between morning and afternoon RSL. Differences above 11% would have been detected by our methodology, if present. This instead suggests that RSL at Hale crater are not caused by seeping water that reaches the surface, but are best explained as dry flows of granular material.

*Keywords:* Recurring slope Lineae, RSL, CaSSIS, HiRISE, Mars, Relative albedo, THEMIS

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## 1. Introduction

The origin of Recurring Slope Lineae (RSL) is one of the most controversial science questions regarding present-day surface activity on Mars. They appear as narrow ( $< 5$  m) low-albedo streaks, often starting from bedrock outcrops and lengthening hundreds of meters down Martian steep slopes at equatorial and mid-latitudes (McEwen et al., 2011). RSL generally start lengthening during warm seasons, fade during cold ones and recur over multiple Martian years. However, RSL activity can be more complicated than a simple repeating cycle of lengthening and fading, as several well studied sites shows simultaneous lengthening, appearance and fading of RSL (Stillman and Grimm, 2018; Vincendon et al., 2019). Many models have been proposed to explain their origin, but a definitive explanation is still elusive. These can be broadly summarized in three classes: *wet models*, in which RSL are water-dominated features, *dry models*, that explain RSL as dry mass fluxes or aeolian features, and *hybrid models*, in which water plays an indirect role in RSL formation and lengthening.

### 16 1.1. Wet models

17 The temperature dependence of RSL activity suggests that water or brines may  
18 be present (McEwen et al., 2011; McEwen et al., 2014; Stillman et al., 2014; Hu-  
19 ber et al., 2020). Spatial correlation with multi-scale fractures appears to support  
20 groundwater sources (Stillman et al., 2016; Abotalib and Heggy, 2019). However,  
21 topographic relationships cast doubts on these models, as they explain the season-  
22 ality of RSL activity, but require larger volumes of liquids than could be reasonably  
23 present on Mars at these latitudes (Grimm et al., 2014; Chojnacki et al., 2016).  
24 Moreover, many RSL source from local topographic highs, such as ridge crests or  
25 peaks, where a groundwater source is unlikely (Chojnacki et al., 2016). Another wet  
26 process that has been considered to explain RSL formation is the deliquescence of  
27 salts, which occurs when hygroscopic salts absorb water vapor to form a liquid solu-  
28 tion (Gough et al., 2016). For this to happen, temperatures higher than the eutectic  
29 temperature of the solution and relative humidities (RH) greater than their deliques-  
30 cence relative humidity (DRH) are required (Gough et al., 2016). Several laboratory  
31 studies have identified chlorides (Gough et al., 2016; Wang et al., 2019), perchlorates  
32 (Nuding et al., 2014) and chlorates (Toner and Catling, 2018) as potential candidate  
33 deliquescent salts. The required RH values for the deliquescence of  $\text{CaCl}_2$  brines  
34 range from 12.9% when  $T = 273$  K to  $\sim 20.9\%$  at  $T = 233$  K (Gough et al., 2016),  
35 while their eutectic temperature is  $T = 223\text{K}$ . Numerical modeling by Gough et al.  
36 (2016) showed that atmospheric water vapor could sustain the deliquescence of hy-  
37 drated  $\text{CaCl}_2$  brines at 3-cm depth at the Phoenix landing site. However, it is not  
38 clear whether or not the same process can happen at RSL sites (Gough et al., 2016),

39 even though Wang et al. (2019) recently proposed that the deliquescence of sub-  
 40 surface hydrated chlorides can be a thermodynamically viable (but not necessarily  
 41 sufficient) process for triggering RSL activity. The deliquescence of Ca-perchlorates  
 42 is also interesting because of their relatively low DRH (from  $10 \pm 4\%$  at 273 K to  
 43  $55 \pm 4\%$  at 223 K (Nuding et al., 2014)) and eutectic temperature of  $T = 200$  K.  
 44 Finally, chlorates may be even more interesting candidates as they have a lower DRH  
 45 than perchlorates (Toner and Catling, 2018).

## 46 1.2. *Dry models*

47 In these models, RSL lengthening and formation are interpreted with dry mech-  
 48 anisms involving granular flows or aeolian processes (Dundas et al., 2017; Schmidt  
 49 et al., 2017; Vincendon et al., 2019; Schaefer et al., 2019). These have been initially  
 50 invoked to explain the correlation between the angle of repose of granular material  
 51 and the slope angle at which RSL stop (Dundas et al., 2017), although more re-  
 52 cent measurements show that  $\sim 25\%$  of RSL reach slopes below the angle of repose  
 53 (Tebolt et al., 2020; Stillman et al., 2020). In addition, Schmidt et al. (2017) dis-  
 54 cussed morphological inconsistencies between RSL and wet flows, such as the lack of  
 55 terminal or lateral levees; Vincendon et al. (2019) proved that RSL formation occurs  
 56 outside the time-frame compatible with the existence of liquid water and does not  
 57 show a preference for the warmest slopes. Finally, the spectral detection of hydrated  
 58 salts at some RSL sites (Ojha et al., 2015), which would support the presence of  
 59 liquids, was recently proven to not be robust (Leask et al., 2018; Vincendon et al.,  
 60 2019). Although dry flows do not require a source of water, a trigger mechanism has  
 61 not been fully established yet. Schmidt et al. (2017) proposed a Knudsen pump as a

62 trigger mechanism, but it doesn't predict RSL at the times and locations where they  
 63 are observed (Stillman and Grimm, 2018; Vincendon et al., 2019). Vincendon et al.  
 64 (2019) and Schaefer et al. (2019) proposed that RSL are aeolian features resulting  
 65 from the removal of bright dust by winds. A fading mechanism has been recently  
 66 proposed by Vincendon et al. (2019), which showed that the progressive brightening  
 67 of RSL can be attributed to dust deposition. On the other hand Schaefer et al. (2019)  
 68 discovered that the fading of RSL is similar to that of other dust-related albedo fea-  
 69 tures (dust devil tracks, rockfalls) on the basis of relative albedo analyses at Tivat  
 70 crater (45° S, 9° E). They propose that RSL fade due to the widespread removal  
 71 of dust from the neighboring slopes, which progressively darken until matching the  
 72 RSL reflectance. While this mechanism applies well to Tivat crater, it cannot explain  
 73 the concurrent fading and lengthening of RSL observed in several other RSL sites  
 74 (Vincendon et al., 2019; Stillman et al., 2020).

### 75 *1.3. Hybrid models*

76 Other hypotheses envision an indirect role of water in triggering RSL activity.  
 77 Massé et al. (2016) showed that boiling fresh water can trigger granular flows by vio-  
 78 lently displacing grains. While this model is interesting because it requires less water  
 79 than wet-based models, boiling water requires high temperatures that are hardly met  
 80 at the onset of RSL activity in early spring (Stillman and Grimm, 2018; Vincendon  
 81 et al., 2019). More recently, Shoji et al. (2019) proposed that moisture serves to  
 82 stabilize steep slopes in cold seasons, which flow when drying during the warm sea-  
 83 sons. In addition, Bishop et al. (2019) proposed that subsurface brine activity can  
 84 create surface collapse features, perhaps initiating RSL when on steep enough slopes.

86 The High Resolution Imaging Science Experiment (HiRISE, McEwen et al. (2007))  
 87 on board the NASA’s Mars Reconnaissance Orbiter (MRO) mission is the optimal  
 88 instrument to image RSL due to its high pixel scale ( $\sim 0.3$  m/pixel), which allows  
 89 for digital terrain models (DTM) at  $\sim 1$  m spatial resolution. However, the Sun-  
 90 synchronous orbit of MRO limits observation times between  $\sim 2$ -4 PM, during the  
 91 local afternoon.

92 The Colour and Surface Imaging System (CaSSIS, Thomas et al. (2017)), on board  
 93 the ESA ExoMars Trace Gas Orbiter (TGO) mission, images the Martian surface  
 94 at 4.6 m/pixel in four color bands. It carries a rotation mechanism that allows it  
 95 to acquire stereo observations with identical illumination angles for the production  
 96 of DTMs. The  $74^\circ$  inclined orbit of TGO allows CaSSIS to observe the surface  
 97 at different times of day, such as the local morning. This capability is pivotal for  
 98 RSL studies, since morning observations of these features are not possible other-  
 99 wise. The only exceptions are extremely early morning views by Mars Odyssey, with  
 100 poor SNR and much lower spatial resolution. Morning activity can provide great  
 101 insights on the nature and formation mechanism of RSL. Laboratory studies (Gough  
 102 et al., 2016) and analyses of data from both the Rover Environmental Monitoring  
 103 Station (REMS) on board Curiosity and the Thermal and Electrical Conductivity  
 104 Probe (TECP) on the Phoenix lander shows that daily maximum RH values occur  
 105 during the early morning of local summer (Steele et al., 2017; Fischer et al., 2019),  
 106 suggesting that these local hours are the most favourable for deliquescence. If RSL  
 107 are liquid-based flows, their activity should increase in the morning, when both tem-

108 perature and air humidity are high enough to favor the deliquescence of salts and  
 109 increase the stability of brines. Under this scenario, dehydration would occur in the  
 110 afternoon, so we would also expect RSL to be darker in the morning than in the  
 111 afternoon. Instead, if RSL are caused by the melting of shallow subsurface ice (such  
 112 as from a deep groundwater source), then they should be darker in the afternoon.  
 113 This assumes that the quantity of water or brines at play is relatively small, so that  
 114 evaporative losses exceed the supply of water (Hillel, 2004). If instead RSL have a  
 115 high water content, pore water concentration would not be affected by evaporation  
 116 and there wouldn't be any albedo change (Pommerol et al., 2013; Levy et al., 2014).  
 117 The latter case, however, may not be in agreement with the very low water content  
 118 of RSL estimated at Garni crater (Edwards and Piqueux, 2016). Finally, if RSL are  
 119 dry flows, then we do not expect any albedo change between the observations.  
 120 In this study we present the first observations of RSL performed by CaSSIS during  
 121 the local morning and compare them with HiRISE observations acquired one month  
 122 earlier in the afternoon. In particular, we search for any differences in their over-  
 123 all morphology (i.e. length, slope, aspect) and report relative albedo measurements  
 124 performed on morning and afternoon images. We analyze the thermal conditions of  
 125 the surface and shallow sub-surface at the time of the CaSSIS observation to assess  
 126 whether temperatures would either allow melting of brines or deliquescence of salts.

