Reviews of Geophysics

REVIEW ARTICLE
10.1029/2018RG000617

Key Points:
- We provide a systematic survey and evaluation of the literature covering morphological characteristics of slope streaks
- We present a novel analog environment, Salar de Uyuni in the Bolivian Altiplano, where slope streaks are formed solely by deliquescence
- We offer perspectives on the probable mechanisms driving global-scale slope streak formation on contemporary Mars

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Citation:
Bhardwaj, A., Sam, L., Martín-Torres, F. J., & Zorzano, M.-P. (2019). Are slope streaks indicative of global-scale aqueous processes on contemporary Mars? *Reviews of Geophysics*, *57*, 48–77. https://doi.org/10.1029/2018RG000617

Received 7 JUL 2018
Accepted 29 NOV 2018
Accepted article online 20 DEC 2018
Published online 9 JAN 2019

Are Slope Streaks Indicative of Global-Scale Aqueous Processes on Contemporary Mars?

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Abstract Slope streaks are prevalent and intriguing dark albedo surface features on contemporary Mars. Slope streaks are readily observed in the equatorial and subequatorial dusty regolith regions with low thermal inertia. They gradually fade over decadal timescales. The proposed mechanisms for their formation vary widely based on several physicochemical and geomorphological explanations. The scientific community is divided in proposing both dry and wet mechanisms for the formation of slope streaks. Here we perform a systematic evaluation of the literature for these wet and dry mechanisms. We discuss the probable constraints on the various proposed mechanisms and provide perspectives on the plausible process driving global-scale slope streak formation on contemporary Mars. Although per our understanding, a thorough consideration of the global distribution of slope streaks, their morphology and topography, flow characteristics, physicochemical and atmospheric coincidences, and terrestrial analogies weighs more in favor of several wet mechanisms, we acknowledge that such wet mechanisms cannot explain all the reported morphological and terrain variations of slope streaks. Thus, we suggest that explanations considering both dry and wet processes can more holistically describe all the observed morphological variations among slope streaks. We further acknowledge the constraints on the resolutions of remote sensing data and on our understanding of the Martian mineralogy, climate, and atmosphere and recommend continuous investigations in this direction using future remote sensing acquisitions and simulations. In this regard, finding more wet and dry terrestrial analogs for Martian slope streaks and studying them at high spatiotemporal resolutions can greatly improve our understanding.

Plain Language Summary Slope streaks are prevalent surface features on contemporary Mars. They have dark albedo and are abundant in the equatorial and subequatorial latitudes. The exact mechanisms behind their formation and development are still unknown, and several hypotheses have been proposed based on the physicochemical and geomorphological properties of slope streaks. These features generate a common interest because several hypotheses have linked them with transiently flowing liquid water on the Martian surface. Such probable linkages with Martian liquid water can have wide implications for understanding habitability conditions and ongoing water cycles on Mars and for evolving planetary protection policies to prevent possible contamination of Martian surface during future missions. Therefore, here we perform a systematic evaluation of the literature covering morphological and flow characteristics of slope streaks for water-driven or dry dust avalanche mechanisms. We discuss the probable limitations of the various proposed models for slope streak development and provide perspectives on the plausible processes driving global-scale slope streak formations on Mars. Continuously improving satellite and rover observations of Martian surface, topography, climate, and minerals are bound to improve our understanding of slope streaks in the coming years.

1. Introduction

The quest of finding habitable conditions or life outside our planet has always fascinated mankind. Certainly, the focus of this quest more often than not revolves around the search for water in its various phases (Kasting, 1997). Within our solar system, Mars is the most Earth-like planet in terms of habitability as it displays the best combination of the highest Earth similarity index (ESI) of 0.7 based on physical

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determinants such as mass, radius, and temperature and the relative planetary habitability index (PHI_{rel}) of 0.6 based on physicochemical markers such as substrate stability, available energy, suitable chemistry, and liquid stability (Schulze-Makuch et al., 2011). In simpler words, the Martian regolith contains salts and water (in frozen and/or possibly transiently liquid states); the Martian atmosphere displays a relatively moderate temperature range for the existence of life (as we know it); Mars has moderate gravity (~38% of Earth) to enable future colonization; the Martian obliquity (~25°) is close to that of Earth (~23.5°); and the Martian day length is only ~40 min greater than that of Earth. Until the first manned Mars mission comes into play, all Martian studies rely on varieties of sensors mounted on orbiters and rovers, numerical simulations, and data collection in different electromagnetic wavelengths and experimental conditions. A significant part of this remote sensing-based research focuses on studying the Martian landforms and surface features through the interpretation of images obtained at sufficiently high spatial and temporal resolutions for finding evidence of past water movement and present-day transient aqueous processes. Such research over the years has provided extremely valuable information regarding the Martian landscape evolution (e.g., Carr, 1986, 1987; Carr & Clow, 1981; Carr & Wänke, 1992), geological regimes (e.g., Carr & Head, 2010; Carr & Wänke, 1992; Dohm et al., 2008; Fairén, 2010), geochemistry (e.g., Christensen et al., 2000; Niles et al., 2013; Schaefer, 1993), geophysics (e.g., Carr & Wänke, 1992), geomorphology (e.g., Baker, 1979; Christensen et al., 2000), glaciology (e.g., Bhardwaj et al., 2016; Bhardwaj & Martin-Torres, 2016; Head & Marchant, 2003), climatic shifts (e.g., Carr & Clow, 1981; Fairén, 2010; McKay & Davis, 1991; Pollack et al., 1987), and global-scale atmosphere-regolith interactions (e.g., Carr, 1986, 1987; Fairén, 2010; McKay & Davis, 1991).

Several surface manifestations and observations have been linked with potential water in the liquid state as a result of brine formation (Figures 1, 2, and 3) on contemporary Mars. The most likely but highly debated possible briny features per the published literature are slope streaks (e.g., Ferris et al., 2002; Kreslavsky & Head, 2009; Miyamoto et al., 2004; Schorghofer et al., 2002) (Figure 1), recurring slope lineae (RSL; e.g., McEwen et al., 2011; Ojha et al., 2015; Figure 2), and dark dune spots (DDS; e.g., Kereszturi et al., 2009, 2010, 2011; Martinez et al., 2012; Möhlmann & Kereszturi, 2010; Figure 3). For the interested readers, an excellent review of these briny features and their intercomparisons can be found in Martínez and Renno (2013). The focus of the present review is the frequently observable, prevalent, and intriguing surface features on contemporary Mars called *slope streaks*. Slope streaks are readily observed in the equatorial and subequatorial dusty regolith regions with low thermal inertia (Chuang et al., 2007; Ferris et al., 2002; Kreslavsky & Head, 2009; Miyamoto et al., 2004; Phillips et al., 2007; Schorghofer et al., 2002; Sullivan et al., 2001). Slope streaks display significantly darker albedo than their surroundings (Kreslavsky & Head, 2009) that gradually lightens and eventually fades over decadal timescales (Schorghofer et al., 2007). These lighter forms of slope streaks are often referred to as *light slope streaks* in the literature (Schorghofer et al., 2007). Unlike DDS (Figure 3) and RSL (Figure 2), slope streaks (Figure 1) are not seasonal features and are mostly situated in equatorial latitudes (Martínez & Renno, 2013); subsequent increases in their lengths or recurrences are rarely observed (Bhardwaj et al., 2017). In Figure 4, we show several of the most commonly observed morphologies of Martian slope streaks (i.e., linear, curved, fan shaped, and splitting/branching) and thorough characterization of slope streaks based on their morphological characteristics can further provide several morphological subclasses. The focus of our review is to bring all the published literature on slope streaks together, compile the information, and evaluate the proposed mechanisms. In the subsequent sections, we take another look at the proposed mechanisms through discussions on the basic observations, the global distribution of slope streaks, their morphology and topography, flow characteristics, physicochemical and atmospheric coincidences, and a terrestrial analogy to better understand the probable scenarios leading to their appearance and sustenance.

2. Basic Observations

The earliest sightings of slope streaks were made on some of the highest resolution Viking Orbiter (Soffen, 1977) images (e.g., Ferguson & Lucchitta, 1984; Morris, 1982; Williams, 1991). Since then, the observational capabilities have continuously improved with the advent of higher-resolution satellite sensors such as the Mars Orbiter Camera (MOC; Malin & Edgett, 2001), High Resolution Stereo Camera (Neukum & Jaumann, 2004), Context (CTX) Camera (Malin et al., 2007), and High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007). In Figure 5, we observe slope streaks in the same region of

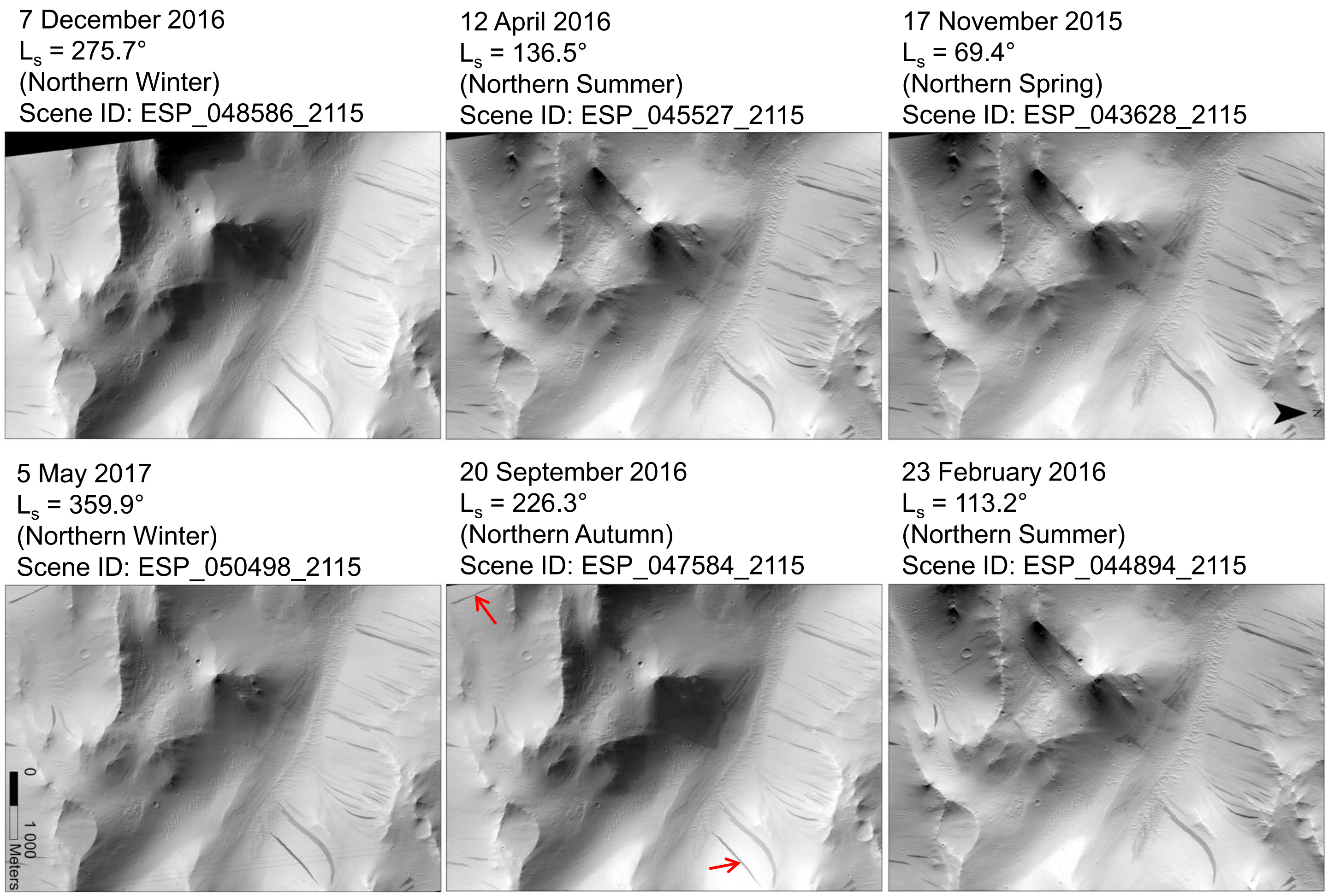

Figure 1. Slope streaks north of Olympus Mons in different seasons (scene center latitude [centered] 31.166° and longitude [east] 226.02°; all images were acquired between ~14:00 and 15:00 local Mars time). The red arrows mark the appearance of new slope streaks. HiRISE image credit: NASA/JPL/University of Arizona.

Arabia Terra using multiple sensors at different resolutions; starting from the Viking 1 Visual Imaging Subsystem Camera A scene in 1978 to the latest 2014 HiRISE image. The improvement in the visual interpretation and the temporal evolution of the slope streaks are visible in Figure 5. The length of slope streaks can vary from tens to thousands of meters, but they usually start as a point phenomenon, and their width rarely crosses three metric digits in the upper reaches (Bhardwaj et al., 2017). This feature explains the observational constraints in the earliest sightings (e.g., Ferguson & Lucchitta, 1984; Morris, 1982; Williams, 1991) made on ~40-m spatial resolution Visual Imaging Subsystem Camera A images (Figure 5a), which rendered it nearly impossible to perform precise photogrammetric evaluations of the initiation zones and the terrain of the slope streaks. This observational limitation also gave rise to the still ongoing speculations about the source of origin of these slope streaks.

