Morphology of slope streaks within Nicholson crater, Mars: records of recent wind activity

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Wind is currently the dominant active geological agent bringing about constant changes over the Martian surface. One of the most conspicuous resultant morphology derived is the formation of slope streaks, highly transient features that tend to develop and may completely disappear within a few ten of years. In this article a detailed analysis on the pattern, morphology and appearance of slope streaks within the central mound of the Nicholson crater on Mars, has been made and plausible reasons for their formation as well as darkening and fading mechanisms are discussed. We focus on some observations which indicate the role of wind in carving specific streak patterns. The morphological observations discussed, strongly support active aeolian processes and provide evidences in favour of the dust avalanche theory for the formation and current morphology of slope streaks in the Nicholson crater.

Keywords: Aeolian activities, craters, morphology, slope streaks

Introduction and objectives

INDICATIONS on the presence of ripple morphology and dune migration at various locations provide evidences on the currently active aeolian processes over the Martian surface[1]. In addition, Mars rover observations and high-resolution images from orbiters also point towards evidences on widespread aeolian erosion and depositional processes[1,2]. Aeolian landforms can occur on almost any solid planetary surface having an atmosphere and are created as a result of interaction of wind with rocks and soils of that region[3], and provide insight on the varying wind systems on a global scale. Large-scale erosional, transportation and depositional morphology is evident from the images showing ubiquitous presence of aeolian landforms such as sand dunes, slope streaks, yardangs, sand ripples, sand sheets and deflation pits. Extensive presence of yardangs and of slope streaks at various locations on Mars have been detected and studied earlier[4,5]. In some cases the aeolian features are completely ephemeral and relate only to the lifting and settling of atmospheric dust, whereas certain features like dune fields, yardangs and ventifacts are more persistent and require significant time for their development[6]. Understanding of landform morphology helps reveal how in combination with previous active processes the sedimentary history of a region has eventually modified itself in response to a complex alternating process of dust accumulation and erosion brought down due to still active aeolian processes[7]. Study of Martian aeolian activity leads to an understanding of the forces that have sculpted the planet's face over the past billion years or more, and to the potential discovery of climate shifts recorded in surface wind features that reflect ancient wind patterns.

This article deals with a detailed discussion on the slope streak morphology within the ~100 km diameter Nicholson crater lying at the southern edge of Amazonis Planitia and in close vicinity to the Medussae Fossae Formation (MFF) on Mars. This region is of particular interest due to the presence of its notable central peak and a massive central mound of sedimentary deposits. The mound rises above the crater floor by ~3.5 km, with a length of 55 km and 37 km width, and having a central peak rising above the crater rim. The intra-crater mound morphology appears to be distinctly different from the smooth-textured crater floor from where it rises. Aeolian-borne slope streaks observed here are a resultant effect of wide-scale interactions between soil and wind that comprise the region's surface. In addition, the equatorial location of Nicholson crater also favours widespread aeolian activities. The observations made here are based on the large-scale active sediment and wind transport system prevailing within the Nicholson crater. In this region, modifications in the landforms subsequent to their formation have always been influenced by frequent episodic wind-borne processes. This crater exhibits a zone of complex processes and a detailed morphological study would thus lead to a better understanding of its morphological evolution and alterations that occurred with time.

Slope streaks, their occurrence and morphology

Mars Orbiter Camera (MOC) on-board Mars Global Surveyor (MGS) which started operating in September 1997 has returned images of numerous dark and bright slope streaks[8–10]. MOC has obtained >30,000 high-resolution

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images, many even at <5 m/pixel. All the images show the distinct presence of slope streaks at various locations, confirming one of the most widespread features occurring on Mars[11]. Streaks on steep Martian slopes are modern enigmatic features first observed in Viking Orbiter images[11–16], but no plausible explanations on their origin as well as morphology could be given due to the resolution limitations of earlier data. They exhibit a fan-shaped pattern, are thought to originate from a point source and are strongly believed to be erosional features. It has also been observed that certain areas show the possibility of an alternate cycle of dark and bright streak formation. This phenomenon probably implies a continual active dust transportation and deposition process[11]. The most striking and common characteristic observed in streaks is their gradual fading with time. New streaks have a distinct darker tone showing greatest contrast to their surroundings, whereas older streaks exhibit less contrast suggesting their gradual fading with time[17,18]. New streaks represent around 10% contrast with the surrounding slope materials. The albedo variations among individual dark streaks on the same slope may also suggest a time sequence in which the darkest features are the youngest, possibly dating only from the last dust depositional event in the area[11]. It has been observed that the appearance of slope streaks does not depend on illumination angle and viewing geometry. Dark streaks always appear dark and bright always appear bright in repeat images[17]. The variation in streak occurrence is much larger and on a broader scale. In some localities nearly every slope bears streaks, whereas in other locations we hardly come across the presence of any distinct slope streaks. Regions bearing slope streaks show distinct surface layer properties such as high albedo, low thermal inertia and spectral signature of fine dust and its movement along the existing slope. Also, slope streak occurrence shows no correlation with the bedrock geology indicating the formation to be related to the surface layer properties and not with the geologic settings[19]. Depending on the availability of sand supply, varying topographical gradients and latitudinal difference, the mode of origin may differ. Based on these constraints, various theories have been proposed for the possible mode of its formation. Although terrestrial analogues have proved to be a potential and widely used method for understanding the morphological similarity of remotely observed planetary features, due to the absence of actual field observations and data, such similarity may only serve as a hint. Any inference based on morphological similarity also needs to be accompanied by detailed analysis on whether or not the suggested mechanism is consistent with the extra-terrestrial conditions[19].

Datasets and methodology

We have used High Resolution Imaging Science Experiment (HiRISE) data having 25 cm/pixel spatial resolution[20] and Mars Reconnaissance Orbiter CTX (context camera) data having 6 m/pixel spatial resolution[21]. For the present analysis, we have particularly used CTX images as they provide full coverage and also since the larger field of view proves more beneficial in studying the changing streak morphology[5]. In addition, the appearance of certain morphologies such as slope streaks is independent of illumination and viewing geometry of CTX data[17]. High-resolution images provide the ability to image and derive topography of features at metre and smaller scales through which it is now possible to infer precise morphology, probable mode of formation as well as obtain parameters such as slope, altitude, etc. which could not be achieved earlier[22]. Identification and interpretation of geomorphic features have been carried out on the basis of their planimetric or two-dimensional configurations that include albedo, colour or tone, and their association and variation relative to each other[23]. The prominent morphologies and probable mode of origin are discussed in the following sections.