## 127 **2. Data**

128 The study region is the central peak of Hale crater ( $-35.7^\circ$  N,  $323.5^\circ$  E, see figures  
 129 (2a, b)), where several areally extensive RSL have been discovered so far, making it



130 an ideal site to be investigated with CaSSIS. RSL in Hale were first reported by Ojha  
 131 et al. (2014) and then analyzed by different authors (Stillman et al., 2014; Dundas  
 132 et al., 2017; Stillman and Grimm, 2018). Stillman and Grimm (2018) reported that  
 133 RSL activity in general may occur in one or two pulses, where RSL fade partially or  
 134 completely and then re-appear in the same year. The RSL at Hale crater are peculiar  
 135 because they seem to experience three pulses of activity (Stillman and Grimm, 2018),  
 136 unlike any other sites analyzed on Mars so far. Our RSL observations span an  $L_s$   
 137 range between  $331.5^\circ$  and  $347.4^\circ$ , within the third pulse proposed by Stillman and  
 138 Grimm (2018), allowing us to confirm its presence at Hale crater. In order to study  
 139 whether there is a diurnal dependence in the activity of RSL, an ideal dataset would  
 140 include two observations of an RSL site acquired during the same Martian day,  
 141 the first one with CaSSIS in the morning and the second one with HiRISE in the  
 142 afternoon. In our case, the observations were acquired during late southern summer,  
 143 one month apart. The HiRISE image was acquired on  $L_s = 331.5^\circ$  at 14:06 local time,  
 144 while the CaSSIS image was acquired on  $L_s = 347.4^\circ$  at 11:13 local time. This time  
 145 interval may be too big to minimize seasonal changes between images, such as fading  
 146 of RSL, which typically happens during this season at southern hemisphere sites.  
 147 However, this issue may not be important for Hale crater, where fading was reported  
 148 to occur only after  $L_s > 7^\circ$  for both MY 30 and 31 (Stillman and Grimm, 2018),  
 149 well after the  $L_s$  of our observations. For this reason, we are confident that fading is  
 150 not influencing our analysis. Moreover, RSL at Hale crater are “rejuvenated” by a  
 151 third pulse of activity which occurs just before  $L_s = 331.5^\circ$ . The occurrence of this  
 152 third pulse of activity is illustrated in figure (1). HiRISE image ESP\_057\_569\_1440,

153 acquired at  $L_s = 286.6^\circ$ , shows dense RSL coverage (see fig. 1a), while the subsequent  
 154 HiRISE image ESP\_058618\_1445, acquired at  $L_s = 331.5^\circ$ , shows smaller RSL in the  
 155 same places (see fig. 1b). These further lengthened in the subsequent CaSSIS image  
 156 MY34\_005640\_218.2, acquired at  $L_s = 347.4^\circ$  (see fig. 1c). This means that the RSL  
 157 had completely faded and had started lengthening again between the first two images  
 158 (1a,b) and continued lengthening between  $L_s = 331.5^\circ$  and  $L_s = 347.4^\circ$ . This is also  
 159 confirmed by the analysis of HiRISE images of Hale crater in previous Martian Years  
 160 reported by Stillman and Grimm (2018). In particular, from figure S9 of Stillman  
 161 and Grimm (2018) we see that RSL lengthening occurs between  $341.9^\circ < L_s < 7^\circ$   
 162 in MY 31 and  $326.5^\circ < L_s < 7^\circ$  MY 32. This means that despite the HiRISE and  
 163 CaSSIS images analyzed here being taken 30 days apart, the mechanisms responsible  
 164 for RSL lengthening are active during this period and any seasonal fading can be  
 165 considered negligible, allowing us to compare RSL albedos between the two images.  
 166 In the following sections we will describe our dataset, summarized in figure (2), which  
 167 combines HiRISE (section 2.1), CaSSIS (section 2.2) and Thermal Emission Imaging  
 168 System (THEMIS; Christensen et al. (2004)) (section 2.3) observations. Image IDs  
 169 and observation details for each of the products we used are detailed in Appendix  
 170 A.

## 171 2.1. *HiRISE data*

172 We used the latest publicly available HiRISE image of the central peak of Hale  
 173 crater, ESP\_058618\_1445, acquired on 27 January 2019 at 14:06 Mars local time  
 174 and with a  $L_s = 331.5^\circ$ , as well as the corresponding HiRISE DTM and orthophoto  
 175 of the region. The RED channel (McEwen et al., 2007) of the HiRISE image was

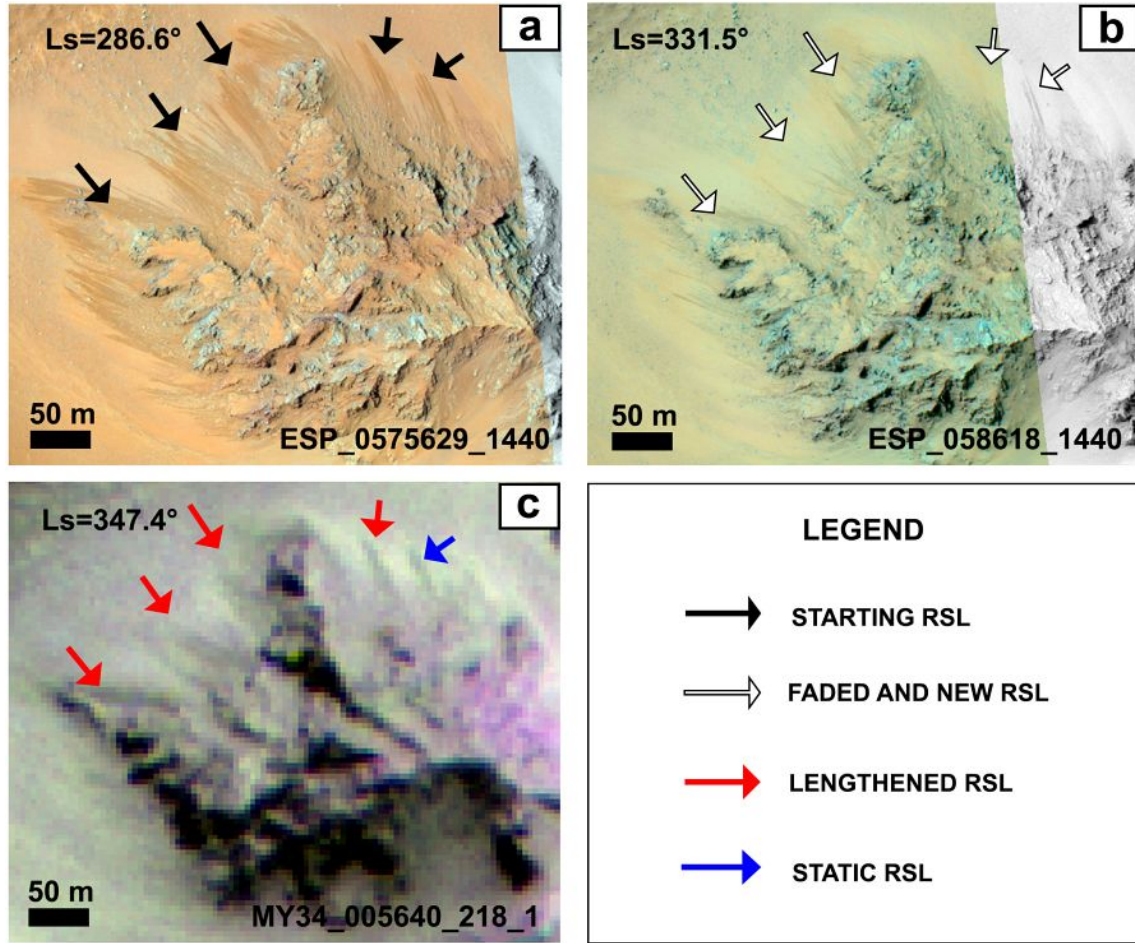


Figure 1: RSL activity during the 3rd pulse at Hale crater. a) HiRISE image showing areally extensive RSL, indicated by black arrows, at  $L_s = 286.6^\circ$ . b) The same area but observed at  $L_s = 331.5^\circ$ . White arrows indicate the same RSL in a) that faded and restarted their lengthening phase. c) Colour composite of the RED, PAN and BLU filters of CaSSIS image MY34\_005640\_218\_2 taken at  $L_s = 347.4^\circ$  and showing that some a RSL in n) remained static (blue arrow) while others (red arrows) further lengthened with respect to the previous image. Areal extents of RSL in this area are mapped in figure (10).

176 orthorectified on the DTM using the NASA Ames Stereo Pipeline (Moratto et al.,  
 177 2010). To obtain reliable slope and aspect measurements, we adapted the technique  
 178 of Schaefer et al. (2019) to reduce noise and systematic artifacts present in the DTM  
 179 and calculated slope and aspect maps using ArcGIS (Burrough and McDonell, 1998).  
 180 In particular, the DTM was resampled at 2m resolution and smoothed with a 10 m  
 181 radius moving average as in (Schaefer et al., 2019). The aligned HiRISE DTM, image,  
 182 aspect and slope maps are shown in figure (2). More details about the HiRISE data  
 183 products used in the analysis are provided in Appendix A.

## 184 2.2. *CaSSIS data*

185 The central peak of Hale crater was imaged by CaSSIS on 26 February 2019 at  
 186 11:13 Mars local time, with a  $L_s = 347.4^\circ$ , in stereo mode and with the near infrared  
 187 (NIR), red (RED), panchromatic (PAN) and blue (BLU) filters (Thomas et al.,  
 188 2017). From the CaSISS stereo pair MY34.005640\_218\_1, a DTM and radiometrically  
 189 calibrated orthophoto of the PAN channel of the second image in the stereo pair  
 190 (i.e. MY34.005640\_218\_2) were obtained using the 3DPD photogrammetric pipeline  
 191 described in Simioni et al. (2017). The CaSSIS orthophoto was then manually co-  
 192 registered to the aligned HiRISE dataset in ArcGIS. The footprint of the CaSSIS  
 193 stereo pair is shown in figure (2b) and a color composite image obtained by combining  
 194 the overlap of the RED, PAN and BLU channels is shown in figure (2c).