With the insertion of the Mars Global Surveyor MOC into Martian orbit in September 1997, its narrow-angle camera imaging (~1.5–12 m per pixel) provided an exceptional opportunity to observe slope streaks (e.g., Aharonson et al., 2003; Ferris et al., 2002; Miyamoto et al., 2004; Phillips et al., 2007; Schorghofer et al., 2002, 2007; Sullivan et al., 2001). Such remote sensing capabilities continued to improve with the introduction of the Mars Reconnaissance Orbiter in 2005 equipped with a CTX, submeter-resolution HiRISE imager, and high-resolution and hyperspectral Compact Reconnaissance Imaging Spectrometer for Mars imager. Our knowledge about the topographical and mineralogical characteristics of slope streaks has been greatly enhanced during the past two decades with unprecedented spatial and spectral improvements in remote sensors and computing capabilities, but the ambiguity regarding the origin and propagation of slope streaks still persists as the scientific community is divided on several probable dry (e.g., Baratoux et al., 2006; Burleigh

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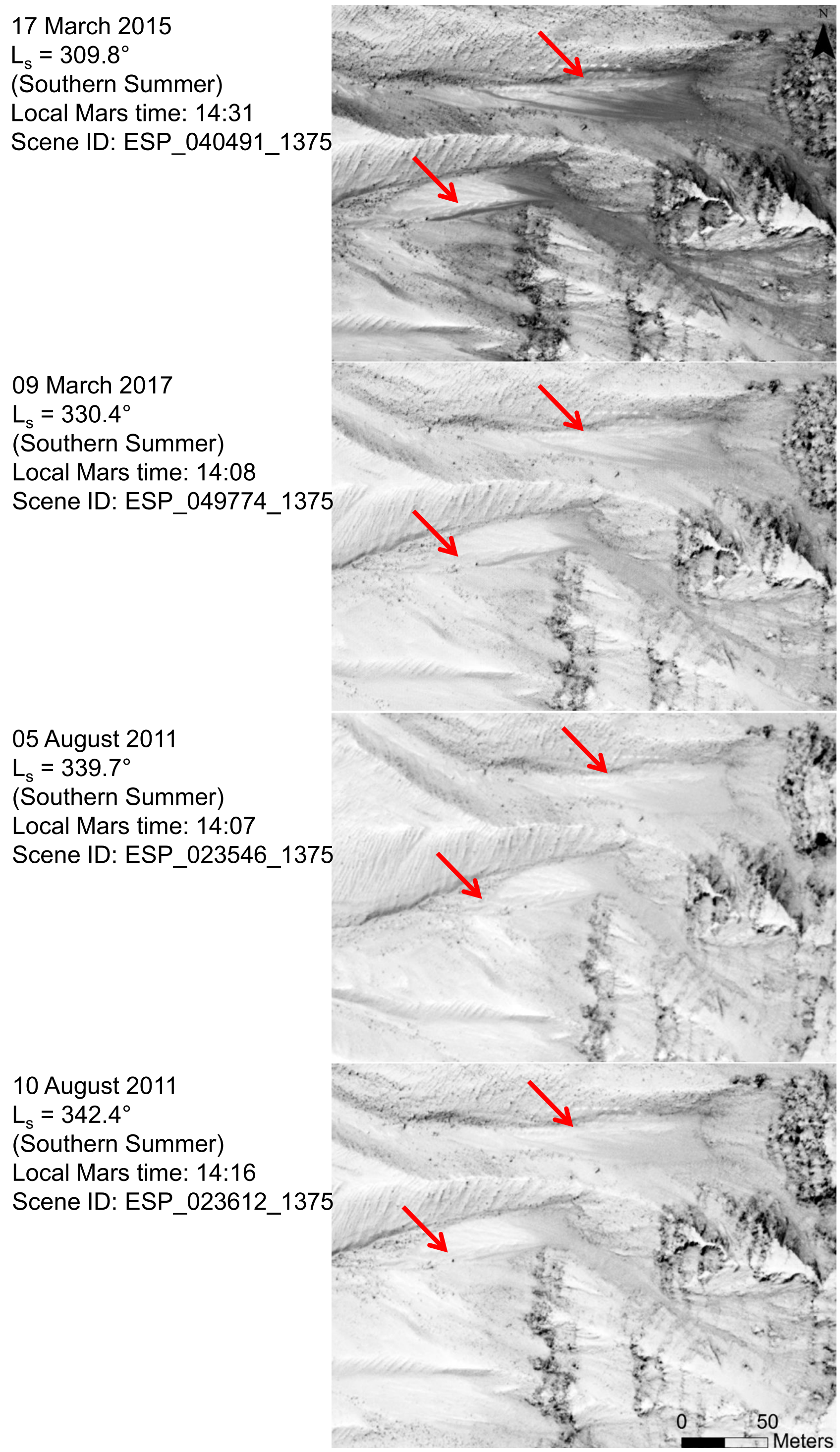

Figure 2. Appearance and disappearance of recurring slope lineae during the southern summer (scene center latitude [centered] −42.229° and longitude [east] 202.184°; all images were acquired between ~14:00 and 14:30 local Mars time) in Newton Crater. The red arrows mark the slopes where the recurring slope lineae develop (darkening in the topmost image) and subsequently disappear. The images follow a seasonal order (increasing solar longitudes). HiRISE image credit: NASA/JPL/University of Arizona.

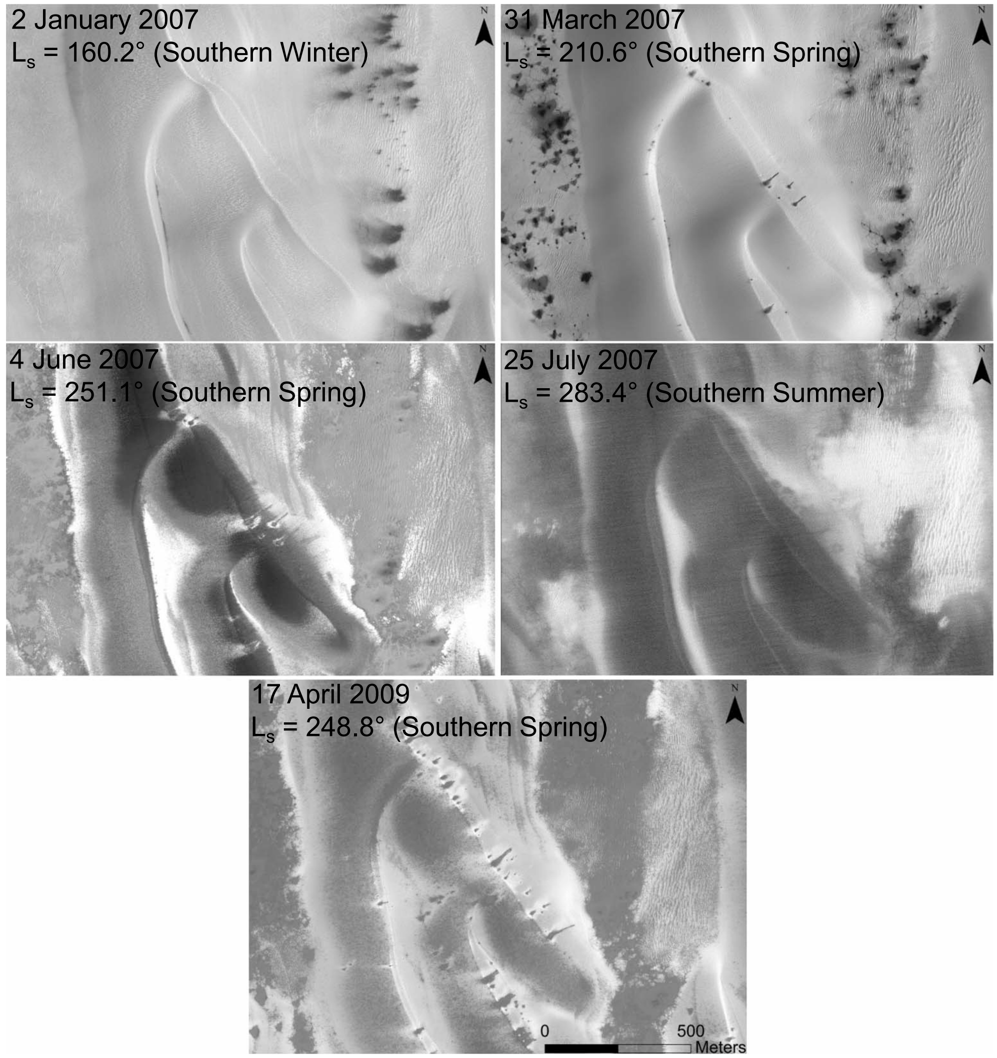

Figure 3. Appearance and disappearance of dark dune spots (DDS) in different seasons (scene center latitude [centered] −72.071° and longitude [east] 179.507°; all images were acquired between ~15:00 and 16:00 local Mars time) in Richardson Crater. In the 2 January 2007 image near the end of southern winter (HiRISE image PSP_002041_1075), developing DDS can be observed toward the eastern margin. In the 31 March 2007 image of the start of southern spring (HiRISE image PSP_003175_1080), more DDS can be seen forming across the scene. In the 4 June 2007 (HiRISE image PSP_004006_1080) and 17 April 2009 (HiRISE image ESP_012774_1080) images near the end of southern spring, the disappearing DDS can be observed. The 25 July 2007 image (PSP_004665_1080) represents the summer season, and all the DDS have disappeared. L_S stands for solar longitude. The images follow a seasonal order (increasing solar longitudes). HiRISE image credit: NASA/JPL/University of Arizona. HiRISE = High Resolution Imaging Science Experiment.

et al., 2012; Chuang et al., 2007; Morris, 1982; Phillips et al., 2007; Sullivan et al., 2001) and wet (e.g., Bhardwaj et al., 2017; Ferguson & Lucchitta, 1984; Ferris et al., 2002; Kreslavsky & Head, 2009; Miyamoto et al., 2004) mechanisms explaining their origin (Figure 6). Slope streaks are present predominantly between latitudes ±40° (Figure 7), and they appear throughout the year in low thermal inertia and high-albedo terrain with fine dust deposition (Sullivan et al., 2001). Bhardwaj et al. (2017) reported three hot spots of slope streaks based on a geo-statistical analysis: (i) west of Olympus Mons, (ii) in the southern part of Arabia Terra, and (iii) south of Elysium Rise. In addition, the presence of slope streaks has been reported in several new locations in western Kasei Valles, Valles Marineris, and north of Apollinaris Patera using updated HiRISE-based mapping (Bhardwaj et al., 2017). Considering the reported morphological, seasonal, and terrain variability in the RSL populations in Valles Marineris (Stillman et al., 2017), the presence of slope streaks on similar slopes can be interesting and reveal possible

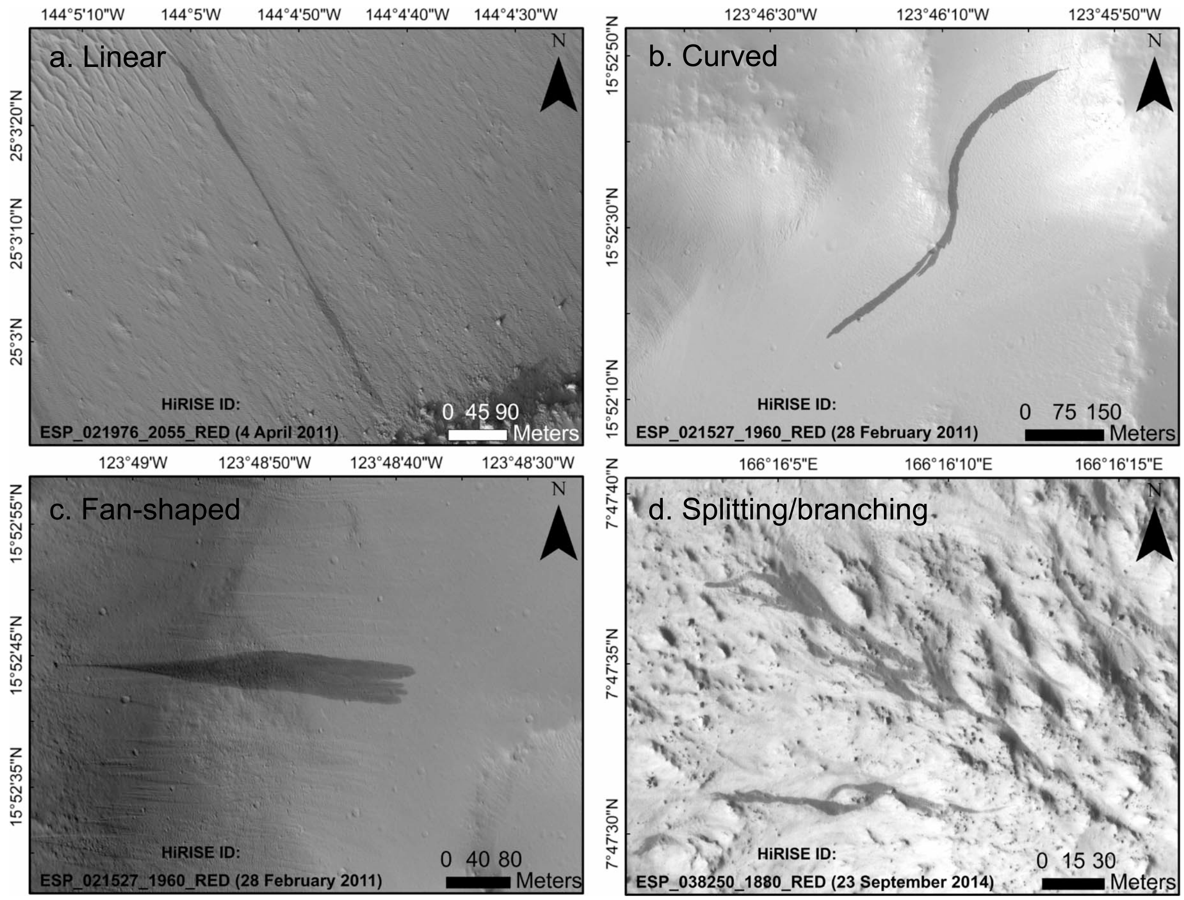

Figure 4. Several of the most commonly observed morphologies of slope streaks. (a) Linear, (b) curved, (c) fan-shaped, and (d) splitting/branching. HiRISE image credit: NASA/JPL/University of Arizona.

contrasting (or similar) mechanisms for their formations, given the availability of more high-resolution stereo or terrain data in the coming days.

Slope streaks display widely varying morphologies (Figure 4) and dimensions as the total length may range from about a few meters to several kilometers (Brusnikin et al., 2016). The typical morphology of slope streaks usually displays a starting point upslope with gradual widening toward the downslope termini and thus indicates the possible involvement of some flow or mass movement. Slope streaks are capable of following very gentle slopes and are reportedly able to climb even a few meters of obstacles in their flow paths (Bhardwaj et al., 2017; Brusnikin et al., 2016). Slope streaks appear to be singular events formed within a short temporal span, and their recurrence or lengthening is extremely rarely observed (Bhardwaj et al., 2017). However, Kreslavsky and Head's (2009) mechanism suggests that the short temporal span of slope streak formation does not necessarily signify an extremely transient aqueous phase in these features if slope streaks are formed by wet mechanisms. According to Kreslavsky and Head (2009) brine can persist for longer durations and thus can have significance for supporting any extraterrestrial life. Due to the unavailability of repeat images with high temporal resolutions, it is difficult to comment on the exact total duration of their formation, but based on the proposed hypotheses, it can be constrained between a few minutes and several hours. Their formation patterns and rates are highly inhomogeneous in the spatiotemporal domain, and while they have dark albedo in the beginning, they brighten and even fade away on decadal scales (Schorghofer & King, 2011). Several physicochemical concurrences have been reported for the slope streaks. Nearly 83% of the regions with slope streaks display above-average Cl concentrations (>0.5% by weight) in the regolith, ~82% of the regions with prevalent slope streaks show the highest hydration levels outside the poles (>4% by weight) in their regolith, and ~95% of the slope streak regions (SSR) exhibit the highest Fe concentrations (>12% by weight) in the surface regolith (Bhardwaj et al., 2017). An observation derived from the