Results and discussion

Observations on slope streak morphology and its probable origin

With the ceasing of fluvial and glacial activities on Mars, aeolian activity has been the only process playing a crucial role in extensively forming new features, as well as modifying and resurfacing of the existing landforms. Slope streaks are one of the most conspicuous resultant features brought about by extensive aeolian processes. They are highly transient in nature and may show sudden formation or removal on comparatively much smaller timescales, although in many cases they may be visible for at least a few decades. Formation of slope streaks involving the role of water and aqueous discharge has been assumed by many researchers, but by far, the most widely accepted theory is the dry granular flow by air fall dust processes. Here we discuss some of the recent streak modification processes and evidences for the proposed mode of streak formation within this crater.

Triggering mechanisms for aeolian processes

Processes of aeolian erosion occur or are triggered when the shear stress due to wind on any surface crosses its ability to resist the material strength. As soon as this limit is exceeded, the process of material detachment and its gradual movement may be initiated. Thus, when the wind shear velocity, also known as the ‘threshold shear velocity’, exceeds a certain specified value (that depends on the rock type or material type which defines its strength) erosion is triggered. This threshold velocity for a particle movement is observed to increase with increase in grain size, which in turn largely responds to the topographic gravity. Another important triggering mechanism includes the inherent rock properties of the region such as surface roughness, grain size characteristics and their total stability or particle strength or cohesiveness. A region with higher clay content may be more cohesive than that having less clay content. The regions which are drier are assumed to be those of less clay content and are thus easily susceptible to wind erosion[24].

Triggering mechanisms and features of slope streaks

Slope streaks on Mars are mostly initiated in a small localized area or at a point which sometimes is not possible to detect, but in some MOC images these initiation points often appear as knobs, crater rims, individual boulders, impact craters or rock outcrops, or other similar areas of localized steepening[11,25]. Some boulders along slopes are eroded materials from the top of the slope that have rolled down under gravity[26]. Digitation and branching strongly indicate that streak formation involves a ground-hugging flow in which material could have been deflected around minor obstacles such as boulders or small ridges or dunes as it moved downhill.

The streak is usually divided into two sections – upslope and downslope. From the upslope section, it eventually spreads outward from its point of origin. The streaks represent a typical sharp, acute upslope end which is an assumed point of emergence, apex or also termed as point source and lobate to branching/braided/fan-shaped/ digitating downslope end. The upslope ends also show distinct presence of a small crater, boulder or a small, continuous ridge which is possibly made of sand material (Figure 1). These observations strongly suggest some manner of initiation at the point of emergence and later propagation of the material from the upslope towards the downslope end of the streak. As observed earlier, the streaks always have a tendency to follow large-scale change in response to the topographic gradients and act in multiple ways with respect to smaller or larger topographic obstacles. They are often observed to extend through them, whereas in certain cases they may go around and leave obstacles as detached islands[19]. We also observed that the streaks showed a prominent downslope widening in all cases in response to the surface gradient.

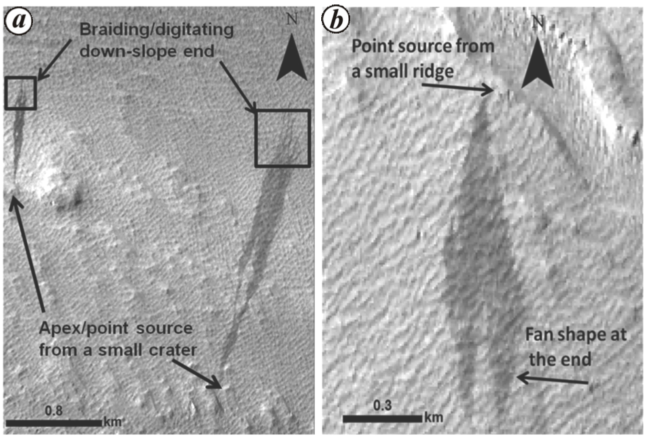

Figure 1 ***a***, ***b***. A representative example of slope streaks from portions of CTX image B21_017797_1801. The streaks show a typical assumed point source from a crater/boulder/ridge and a fan-shaped/ digitating/braiding pattern at the end.

Slope streaks showing presence of probable sand mounds preserving the existing texture

We observed the presence of a large number of such slope streaks scattered within the Nicholson central mound (Figure 2), which seemed to have preserved the texture and roughness of the underlying surface without any distortion in the streak or the underlying morphology. Such observations have also been made earlier[27]. There are no evidences to prove that the streak formation diminishes the existing slope textures either by erosion or by mantling and obscuring[11]. The pre-existing slope textures remain completely unaffected and unaltered by the formation of slope streaks. Presence of these streaks points to the fact that the linear mounds would have formed earlier than the overlying slope streaks; else the mounds would have altered and smoothened the pre-existing streak morphology. Presence of linear sequence of sand

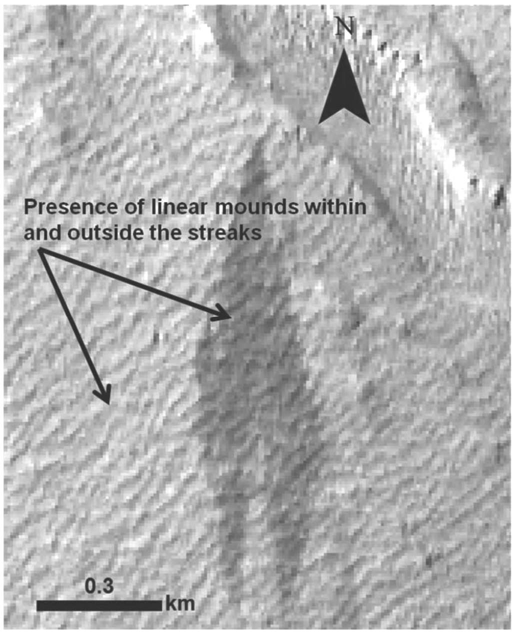

Figure 2. Presence of distinct, small, linear mounds within and outside the streaks. The image shows how the slope texture is preserved within the streak interior. We see no evidence that the streak formation brings any alteration or obscures the pre-existing slope textures by erosion or mantling. Existing surface roughness always remains unaltered.

mounds also points towards aeolian erosional activities persisting in the region. Such morphology is essentially observed on the central mound, whereas in the regions between the central mound and floor of the crater, the streaks and their adjoining areas appear to be much smoother, devoid of mounds or only showing much less mass of mounds in a specific area of the streak (Figure 3).