## 195 2.3. *THEMIS data*

196 We used the MARSTHERM web interface (Putzig et al., 2013) to process THEMIS  
 197 infrared observations within  $\pm 5^\circ$  of  $L_s$  of the CaSSIS image and derive thermal in-

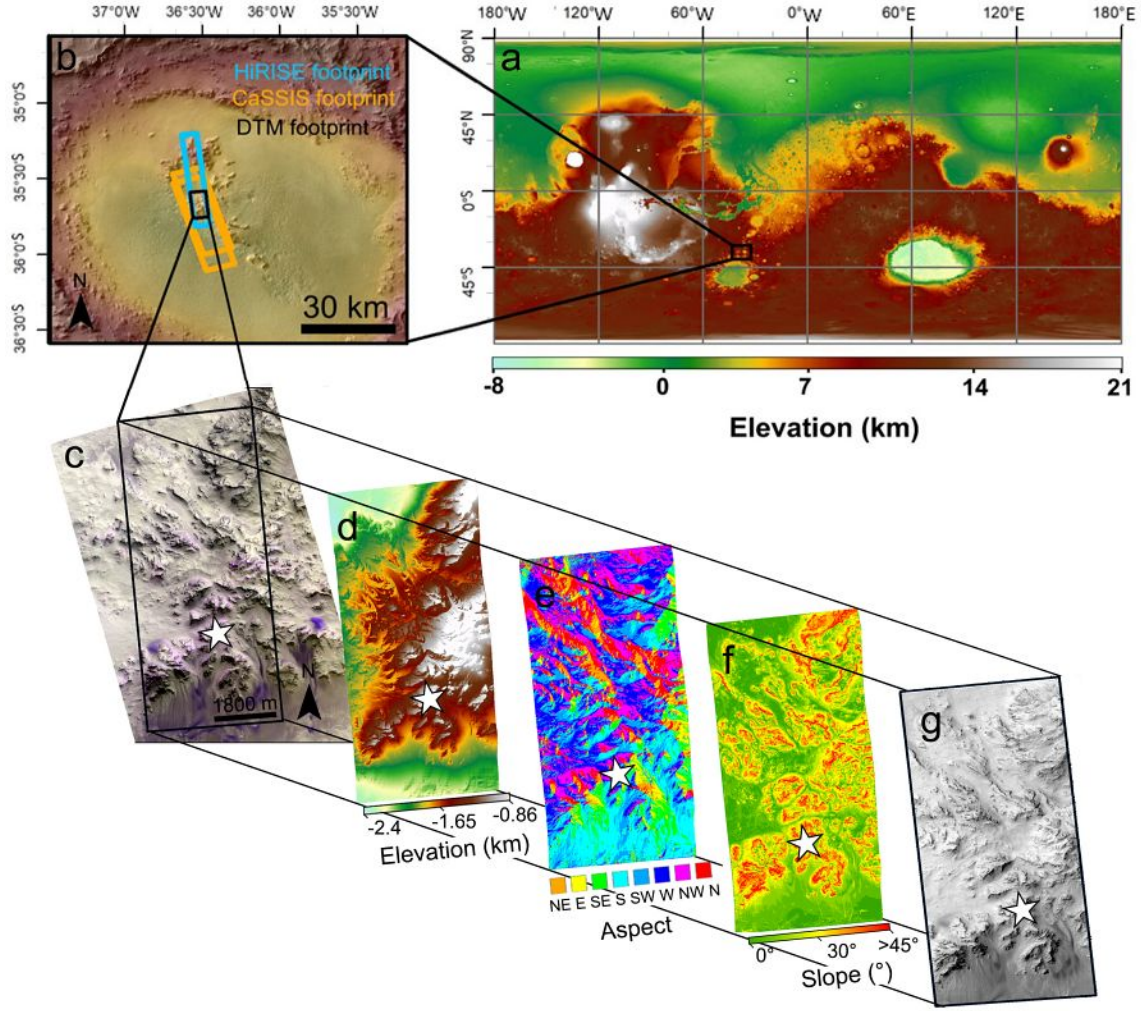


Figure 2: Schematic description of our dataset. a) Mars Orbiter Laser Altimeter (MOLA) colorized elevation map of Mars showing the location of Hale crater (black rectangle). b) MOLA colorized elevation map overlaid on THEMIS infrared daytime mosaic showing the central peak of Hale crater and the footprints of our observations. c) RGB color composite of the RED, PAN and BLU filters of CaSSIS image MY34\_005640\_218\_2 depicting the central peak of Hale crater. d) HiRISE DTM, e) aspect and f) slope maps generated from the HiRISE DTM and g) HiRISE image ESP\_058618\_1445 projected onto the HiRISE DTM. The white star indicates the location of figure (1).

198 ertia maps of Hale crater at 100 m resolution. As is customary for Martian thermal  
 199 modeling studies (Edwards and Piqueux, 2016; Fergason et al., 2006), we considered  
 200 only nighttime observations. The final thermal inertia map was obtained by comput-  
 201 ing the median thermal inertia value at each pixel from all the selected observations.  
 202 The thermal inertia map was then used to simulate surface and subsurface temper-  
 203 atures at Hale crater, as described in section (3.3).

### 204 **3. Methods**

#### 205 *3.1. General properties*

206 We first identified all RSL that were resolved in both the HiRISE and CaSSIS  
 207 images. Sometimes the RSL identified on the HiRISE image occurred in clusters  
 208 of several lineae, spanning multiple CaSSIS pixels, but separated by distances lower  
 209 than the CaSSIS resolution. In these cases we did not consider the single RSL, not  
 210 resolved by CaSSIS, but the whole cluster. We mapped the envelope of each RSL,  
 211 or cluster of RSL, in both images. To better compare the two images and cross-  
 212 check any detected lengthening, we also resampled the HiRISE image at the CaSSIS  
 213 resolution by summing all HiRISE pixels within a CaSSIS pixel and mapped the  
 214 RSL envelopes on the resampled image. Examples of “changed” and “static” RSL,  
 215 including their mapped envelopes are seen in figure (3). If a significant RSL length-  
 216 ening could be detected using both the original and resampled images, we labeled  
 217 the RSL as “changed”, otherwise as “static”. To take into account uncertainties in  
 218 the comparison from any residual misalignment and/or differences in resolution and  
 219 illumination between the two images, we considered a lengthening to be statistically

220 robust only if greater than 1 CaSSIS pixel. This threshold is much lower than the  
 221 typical lengthening that should occur between the two images,  $\sim 60\text{--}100\text{ m}$  given the  
 222 average RSL advance rates (Levy, 2012; Stillman et al., 2016). To distinguish dark-  
 223 ening caused by illumination conditions (i.e. topographic shading) from real RSL in  
 224 the CaSSIS image we also considered the relative orientation between the slopes and  
 225 the direction of the Sun, and avoided comparison of albedo features within highly  
 226 shaded regions. Finally, we measured the mean slope and aspect at the termination  
 point of every mapped RSL in the HiRISE image.

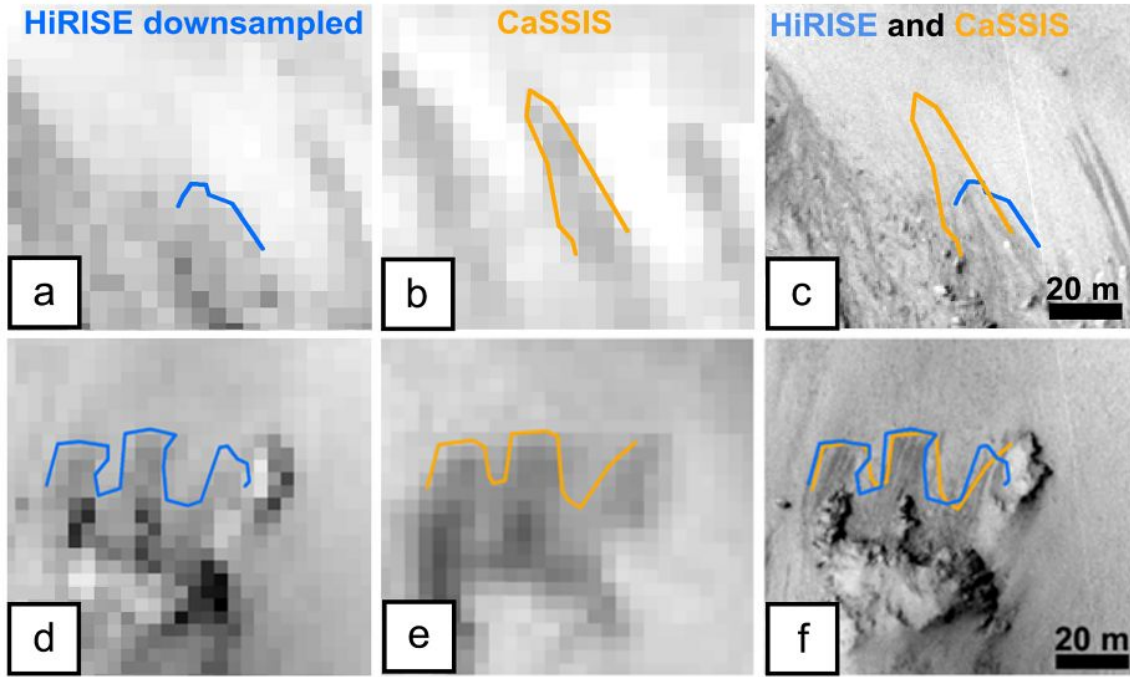


Figure 3: Examples of “changed” (upper row) and “static” (lower row) RSL envelopes mapped in blue on the downsampled afternoon HiRISE image (a,d) and in orange on the morning CaSSIS image (b,e). Panels (c) and (f) Show their comparison on top of the original HiRISE image.

227



### 228 3.2. Relative albedo

229 The relative albedo is the ratio between the reflectance ( $I/F$ ) of two atmospher-  
230 ically corrected regions of the surface that have the same illumination conditions  
231 (Daubar et al., 2016). Our goal is to assess if RSL are darker, and thus potentially  
232 wetter, in the morning with respect to the afternoon. We compute the RSL relative  
233 albedo as the ratio between the reflectance of an RSL region and the reflectance of  
234 a nearby RSL-free region with the same illumination conditions, that is assumed to  
235 not have “changed”. We only compare the CaSSIS PAN channel with the HiRISE  
236 RED channel. As these two filters closely correspond one to each other, the consis-  
237 tency between HiRISE and CaSSIS measurements is granted (Thomas et al., 2017).  
238 A complete multi-band analysis taking into account for differences between the CaS-  
239 SIS RED and NIR and the HiRISE IR filters is left for a future work. In order to  
240 perform relative albedo measurements, it is necessary to first identify regions with  
241 similar slope and aspect, and in turn similar incidence angles. To do this, we first  
242 selected a set of regions of interest (ROI) from the previously identified RSL in both  
243 images (RSL ROI). To ensure that each RSL ROI is dominated by RSL signal, we  
244 used the HiRISE image for the selection and kept that same ROI in the CaSSIS  
245 image. Their mean slope and aspect were measured using ArcGIS. For each RSL  
246 ROI, we defined a corresponding background (BK) ROI in a nearby region, with  
247 similar mean slope and aspect but without RSL in either images. Where a suitable  
248 BK ROI could not be found, we did not include the RSL in the relative albedo anal-  
249 ysis. This criterion proved to be the most restrictive, resulting in a relatively low  
250 number of suitable ROIs for relative albedo measurement, as discussed in section