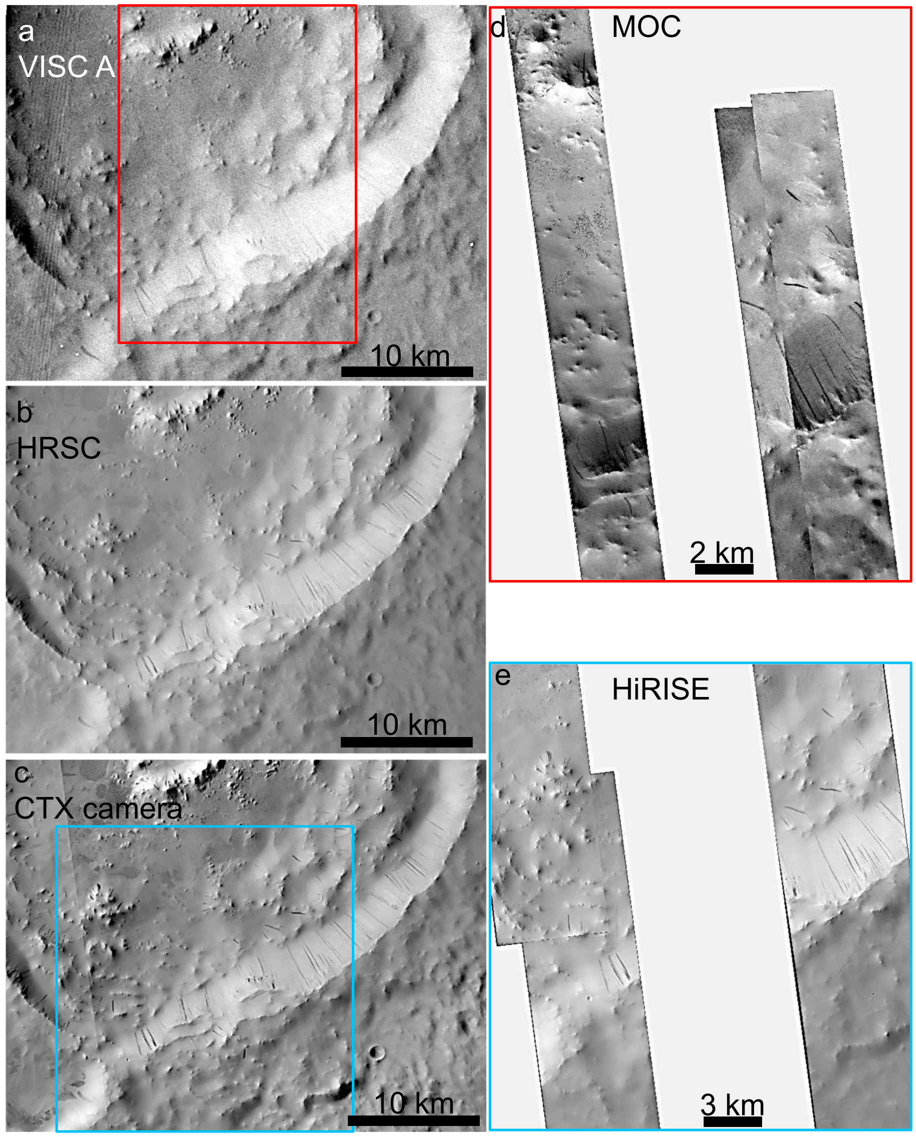

Figure 5. Multitemporal and multiresolution observations of slope streaks in the same region of Arabia Terra (latitude [centered]: 8.812°, longitude [east]: 40.057°) using various satellite sensors. (a) VISC A (image ID: 713A13, acquisition date: 31 May 1978, resolution: 40 m). (b) HRSC (image ID: H5238_0000_ND3, acquisition date: 30 January 2008, resolution: 12.5 m). (c) Mosaic of 2 CTX scenes (description [left to right]: (1) image ID: B20_017473_1874_XN_07N32, acquisition date: 19 April 2010, resolution: 5.47 m; (2) image ID: P21_009192_1890_XN_09N320W, acquisition date: 12 July 2007, resolution: 5.61 m). (d) Mosaic of three MOC scenes (description [left to right]: (1) image ID: R1002664, acquisition date: 16 October 2003, resolution: 3.08 m; (2) image ID: R1201917, acquisition date: 17 December 2003, resolution: 3.08 m; (3) image ID: R1601030, acquisition date: 13 April 2004, resolution: 3.1 m). (e) Mosaic of 3 HiRISE scenes (description [left to right]: (1) image ID: ESP_037015_1890, acquisition date: 19 June 2014, resolution: 54.9 cm; (2) image ID: ESP_027244_1890, acquisition date: 19 May 2012, resolution: 27.3 cm; (3) image ID: PSP_009192_1890, acquisition date: 12 July 2008, resolution: 27.7 cm). VISC A image credit: NASA/JPL/USGS; CTX image credit: NASA/JPL-Caltech; HRSC image credit: ESA/DLR/FU Berlin; MOC image credit: NASA/JPL/Malin Space Science Systems; HiRISE image credit: NASA/JPL/University of Arizona. VISC A = Visual Imaging Subsystem Camera A; HRSC = High Resolution Stereo Camera; CTX = Context; MOC = Mars Orbiter Camera; HiRISE = High Resolution Imaging Science Experiment.

Mars Global Surveyor Thermal Emission Spectrometer data for seasonally averaged water vapor column abundance reveals that ~95% of the SSR concur with average-to-the highest water vapor column abundances in equatorial and subequatorial regions (Bhardwaj et al., 2017). The yearly average of surface temperatures is ≥210 K for ~95% of the SSR within latitudes ±40° (Bhardwaj et al., 2017).

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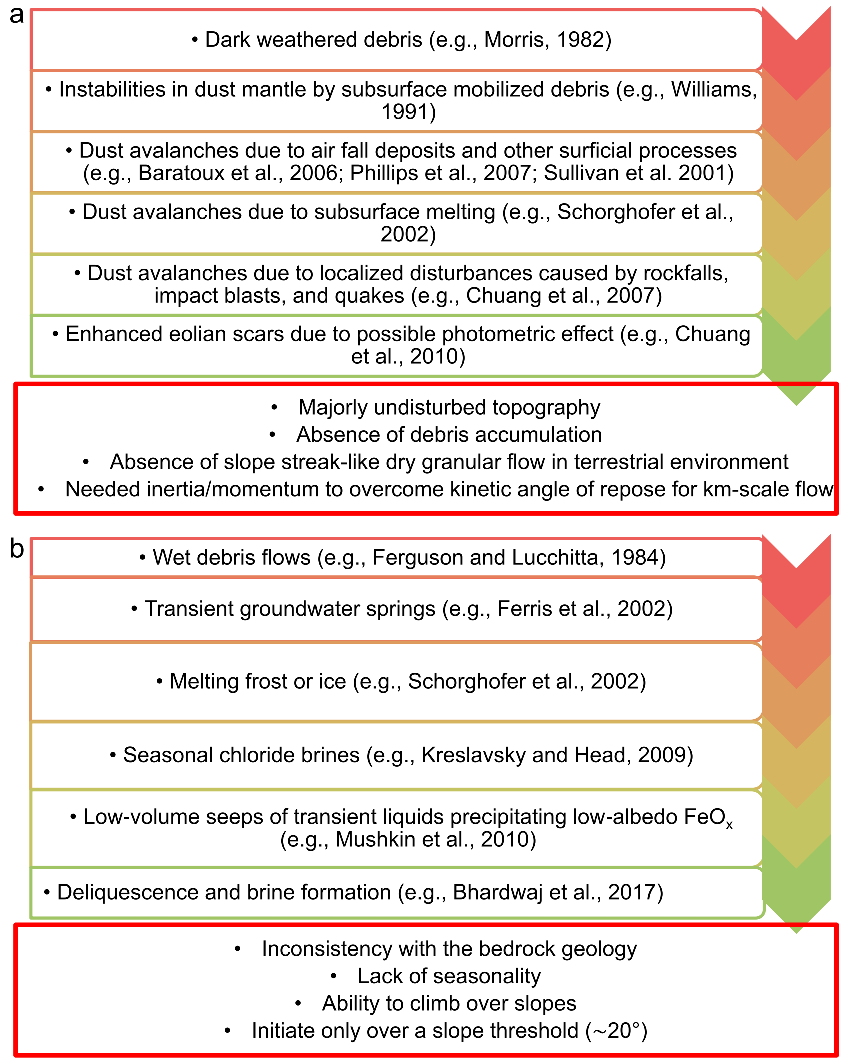

Figure 6. Mechanisms for slope streak formation proposed in the literature. (a) Dry mechanisms and (b) wet mechanisms. The issues mentioned in the red boxes need further explanation and research in view of the proposed mechanisms. These issues within the red boxes pertain to different specific models and are elaborated in the texts.

3. Hypotheses for Formation

The proposed mechanisms in published literature for formation of slope streaks vary widely. Figure 6 highlights several of the prominent dry (Figure 6a) and wet (Figure 6b) mechanisms proposed for slope streak formation along with the main issues, which need further explanation and research in view of the proposed mechanisms. As noted before, slope streaks are dark albedo features and preliminary look at these features suggests possible involvement of some flow or mass movement (either wet or dry). In the first observations of slope streaks made by Morris (1982), slope streaks were interpreted as dark weathered debris since information about their continuous formation on contemporary Mars was not yet available. The coarse resolution Viking data were also not the best images for interpreting the morphology of the streaks. However, their typical lobate shapes were sufficient to provoke never-ending interest among scientists. Very soon after this initial reporting on slope streaks, Ferguson and Lucchitta (1984) realized that slope streaks continuously appear in several regions of Mars, and they interpreted slope streaks as wet debris flows. These contrasting interpretations of slope streaks in the initial years of their observation gave rise to the formation mechanism conundrum that even today requires significant exploration. In the subsequent years, several dry formation mechanisms were proposed such as instabilities in the dust mantle by subsurface mobilized debris that ultimately led to dust avalanching (e.g., Williams, 1991), dust avalanches due to air fall deposits and other

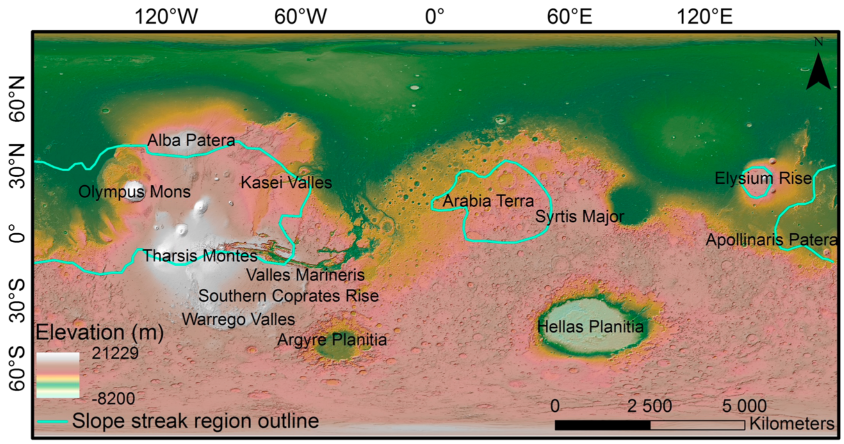

Figure 7. Outlines enclosing the densest slope streak regions on Mars as compiled from the published literature (Aharonson et al., 2003; Bhardwaj et al., 2017; Ferris et al., 2002; Schorghofer et al., 2002, 2007; Sullivan et al., 2001) with respect to the topography. A Mars Orbiter Laser Altimeter elevation and hillshaded view is in the background (courtesy: NASA/JPL/Goddard).

surficial processes (e.g., Baratoux et al., 2006; Phillips et al., 2007) or subsurface melting (e.g., Schorghofer et al., 2002), appearance of avalanche scars as slope streaks due to some possible photometric effect (e.g., Chuang et al., 2010), and localized disturbances caused by rockfalls, impact blasts, and quakes that eventually led to dry mass movements (e.g., Chuang et al., 2007). All these mechanisms have their own merits, and the main questions that need detailed investigations in the backdrop of such mechanisms are as follows: (i) Why does the vast majority of slope streaks display mostly undisturbed topography at HiRISE resolutions? (ii) Why do we not observe any debris accumulation at the extremities of the slope streaks at HiRISE resolutions? (iii) Why are slope streak-like dry granular flows not reported in terrestrial environments? (iv) How can dry mass movement within slope streaks have the needed inertia/momentum to overcome the kinetic angle of repose for kilometer-scale flow under Martian gravity? Some answers to these questions posed by the dry mechanisms for slope streak formation point to the spatial resolution limitations of even the highest-resolution HiRISE data. The topographical changes or the accumulated debris can be minute enough not to be discerned by the HiRISE observations. Other answers point toward the significantly vigorous atmospheric dynamics on Earth as compared to that on Mars, which can quickly displace any fine dust deposits after dry avalanching.

Similarly to the dry mechanisms, several proposed wet mechanisms have their own explanations for describing the formation, rheology corresponding to wet mass movements, and morphology of slope streaks. Ferris et al. (2002) proposed the involvement of transient groundwater springs in initiating slope streaks, while Schorghofer et al. (2002) proposed a mechanism based on melting frost or ice. Kreslavsky and Head (2009) further highlighted a possible role for seasonal chloride brines in slope streak formation, while Mushkin et al. (2010) provided a mechanism in which low-volume seeps of transient liquids generate low-albedo iron oxide precipitates as slope streaks. Such wet models have either highlighted or have tried to answer other relevant questions pertaining to slope streaks such as the following: (i) Why is there a lack of universal consistency between slope streak occurrences and bedrock geology, thus constraining the proposed springs/seepage mechanisms? (ii) Why do we not observe significant seasonality in slope streak formations at the global scale on Mars? (iii) How can slope streaks climb over obstacles if they are aqueous flows? (iv) Why is a certain degree of steep slope needed for their initiation in most cases? There has been some degree of seasonality for slope steak formations as reported recently (Heyer et al., 2018). Also, wicking or capillarity (e.g., Bhardwaj et al., 2017; Kreslavsky & Head, 2009) has been proposed as a possible explanation for long-distance and antigravity movements of slope streaks. In addition, the concurrence of slope streaks in low thermal inertia regions on Mars can have implications for explaining both dry and wet mechanisms. Low thermal inertia leads to high diurnal variability in surface temperatures with possible sudden heat-related morphological changes in the fine dust grains, allowing the possibility of dry mass movements within the top several centimeters of the regolith. Similarly, the low thermal inertia can explain wet mechanisms by facilitating the needed temperature changes in the top regolith layers increasing deliquescence possibilities or frost melting. Nevertheless, we discuss such questions and models further in the subsequent sections.

4. Discussion on Common Observations and Proposed Hypotheses

As highlighted in the previous section, there are several questions related to published formation mechanisms for slope streaks that are either yet to be answered or they have been partially answered and there is still some scope of investigation. In the sections below, we first try to regroup the common observations on slope streaks and then use them to further analyze the supporting evidence for or against these mechanisms.

4.1. Global Distribution and Formation Rates

As shown in Figure 5, a remotely sensed image that has ~10 m or better spatial resolution can be helpful in identifying the presence of slope streaks. However, due to the widely varying dimensions of slope streaks (Bhardwaj et al., 2017) and the possibility of studying the terrain, selecting the submeter-resolution HiRISE scenes is preferable for identifying and characterizing slope streaks. Since 2001, several researchers (Aharonson et al., 2003; Bhardwaj et al., 2017; Rifkin & Mustard, 2001; Schorghofer et al., 2002, 2007; Sullivan et al., 2001) have gathered information on the global distribution of Martian slope streaks. Figure 7 shows the extents of the densest SSR on Mars. Although the abovementioned studies have reported several isolated and scattered sites outside the boundaries displayed in Figure 7, a common consensus is that the SSR coincide well with the regions of high dust content (Ruff & Christensen, 2002), low thermal inertia (Ruff & Christensen, 2002), and low abundance of exposed rocks (Christensen, 1986) (Figure 8).

Sullivan et al. (2001) provided the initial information on the global distribution of the slope streaks using MOC images during its first years of operation. This inventory was not exhaustive due to limited high-resolution spatial coverage at that time, but the work gave a fairly good idea about the most prominent SSR on Mars. In the same year, another inventory by Rifkin and Mustard (2001) using MOC also confirmed these SSR and Ferris et al. (2002) used the Rifkin and Mustard (2001) inventory to make several interesting inferences about their probable linkages with the geological histories of magmatic, tectonic, and fluvial activity, and potential ground ice/magma interactions. However, in the subsequent years when more SSR were marked using newer images (e.g., Aharonson et al., 2003; Schorghofer et al., 2002, 2007), the lack of correlation between slope streak occurrences and bedrock geology at local scales became apparent and suggested that slope streaks were more a surface phenomenon than purely geological (Kreslavsky & Head, 2009).