Streaks exhibiting a curved pattern pointing towards strong topographic constraints and a probable wind role

Slope streaks form on slopes associated with features such as escarpments and crater walls, and closely follow the local topography. They have hence been considered to result from gravitationally driven mass movement such as dry avalanches[9].

Although the streak formation is strongly governed by the topographic gradient[5], i.e. it is entirely gravity-driven with wind flow having no role to play, our studies show specific prominent curved pattern at certain locations, in a few streaks, which probably points towards the role of wind in shaping the morphology. However, we do not assume the formation of streaks to be governed by wind direction, but wind may play a role in shaping its pattern. Subsequent to the streak formation, the pattern and texture we come across, suggest that certain streaks may be governed or influenced by the local wind conditions aggravating their down-slope movement. We observed a curved pattern on the slopes as well as between the eroded crater rim regions. Although the margins are much beyond the resolvable relief limit, the edges of these streaks present a smooth texture. It thus seems that the streaks are intricately capable of moulding and shaping themselves in the direction of wind under the effect of topography, thereby exhibiting a definite curved pattern. This is more significantly identified on the central peak region where the topographic difference in the elevation can be higher; the total mass concentration of the sand material might also be higher compared to the lower region. Thus topography along with wind could have played an important role in bringing about a smooth, rounded and curved pattern (Figure 4).

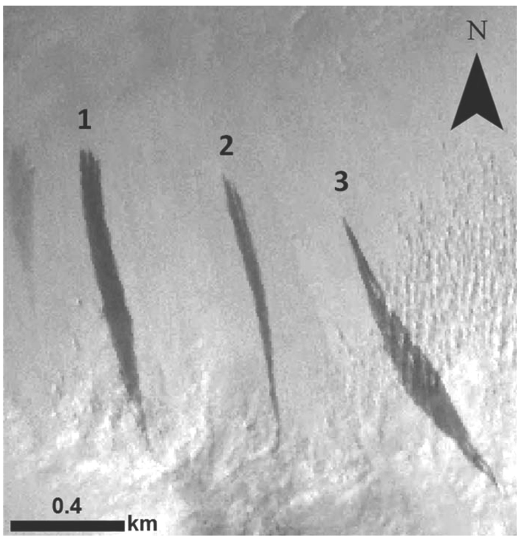

Figure 3. Streaks 1 and 2 show a smooth texture within and outside, whereas streak 3 shows a rough texture in the central part which extends outside the streak area as well. North is up and illumination is from the bottom. All the three are recent streaks as distinguished from the dark tone.

Gradual fading and abrupt discontinuity in the streaks representing fresh material flow and gradual deposition

We also identified few streaks which show a clear gradual tonal transition from intermittent to faded ones. Fresh flow of sand and eventual settling are expected to lead to a gradual fading of streaks[28]. From the observations we assume that these areas show strong evidences of more surface dust deposition. We also notice that a few intermittent streaks, especially on the central peak and the left side of the mound show a sudden cut-off in their continuity or abrupt fading between the streaks, indicating that some material might have got deposited above it diminishing and obscuring the relief of the streak in between; this is attributed to the local undulations (Figure 5).

Redevelopment, reformation and cross-cutting of slope streaks

At certain locations, slope streaks have a strong tendency to redevelop near the pre-existing streaks, or at times a cross-cutting relationship exists between the neighbouring streaks. This gives us an idea to locate the regions which are more likely to develop slope streaks than the surrounding areas (Figure 6). This can be further observed by a detailed comparison of few overlapping older and recent satellite imageries. Newly formed streaks are always dark, and are darker than any other older streaks in the same region. Where cross-cutting relationships between neighbouring streaks are observed, the younger streaks are always darker (Figure 7). This indicates that the streaks brighten with time and sometimes may also become brighter than their surroundings, before completely fading. Similar observations have also been made earlier[19].

Examples of recent albedo-based evidences for the formation of new slope streaks surrounding the central peak region

Formation of new streaks is a continuous process on Mars, wherever the surface is provided with fresh dust