251 (4.2). Figure (4) shows examples of some selected ROIs. We extracted the mean  
 252 I/F and its standard deviation for each BK and RSL ROI and applied a first order  
 253 atmospheric correction by subtracting the I/F value of the darkest pixel within shad-  
 254 ows in the overlapping region of the two images from  $IF_{RSL}$ . To take into account  
 255 the different resolutions of the two images, for HiRISE we used the mean I/F in a  
 256  $4.6 \times 4.6$  m square area around the darkest pixel within shadows. Although this kind  
 257 of atmospheric correction can be inaccurate in steep topography, it is often adopted  
 258 when performing relative photometry (Daubar et al., 2016; Schaefer et al., 2019). In  
 259 addition, more precise use of shadows areas for this purpose could be performed if  
 260 required (Hoekzema et al., 2011). In our case, however, we only apply the atmo-  
 261 spheric correction to the RSL ROIs and not to the BK ones. The rationale behind  
 262 this approach is to take into account the non-linear effect of aerosols on the apparent  
 263 reflectance of a surface, meaning that low-albedo surfaces are more brightened by  
 264 diffuse light than high albedo ones (Vincendon et al., 2007). We finally computed  
 265 the relative albedo as:

$$RA_* = \frac{IF_{RSL} - IF_D}{IF_{BK}} \quad * \in \{H, C\} \quad (1)$$

266 where  $RA_*$  is the RSL relative albedo, computed either from the original HiRISE  
 267 ( $* = H$ ) or CaSSIS ( $* = C$ ) images.  $IF_{RSL}$  is the mean I/F extracted from an  
 268 RSL ROI.  $IF_D$  is the I/F of the darkest shadowed pixel and  $IF_{BK}$  is the I/F of  
 269 a BK ROI. We compute uncertainties for the HiRISE and CaSSIS relative albe-  
 270 dos applying standard error propagation (see Appendix B). The significance of any  
 271 difference between the HiRISE and CaSSIS relative albedos is established applying

272 standard statistical tests. We use the Kolmogorov-Smirnov (*KS*, Massey (1951))  
 273 and Wilcoxon (*W*, Wilcoxon (1945)) signed-rank statistical tests to assess if the  
 274 HiRISE and CaSSIS relative albedos are sampled from the same distribution. We  
 275 apply the Anderson-Darling (*AD*, Anderson and Darling (1954)) and Shapiro-Wilk  
 276 statistical tests (*SW*, Shapiro and Wilk (1965)) to assess if the differences between  
 277 the two distributions are stochastic. From each test, a  $p$ -value is computed and  
 278 compared with the customary 0.05 threshold. All tests and the  $p$ -value compu-  
 279 tations are performed using routines implemented in the `nortest` library (Gross  
 280 and Ligges, 2015) (<https://CRAN.R-project.org/package=nortest>) of the R pro-  
 281 gramming language (R Core Team, 2019).

### 282 *3.3. Thermal analysis*

283 We simulated diurnal surface and subsurface temperatures on the region depicted  
 284 in figure (5a) at the time of the CaSSIS observation using the thermal model of  
 285 Schorghofer et al. (2019). This model solves the 1D thermal balance and diffusion  
 286 equations in a rough surface, taking into account the contribution of 3D topography  
 287 to the surface energy balance. Examples of modeled diurnal surface and subsurface  
 288 temperature maps are shown in figure (6). We focused only on this region because  
 289 it hosts many large RSL on multiple slope orientations and allowed us to reduce  
 290 computation time. Within this region we defined different study zones, as depicted  
 291 in figure (5b). To account for the different thermal behavior of different materials  
 292 within our region, we distinguished between zones composed of exposed bedrock (i.e.  
 293 those starting with “B” in figure (5d) and zones composed of finer material, like  
 294 regolith (i.e. those starting with “S” in figure (5d)). For the former we estimate a

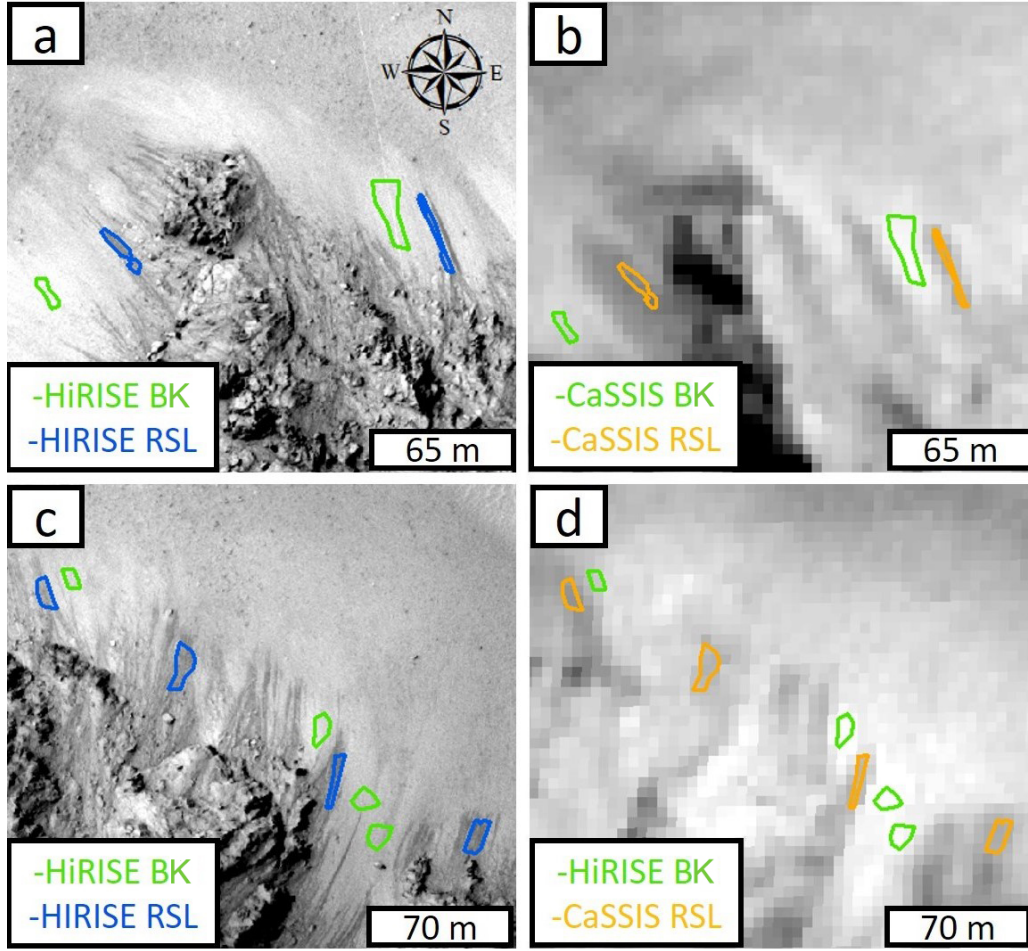


Figure 4: a,c): examples of RSL ROI (blue) and BK ROI (green) used to extract the mean I/F of RSL and RSL-free regions and their uncertainty from the HiRISE image. b,d): examples of RSL (orange) and BK (green) ROIs used to extract the mean I/F of RSL and RSL-free regions and their uncertainty from the CaSSIS orthoimage.

295 mean thermal inertia of  $772^{+188}_{-130}$  TIU, and for the latter we estimate a mean thermal  
 296 inertia of  $540^{+128}_{-122}$  TIU (TIU is thermal inertia units, i.e.  $\text{J m}^{-2} \text{s}^{-0.5} \text{K}^{-1}$ ). Thermal  
 297 inertia and  $3\sigma$  uncertainties were estimated by computing the mean, maximum and  
 298 minimum values of pixels within the “BEDROCK” and “SLOPE” ROIs defined in

299 the thermal inertia map and depicted in figure (5d). These estimates are used, along  
 300 with a DTM of the region, to simulate the mean, maximum and minimum diurnal  
 301 temperature profiles at the surface and at 10 and 20 cm depth, as in (Chevrier and  
 302 Rivera-Valentin, 2012). Although the thermal model has already been validated by  
 303 Schorghofer et al. (2019) at Palikir crater, we also checked that the simulated tem-  
 304 peratures of our zones agreed with the nighttime THEMIS IR observation I59655010,  
 305 acquired at a  $L_s = 348.8^\circ$ , close to the CaSSIS image  $L_s$ . THEMIS surface temper-  
 306 atures were obtained using the <https://www.thmproc.mars.asu.edu> website and  
 307 are reported in figure (9).

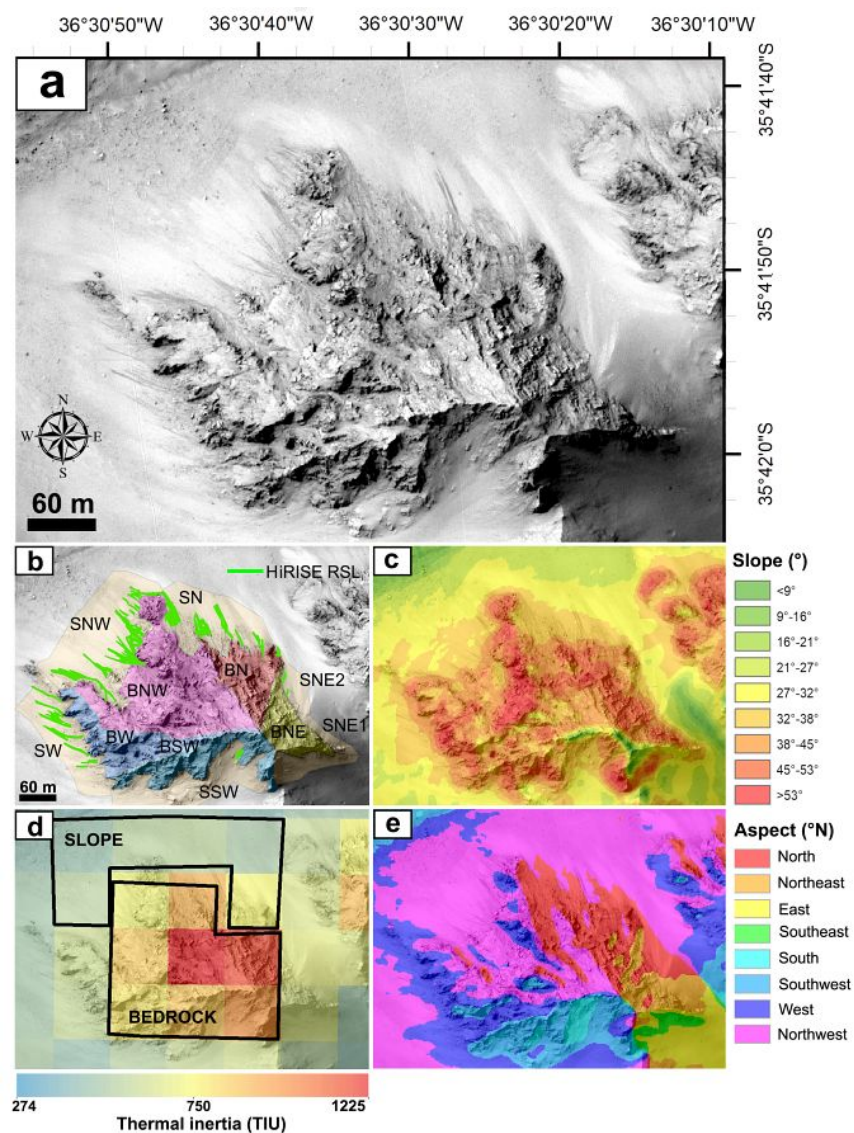


Figure 5: a) HiRISE image ESP\_058618\_1445 showing the selected region for the thermal analysis. b) Definition of zones where we simulated temperature profiles. c) Slope map. d) THEMIS-derived thermal inertia map. Black polygons represent the “BEDROCK” and “SLOPE” ROIs used to extract the thermal inertia of the bedrock material and the regolith, respectively. e) Aspect map.