Over these past years, several studies have also monitored the rates of appearance or formation of slope streaks. Sullivan et al. (2001) determined a formation rate of ~1 per year for an impact crater in Schiaparelli Basin. In a detailed study, Aharonson et al. (2003) performed a survey of 173 randomly distributed colocated image pairs and reported a 7% rate of formation of new streaks per existing streak in a Martian year between 1998 and 2002. They reported the highest rate of ~12% in the regions around and south of Olympus Mons. Schorghofer et al. (2007) reported a rate of 3% per existing streak per Mars year for the Olympus Mons aureole with a smaller number of image samples, but their analysis had a larger temporal domain based on Viking/MOC overlaps spanning nearly two and a half decades. Bergonio et al. (2013) further extended this temporal domain to three decades using comparable resolution Viking/CTX overlaps in the Lycus Sulci region and reported a formation rate of 4.7% per existing streak per Mars year. In a recent study, Bhardwaj et al. (2017) highlighted that in several regions the formed slope streaks are too small to be clearly resolved even in ~5 m spatial resolution images. This small size means that newly formed slope streaks can be hard to recognize in CTX or MOC images. Such small streaks are abundant in Arabia Terra, and an example of such a scenario is given in Figure 9 where even the largest of the slope streaks cannot be clearly demarcated in the CTX scene (red arrows) as they resemble the shadows cast by topographic relief or gullies. The width of such streaks does not exceed the dimensions of a pixel in the CTX images. The smaller slope streaks marked by the violet arrows are visible only in the HiRISE image. Such small slope streaks were also highlighted by Bergonio et al. (2013).

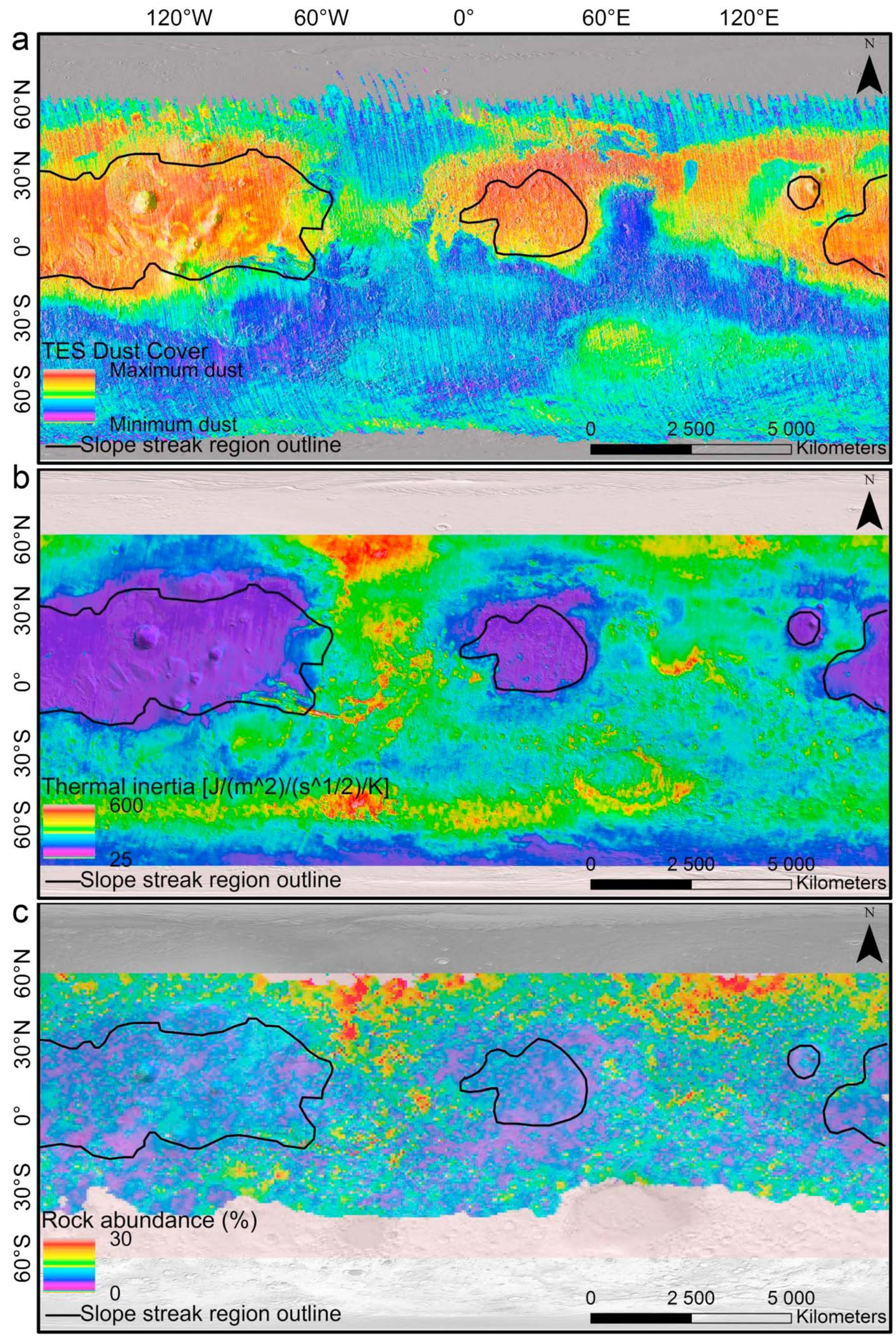

Figure 8. Concurrences of slope streak regions with (a) Thermal Emission Spectrometer-derived dust cover (Ruff & Christensen, 2002), (b) Thermal Emission Spectrometer-derived thermal inertia (Ruff & Christensen, 2002), and (c) Viking Infrared Thermal Mapper-derived exposed rock abundance (Christensen, 1986). These maps have been generated using the data freely available as Mars global data sets (https://www.mars.asu.edu/data/) provided by Arizona State University. A Mars Orbiter Laser Altimeter hillshaded view is in the background (courtesy: NASA/JPL/Goddard).

Thus, this comparison raises a valid point that utilizing images from sensors having significantly different spatial resolutions should be avoided for estimation of formation rates. Keeping this in view, Bhardwaj et al. (2017) used the same formula as suggested by Aharonson et al. (2003) and reported a rate of appearance of 12% new streaks per existing streak per Martian year on the repeat HiRISE images of two different craters in the Elysium Planitia region. These authors extended the HiRISE temporal domain to nearly a decade and

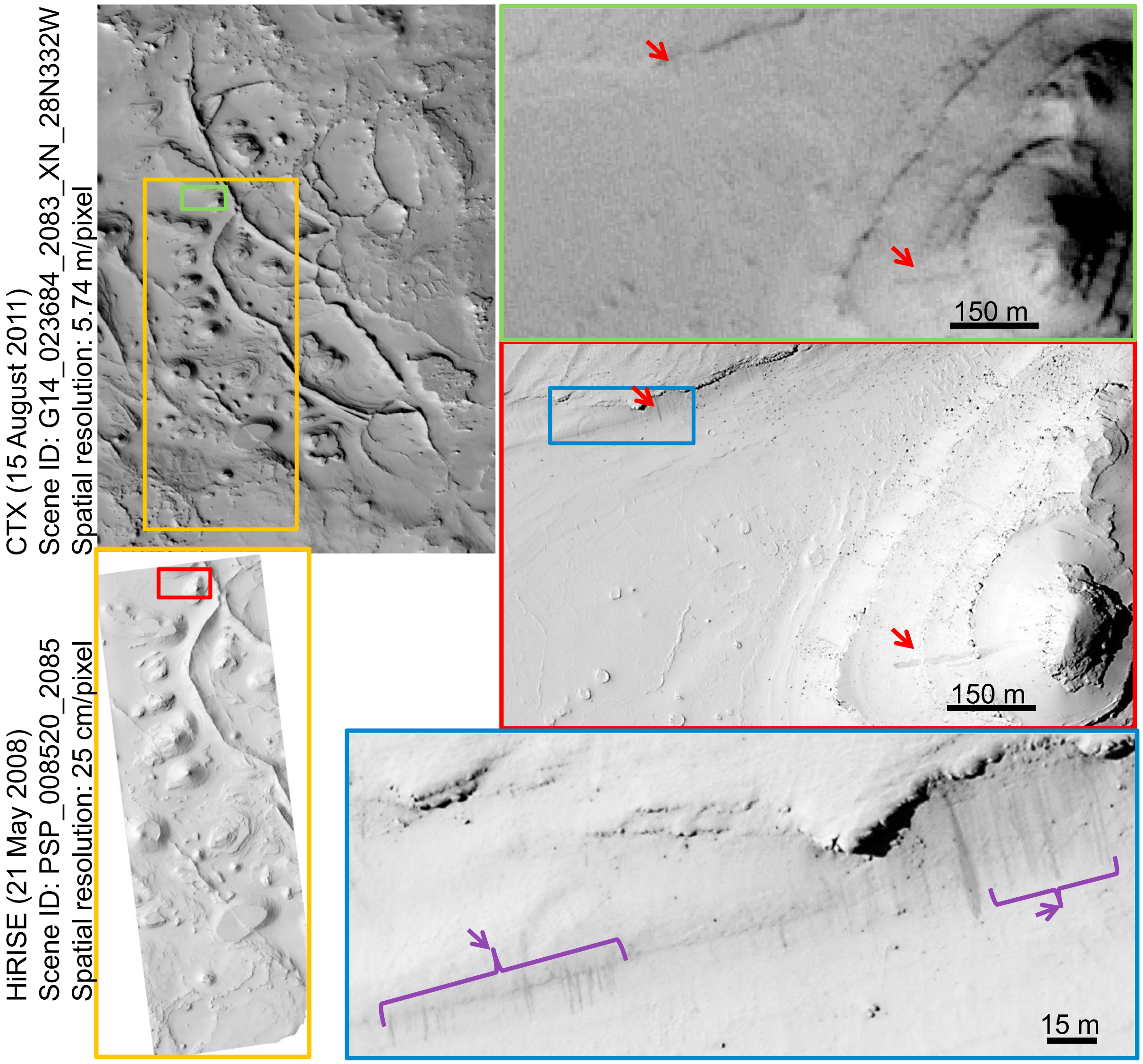

Figure 9. Extremely small slope streaks in Arabia Terra (latitude 28.36° and longitude 27.97°). The red arrows show the larger slope streaks that are also visible in the CTX image. The violet arrows show the smaller slope streaks, visible only in the HiRISE image. CTX image credit: NASA/JPL-Caltech; HiRISE image credit: NASA/JPL/University of Arizona. CTX = Context; HiRISE = High Resolution Imaging Science Experiment.

reported the high-resolution formation rate calculation. Thus, such calculations are highly dependent on the spatial resolutions of the image pairs used as well as on the study area and presently do not show much uniformity. A high formation rate for such features in several regions is also relevant in view of the facts that the factors promoting dry mass movements (seismicity, rockfalls, and impact blasts) are not as frequent or widespread on contemporary Mars at the global scale. Particularly, the most commonly ascribed reasons behind slope streak dry mass movements are rockfall events and Figure 8c clearly confirms that SSR having the least abundant exposed rocks. Similarly, seismicity on Mars is yet unconfirmed, and the planet is also considered tectonically inactive.

4.2. Morphology and Topography

Slope streaks display highly variable dimensions and topographical characteristics (Bhardwaj et al., 2017; Brusnikin et al., 2016). Based on the MOC images, Sullivan et al. (2001) provided the first detailed morphological characterization of slope streaks. Sullivan et al. (2001) and the subsequent research articles emphasized the sharp margins, absence of any relief or debris accumulation, acute points of initiation, branched ends, and considerably variable dimensions even on the same slopes. The usual range of lengths as mentioned by Sullivan et al. (2001) was between 300 and 1,500 m, and the reported widths typically varied up to a maximum of 200 m. A recent survey of ~1,000 randomly selected slope streaks by Bhardwaj et al. (2017) reported the lengths varying from 14 to 1,600 m, widths from 1 to 148 m, and areas from 6 to 84,800 m^2. Based on their observations, Sullivan et al. (2001) proposed dry dust avalanches and subsequent oversteepening of air fall deposits to explain the formation of slope streaks. These authors established an analogy between slope streaks and terrestrial dry snow avalanches based on the morphological similarities. Sullivan et al. (2001) mentioned low angles of internal friction and low Martian gravity behind the slope failures on a wide range of gradients and subsequent loss of avalanching dust particles to the atmosphere instead of terminal debris accumulation. Given the limitations in Mars environmental data and submeter-resolution remote sensing data, they stated the probable presence of a thin failed layer depth that was unresolved at MOC resolutions, thus completely attributing slope streak formation to dry dust avalanching. Later, Chuang et al. (2007, 2010) claimed that the failed layer depth was on the order of a meter or less using shadow length measurements in HiRISE images for several slope streaks. These authors also attributed the ability to detect topographic relief to the spatial resolutions of the images, low solar illumination, dust abundance, and slope aspect or orientation. Chuang et al. (2007, 2010) suggested that localized disturbances such as rockfalls, impact blasts, and seismic activity were behind the formation of slope streaks. However, the consistent presence of relief for slope streaks is significantly lacking, as Chuang et al. (2007) also agree that in a given area under the same viewing and lighting conditions, a few streaks may display topographic relief, while the majority may not. Based on the limited number of relief observations in particular regions, Chuang et al. (2007) also proposed that the formation of slope streaks required the removal of material through dry avalanching. In the same year, Phillips et al. (2007) reported evidence of mass movement within a single slope streak north of Olympus Mons, and although they did not completely reject the possibility of wet mass transfer, they also did not stress upon any possibility of staining, wetting, or wicking of the surface by liquids as the reason behind slope streak formation. Chuang et al. (2007) further argued that since many slope streaks occur in areas with no significant evidence of fluvial activity in the recent geologic past, no type of wet fluid flow can define the formation of the majority of slope streaks.