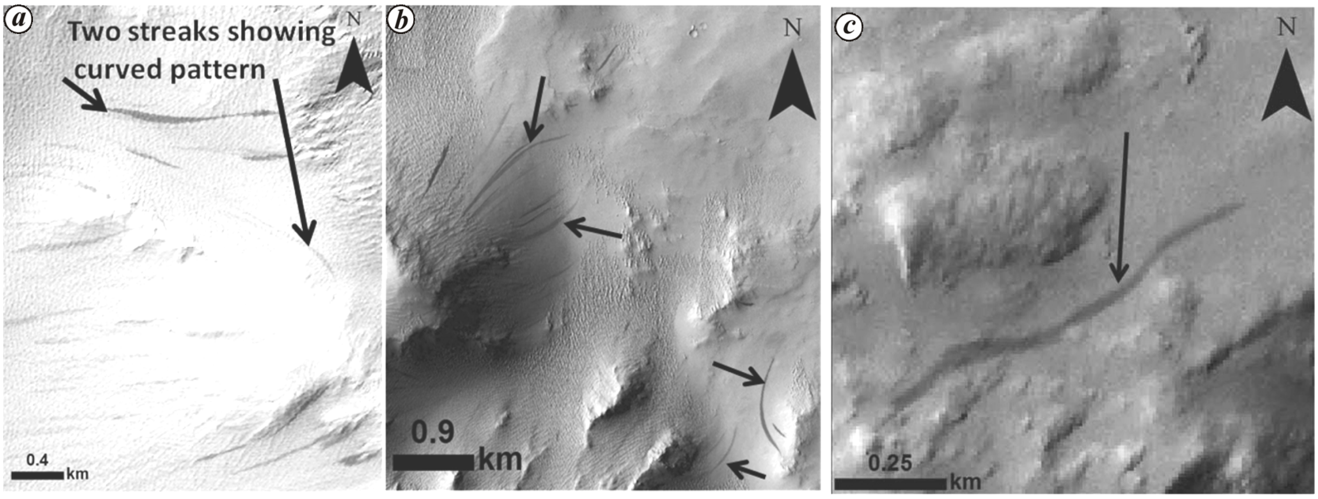

Figure 4. ***a***, Two streaks on the peak of the central mound showing distinct curved pattern probably formed due to the combined effect of subtle changes in topographic gradient and wind turbulence, whereas the rest appear to be straight and follow the slope and topographic gradient. Illumination is from the top. ***b***, Streaks marked with arrows show a prominent curved shape, whereas the remaining adjoining ones are almost straight. Also, the curved streaks do not always seem to follow a definite direction. They sometimes show a multi-directional pattern even within the nearby streaks and are probably formed and moulded according to the gradient and wind direction. Location: left portion of the highly eroded crater rim. ***c***, Similar pattern seen on the north portion of the eroded crater rim.

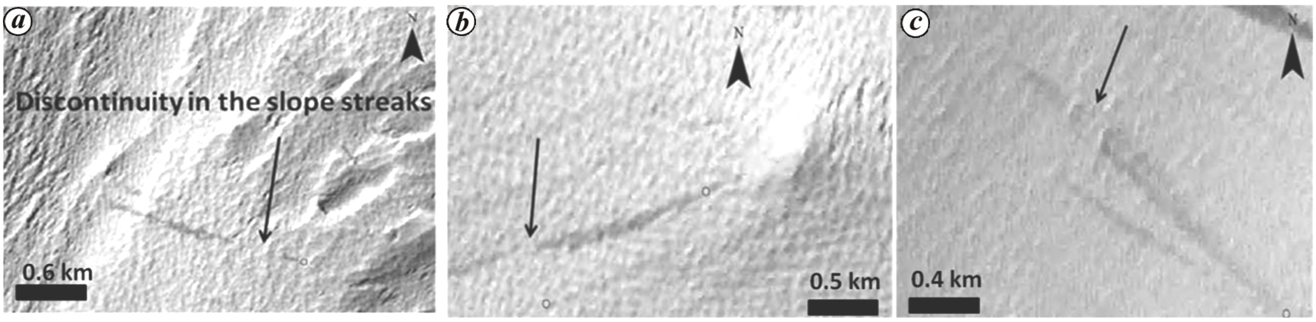

Figure 5 *a–c*. Streaks showing a distinct break in continuity probably due to fresh dust settlement over their surface.

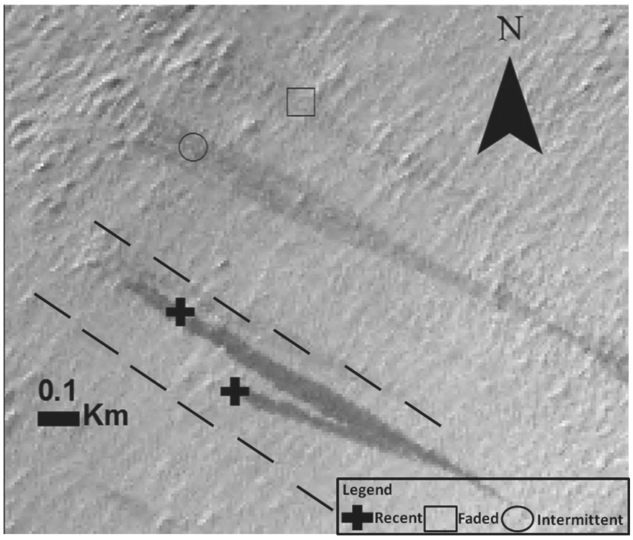

Figure 6. A relatively new streak that has developed near the pre-existing streak. The discontinuous line marks the trail of the pre-existing streak which has now almost diminished.

material. Repeat imaging coverage helps reveal a large number of newly formed streaks. Streak formation is considered to be highly inhomogeneous both in time and space. The estimated mean rate of formation[17,18] ranges from ~3% to ~10% per streak per Martian year[19].

In our study, a total of seven newly formed slope streaks have been identified surrounding the Nicholson crater central peak within a short span of three years. Formation of new slope streaks between 2007 and 2010 has been observed in a crater having a diameter of 2.6 km located NE of the central peak. Analysis of two images, G05_020065_1800 acquired on 6 November 2010 and P12_005798_1804 acquired on 22 October 2007, showed that three distinct slope streaks were formed within a span of 3 years (Figure 8 *a* and *b*). All three newly formed streaks are visible in the G05_020065_1800 CTX image, whereas they are not seen in the P12_005798_1804 CTX image. Similarly, analysis of images P21_009371_1802 acquired on 26 July 2008 and B21_17797_1801 acquired on 14 May 2010 also showed formation of a new slope streak NW of the central peak region between the years 2008 and 2010 (Figure 8 *c* and *d*). Analysis of MOC CTX images B21_17797_1801 acquired on 14 May 2010, P12_005798_1804 acquired on 22 October 2007 and HIRISE image PSP_009727_1800_red JP2 acquired on 23 August 2008 showed the presence of one newly formed streak on the central peak region of the Nicholson crater. The newly formed streak was only seen in B21_17797_1801 MOC CTX image (Figure 8 *e–g*). This implies that it had formed within a short span of two years. In the same CTX coverage two more small streaks could be clearly identified. It can probably be deduced on the basis of their size that these have started forming recently (Figure 8 *h* and *i*). Similar observations were also made when we analysed the CTX images P17_007578_1813 acquired on 8 March 2008 and B17_016096_1800 acquired on 1 January 2010. Apart from the prominent presence of a few new slope streaks, we observed a group of new slope streaks formed within the region covering these particular images (Figure 8 *j–m*). Table 1 provides details of all the images used for the study, and Table 2 provides details on the newly observed slope streaks.