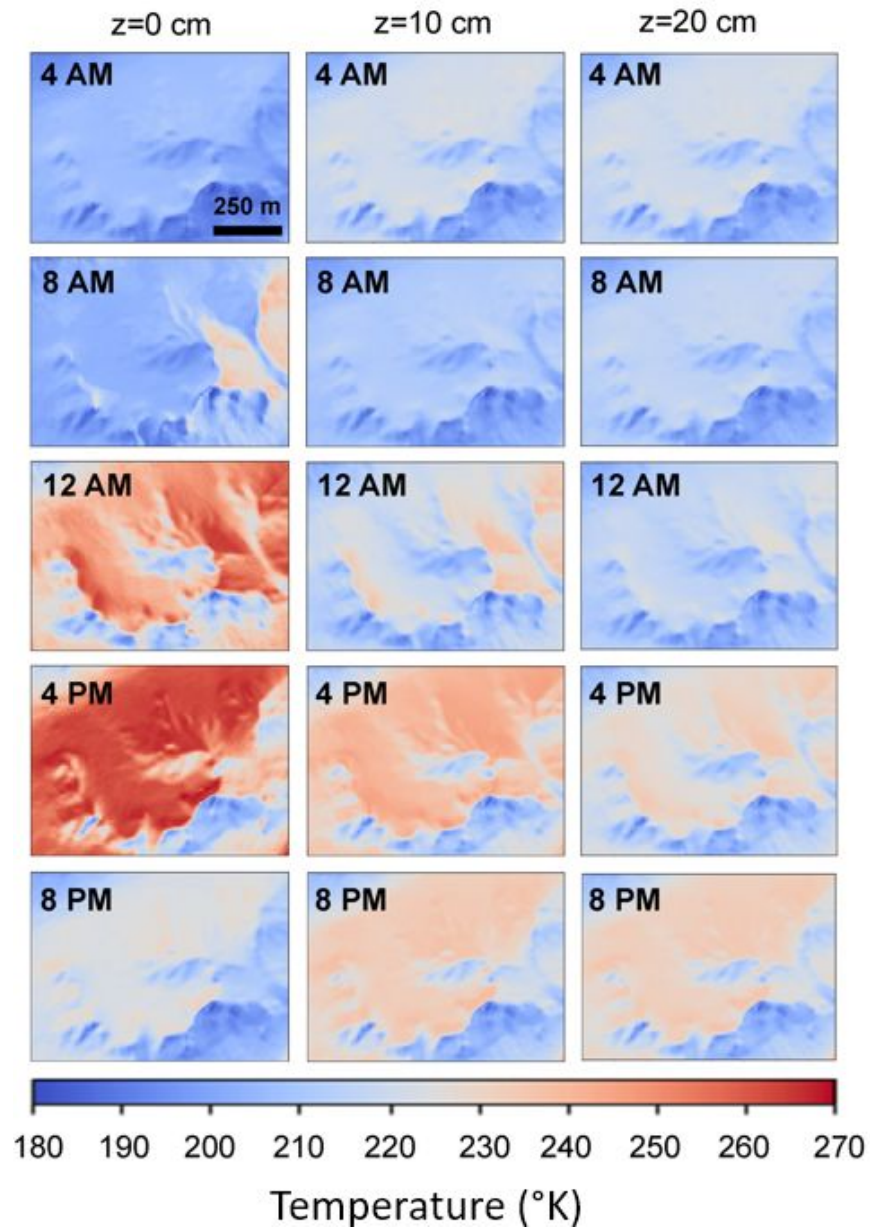


Figure 6: Example of diurnal temperature maps simulated at the surface (left), 10 cm depth (middle) and 20 cm depth (right). The simulations were performed using a THEMIS-derived thermal inertia of 770 TIU and used to extract diurnal temperature profiles for the bedrock.

## 308 4. Results

### 309 4.1. General properties

310 We identified 125 RSL, or groups of RSL in some cases, that were visible in  
311 both the HiRISE and CaSSIS images. Figures (7b,c and d) show examples of RSL  
312 as observed by CaSSIS. All the mapped RSL and their classification in terms of  
313 significant or absent lengthening between the morning and afternoon image are shown  
314 in figure (7a), while their slope and aspect distribution are in figures (8a,b) . In  
315 particular, the aspect distribution in figure (8b) shows that the considered RSL are  
316 found on north, north-west and west facing slopes and that there is no significant  
317 difference between the aspect of “static” and “changed” RSL. On the contrary, the  
318 slope distribution shows a dichotomy between the two classes. Most of the “static”  
319 RSL are found at slopes  $< 30^\circ - 32^\circ$  while most of “changed” RSL are found at  
320 slopes  $> 30^\circ - 32^\circ$ .

### 321 4.2. Relative albedo analysis

322 We performed the relative albedo analysis on a selected sample of 11 RSL. The  
323 relatively low number of RSL considered for the relative albedo analysis is determined  
324 by the selection criteria discussed in section (3.2), i.e. we selected only RSL ROIs  
325 for which we could identify nearby BK ROIs having their same slope and aspect. In  
326 table (1) we report the CaSSIS ( $RA_C$ ) and HiRISE ( $RA_H$ ) RSL relative albedos, their  
327 difference and their  $1\sigma$  uncertainties. We obtain average relative albedos of  $\bar{RA}_H =$   
328  $0.792 \pm 0.032$  for HiRISE and  $\bar{RA}_C = 0.790 \pm 0.029$  for CaSSIS. These are broadly  
329 consistent with the relative albedo values measured by Schaefer et al. (2019) between



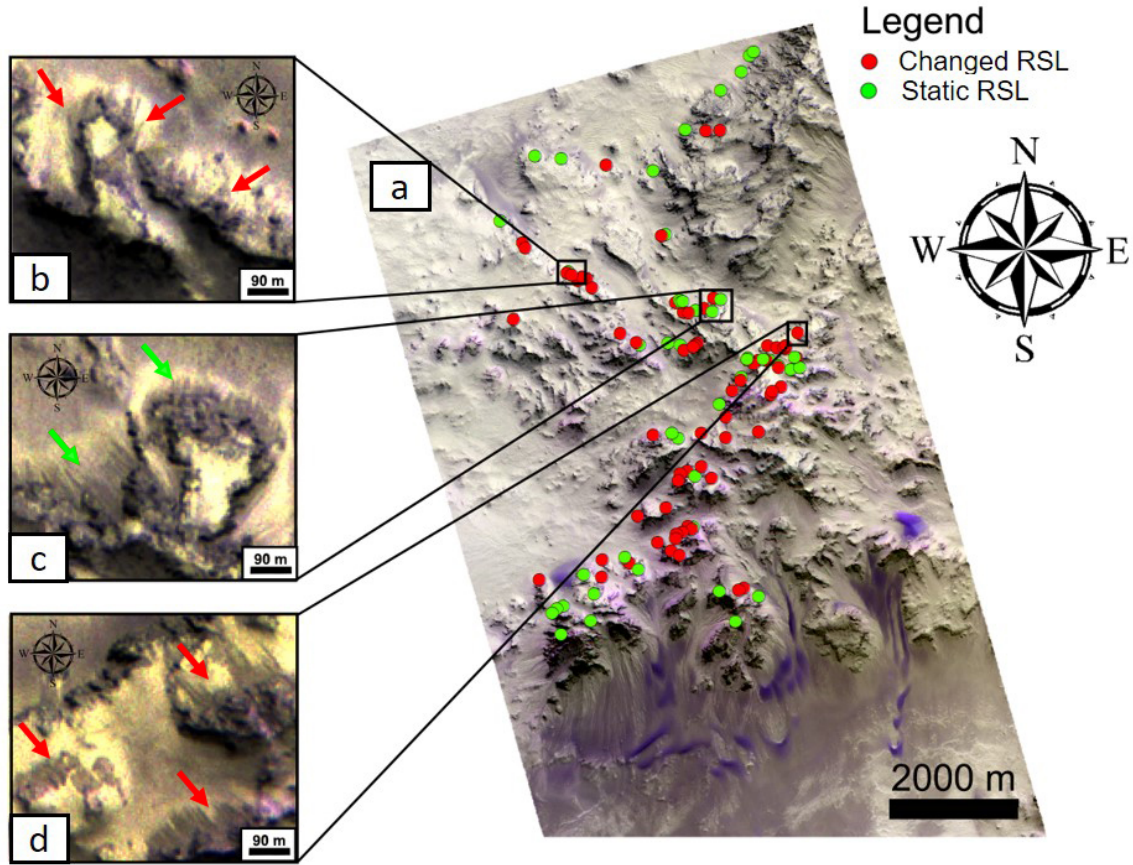


Figure 7: a) RGB color composite of the RED, PAN and BLU filters of CaSSIS image MY34.005640.218.2 depicting the central peak of Hale crater. Red dots indicate “changed” RSL. Green dots indicate “static” RSL. b), c) and d): examples of identified RSL, indicated by black arrows.

330  $L_s = 330^\circ$  and  $L_s = 343^\circ$  at Tivat crater, prior to the fading of RSL, confirming that  
 331 any possible seasonal pattern is not influencing our measurements. The RSL relative  
 332 albedo values reported for each ROI in table (1) show that there are no significant  
 333 differences between the HiRISE and CaSSIS observations. The uncertainty on the  
 334 relative albedo differences in table (1) is given by the sum of the uncertainties on



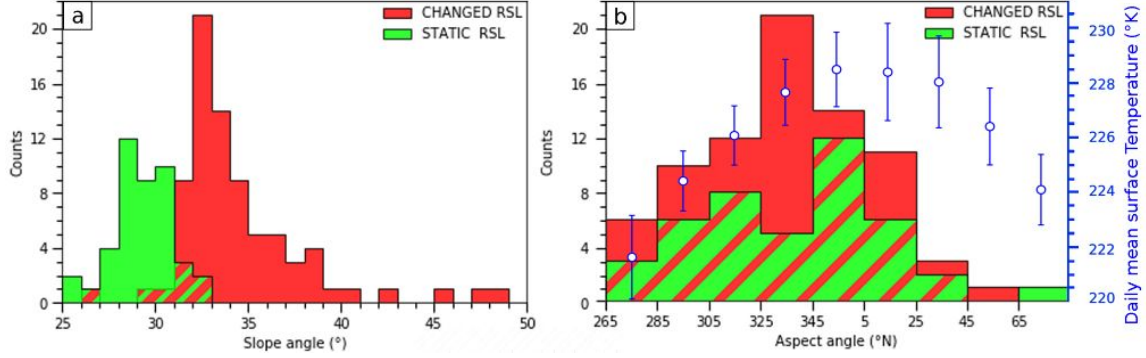


Figure 8: Distributions of a) slope and b) aspect of the termination points for “static” (green) and “changed” (red) RSL. The red-green striped part highlights where the two distributions overlap. The blue dots in b) are daily mean surface temperatures for each aspect bin for the region in figure (5). Error bars indicate the standard deviation within each aspect bin.