Later, Burleigh et al. (2012) presented a new hypothesis based on observations made on another HiRISE scene (PSP_002764_1800) that slope streaks are dust avalanches triggered by the airblasts created by supersonic meteoroids before impact and are not related to seismic shaking after the impact. Observations by Chuang et al. (2007) and Burleigh et al. (2012) unambiguously show that slope streak formation can be triggered by falling boulders and impacts. The fact that we do not know the triggering mechanisms for the majority of streaks does not reduce the significance of these observations. On the other hand, such impact-based triggering does not necessarily reveal a possible dust avalanche mechanism; it means only that streak formation can be a runaway process and can equally be explained by other mechanisms (e.g., Kreslavsky & Head, 2009). Nevertheless, several points to reconsider with respect to these arguments remain in light of a number of recent findings. The first point is the limited number of such observations, that is, only one slope streak by Phillips et al. (2007), several others by Chuang et al. (2007, 2010), and a single HiRISE scene by Burleigh et al. (2012), while the majority of slope streak features that have been reported do not show any material transfer, deposition, relief, or proximity with impact blasts in HiRISE images (Bhardwaj et al., 2017; Brusnikin et al., 2016; Mushkin et al., 2010). Although Chuang et al. (2010) proposed a series of events explaining the appearance and modifications of slope streaks starting with eolian activity where very fine grains strike the surface and trigger dust avalanching followed by airfall dust deposition and infilling, which cause their fading and eliminate any traces of relief, this process does not explain the absence of relief even in the majority of freshly formed slope streaks. Another argument that Chuang et al. (2007) presented for explaining the lack of relief in the majority of slope streaks was that the volume of excavated dust was insufficient to be clearly resolved as shadows in the HiRISE data acquired at 15:00 local true solar time. However, this argument again does not explain the undisturbed topography or the absence of terminal debris accumulation. Nevertheless, we acknowledge the possibility that observing such relief or evidences of mass movements for all or majority of the slope streaks may require even higher than HiRISE resolutions and, thus, should not be taken as a limitation of the theories of mass movements or avalanching (dry or wet). Second, contrary to the suggested dry avalanche mechanisms of Chuang et al. (2007), the signs of rockfalls, impact blasts, and seismic activity have not been observed for the majority of slope streaks sharing the same slopes (Kreslavsky & Head, 2009). However, rockfalls, impact blasts, and seismic activity can be a few of the several other processes, which may promote dry dust avalanches, and their absence for majority of the slope streaks actually indicates the probable presence of some other operational processes instead of the complete absence of dry mass movement. Third, the mechanisms involving staining, wetting, or wicking of the surface cannot be overruled based on the presence of topographic disturbances (mounds) within only one slope streak (e.g., Phillips et al., 2007), while for a majority of the streaks, undisturbed topography and an absence of relief have been extensively reported (Bhardwaj et al., 2017; Brusnikin et al., 2016; Mushkin et al., 2010). Additionally, it has been suggested that surface wetting mechanisms can further initiate slope failure and wet mass movements in the cases of several slope streaks (Bhardwaj et al., 2017), which also explains the presence of relief in the cases of only those few of the slope streaks that undergo such wet mass movement. Thus, instead of ruling out the dry or wet mechanisms right away, one point where we can achieve a common consensus is the possibility of mass transfer within majority of these slope streaks even if presently they are hard to notice. Fourth, fluvial activity in the recent geologic past is not necessarily needed to explain a wet mechanism as several recent findings (e.g., Gough et al., 2016; Martin-Torres et al., 2015; Massé et al., 2014; Ojha et al., 2015; Tennakone, 2016) have shown that atmospheric conditions are consistent with the possible formation of brines at several locations, which can further explain the wet mechanisms behind slope streak development (e.g., Bhardwaj et al., 2017; Kreslavsky & Head, 2009).

Another important surface feature that has been reported from the Olympus Mons region and is well differentiated from slope streaks by Gerstell et al. (2004) is avalanche scar, which also shows a terrestrial analogy with dry snow avalanches. Kreslavsky and Head (2009) suggested a descriptive term *triangular scars* for these features, because their avalanche origin has not been firmly established. These triangular scars display lengths and widths similar to those of slope streaks, but they also have an apparent depth of several meters (4–10 m) contrary to the slope streaks with a seemingly submeter relief (e.g., Chuang et al., 2007) or no relief (e.g., Bhardwaj et al., 2017), an average slope of ~27° as opposed to gentler slopes for several slope streaks reported from regions where triangular scars have not been observed (e.g., Bhardwaj et al., 2017), a fan-shaped bottom-heavy or wide opening angle morphology in contrast to the widely varying morphologies of slope streaks (e.g., Bhardwaj et al., 2017; Brusnikin et al., 2016), and significantly older ages than slope streaks, which appear frequently and are sustained for a few decades. However, Chuang et al. (2007) established an analogy between the two through several arguments further suggesting that these features could be related as part of a continuum of active mass wasting facilitated by dust avalanches. Although we do not completely deny the possibility of such an analogy in several cases, here we also highlight several aspects that need to be considered. Chuang et al. (2007) argued that both of these features occurred in the same equatorial latitudes which is not entirely justifiable as although they show concurrences in some areas of the Olympus Mons region, the global distribution of slope streaks is extremely dense covering mainly the latitudes between +30° and −10° and nearly half of the longitudes (Bhardwaj et al., 2017), while the triangular scars have been extensively reported from the Olympus Mons lower aureole (Gerstell et al., 2004) in addition to several other regions. Chuang et al. (2007) also mentioned the concurrence of both these features in similar geologic settings and local regions, which is debatable, particularly when in more recent years, the independence of slope streaks from the local geology was more firmly established (Kreslavsky & Head, 2009). As their next argument, Chuang et al. (2007) highlighted the presence of a point source origin in the cases of both features, which also does not prove a correlation between them since the point source origin has also been observed for the wet slope streak analogs that have been reported on Earth (Bhardwaj et al., 2017; Head et al., 2007) and is consistent with the explanations involving brine formation and flow mechanisms proposed for the Martian slope streaks (e.g., Bhardwaj et al., 2017; Kreslavsky & Head, 2009).

Figure 10 further explores the possibilities for the origin of slope streaks from the same point as triangular scars in several cases highlighted by Gerstell et al. (2004) and Chuang et al. (2007). Gerstell et al. (2004) focused on only the upper halves of the darker features in MOC images E0501528 (Figure 10a) and M0303927 (Figure 10b) in their paper and suggested that the darker scars, although they appeared to be slope streaks, were actually triangular scars. However, they did not elaborate on why the darker albedo was present in the cases of only a few of the scars (yellow arrows in Figure 10) on the same slopes. One possible explanation can be that these darker scars were relatively newer and that the underlying topography appeared darker than rest of the scars (green arrows in Figure 10). Nevertheless, this logic does not remain valid if we take a close look at the contextual view of the features as shown in Figure 10b. We observe several

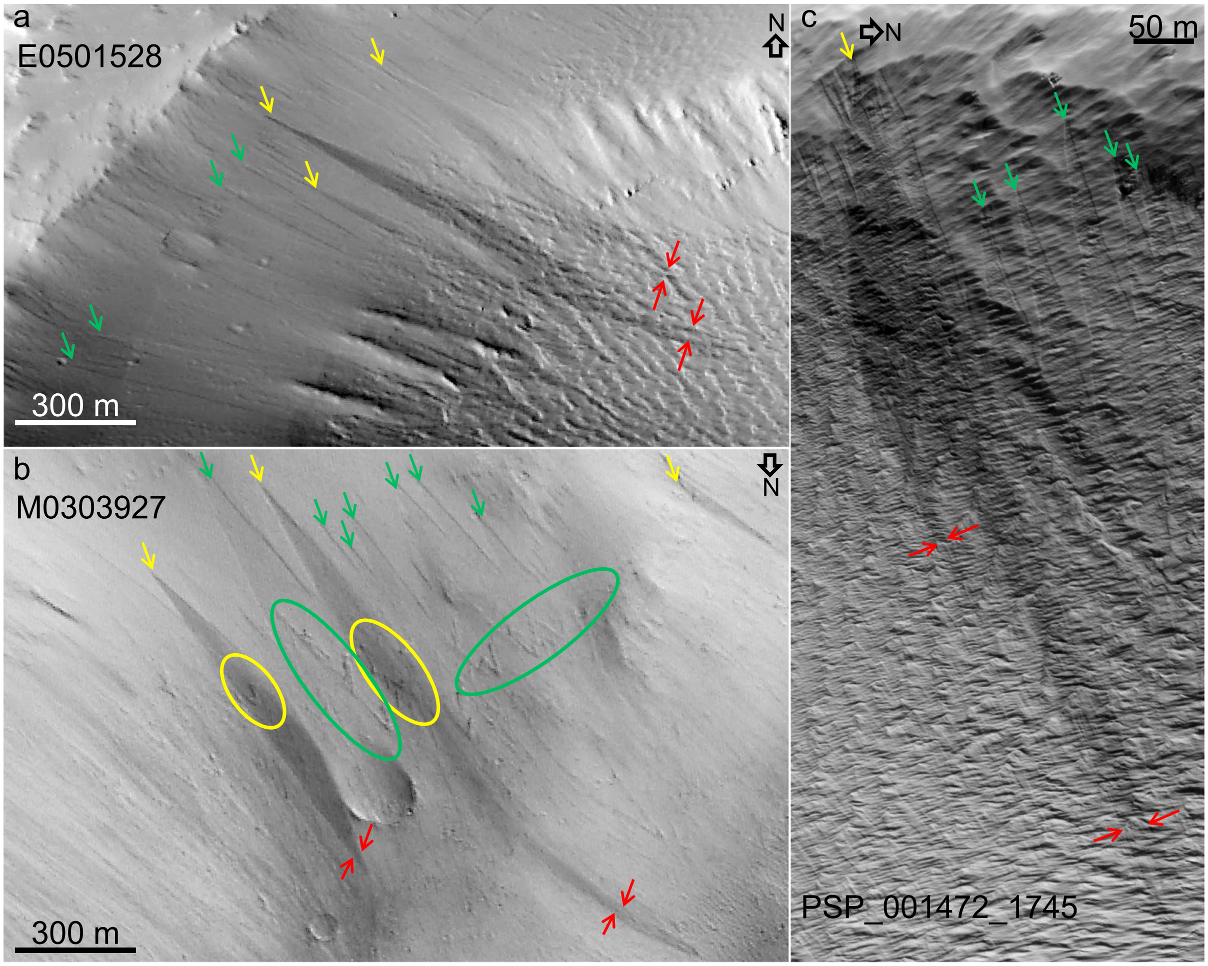

Figure 10. Slope streaks and triangular scars on the same slopes. (a) MOC image ID E0501528 (16 June 2001). (b) MOC image ID M0303927 (21 July 1999). (c) HiRISE image ID PSP_001472_1745 (19 November 2006). The yellow arrows represent the points of origin of dark albedo features, and the green arrows represent the points of origin of brighter triangular scars. The red arrows show the thinning of the terminus of the darker features that gives the features a middle-heavy morphology. Green ellipses and yellow ellipses show the triangular scars in the lower reaches with points of origin in the brighter albedo and darker albedo zones, respectively. MOC image credit: NASA/JPL/Malin Space Science Systems; HiRISE image credit: NASA/JPL/University of Arizona. MOC = Mars Orbiter Camera; HiRISE = High Resolution Imaging Science Experiment.

triangular scars originating in the lower slopes in the avalanche runout zones of both darker (yellow ellipses) and brighter (green ellipses) features. If these lower triangular scars were formed earlier than the higher darker and therefore newer triangular scars, their topography must have been destroyed by the meters-thick newer triangular scars based on the descriptions given by Gerstell et al. (2004). Nevertheless, this situation is not the case and we can clearly see the origin point as well as the entire morphology and topography of the lower avalanche fans in the dark zones (yellow ellipses), similar to those for the lower avalanche fans in the brighter zones (green ellipses). Now, the second situation can be that the lower scars in the dark albedo zones were formed after the higher ones and thus should have displayed darker albedo along and within their avalanche fans in the same manner as the higher dark triangular scars. However, here we can noticeably observe that the dark albedo only follows the fan boundary of the higher scars from where it originated while the avalanche fans of the lower scars are partially getting covered within the dark zones and that too not necessarily following their fan boundaries. Now, if we take another look at the example given by Chuang et al. (2007) and also shown in Figure 10c, where they associated the dark albedo in HiRISE image PSP_001472_1745 with a dust avalanche, this situation appears to be the same on a HiRISE image with better resolution as depicted by Figures 10a and 10b. There are several triangular scars, but only one of them is darker and covers portions of the adjacent triangular scars in the lower reaches without destroying their topography; after passing the avalanche fan of the main scar that restricted its movement sideways, this darker triangular scar shows irregular morphology, further narrowing toward the end (Figure 10c).

Figure 10 also displays a classic case of phenomenological variations (Rosenberger, 2011, 2013) in interpreting the same remote sensing images of slope streaks from different perspectives, leading to multiple inferences. For example, a plausible explanation for observed distribution of dark albedo within fan boundaries in Figure 10 can be provided based on the mechanism suggested by Bhardwaj et al. (2017), on either the possibility of dry dust avalanching, which is more recent and independent of the triangular scars or the possibility of surface wetting with minor downslope mass transfer due to brine formations. If we consider the possibility of brine formations in this case, an avalanche scar can facilitate it by uncovering the underlying mineralogy favorable for brine formation on the slopes by exposing the underlying mineralogy to the atmosphere. If brine formation takes place due to deliquescence, the dark albedo is essentially the result of the formed slope streak that follows the avalanche scar boundaries and does not disturb the topography of the downslope triangular scars. This process can also explain why the dark albedo of the formed slope streak beyond the boundaries of the deeper avalanche fan starts following an irregular morphology and deviates from the typical bottom-heavy fan shape, converging or thinning at the terminus as shown by the red arrows in Figure 10. As Bhardwaj et al. (2017) described, not only can the exposure of deliquescence salts to the atmosphere form slope streaks but also the more important factor is the presence of adequate deliquescence conditions of temperature and relative humidity (RH) during the time of the exposure. Since these are the dustiest regions on Mars, any avalanche scar can become covered with a thin dusty layer within a matter of several hours or days, thus diminishing the chances for deliquescence if favorable atmospheric conditions are not present either at the time of scar formation or later when due to wind and the curvature of the point of scar origin, the overlying dust is dispersed, and the salt species come in contact with the atmosphere. For the latter scenario, the fact that nearly every point of origin for a slope streak displays some curvature or local steepening (Bhardwaj et al., 2017; Miyamoto et al., 2004), which makes it more vulnerable to exposure due to dust removal from external factors such as strong wind, is substantial. This process can further explain why such slope streaks are present in the cases of only a few of the triangular scars on the same slopes. Thus, we conclude that (1) triangular scars are different from slope streaks; (2) triangular scars and slope streaks can coexist on the same slopes; (3) darker albedo triangular scars can be the ones that facilitate the initiation of slope streaks from the same point of origin due to rough curvature and exposure of deliquescent salts to the atmosphere; (4) even if the slope streak originates from the same point, its movement is restricted by the meters-deep avalanche scar boundaries until the end of the avalanche fan, beyond which the streak displays irregular and free movement; and (5) the slope streak does not necessarily disrupt the topography of the triangular scars through which it passes.

4.3. Possible Flow Characteristics

We consider several of the models that have been proposed for describing the flow characteristics of slope streaks by the researchers who do not consider slope streak a mere surface albedo marking or a result of surface staining by brines. Miyamoto et al. (2004) provided a detailed illustration of this topic through both a fluid rheological model and an alternative lubricant-based dry grain flow model. They highlighted the constraints related to Sullivan et al.'s (2001) completely dry flow model such as its inability to explain several morphological (sinuosities, uniform albedo, width fluctuations, bifurcation, and anastomosing patterns) and topographical (occurrences at shallow slopes, and preserved topography) characteristics of slope streaks. The conclusions of Miyamoto et al. (2004) were derived from observations and measurements on MOC images and Mars Orbiter Laser Altimeter topography, thus, making the topographic measurements to be of coarse resolutions. Based on their interpretations of anastomosing patterns, Miyamoto et al. (2004) emphasized the strong control of local topography on slope streak morphology and the slow movements of slope streaks giving them insufficient inertia to flow uphill while analogous terrestrial dry mass movements such as landslides and snow avalanches display considerable runouts owing to their substantial momentum. Miyamoto et al. (2004) also parameterized their numerical flow model for both, an aqueous hypothesis based on variable topography, density, and supply rate and a dry grain flow hypothesis considering viscoplastic, sliding block, and rapid granular flow models. The conclusions of Miyamoto et al. (2004) regarding the nature of slope streak flow are as follows: (1) low viscosity (1 Pa s) and yield strength (1 Pa), (2) quick formation and culmination of the flow, and (3) flow density on the order of several tens of kilograms per cubic meter. Thus, their models rule out a completely dry debris flow origin for streaks on gentle slopes and suggest either a water-dust mixture involvement or a dry granular flow facilitated by some lubrication. As noted above, these conclusions were also based on the analysis of coarse resolution Mars Orbiter Laser Altimeter topography available at that time and with the present accessibility of submeter-resolution HiRISE images and digital elevation models (DEM) capable of revealing minimal topographical perturbations within slope streaks (e.g., Bhardwaj et al., 2017; Brusnikin et al., 2016), at least the estimated flow density proposed by Miyamoto et al. (2004) appears to be an overestimate.