Morphological evidences favouring the dust avalanche origin

As mentioned earlier, various models have been put forth for explaining the potential formation of streaks on the Martian surface, which also explain the gradual fading

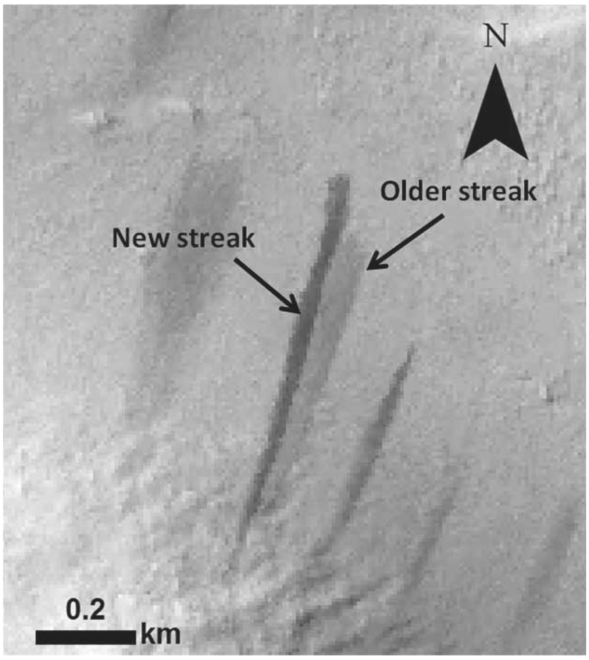

Figure 7. CTX image B21_17797_1801 showing prominent dark streak which is presumably new, truncated by an older, lower-contrast streak. It also shows that new streaks have a tendency to develop in the regions of the pre-existing ones.

and evident contrast of the streaks with time due to further fresh dust deposition[11]. These are discussed below.

In the first model, according to Morris[15], when the erosion-driven disaggregated, dark debris outcrops get mixed with the residual debris, a sharp contrast in streaks is observed. Another model suggests that the streak contrast results from staining and darkening of slope materials by aqueous discharge[29]. Sometimes as a result of over-steepening of highly weathered rock fragments, also commonly known as talus, results in debris flow whereby the talus matter tries to adjust and settle itself more closer to the angle of repose. Due to such minor mass movements of the material, a thin dusty layer gets deposited between the debris. This dusty layer being fresh results in a sharp streak contrast[30]. Recently, a few more wet mechanisms have been studied which include brine liquid flows, a mixed flow of water and dust, and flows through ground-wetting process[13,27,31,32].

Slope streaks interpreted as dust avalanches are also triggered by an impact event as well as by localized rock falls. The topographic relief and triggering mechanisms of slope streaks seem to best fit the models and theories that involve dry dust avalanches. Martian slope streaks and thick avalanche scars are part of a continuous process involving active mass wasting at metre to sub-metre scales[33]. Here we distinctly observed typical digitating distal ends, widening of streaks at the ends, slope streaks showing presence of probable sand mounds, gradual fading and abrupt discontinuity in the streaks representing fresh material flow, and gradual deposition, redevelopment and cross-cutting of the streaks. These characteristics serve as strong key features supporting the air-fall dust process leading to the formation of slope streaks in this region.

Our detailed systematic evaluation and analysis on the type of topography, surface features and landform morphology are consistent with dust avalanche model for the formation of slope streaks within the Nicholson crater. The present data and the equatorial location of the Nicholson crater largely favour the model which explains most streaks to be residual scars from dust avalanches following over-steepening of air-fall deposits.

According to the dust avalanche model, dust accumulates as air-fall deposits and periodically tends to fall downslope due to low pressure and inertia. It involves a ground-hugging material flow, whereby occasionally the movement or flow of the material is obstructed by the presence of small obstacles such as boulders or ridges. In some cases it so happens that the streak is seen to overcome small obstacles and maintain its continuity. Formation of a streak usually initiates when a small patch of dust mantle fails downslope in the form of an avalanche. It is also seen that these types of dust failure initially commence on the uppermost regions of the slopes which are usually the steepest. Knobs, small ridges, or any other surface roughness on the steepest slopes are usually the