335  $RA_C$  and  $RA_H$  and gives us an idea of the minimum albedo difference detectable  
 336 by our methodology. We obtain a mean absolute uncertainty on  $RA_C - RA_H$  of  
 337 0.09, corresponding to an average relative uncertainty of 11%. The relative albedo  
 338 differences reported in table (1) are fully consistent with stochastic variability in  
 339 the two datasets. To demonstrate this, we checked whether the differences between  
 340 the HiRISE and CaSSIS relative albedos follow a normal distribution, applying both  
 341 an Anderson-Darling and a Shapiro-Wilk test of normality. We obtained  $p$ -values  
 342 of  $P_{AD} = 0.48$  and  $P_{SW} = 0.50$ . These are greater than the customary  $\alpha = 0.05$   
 343 threshold, so we cannot reject the null hypothesis that the relative albedo differences  
 344 come from a normal distribution, i.e that they are stochastic. To further cross-check  
 345 our results, we also applied a Kolmogorov-Smirnov and a Wilcoxon signed-rank test  
 346 and assessed the hypothesis that the HiRISE and CaSSIS relative albedos are drawn  
 347 from the same distribution. Both tests failed to reject the null hypothesis, resulting  
 348 in  $p$ -values of  $P_{KS} = 0.99$  and  $P_W = 0.90$  both greater than the  $\alpha = 0.05$  threshold,

ROI	$RA_C$	$RA_H$	$RA_C - RA_H$
1	$0.76 \pm 0.03$	$0.79 \pm 0.06$	$-0.03 \pm 0.09$
2	$0.73 \pm 0.03$	$0.76 \pm 0.05$	$-0.03 \pm 0.08$
3	$0.79 \pm 0.02$	$0.77 \pm 0.06$	$0.02 \pm 0.09$
4	$0.80 \pm 0.02$	$0.75 \pm 0.05$	$0.05 \pm 0.07$
5	$0.78 \pm 0.03$	$0.75 \pm 0.05$	$0.03 \pm 0.08$
6	$0.83 \pm 0.04$	$0.80 \pm 0.06$	$0.03 \pm 0.10$
7	$0.82 \pm 0.03$	$0.85 \pm 0.06$	$-0.02 \pm 0.08$
8	$0.76 \pm 0.02$	$0.81 \pm 0.08$	$-0.05 \pm 0.10$
9	$0.83 \pm 0.04$	$0.79 \pm 0.06$	$0.04 \pm 0.10$
10	$0.79 \pm 0.02$	$0.79 \pm 0.06$	$0.00 \pm 0.08$
11	$0.81 \pm 0.03$	$0.82 \pm 0.07$	$-0.01 \pm 0.10$

Table 1: Relative albedo analysis results.  $RA_C$  and  $RA_H$  are the relative albedos of RSL with respect to nearby RSL-free slopes measured on CaSSIS and HiRISE images, respectively.  $RA_C - RA_H$  is the difference between the CaSSIS and HiRISE relative albedo. Errors are reported as  $1\sigma$  uncertainties.

349 confirming that the detected differences between the HiRISE and CaSSIS relative  
350 albedos are stochastic.

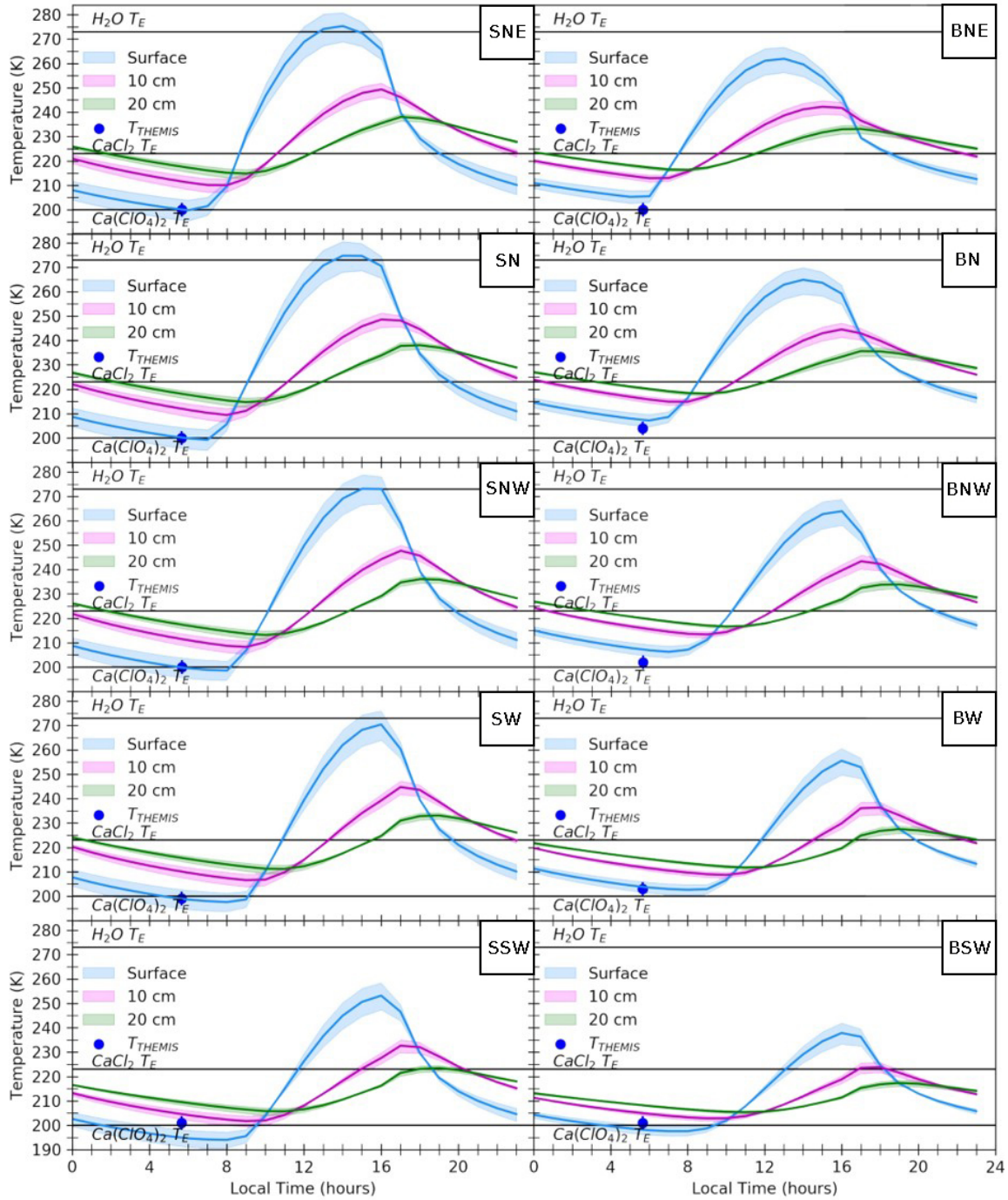


Figure 9: Diurnal temperature profiles (solid lines) with  $3\sigma$  uncertainties (shaded areas) simulated at the surface (light blue), at 10 cm (magenta) and 20 cm depth (green) for the "Slope" (left) and "Bedrock" (right) ROIs defined in figure (5). Blue dots are mean THEMIS surface temperature of each ROI with  $3\sigma$  uncertainties of 2.8 K (Ferguson et al., 2006).

### 351 4.3. Thermal analysis

352 We simulated the thermal environment in a small region within Hale crater,  
353 shown in figure (5). Diurnal surface and subsurface temperature profiles and their  
354 uncertainties for each of the zones in figure (5) are shown in figure (9). In the same  
355 figures, we also show the eutectic temperatures of water ice,  $\text{CaCl}_2$  brine (Gough  
356 et al., 2016) and Ca-perchlorate (Marion et al., 2010), as well as mean THEMIS  
357 surface temperatures for each ROI. From the temperature profiles in figures (9)  
358 we can see that both north-west, north and north-east regions transiently reach  
359 temperatures higher than the melting temperature of water ice only at the regolith  
360 surface, and not on bedrock or in the subsurface. In contrast, the transient melting  
361 of  $\text{CaCl}_2$  or  $\text{Ca}(\text{ClO}_4)_2$  frozen brines is generally supported in all these zones. In  
362 particular, from the temperature profiles in figure (9a) we see that north-east facing  
363 slopes allow the melting of  $\text{CaCl}_2$  at 10 cm in the subsurface from  $\sim 10:00$  local time  
364 until  $\sim$  midnight, and at 20 cm depth from  $\sim 12:00$  to  $\sim 14:00$ . On north facing  
365 slopes (see figure (9b)) melting could occur from  $\sim 11:00$  to  $\sim$  midnight at 10 cm  
366 depth and from  $\sim 13:00$  to  $\sim 15:00$  at 20 cm depth. On north-west facing slopes  
367 (see figure (9c)) melting happens from  $\sim 12:00$  until  $\sim$  midnight at 10 cm depth and  
368 from  $\sim 14:00$  to  $\sim 15:00$  at 20 cm depth. West facing slopes (see figure (9d)) allow  
369 melting of from  $\sim 13:00$  until  $\sim 23:00$  local time at 10 cm depth, and from  $\sim 15:00$   
370 to  $\sim$  midnight at 20 cm depth. Finally, south-west facing slopes permit melting of  
371  $\text{CaCl}_2$  mostly on the regolith and from  $\sim 15:00$  to  $20:00$  at 10 cm depth. At 20 cm  
372 depth, temperatures are mostly below the eutectic temperature of  $\text{CaCl}_2$  brines (see  
373 figure (9e)). In all these cases, melting of  $\text{Ca}(\text{ClO}_4)_2$  is allowed at any hour of the

374 day at all depths, except for north-west, west and south-west facing slopes where  
 375 early morning surface temperatures are very close to 200 K and can reach values as  
 376 low as 190K, below the eutectic temperature of this brine.