Bulmer et al. (2008) were more inclined toward the hypothesis of dry granular flows based on the terrestrial analogy with sand dunes. They ascribed the flow mechanism and size of runout zones of the slope streaks to the mobility of the granules, which further depended on their high sphericity owing to Martian gravity and wind processes. However, this analogy with sand dunes needs some rethinking considering the fact that there is a distinct dissimilarity between the dusty regolith in the SSR and the Martian sand dunes. Martian sand dunes certainly reflect an analogy with terrestrial sand dunes, but the slope streaks on Mars are in the regions covered with very fine dust that is morphologically and spectrally different from coarser sand grains (Ruff & Christensen, 2002).

Mushkin et al. (2010) proposed a different flow mechanism than the conventional granular mass flow. They proposed that the solar insolation warms the deeper substrata through the dusty layer owing to its low thermal inertia, allowing brine formation and seepage through the interstitial spaces in the porous dust layer. However, a prime requisite for such brine formation is not only the temperature but also the presence of moisture or appropriate atmospheric RH conditions. If we consider that brine formation occurred below the dusty layers, then Mushkin et al. (2010) did not elaborate on the possibilities or the extent of subsurface humidity conditions. Nevertheless, they provided an approximate estimate of the amount of brine needed (~1,500 m^3) to seep through the pores of a 5-cm-thick dust layer with 30% porosity to produce a fan shape, a runout length of 1 km, and a width of 0.2 km.

The mechanism proposed by Mushkin et al. (2010) was an addition to the hypothesis suggested by Kreslavsky and Head (2009) who proposed brine formation as the source of slope streaks. However, the hypothesis of Kreslavsky and Head (2009) had a seasonal dependence while later observations have confirmed that slope streaks are seasonally independent (Martínez & Renno, 2013). Nevertheless, Kreslavsky and Head's (2009) study was a significant advancement on this topic in several respects. They were the first to indicate that contrary to the hypotheses of Chuang et al. (2007) and Phillips et al. (2007), triangular scars are different from slope streaks even if the two features have some coincidences. In the previous paragraph, we discuss this in detail and provide evidence distinguishing triangular scars from slope streaks and a possible mechanism that can explain their coincidences. Kreslavsky and Head (2009) also pointed out the morphological, albedo-related, rheological, gravitational, and terrestrial analogy constraints associated with the dry mechanisms for slope streak formation. They further took into account the pressure and temperature constraints for the wet mechanisms and proposed their own hypothesis involving $CaCl_2$-mediated process where brine comes from hydrated salts and ice in the shallow subsurface and not from the atmosphere. Kreslavsky and Head (2009) proposed that during the cold season the ambient temperature decreases to less than the eutectic temperature and $CaCl_2$ and H_2O coexist as hydrated salt and ice. In the warm season, when the temperature crosses the eutectic temperature, brine forms, percolates downward, and refreezes at the bottom, producing an impermeable layer; this process can sometimes form a run-away downslope percolation front in the form of a slope streak (Kreslavsky & Head, 2009). Another important suggestion given by Kreslavsky and Head (2009) was regarding the favorable Martian gravity conditions for ~3 times higher capillarity than that in Earth's regolith, facilitating the outward movement of the brines toward the surface. This idea of high capillarity in supporting brine movement was further explored by Yakovlev (2010, 2011). Yakovlev (2010, 2011) suggested that the point initiation of a slope streak is followed by the consecutive distribution of the ice melting process downhill under the influence of low gravity and high capillarity without any energy or mass transfer. However, his hypothesis did not consider deliquescence-based brine formation and it also did not discuss the thermal and physical constraints for ice melting or the nature and abundance of this subsurface ice for all the SSR on Mars.

To establish a brine-based flow mechanism for slope streaks, Kreslavsky and Head (2009) suggested a need to first investigate the seasonality of the streaks, model the surface skin temperature regime at better spatial and temporal resolutions, and perform more high-resolution morphological and topographical observations to establish the probable wet mechanism. In this regard, Bhardwaj et al. (2017) looked again at these recommendations by Kreslavsky and Head (2009). The aspect of nonseasonality for slope streaks is already established (Schorghofer & King, 2011), and Bhardwaj et al. (2017) proposed the surface formation of brines when the salts come into contact with favorable atmospheric conditions instead of a subsurface origin for the streaks as proposed by Kreslavsky and Head (2009), thus eliminating the seasonality constraints.

In contrast, a recent study by Heyer et al. (2018), who used the closest temporal images for the same regions to observe slope streak appearances, reports the highest formation rates during the summer months (2 to 72 times higher than in winter months). This well-defined seasonal peak in slope streak appearances certainly deserves another look for defining the seasonality of these features. Heyer et al. (2018) further report a good correlation between the surface temperatures and streak formation rates, which can explain why these features are not entirely seasonal as RSL are. If we consider slope streaks a result of transiently favorable deliquescence conditions, then in the lower latitudes, these conditions are attainable transiently throughout the year as the surface temperature conditions vary within a narrow range. They are, however, more easily attainable during the summer months, thus possibly increasing the seasonal formation rates of slope streaks. Bhardwaj et al. (2017) also proposed that the surface temperatures are the key factor that should be investigated to better understand the formation mechanisms of slope streaks due to their rapid development and short-lived nature.

Wilson et al. (2016) advanced a similar view regarding the appearance of RSL discounting any subsurface contribution to their origin. With the continuously evolving and improving Mars Climate Database (MCD; Millour et al., 2015), we now also have the atmospheric and climatic conditions modeled at higher spatial and temporal resolutions with better accuracy. In fact, using simulations for the water vapor column, average annual mean and surface skin temperatures, average annual solar radiative flux to surface, and sol-to-sol variability in annual surface temperature from the latest version of the MCD, Bhardwaj et al. (2017) reported that all the identified SSR displayed perennially favorable temperature conditions (annual average of surface temperatures >223 K) for $FeCl_3$ and $CaCl_2$ brines. Bhardwaj et al. (2017) stressed the reason behind the nonseasonality of slope streaks by showing that the surface skin temperature in the SSR daily at some point of time crosses the eutectic temperature thresholds (~223 K) for $FeCl_3$ and $CaCl_2$ salt species in the regolith. Bhardwaj et al. (2017) also stated that in addition to the perennially high solar insolation and diurnal surface temperature variability in the SSR, the average sol-to-sol surface temperature variability is <2 K and that with the high water vapor column throughout the year in the SSR, the probability of diurnal control (and not seasonal) on slope streak formation is predominant.

Following the third recommendation by Kreslavsky and Head (2009) regarding high-resolution morphological and topographical observations, Bhardwaj et al. (2017) utilized five precise and high-resolution DEMs from different SSR containing abundant slope streaks to compile data on the topographical and morphological parameters of slope streaks. They displayed the morphological differences between low-volume dry mass wasting and slope streaks on the same slopes in Zunil Crater. Bhardwaj et al. (2017) also reported the presence of surface curvature or bending in the cases of nearly all the points of initiation and reported the process of deliquescence to be a surficial point phenomenon starting on the curved and rugged slopes since such slopes ensure less dust cover. This thinner dust layer along with the lower thermal inertia of the SSR makes the top few centimeters of regolith layers more prone to deliquescence in the event of any unsettling factor such as a rockfall impact or strong wind capable of removing this moderate dust layer.

Bhardwaj et al. (2017) pointed out the favorable topographic aspect distribution in the SSR, where ~70% of the sampled slope streaks displayed slope orientations that followed the Sun during a Martian day (east-northeast to west-southwest). Based on this observation, Bhardwaj et al. (2017) stressed their hypothesis derived from the MCD data sets that slope streaks are a result of diurnal deliquescence favoring conditions instead of seasonal. Another aspect where Bhardwaj et al. (2017) agreed with Kreslavsky and Head (2009) was the role of capillarity in facilitating the movements of slope streaks, not in vertical manner from a subsurface source of origin (e.g., Kreslavsky & Head, 2009), but in its horizontal movement through the fine dusty regolith of the SSR. This capillarity is strengthened due the weaker gravity of Mars that pulls less water inward. Furthermore, the osmotic forces that originate from the attraction between water molecules and cationic solutes generated via acid displacement reactions (Clark & Van Hart, 1981) and draw the water molecules toward slope streak margins support the capillarity. In addition, the narrow capillary columns that are provided by the fine-textured dust in the SSR facilitate the long-range propagation of slope streaks on gentle slopes.

Undoubtedly, laboratory simulations of such features under Martian conditions can shed more light on their formations. Conway et al. (2011) performed lab simulations under Martian temperature and pressure conditions and for a fixed slope angle (14°) to study the erosive capacity, runout, and resulting morphologies of flowing water. They reported that the conditions of low temperature and low pressure do not negatively affect the erosion rate and flow speed and that in several instances, the water phase is short-lived but can flow even faster under such conditions due to the lack of infiltration facilitated by the formation of ice below the liquid-sediment contact and the gas bubbles of boiling water under low pressure, thus enhancing the runout even on gentle slopes. If we consider the wet hypotheses for slope streak formation then Conway et al.'s (2011) observations explain the possible extremely transient liquid water phase and quick formation of the slope streaks. Conway et al. (2011) also discussed this hypothesis and its implications for two Martian features: gullies and slope streaks. In the subsequent years, Jouannic et al. (2015) explored such simulations exclusively for Martian gullies while Massé et al. (2016) performed another detailed simulation analysis covering all the proposed water-related features (RSL, slope streaks, gullies, and DDS) for a fixed but steeper angle of ~30° (corresponding to the dynamic angle of repose). Massé et al. (2016) explained why the hydrous signatures for these features are hard to find through the present Martian hyperspectral imaging instruments (Infrared Mineralogical Mapping Spectrometer and Compact Reconnaissance Imaging Spectrometer for Mars) as the spectral signature of intergranular water is below the spectral and spatial detection thresholds of these instruments. However, one of the main conclusions by Massé et al. (2016) was that small amounts of metastable liquid water are capable of a higher morphological impact than brines at any given surface pressure. This conclusion favors the brine hypotheses (e.g., Bhardwaj et al., 2017; Kreslavsky & Head, 2009) over the melting ice or frost hypotheses (e.g., Schorghofer et al., 2002) for slope streak formation because unlike gullies, slope streaks have the least detected morphological disturbances.

A recent dry-based numerical simulation for RSL (Schmidt et al., 2017) proposes the pumping of rarefied gas through the porous Martian soil due to temperature contrasts causing dust avalanching as another probable viscosity-related explanation. This model justifies the RSL seasonality through the photophoretic effect caused by solar radiation that seasonally modifies the angle of repose of the granular material, causing the dry flows. In contrast, such seasonality is not observed in slope streaks, and they display even gentler slope angles than the ones needed to overcome the angle of repose favorable for dry flows under Martian gravity. Therefore, this gas-triggered dry avalanche model (Schmidt et al., 2017) along with some involvement of subsurface-to-surface fluidized flows coming with gas bursts can possibly explain the events responsible for slope streak formation.

Thus, we conclude the viscosity-related considerations with several main points: (1) The initial observations based on MOC images (e.g., Sullivan et al., 2001) or limited numbers of HiRISE images (e.g., Chuang et al., 2007) proposed dry mass movements as the reason for slope streak formation, and this inference was mostly a result of observational constraints (low spatial resolutions and smaller numbers of submeter-resolution images at the time); (2) dry mechanisms (e.g., Schmidt et al., 2017) cannot be immediately rejected as in combination with some subsurface fluid sources (e.g., Fischer et al., 2014; Rivera-Valentín et al., 2018), they can provide a better explanation for a vast majority of slope streaks; (3) among the proposed wet mechanisms, a surface brine formation mechanism seems more favorable than a subsurface brine origin as the former agrees better with the rheological and topographical constraints; (4) more rheological lab simulations for reduced gravity conditions, controlled Martian environments, and terrain scenarios (considering slope, aspect, and curvature) are needed for various Martian regolith simulants with different grain sizes; and (5) with the constant influx of submeter-resolution images and DEMs and improvements in the MCD, the origin and rheology of the slope streaks will be better understood in the near future.

4.4. Surficial and Atmospheric Correlations With SSR

The concurrence of the SSR with the surficial and atmospheric conditions that may promote or suggest brine formation is the least studied topic in slope streak research. Climatic simulations for Mars have significantly improved in recent years and can assist such studies in a major way. Here we try to take a fresh look at this subtopic. Ferris et al. (2002) were the first authors to investigate the geographical and geological correlations with slope streaks and based on the coexistence of streaks with volcanic deposits, Ferris et al. (2002) proposed magmatically driven hydrothermal groundwater activity leading to seasonal subsurface interstitial ice melting and discharge as slope streaks. Based on the observations of Rifkin and Mustard (2001), Ferris et al. (2002) noted the western Tharsis Montes and the Northwestern Slope Valleys as the densest SSR. Ferris et al. (2002) mentioned that this dense slope streak population coexisted with the margin of the highland-lowland boundary marked by a discontinuous band of wind-etched materials consisting of ash-flow tuffs. In addition, Ferris et al. (2002) stated the coincidences with the regions of magmatic, tectonic, and fluvial activity, further suggesting potential ground ice/magma interactions. Although we acknowledge that the slope streaks are prevalent in volcanic deposits, now we also know that the slope streak populations are widespread throughout significantly varying geological regimes (Kreslavsky & Head, 2009); thus, the hypothesis proposed by Ferris et al. (2002) lacks universal applicability in addition to the uncertainty regarding the availability of large groundwater reservoirs and magmatic activity in SSR.

In the same year, Schorghofer et al. (2002) also reported a global-scale correlation analysis with terrain (e.g., slope and orientation) and surface (e.g., thermal inertia and temperature) parameters based on the inventory derived from the MOC images available at that time. They concluded that all slope streaks formed only in the areas with peak surface temperatures exceeding 275 K and that 90% of them are found in the lowest thermal inertia regions ($<130\ \mathrm{Jm^{-2}K^{-1}s^{-1/2}}$) with steep slopes (root-mean-square slope > 0.9°) and sun-facing orientations, thus suggesting that phase changes in water were responsible for triggering the mass movements. Based on geographically weighted regression and spatial autocorrelation analyses, Bhardwaj et al. (2017) further established high concurrence rates among deliquescent salt-forming elements such as Cl and Fe, and hydration levels along with the presence of slope streaks. They also indicated the high spatial correlation of the SSR with the satellite-observed and simulated yearly water vapor columns and deliquescence-favoring surface temperatures as a basis for suggesting a plausible present-day regolith-atmospheric water vapor cycle in the SSR. However, this aspect of regolith-atmospheric water interchange needs a detailed discussion in view of several recent articles, which mainly focused on RSL; this discussion is presented in the next section.