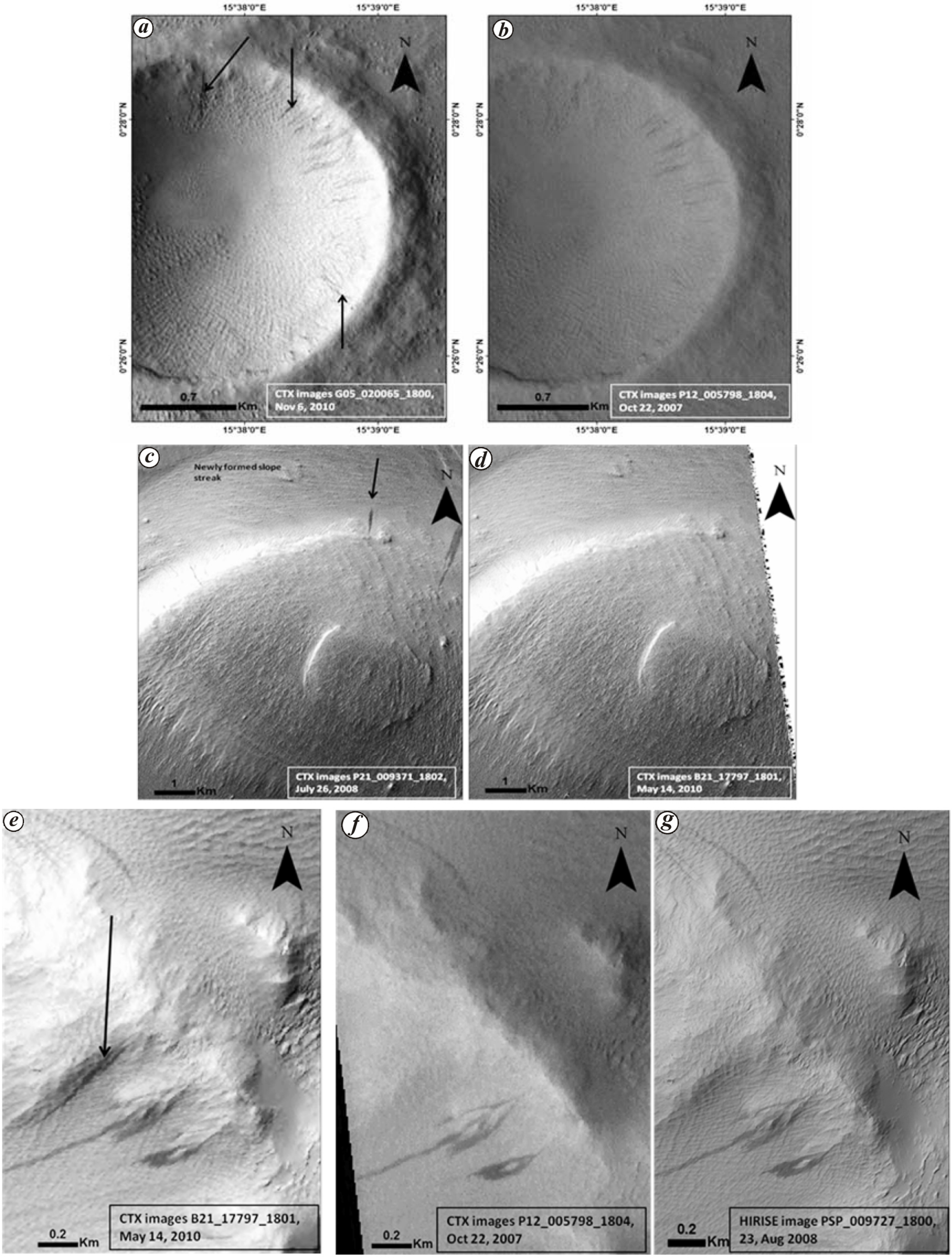

Figure 8. (*Contd*)

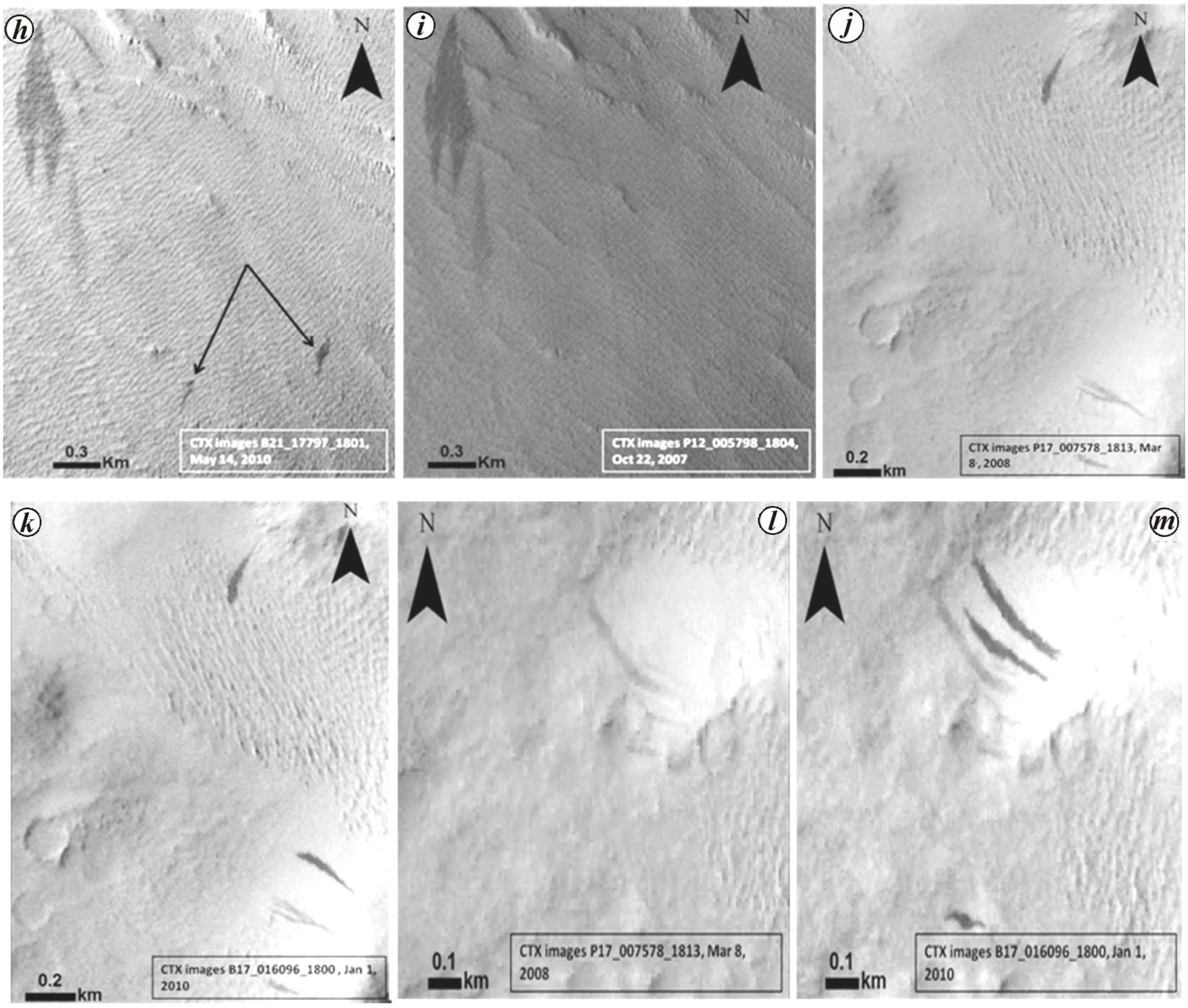

Figure 8 ***a–m*****.** Temporal comparison of CTX and HiRISE images showing the presence of newly formed slope streaks within a time range of 2–3 years.

Table 1. List of the images used in the present study

Image no.	Location and coordinates	Date of acquisition
MOC CTX image B01_009938_1811	1.14°N, 194.87°E	8 September 2008
MOC CTX image B21_17797_1801	0.12°N, 195.53°E	14 May 2010
MOC CTX image P21_009371_1802	0.19°N, 195.25°E	26 July 2008
MOC CTX image P16_007367_1813	0.40°S, 196.32°E	21 February 2008
MOC CTX image P12_005798_1804	0.42°N, 195.73°E	22 October 2007
MOC CTX image G05_020065_1800	0.05°N, 195.85°E	6 November 2010
MOC CTX image G04_019854_1801	0.13°N, 194.95°E	21 October 2010
MOC CTX image B17_016096_1800	0.05°N, 194.92°E	1 January 2010
HIRISE image PSP_009727_1800	0.17°N, 195.57°E	23 August 2008
MOC CTX image P17_007578_1813	1.39°N, 194.49°E	8 March 2008

locations from which the dust avalanche progresses or is triggered. Gradually as the speed of the material flow increases, some portion of the avalanching dust particles gains sufficient kinetic energy to be lost to the atmosphere in suspension, thus limiting the momentum of the descending avalanche front. The equilibrium speed, where the amount of material lost to the atmosphere is balanced by the amount of material added as the avalanche descends, decreases with decreasing gradient. The mass movement process of slope streak formation involves continual addition of fresh dust matter, leaving the underlying slope materials unaffected. Regions where dark and bright slope streaks currently form and fade in of a cyclic process are probably those which are closely