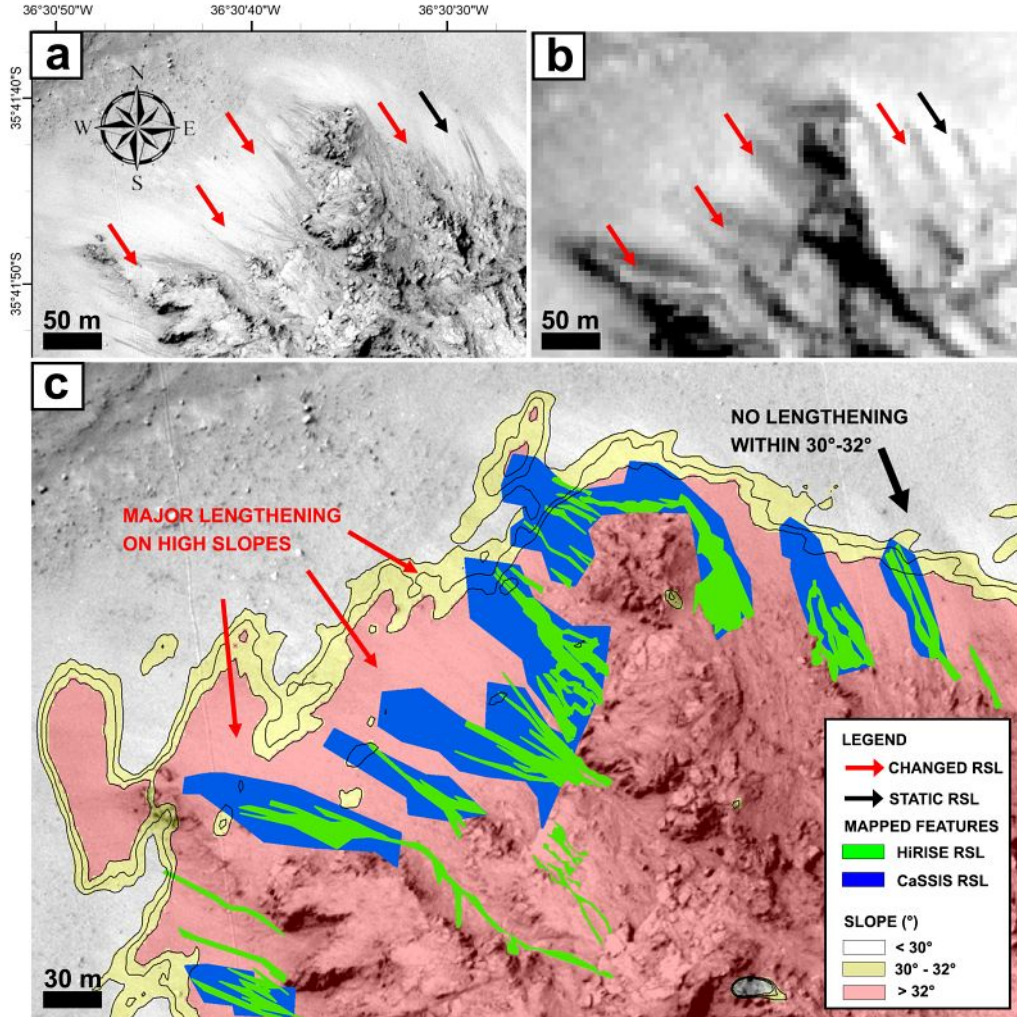


Figure 10: Mapping of HiRISE and CaSSIS RSL. a) HiRISE image depicting both “static” (black arrows) and “changed” RSL (red arrows) on the central peak of Hale crater. b) CaSSIS image showing the same RSL as in panel a). c) Mapping of HiRISE (green) and CaSSIS (blue) RSL overlain on a discretized slope map. The red part is where slopes are  $> 32^\circ$ , the yellow part is for slopes between  $30^\circ$  and  $32^\circ$ .



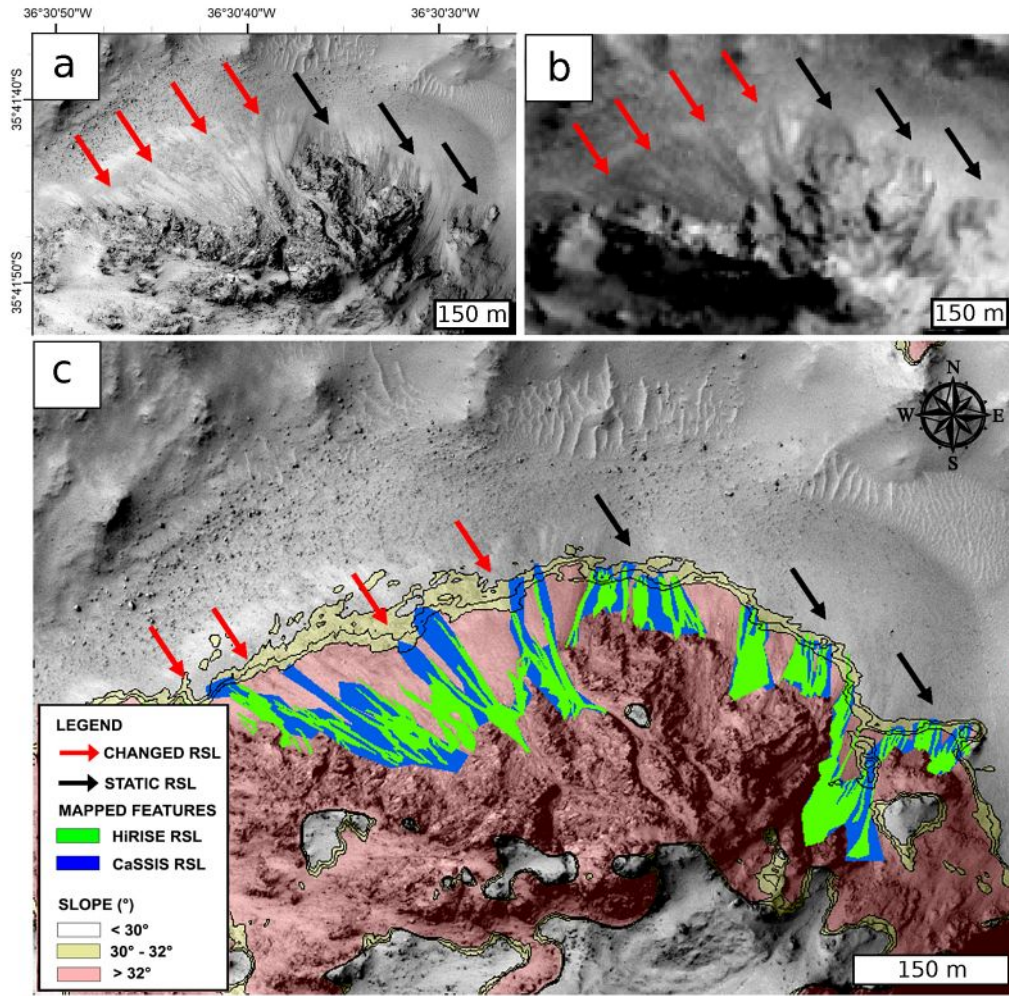


Figure 11: Mapping of HiRISE and CaSSIS RSL. a) HiRISE image depicting both “static” (black arrows) and “changed” RSL (red arrows) on the central peak of Hale crater. b) CaSSIS image showing the same RSL. c) Mapping of HiRISE (green) and CaSSIS (blue) RSL overlain on a discrete slope map. The red part is where slopes are  $> 32^\circ$ , the yellow part is for slopes between  $30^\circ$  and  $32^\circ$ .

## 5. Discussion

Since at Hale we observe RSL starting on bedrock outcrops (figure (10c)), which generally have lower temperatures than the freezing point of water ice but higher

380 than the considered brines, the latter are more likely than flows of seeping water.  
 381 Moreover, exposed water ice is not predicted to form on equator-facing slopes at  
 382 latitudes comparable to that of Hale crater (Schorghofer et al., 2019), and it is not  
 383 observed by spectral instruments sensitive to micrometer-thick surfaces of water frost  
 384 (Vincendon et al., 2010). Liquid brines may form via a) melting of a subsurface reser-  
 385 voir or b) deliquescence of salts. In the first case, either a reservoir near the surface  
 386 or a subsurface deposit, which would be exposed by fractures, are necessary. The  
 387 fractured rocky outcrops in the central peak of Hale crater might host these shallow  
 388 brine reservoirs. In such a case, brine melting would occur when subsurface tem-  
 389 peratures rise above their eutectic temperature, i.e. from mid-afternoon to evening  
 390 hours, depending on its depth and slope orientation. This is because ice is more  
 391 likely to be found in the shallow subsurface than at the surface at these latitudes.  
 392 In particular, our thermal analysis suggests that melting of  $\text{CaCl}_2$  brines should be  
 393 favored on north-east, followed by north, north-west, west and south-west facing  
 394 slopes. Melting of  $\text{Ca}(\text{ClO}_4)_2$  brine is generally possible on all slopes, as it can oc-  
 395 cur over most of a Martian day. However north-east, north and north-west facing  
 396 slopes are favored since their subsurface temperature is always higher than 200K at  
 397  $L_s = 347.4^\circ$ . This can also be explained by considering the dependence of daily mean  
 398 surface temperature from the slope aspect, depicted in figure (8). This predicts that  
 399 north-east, north and north-west facing slopes have the highest daily mean surface  
 400 temperatures. As a consequence, brines melting is favoured on these slopes. This  
 401 picture hence suggests that if RSL are formed through melting of shallow subsurface  
 402 brines, they should form and lengthen from noon and early-afternoon to evening

403 hours favouring north-east, north and north-west facing slopes.  
 404 In the case of deliquescence, the main parameters constraining RSL activity are sur-  
 405 face temperature and relative humidity. As shown in figure (9) surface temperatures  
 406 are above the eutectic temperature of  $\text{CaCl}_2$  from  $\sim 8:00$  to  $\sim 19:00$ - $20:00$  Mars  
 407 local time, depending on the slope orientation and thermal inertia. However, the  
 408 RH may not be high enough during these hours. In particular, (Steele et al., 2017)  
 409 and (Fischer et al., 2019) show that from  $\sim 8:00$  to  $\sim 19:00$ - $20:00$ , RH values are  
 410 below 5% both at Gale crater and at the Phoenix landing site during local summer.  
 411 This makes perchlorates more interesting candidates, because surface temperatures  
 412 are above their eutectic temperature at any time of day, except for north-west, west  
 413 and south-west facing and slopes during early morning. If RSL are deliquescence-  
 414 related features, we should see a similar aspect preference as that expected for the  
 415 melting of brines, but more shifted towards north-east facing slopes. In fact, these  
 416 slopes reach higher surface temperatures at earlier local times, at a time when air  
 417 relative humidity is higher (Gough et al., 2016; Steele et al., 2017; Fischer et al.,  
 418 2019), which enhances deliquescence. The aspect distribution in figure (8b) suggests  
 419 quite a different picture, showing a preference for north, north-west and west facing  
 420 slopes over north-east facing slopes. An example of this behavior is also illustrated  
 421 in figures (10) and (11) where RSL sourcing from north-east facing slopes are fewer  
 422 in number and less extensive than on north, north-west and even west facing slopes.  
 423 This aspect distribution may be an indication that RSL lengthening is not associated  
 424 with surface moisture, deliquescence of salts or melting of brines. Another option  
 425 may instead be that deliquescence occurs during sunset instead of early morning