4.5. Hypothetical Explanations Concerning Regolith-Atmosphere Interaction

We understand that RSL and slope streaks are significantly different in form and location (Martínez & Renno, 2013). Additionally, we do not envision a very similar origin for both of these features (although, this might be a possibility) and do not intend to use the observations of RSL as evidence for the envisioned mechanism for slope streaks. The only point that we are considering when we mention RSL along with slope streaks here is to take another look at the possible presence of transiently liquid water in both features in terms of evidence of local-scale atmosphere-regolith water interchanges. Coincidence of fog is one such piece of evidence, and we should not consider slope streaks in isolation from RSL at global scales as they can coexist in several regions (e.g., Valles Marineris). Fog and clouds are two of the easily observable markers of possible moisture or an active water cycle at local scales (Pottier et al., 2017). Based on this premise and near-surface temperature and wind circulation simulations, Leung et al. (2016) proposed that the observed fogs and clouds were potential indicators of a local water source in Valles Marineris and a probable explanation for the dense RSL sites within the canyon (Figure 11). Their simulation results displayed a localized circulation within the valley that can explain the presence of nocturnal clouds and fogs in Valles Marineris and not over the surrounding terrain. This result can give an additional explanation for the RSL water budget simulations by Grimm et al. (2014) who reported that most of the discharged water is lost to evaporation and the derived water volumes surpass those that can be supplied by the annual melting of subsurface ice, thus suggesting a significant atmospheric contribution through deliquescence mediated by an active water cycle. In this regard, it is important to look at the global distribution of the observed fog phenomena on Mars (Möhlmann et al., 2009) with respect to the confirmed and candidate RSL sites (Stillman et al., 2017) and SSR outlines (Figure 11). Figure 11 also displays four “RSL regions” as proposed by Stillman et al. (2016, 2017) based on their latitudinal and regional density. These RSL regions are the areas which have highest possibility to reveal even more RSL in future HiRISE acquisitions. Now, a look at the fog presence with respect to these RSL regions will make the coexistence even more appreciable. In addition, Figure 12 shows the equatorial and subequatorial regions, which have significantly higher water content (Wilson et al., 2018) than previous coarser-resolution estimates (Feldman et al., 2004), and Figure 13 presents a composite of all the available HiRISE stamps for northern (above 0° latitude, L_s = 90–180°) and

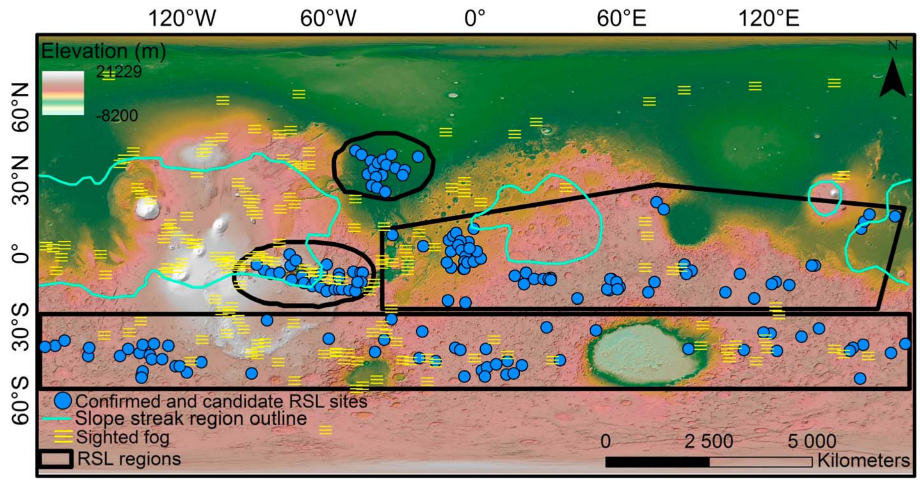

Figure 11. Global distribution of sighted fog (Möhlmann et al., 2009) with respect to the confirmed and candidate RSL sites and slope streak region (SSR) outlines. Confirmed and candidate RSL sites were compiled by Wilson et al. (2016) using data from McEwen et al. (2011), Stillman et al. (2014, 2016), and Dundas and McEwen (2015), and we have updated them and added four RSL regions from Stillman et al. (2017). Outlines enclosing the densest SSR on Mars are compiled from the published literature (Aharonson et al., 2003; Bhardwaj et al., 2017; Ferris et al., 2002; Schorghofer et al., 2002, 2007; Sullivan et al., 2001) with respect to the topography. Mars Orbiter Laser Altimeter elevation and hillshaded view is in the background (courtesy: NASA/JPL/Goddard). RSL = recurring slope lineae.

southern summer (below 0° latitude, L_s = 270–360°) seasons, which are ideal for identifying the RSL. Möhlmann et al. (2009) discussed the fog phenomena on Mars based on sightings in High Resolution Stereo Camera images until orbit 4133 and used the simultaneous temperature profiles obtained from the Mars Express Planetary Fourier Spectrometer to establish water ice (not frozen CO_2) as the cause of these fog observations. These authors further reported local orographic effects as the main supporting or explanatory factors for the fog distribution with the least influence of the global distribution pattern of atmospheric vapor or regional subsurface water content. This observation does not mean the absence of local-scale atmosphere-regolith interactions, but it signifies that such interactions are not necessarily needed to explain the fog. When we plotted these fog sightings with respect to the SSR and RSL regions (Figure 11), we could observe a degree of concurrence in several regions, with the majority of the fog sites falling within the regional boundaries. Although a congruence with individual RSL sites (not the RSL

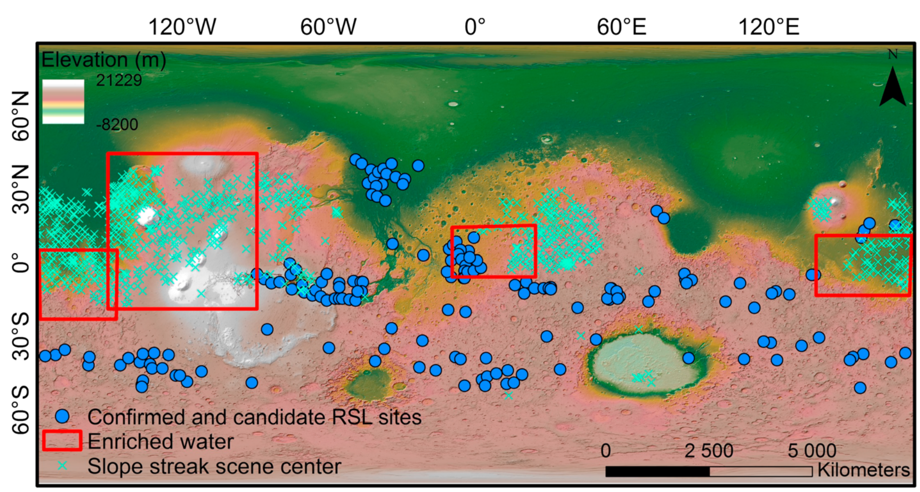

Figure 12. Equatorial locations of enriched water concentrations (Wilson et al., 2018) with respect to the confirmed and candidate recurring slope lineae sites (Stillman et al., 2017) and slope streak scene centers (Bhardwaj et al., 2017). Mars Orbiter Laser Altimeter elevation and hillshaded view is in the background (courtesy: NASA/JPL/Goddard).

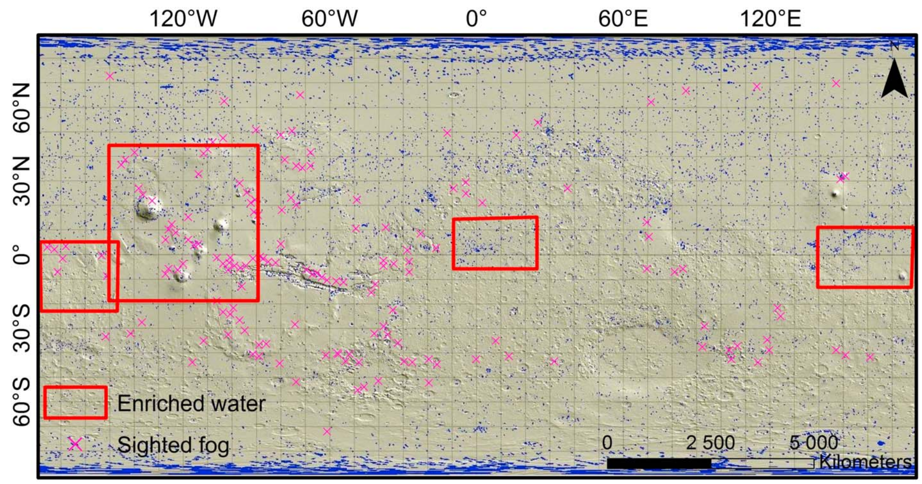

Figure 13. A composite of HiRISE stamps (blue rectangles) available until 2 October 2017 on the Java Mission-planning and Analysis for Remote Sensing (JMARS) software for northern (above 0° latitude, L_S = 90–180°) and southern summer (below 0° latitude, L_S = 270–360°). Equatorial locations of enriched water concentrations (Wilson et al., 2018) and global distribution of sighted fog (Möhlmann et al., 2009) are shown with respect to the summer HiRISE scenes suitable for RSL observations. Mars Orbiter Laser Altimeter hillshaded view is in the background (courtesy: NASA/JPL/Goddard).

regions as described by Stillman et al. (2017)) was not very obvious, this lack can be attributed to the incompleteness of both fog and RSL inventories owing to the data constraints. RSL sites can be observed only in the highest resolution HiRISE images during summer seasons, and as visible in Figure 13, the total global coverage of such seasonal scenes is less than 1% (Sidiropoulos & Muller, 2015) and in most of the instances does not coincide with the fog scenes of Möhlmann et al. (2009), which themselves need updating.

The apparent lack of correlation between slope streak occurrences and bedrock geology at local scales further suggests that the streaks are more a surface phenomenon (dry or wet) than a geological one (Kreslavsky & Head, 2009). However, it is also true that the modeled environmental conditions put further constraints on the brine formation possibilities in form of RSL or slope streaks in the present Martian conditions. Furthermore, even if the environmental conditions are compatible for deliquescence to occur, there is experimental evidence (Fischer et al., 2014) suggesting that bulk deliquescence might not be rapid enough during the short periods of the day in which the environmental conditions are compatible with brine formation. This evidence can constrain the brine hypothesis for bulk RSL formation during a Martian sol in the warmest season but probably for slope streaks which are singular events occurring over a temporal span in a given area, rapid bulk deliquescence is not needed on a particular sol or in a specific season. Another recent study (Primm et al., 2018) shows that once brines are formed, the process of dehydration can be very slow and that the brines can be stable much longer than previously expected which can possibly explain the kilometer-long paths traveled by the slope streaks on a gentle slope. Moreover, the experimental results of Fischer et al. (2014) also suggest liquid brine formations in minutes after the salts come into contact with water ice, indicating water frost or ice on the surface and in the shallow subsurface may be another probable source of moisture to facilitate sapping even if the required atmospheric RH conditions are not met. One more recent article (Rivera-Valentín et al., 2018) based on in situ Mars Science Laboratory observations for Gale Crater also suggests higher possibilities for subsurface brine initiation.

In this regard, we can also take Gale Crater as a case study, which is representative of a dry environment and has been investigated thoroughly using the Curiosity Rover. The diurnal and seasonal variations in the surface and near-surface temperatures affect the stability of water held in hydrate forms, which further depends on the RH. It has been speculated that the atmospheric water content can often be too small to trigger the deliquescence-based wetting mechanisms. In the case of Gale, using orbiter data, Dundas and McEwen (2015) found 58 possible RSL sites in the vicinity of Curiosity's traverse route, which later also prompted a debate on diverting its path away from such sites (http://www.nature.com/news/mars-contamination-fear-could-divert-curiosity-rover-1.20544). We explain here that both the subsurface and nearby atmosphere can act as local sources of water for the development of features such as RSL and slope streaks. Steele et al. (2017) performed mesoscale simulations of the diurnal water cycle in Gale Crater and its surroundings for three specific times in a year and compared them with Curiosity's Rover Environmental Monitoring Station diurnal RH measurements to deduce that the observed RH values can be matched only by taking into account the diffusion in and out of the regolith through adsorption/desorption as a compensatory factor. When Steele et al. (2017) considered regolith-atmosphere interactions, they observed a twofold to threefold decrease in the amount of vapor reaching the crater floor during the evening and night and attributed this change to vapor diffusion into the regolith along the crater walls. During the day, wind-mediated upslope vapor transport occurs through desorption from the regolith up the crater walls and reaches a few hundred meters into the atmosphere at convergence boundaries. According to this model and the analogy, the results at Gale Crater can be taken as representative of the probable vapor exchanges at other craters and SSR in the mesoscale domain, indicating that an intense regolith-atmosphere water interchange may actually also be present in seemingly dry regions. This inference can also be supported by another recent analysis by Wilson et al. (2018).

The Curiosity Rover also has an active neutron sensor called the *Dynamical Albedo of Neutrons* (DAN) instrument (Mitrofanov et al., 2012) to investigate the presence of subsurface water with a sensitivity for the top 60 cm of the surface (Mitrofanov et al., 2014). While DAN in situ measurements suggest an average abundance of 2.1–2.7 wt% of water-equivalent hydrogen (Mitrofanov et al., 2014), the High Energy Neutron Detector instrument onboard the Mars Odyssey Gamma Ray Spectrometer suite reports 5 wt% water-equivalent hydrogen (Mitrofanov et al., 2016), which further increases to 8.0 ± 0.4 wt% after the resolution improvement analysis performed by Wilson et al. (2018) on the Mars Odyssey Neutron Spectrometer (MONS) data. Wilson et al. (2018) attributed these measurement discrepancies to the varying penetration depths of the in situ DAN (60 cm) and orbital sensors (up to 1 m) and further suggested that at Gale, deeper regions are more hydrated than the surface and the near-surface regolith. Now this inference combined with the deductions of Steele et al. (2017) indicates that the shallower subsurface tends to be less hydrated presumably because of the active water exchanges with the atmosphere at diurnal scales.

Observing more coincidences between geochemistry and proposed wet features (e.g., Figure 12) becomes more important in light of several other conclusions drawn from the Wilson et al. (2018) study where using a pixon image reconstruction technique, they improved twofold the spatial resolution of the map of the near subsurface hydrogen distribution on Mars originally derived from the MONS data (Feldman et al., 2004). Interestingly, they observed four regions marked by red rectangles in Figure 12, which showed significantly higher water concentrations than previously estimated. They attributed this equatorial and subequatorial water to the hypothesis of high orbital obliquity in the recent geologic past. Wilson et al. (2018) further plotted RSL sites on the new map, reported a poor correlation and proposed that RSL are not fed by large subsurface aquifers but either by small aquifers or by the deliquescence of salts with an additional possibility of dry granular flows. Such possible deliquescence again supports a local regolith-atmosphere interchange of water. However, there is another aspect to explain these results. As Figure 13 makes clear, the coverage of summer HiRISE scenes within these water-enriched regions is too sparse to actually comment on the concurrences. Nevertheless, if we observe the presence of slope streaks mapped by Bhardwaj et al. (2017) using all the available CTX and HiRISE images in these regions, we can clearly see a very high concurrence (Figure 12). In contrast to the high obliquity hypothesis, the high water concentrations can be attributed to the heightened subsurface frozen or liquid aqueous phase in the pore spores provided by the possible deliquescence-related features such as RSL or slope streaks. Slope streaks are perennially forming features, and if they are a result of brine formations then they could be playing a prominent role in maintaining the heightened near subsurface water content. Correlating such observations with the Martian cryobrines (Möhlmann, 2011; Möhlmann & Thomsen, 2011) also needs consideration of not only their liquid states but also their frozen states (Primm et al., 2017) as such cryobrines can display both frozen and liquid phases at diurnal and seasonal scales. This can further discourage the overdependence of plausible explanations on the Wilson et al.'s (2018) findings about the subsurface aquifer or subsurface ice alone and can better establish a connection between the surficial brines and the subsurface water recharge. Nevertheless, given the coarse spatial resolution of MONS data, a cautious approach will be to perform such congruence analysis using a better resolution H-abundance data at local scales before establishing if slope streaks are actually contributing to the observed increased hydrogen content.