Table 2. Details of the images used for documentation of newly observed slope streaks

Image no.	Location coordinates	Date of acquisition	Location	No. of slope streaks observed
MOC CTX image G05_020065_1800 and MOC CTX P12_005798_1804	0.05°N, 195.85°E and 0.42°N, 195.73°E	6 November 2010 and 22 October 2007	NE of central peak	Three streaks observed in CTX image G05_020065_1800
MOC CTX image B21_17797_1801 and MOC CTX image P21_009371_1802	0.12°N, 195.53°E and 0.19°N, 195.25°E	14 May 2010 and 26 July 2008	NW of central peak	One streak observed in MOC CTX image B21_17797_1801
MOC CTX image B21_17797_1801, MOC CTX image P12_005798_1804 and HIRISE image PSP_009727_1800_red JP2	0.12°N, 195.53°E; 0.42°N, 195.73°E and 0.17°N, 195.57°E	14 May 2010, 22 October 2007 and 23 August 2008	On central peak	One streak observed in MOC CTX image B21_17797_1801
MOC CTX image B21_17797_1801, and MOC CTX image P12_005798_1804	0.12°N, 195.53°E and 0.42°N, 195.73°E	14 May 2010 and 22 October 2007	North of central peak	Two streaks observed in MOC CTX image B21_17797_1801
MOC CTX image P17_007578_1813 and B17_016096_1800	1.39°N, 194.49°E and 0.05°N, 194.92°E	8 March 2008 and 1 January 2010	Left portion of the crater rim	Total four streaks observed in MOC CTX image B17_016096_1800. We also observed scattered groups of many new, small streaks within this region.

associated with low thermal inertia and possibly where dust is currently accumulating as well as settling. The process involved is analogous to that observed on terrestrial avalanches of over-steepened dry loose material resulting in shallow avalanche scars. It also suggests that air-fall dust deposition results in the burying of most of the underlying surface on the slope and continues to accumulate until a critical thickness is reached. The weak, dusty layer under very low thermal inertia and due to the effect of topographic gradient gradually fails to further accumulate under its own weight and starts moving downslope with less resistance, and also carrying additional material on the way. Dry, loose dust avalanches commonly originate near knobs and localized roughness. Streak contrast is thus caused by the partial removal or exhumation of buried matter which is eventually exposed and usually dark in tone[11].

A detailed methodical analysis on the pattern, morphology and appearance of slope streaks within the Nicholson crater has been made on the basis of which the process we favour for streak formation and its apparent contrast describes most slope streaks to be formed from dust avalanches following over-steepening of air-fall deposits as stated in the last model[11,33]. We also bring into account a few observations which indicate the role of wind in carving specific streak patterns. The morphological observations discussed, strongly support active aeolian processes and provide evidences in favour of the dust avalanche theory for the formation and current morphology of slope streaks within the Nicholson crater.

Since these are surface albedo features, the streaks can be easily distinguished as older, recent and intermittent on the basis of their distinct tonal variation. Given that the new slope streaks have a stronger contrast, the relative albedo difference within the same MOC image has been compared to understand the gradual variation between the recent, intermittent and oldest (completely faded) streaks (Figure 9).

Observed length and width, and analysis on the growth rate of new slope streaks

The largest slope streaks are usually a few kilometres long and up to a few hectometres wide. Their length is apparently limited by the maximum length of relatively steep slopes. Smaller streaks are often observed, down to the image resolution[19]. Within the Nicholson crater we observed maximum streak length to be around 2–3 km with a maximum width of 0.15–0.2 km.

At present we do not have a precise knowledge on whether the streaks grow with time and if so, at what rate. We have inferred the possible growth rate (though by no means at a steady rate) of a few newly formed slope streaks. These have been formed recently and probably may still be actively growing by the gradual addition of fresh sand material and its gradual downslope movement in response to topography. The gradual streak growth also points towards the fact that the region is continuously supplied with fresh dust at specific locations, which may be a major factor for further streak growth. From the analysis of CTX images P17_007578_1813 acquired on 8 March 2008 and B17_016096_1800 acquired on 1 January 2010, we could measure the growth of three streaks on the right side of the eroded crater rim (Figure 10). As observed from Figure 10 *b*, the streak appears to have increased by 0.22 km. Figure 10 *d* shows an increase by 0.64 km and Figure 10 *c* shows a prominent increase by 0.14 km within a span of 2–3 years. In all the three cases where we could measure the rate of streak growth by a comparative image analysis, we observed that the growth took place in January. The exact mechanism leading to streak growth during the specific period is still not well understood, but the most possible reason could be attributed to the higher dust activities and warmer temperature conditions leading to increased streak formation and growth.

Dependence of streaks on season and temperature

A few images were compared and studied to infer any plausible relationship between new streak formation and its fading depending on different seasons.

Comparison of CTX images P17_007578_1813 acquired on 8 March 2008, having coordinates (1.39°N, 194.49°E) and G04_019854_1801 acquired on 21 October 2010 (0.13°N, 194.95°E) showed that new streaks distinctly appeared to be larger in the later image than the previous one; all the streaks appeared to be darker and more prominent as well in the later image.

Similar comparison between CTX images P21_009371_1802 acquired on 26 July 2008 (0.19°N, 195.25°E) and G04_019854_1801 acquired on 21 October 2010 (0.13°N, 194.95°E) showed that the rate of fading increased in July than in October. We have also observed that more number of streaks were prominently visible during October rather than in July.

Another similar comparison within CTX images B21_17797_1801 acquired on 14 May 2010 (0.12°N, 195.53°E) and G05_020065_1800 acquired on 6 November 2010 (0.05°N, 195.85°E) showed more fading rate during May compared to November.