426 when temperatures fall and relative humidity rises, as suggested by (Tebolt et al.,  
 427 2020). In this case, west-facing, north-west and north facing slopes may be favoured  
 428 as they have slightly higher evening surface temperatures, possibly explaining the  
 429 aspect distribution at Hale crater. While this is in principle consistent with our as-  
 430 pect distribution, it is not supported by either laboratory experiments (Gough et al.,  
 431 2016), REMS (Steele et al., 2017) or TECP data (Fischer et al., 2019), which suggest,  
 432 instead, that early morning hours should be more favourable for deliquescence than  
 433 evening hours. Moreover, it may not be in agreement with the very low water con-  
 434 tent of RSL estimated from nighttime IR observations (Edwards and Piqueux, 2016).  
 435 Detailed, high-resolution modeling may be necessary to further explore the precise  
 436 interplay between temperature and relative humidity at RSL locations and quantify  
 437 the best periods for deliquescence. An indication that RSL at Hale crater may be  
 438 dry flows is that their lengthening stops at slope angles  $\sim 30^\circ$  (Dundas et al., 2017).  
 439 We also detect this behavior in our slope distribution in figure (8a) and in figures  
 440 (10,11), which show that RSL lengthening is generally correlated with the presence  
 441 of slopes steeper than  $\sim 30^\circ - 32^\circ$ . On the contrary, RSL that already reached slopes  
 442 within this range or shallower remained static. This dichotomy is shown in figure  
 443 (8a), where there is a significant difference between the “changed” and “static” slope  
 444 distributions. This dichotomy is expected for dry flows that stop when they reach  
 445 the angle of repose, producing the observed sample of “static” RSL, and lengthen  
 446 on steeper slopes, producing the observed sample of “changed” RSL. In one case, we  
 447 also detect a RSL that lengthened at a slope angle of  $\sim 26^\circ$ . A similar behaviour has  
 448 also been detected by Stillman et al. (2020) and Tebolt et al. (2020). Although, in

449 principle, this would support wet-based flows, the fact that they occur with a very  
 450 low frequency suggests that these RSL could be statistical outliers (Stillman et al.,  
 451 2020). As such, it is possible that additional and/or different mechanisms may be at  
 452 play in this sample of RSL. Dedicated analyses considering statistically significant  
 453 occurrences of these RSL and consideration of uncertainties in the DTM used for  
 454 computing the slope values may be necessary to reach a definitive conclusion. Our  
 455 comparison of HiRISE and CaSSIS RSL relative albedo indicates that there are no  
 456 significant diurnal variations between 11:13 and 14:06 local time, a result expected  
 457 for dry flows. However, it may be also possible that significant dehydration has  
 458 already occurred at 11:13, producing the observed result independently from how  
 459 RSL form, or that the relative albedo differences at play are lower than 11%. If  
 460 RSL are formed through deliquescence, the importance of this issue depends on salt  
 461 composition and its interaction with the regolith, as these both affect the DRH and  
 462 ERH (efflorescence relative humidity) of the solution (Nuding et al., 2014). In par-  
 463 ticular, Nuding et al. (2014) showed that liquid  $\text{Ca}(\text{ClO}_4)_2$  brines persist with very  
 464 low RH values. Therefore, if liquid brines form on early morning they may persist  
 465 until late morning in a metastable state and dehydrate during the afternoon. Again,  
 466 detailed near-surface relative humidity modeling should be performed to determine  
 467 whether these processes are occurring at RSL sites. Another interpretation of our  
 468 relative albedo measurement, which is not supported by thermal studies (Edwards  
 469 and Piqueux, 2016), is that the water supply exceeds evaporative losses. In this case  
 470 dehydration does not occur and there is no significant albedo variation (Hillel, 2004).  
 471 Future observations acquired during early morning will help to better characterize

the diurnal albedo of RSL. Nevertheless, the relative albedo measurements reported here could provide a useful validation for modeling and experimental studies of RSL.

In summary, our result collectively support dry flows as responsible for RSL lengthening. The triggering mechanisms which initiate these flows may involve thermal creep (Schmidt et al., 2017; Schaefer et al., 2019), or aeolian processes (Vincendon et al., 2019). In particular, the latter would also be able to describe the temporal evolution of RSL activity during the third pulse shown in figure (1) (Vincendon et al., 2019). While our results support dry flows models, brines and more generally volatiles may still play an indirect and concurrent role in RSL formation by triggering dry mass fluxes (Massé et al., 2016; Wang et al., 2019; Bishop et al., 2019), but our data does not provide any additional insight on RSL triggering.

## 6. Summary and Conclusions

We presented the first CaSSIS observation of RSL obtained during local morning at Hale crater, Mars. We identified a set of 125 RSL and studied their overall morphology, slope and aspect distributions and analyzed their thermal environment. We performed an initial comparison of their relative albedo using morning CaSSIS and afternoon HiRISE observations. Our comparison of RSL, as viewed through HiRISE and CaSSIS, 30 days later, reveals that most RSL lengthening occurred where slopes  $> 30^\circ - 32^\circ$  were available. Instead, RSL on slopes  $> 30^\circ - 32^\circ$  remained generally static. This result supports a dry granular flow dynamics, as suggested by other authors (Dundas et al., 2017; Vincendon et al., 2019; Schaefer et al., 2019; McEwen et al., 2019). The simulated diurnal surface and subsurface temperature

494 profiles at Hale crater suggest that melting of brines and deliquescence of salts would  
495 be both favoured on north-east facing slopes, followed by north and north-west facing  
496 slopes. However, this pattern is different from our observed aspect distribution of  
497 “changed” RSL at Hale crater, suggesting that RSL lengthening is not controlled by  
498 surface moisture, deliquescence of salts or melting of brines. We compared HiRISE  
499 and CaSSIS RSL relative albedo between 11:13 and 14:06 local time, respectively,  
500 and found no significant differences, another result expected for dry flows. Our  
501 measurements could provide a useful validation for future models and experimental  
502 studies on RSL formation and lengthening. We conclude that the RSL at Hale  
503 crater are best explained as dry flows, in agreement with the conclusions of other  
504 authors (Dundas et al., 2017; Vincendon et al., 2019; Schaefer et al., 2019; McEwen  
505 et al., 2019). These may be triggered through thermal creep (Schmidt et al., 2017;  
506 Schaefer et al., 2019), aeolian processes (Vincendon et al., 2019), or very limited brine  
507 activity (Massé et al., 2016; Wang et al., 2019; Bishop et al., 2019). Future CaSSIS  
508 observations of RSL sites acquired earlier in the morning, in combination with same-  
509 day afternoon HiRISE images, will be pivotal in improving the characterization of  
510 the diurnal activity of RSL and will provide a clearer picture of their formation  
511 mechanism.

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#### **Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

## 531 Appendix

532 In Appendix A we report some details of the products used for the analysis,  
 533 such as image IDs, resolution, solar longitude, local solar time, incidence, emission  
 534 and phase angles. In Appendix B we show details on the error propagation for  
 535 computation of relative albedo uncertainties.

### 536 Appendix A. Dataset details

537 We report in table (A.2) some details on the data products defined in section (2)  
 of the main text.

Product type	ID	Resolution m	$L_s$ ( $^\circ$ )	LTST hh:mm	Incidence ( $^\circ$ )	Emission ( $^\circ$ )	Phase ( $^\circ$ )
HiRISE orthoimage	ESP_031203_1440_RED_C_01_ORTHO	0.25	287.7	14:40	37.0 <sup>†</sup>	13.9 <sup>†</sup>	23.5 <sup>†</sup>
HiRISE Image	ESP_058618_1445_RED	0.50	331.5	14:06	37.0	4.0	40.7
HiRISE DTM	DTEEC_030715_1440_030570_1440_A01	1.00					
CaSSIS stereo image 1	MY34_005640_218_1	4.65	347.4	11:13	32.8	11.4	23.4
CaSSIS stereo image 2	MY34_005640_218_2	4.65	347.4	11:13	32.8	10.6	40.1
THEMIS IR image	I01144003	100.00	344.1	03 : 18	119.1	0.7	118.7
THEMIS IR image	I59655010	100.00	348.4	05 : 40	84.6	1.9	84.4
THEMIS IR image	I67826009	100.00	341.1	06 : 30	91.2	0.7	91.1

Table A.2: Summary of the products used in the analysis. Solar longitude ( $L_s$ ), Local time (LTST), incidence, emission and phase angles are taken from <https://www.uahirise.org> for HiRISE, and from <http://viewer.mars.asu.edu/> for THEMIS. <sup>†</sup>The reported incidence, emission and phase angle refers to the corresponding HiRISE Reduced Data Record (RDR) product.

538

### 539 Appendix B. Relative albedo uncertainty

540 We defined the relative albedo (see text for details) as:

$$RA_* = \frac{IF_{RSL} - IF_D}{IF_{BK} - IF_D} \quad * = H, C \quad (\text{B.1})$$

where  $RA_*$  is the RSL relative albedo and  $*$  is  $H$  for HiRISE and  $C$  for CaSSIS.  $IF_{RSL}$  is the mean I/F extracted from an RSL ROI.  $IF_D$  is the I/F of the darkest shadowed pixel and  $IF_{BK}$  is the I/F of a BK ROI. To compute the uncertainties in our relative albedo measurements, we used a standard error propagation approach. In particular, we performed the following approximation:

$$\sigma_{IF_{RSL}-IF_D} \sim 2 \cdot \sigma_{IF_{RSL}} \quad (\text{B.2})$$

$$\sigma_{IF_{BK}-IF_D} \sim 2 \cdot \sigma_{IF_{BK}} \quad (\text{B.3})$$

where  $\sigma_{IF_{RSL}-IF_D}$  and  $\sigma_{IF_{BK}-IF_D}$  are the uncertainties of the numerator and denominator of equation (B.1). This approximation is justified for two reasons: first, we do not have an unambiguous way to define a ROI within shadows in and retrieve its mean flux and its standard deviation. Second, we do not know the errors on the HiRISE or CaSSIS radiometric calibration equations and thus we cannot propagate the uncertainty on the Digital Number (DN) of the darkest shadowed pixel. Instead, we can reasonably expect its uncertainty to be of the same order of magnitude as the uncertainty in  $IF_{RSL}$  and  $IF_{BK}$ . With this approximation, the uncertainty on relative albedo measurements may be propagated as:

$$\begin{aligned}\sigma_{A_*} &= \sqrt{\left(\frac{\partial A_*}{\partial(IF_{RSL} - IF_D)}\sigma_{IF_{RSL}-IF_D}\right)^2 + \left(\frac{\partial A_*}{\partial(IF_{BK} - IF_D)}\sigma_{IF_{BK}-IF_D}\right)^2} = \\ &= A_*\sqrt{\left(\frac{2\sigma_{IF_{RSL}}}{IF_{RSL} - IF_D}\right)^2 + \left(\frac{2\sigma_{IF_{BK}}}{IF_{BK} - IF_D}\right)^2}\end{aligned}$$

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