Cryobrines or liquid brines with eutectic temperature below 273.15 K have been demonstrated to be transiently stable under the present Martian atmospheric conditions of temperature and RH (e.g., Chevrier et al., 2009; Chevrier & Rivera-Valentin, 2012; Martin-Torres et al., 2015; Möhlmann & Thomsen, 2011; Zorzano et al., 2009). When brine freezes, it produces a mixture of ice and crystalline salts and several studies have focused on such ice and crystalline salts (e.g., Primm et al., 2017; Stillman & Grimm, 2011; Toner et al., 2014). The recent findings of Primm et al. (2017) are very relevant in explaining the metastability of the cryobrines as their simulations not only relied on the equilibrium thermodynamic considerations of salt supersaturation at low RH but also took into account the aspect of supercooling (supersaturation with respect to ice) at high RH, thus indicating a plausible prolonged aqueous state through equilibrium ice formation. This process can explain the kilometer-long slope streaks. This idea also indicates the possibility of a larger contribution of the cryobrines to the subsurface water recharge through seeping, which otherwise is expected to be constrained by instant freezing and subsequent sublimation. Thus, a possibility arises where the local-scale water cycle originating through deliquescence and visible through the fogs and clouds is also actively contributing to the subsurface and is observable in the spectrometer data.

5. Terrestrial Analogies for Martian Brines

One prime difference between the RSL and slope streaks is the presence of highly dusty regolith (high albedo) in case of slope streaks which is absent in RSL regions (low albedo; Martínez & Renno, 2013; Stillman et al., 2017). The presence of dust and thus the difference in the formation and propagation of these features can explain the rest of the differences such as recurrences, sizes, morphology, and seasonality (Bhardwaj et al., 2017). The surface and environment on Earth is significantly more dynamic than that on Mars, and the conditions that can favor the formation of natural brines or streaks are also more difficult to encounter. Several terrestrial analogs have been observed (e.g., Bhardwaj et al., 2017; Dickson et al., 2013; Gough et al., 2017; Head et al., 2007; Levy, 2012; Levy et al., 2011), which display seasonality like that of RSL but have morphology and sizes closer to those of slope streaks. Additionally, finding regions with high dust content such as the SSR on Mars and with favorable atmospheric deliquescence conditions is nearly impossible on Earth and even if any slope streak-like feature is formed, there is always the possibility that any precipitation event or dust storm can erase it. Therefore, if we consider the probable wet origin of Martian slope streaks then in order to understand the geochemical origin, formation, and rheology of slope streaks in the natural environment through terrestrial analogy, we have to rely on seasonal terrestrial streaks or brines. The most relevant aspect of this analogy is that all the reported terrestrial slope streak analogs have been proved to be manifestations of aqueous processes.

Terrestrial analogs for the slope features have been reported from the McMurdo Dry Valleys, Antarctica (e.g., Bhardwaj et al., 2017; Dickson et al., 2013; Gough et al., 2017; Head et al., 2007; Levy, 2012; Levy et al., 2011). Head et al. (2007) reported terrestrial slope streaks from the Upper Wright Valley and attributed their formation to seasonal snowpack melting and subsequent percolation of the meltwater into the dry substrate to the top of the impermeable permafrost layer leading to streak migration downslope. After extending to the contact with the finer-grained colluvium in the lower reaches, capillarity comes into the picture drawing the moisture toward the surface, which results in the wetting of the surface in the form of streaks. Streak dimensions are directly proportional to the volume of the source snowpack. Head et al. (2007) also reported several bright streaks adjacent to the dark streaks and considered them to be desiccated old streaks. They attributed the relative brightness of such streaks to salts deposited by the moisture. Thus, the mechanism proposed by Head et al. (2007) was not related to deliquescence. Levy et al. (2011) reported more such analogs from the adjacent Taylor Valley and called them water tracks. Although like Head et al. (2007), they also reported that the features were a result of snow and ice melts but based on the geochemical and geomorphological analyses, they established that these water tracks actively transported the salts and other solutes across the valley. Based on these geomorphological and seasonal similarities, Levy (2012) further proposed an analogy between the water tracks and RSL. Dickson et al. (2013) reported such $CaCl_2$-rich briny water tracks as the prominent source making the Don Juan Pond (DJP) at the lowest point in the South Fork of the Upper Wright Valley the most saline natural water body on Earth (Dickson et al.,

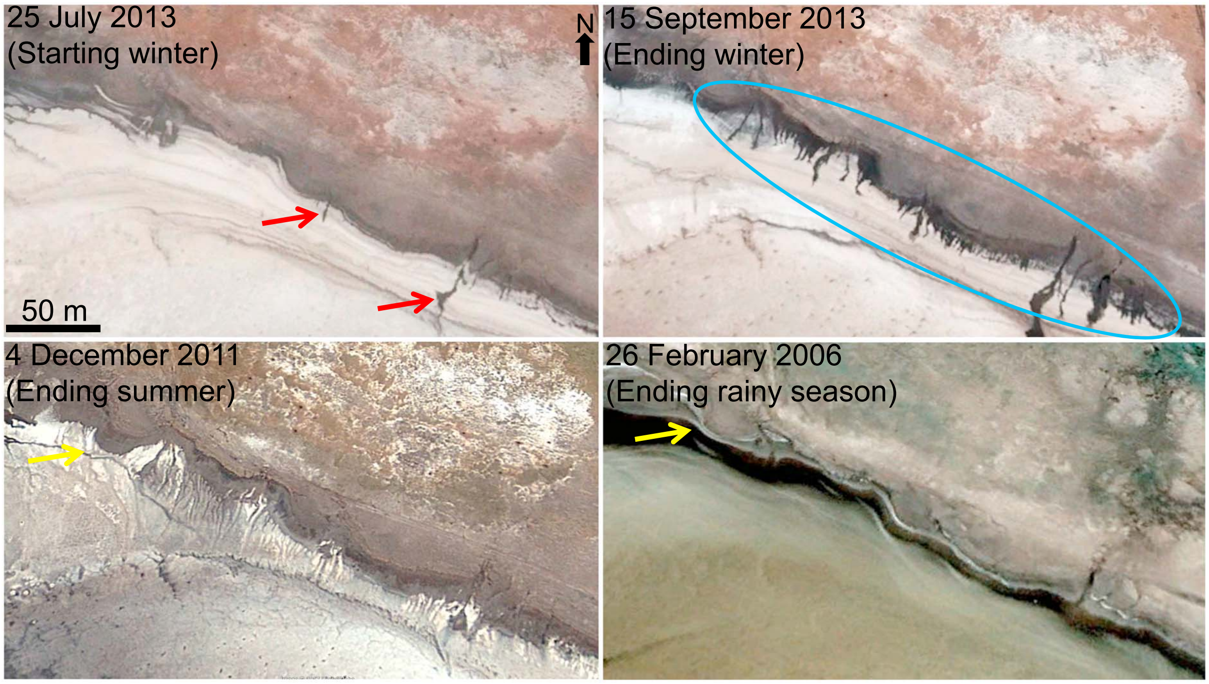

Figure 14. Seasonal slope streak appearance (red arrow, blue ellipse) and disappearance near Tahua, Salar de Uyuni, as observed in the available high-resolution temporal images on Google Earth. The yellow arrows highlight the appearance of a brine stream in December with the start of rainfall and its growth during the highest rainfall months of January and February. The data provider for the Google Earth images used is CNES/Airbus.

2013; Meyer et al., 1962) and anticipated the possibility of a transient DJP-like hydrological system near the RSL sites on Mars. However, the focus of the Dickson et al.'s (2013) research was not to study the mode of origin of the brines but to observe the contribution of such brines to the DJP.

Gough et al. (2017) provided significant laboratory-simulated and field-based observational evidence that brine formation via deliquescence by $CaCl_2$ salts during the summer and autumn months might be a more prominent reason for the origin and enrichment of water track, found near the DJP than thought earlier. They reported that the soluble salt component of DJP soils began to deliquesce between 19% and 46% RH in the temperature range of −30 to +15 °C and further confirmed these lab simulations through 6 months of field data from the DJP.

Here we suggest another Mars-like environment on Earth that has not yet been explored as a slope streak or RSL analog site: Salar de Uyuni in the Altiplano of Bolivia. This region is the largest salt flat on Earth with an area of ~10,000 km^2 (Risacher et al., 2003) at an altitude of 3,653 m above sea level (Baker et al., 2001). May to September are the coldest and driest months with zero rainy days on average, an average RH of 34%, and an average minimum temperature of −7.5 °C (Lamparelli et al., 2003), thus making Salar de Uyuni an ideal place to study its famous brines (Rettig et al., 1980; Risacher & Fritz, 2009) in analogy with the Martian brines. With a confirmed location outside the permafrost zone (Rangecroft et al., 2016), no precipitation and minimal climatic dynamics during the winter months (Lamparelli et al., 2003), and no possibility of either permafrost or seasonal snowpack melt contributions to the formation of streaks unlike in Antarctica, the brines in Salar are solely a result of salt deliquescence and can give us important clues about the formation and flow of the proposed Martian brines. This deliquescence or sapping can be facilitated by either atmospheric water or shallow subsurface water, respectively, and we cannot comment on the fractional characterization of the sources yet; however, this question can be a future topic of research. The brines in Salar de Uyuni have Na^+, Ca^{2+}, and K^+ as the dominant cations and SO_4^{2-} and Cl^- as dominant anionic species (Risacher & Fritz, 2009). Thus, these brines are prominently chloride and sulfate brines. In Figure 14, we have compiled several high-resolution Google Earth images from different seasons to show the appearance and disappearance of the slope streaks near the slopes of Tahua, north of the Salar. In the 25 July 2013 image, which corresponds to the starting days of winter, the minimum temperature increasing to −9.3 °C

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and a RH of 33% (Lamparelli et al., 2003) facilitate the initiation of the streaks (red arrows). The 15 September 2013 image represents the end of winter with minimum temperatures slightly higher (−5.4 °C), but the deliquescence conditions still favorable due to the simultaneous rise in the RH (38%; Lamparelli et al., 2003), and entire slopes are covered with well-developed streaks (blue ellipse). The desiccation of these streaks is clearly visible in the 4 December 2011 image when the summer is ending with the minimum temperatures well above 0 °C, and by the end of rainy season (26 February 2006), a well-formed brine stream with contributions from rain water can be seen. This analog site is easy to reach and perform field experimentation, terrain mapping, observation, and sampling and in the future can contribute greatly to the brine analogy research.

6. Synthesis and Conclusions

The slope streak conundrum needs proper investigation in the near future owing to its widespread implications for all the scientific disciplines pertaining to ongoing Mars research. In the starting days of slope streak research at higher resolutions during the initial years of this century, the results widely favored dry mechanisms partly owing to the absence of submeter resolution images and partly due to the lack of contextual studies at global scales. However, with the complete global coverage by the CTX imager, more than a decade of HiRISE data, and significant improvements in our understanding of the seasons and weather parameters on Mars, the number of studies supporting wet mechanisms has constantly increased. Improvements in computational efficiency, photogrammetry, and data dissemination, and better facilities for laboratory simulations during the past decade have also contributed significantly to our knowledge about the probable water-related surface features on Mars.

In this review, we have particularly focused on several very recent studies (e.g., Gough et al., 2016, 2017; Grimm et al., 2014; Leung et al., 2016; Massé et al., 2016; Pottier et al., 2017; Stillman et al., 2016, 2017; Wilson et al., 2018), which provide us some direct or indirect deductions on possible formation and flow mechanisms, brine compositions, and deliquescence possibilities for slope streaks as explained in the text. We infer that studying slope streaks as isolated surficial manifestations is not ideal for improving our knowledge of the streaks and that this topic warrants a holistic approach combining both atmospheric and surficial processes covering a wider geographical and temporal domain. Particularly, investigations on regional- or local-scale water cycles in the SSR should be a main focus of future slope streak research because with the available evidence detailed in this paper, we cannot deny a plausible regolith-atmosphere water interchange in the SSR. In addition, the involvement of dry processes cannot be completely overruled as there are several manifestations within slope streaks (e.g., Burleigh et al., 2012; Chuang et al., 2007, 2010; Phillips et al., 2007) that are rare but can be better explained through dry mechanisms or through a combination of both dry and wet mechanisms.

Another focus area for future slope streak explorations should be to acquire and utilize more submeter-resolution stereopairs for detailed photogrammetry and topographic measurements. These data can greatly aid in our understanding of the flow characteristics of slope streaks if they are actually formed by dry or wet mass movements. A prime need is not only to study the topography using a single DEM but to generate multitemporal DEMs using closely acquired images in order to estimate any topographic disturbance in the event of a new slope streak formation. This comparison can tell us about the extent of mass transfer, if any, within a slope streak. However, we believe that even HiRISE resolutions are probably not enough to provide precise mass transfer information for a majority of slope streaks.

A direct impact of the new findings, which weigh slightly more toward wet mechanisms for slope streak formations, will be on the planetary protection policies for future Mars missions. On the one hand, it would be of great scientific interest to land near a slope streak and to explore it more, but on the other hand, the possibility of moisture in the regolith could cause biological contamination of the Martian surface. Additionally, the expected acidic nature of the brines could be disastrous for the rover instrumentation. An increase in brine research investments is imperative given such findings (Martin-Torres & Zorzano, 2017). In terms of slope streak research, a conclusive statement of our review paper is that although there is recent evidence for plausible aqueous processes in slope streaks, we should exercise an unbiased and holistic approach toward our continued future exploration of slope streaks using better resolution and quality data sets. We acknowledge that such wet mechanisms cannot universally explain all the reported morphological and rheological variants of slope streaks and the explanations that take into account both dry and wet processes should be preferred. The next step should be aimed toward finding more wet and dry terrestrial analogs for slope streaks and studying them at high spatiotemporal resolutions to understand the formation constraints for the Martian slope streaks.

Acknowledgments
We acknowledge the editorial board of Reviews of Geophysics for inviting the submission of this review article. We extend our gratitude to the efforts of the handling editor and the reviewers. We thank NASA, JPL-Caltech, JPL/Goddard, University of Arizona, Malin Space Science systems, Arizona State University, USGS, ESA/DLR/FU Berlin, and Google Earth for providing various satellite images, maps, and JMARS software free of charge. The paper is theoretical, and no new data have been generated during the work. All the used satellite images of Mars can be rendered on JMARS software using the image ID provided in the respective figure captions, and the image sources have also been duly acknowledged in the respective figure captions. The maps in various figures have been created using ArcGIS version 10.4 (http://desktop.arcgis.com/en/arcmap/latest/get-started/setup/arcgis-desktop-quick-start-guide.htm). Although we have cited all the previous research results used in the paper, we here acknowledge the efforts of all those researchers in providing the essential inputs for our study. A. B. acknowledges the Swedish Research Council for supporting his research in cold arid environments. L. S. acknowledges the German Academic Exchange Service (DAAD) for her PhD scholarship.

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