Some previous observations indicate that the streaks even in the coldest environment formed more prominently on the warmer south-facing slopes than on the other regions[5]. Our investigation using CTX images of different dates suggests that the fading rates appear to be higher during March, June and July in comparison to October and November. Temperature is affected largely by latitude, topographic slope and slope orientation. Most plausible reason here seems to be the temperature variability. Higher temperatures during certain months may be a major triggering factor for increased dust activities leading to eventual dust avalanches and streak formation. Table 1 provides details of the images investigated.

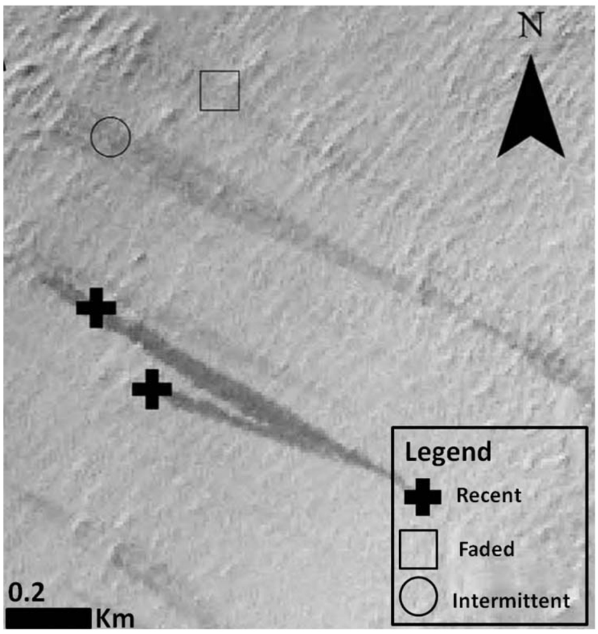

Figure 9. A close view of all three types of slope streaks. They are distinguished on the basis of their observed tonal difference. New streaks tend to have stronger contrast than old streaks in the same MOC image.

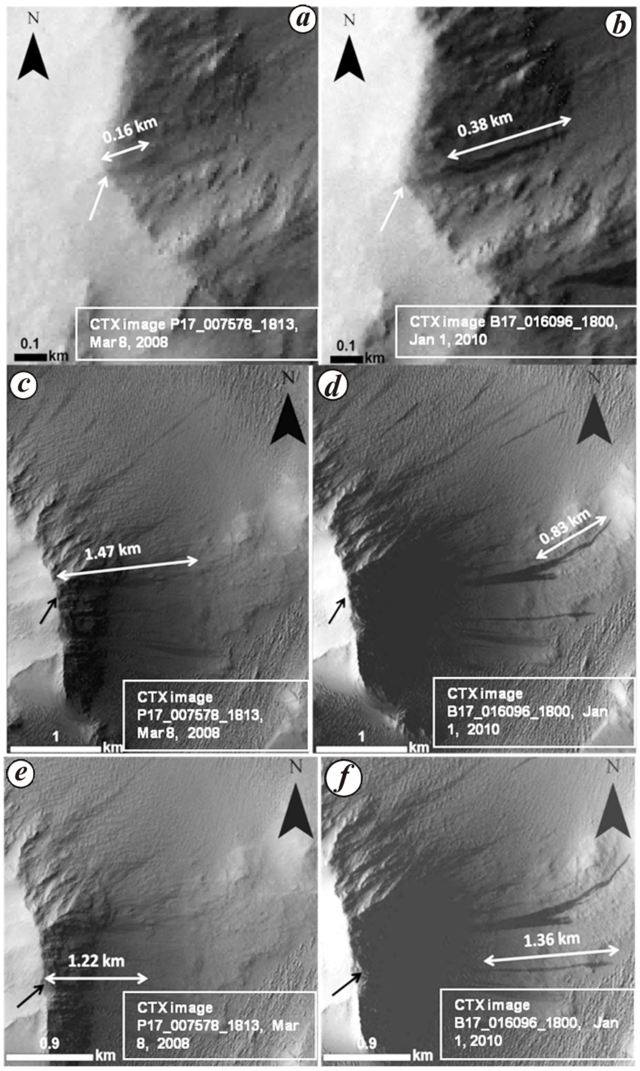

Figure 10 ***a–f*****.** Comparison of CTX images P17_007578_1813, 8 March 2008 and B17_016096_1800, 1 January 2010 showing distinct presence of new slope streaks. Growth rate of streaks has been inferred. (***a***) and (***b***) show an increase of 0.22 km, (***c***) and (***d***) show an increase of 0.64 km, while (***e***) and (***f***) show an increase of 0.14 km within less than 2 years.

Summary and conclusion

Identification of numerous slope streaks of all classes and their changing morphology, as well as formation of new slope streaks in recent years present strong evidence of recent and continuing aeolian processes in this region. The morphological evidences and distinct characteristics of the slope streaks observed, support the dust avalanche model for their origin. All the newly formed streaks appear to have been formed within a short span of 2–3 years, through which it can be inferred that this period would have been an active one in terms of dust activities. The gradual increase in the size of the slope streaks also around the same period strongly suggests that this is due to currently active wind processes on the Martian surface, implying simultaneous fresh material transport and deposition at specific locations. Identification of such activity has directly and indirectly helped in understanding the regions which are more prone to aeolian modifications. Appearance of prominent streaks during specific months also provides an understanding on the higher probability of dust supply and wind activity during certain seasons and months. Although it is difficult to precisely indicate the specific mechanism for the sudden appearance and fading of streaks during particular months, it can be indirectly attributed to higher temperatures during specific months that seem to be a triggering factor for increased dust activities leading to sporadic appearance as well as higher fading rate during certain seasons. The equatorial region of Mars as on date does not show any large-scale seasonal weather variability and seasonal snow or frost accumulation. Additionally, slopes are the regions which are warmer during nights due to partial shielding of the cold sky compared to the flatter regions. The daytime temperature can be higher or lower again depending on the location, orientation of the slope and season. According to Schorghofer *et al.*[9], the regions with low thermal inertia are those where the temperature exceeds 275 K and frequently reaches as high as 300–375 K. With a very low atmospheric pressure, these are also the suitable zones having low thermal inertia aggravating the streak activities[19]. The streaks on Mars are formed largely during the late spring and summer seasons, when the equatorial region receives maximum sunlight and may gradually fade or the rate of formation may decrease as the temperature decreases. The Nicholson crater located in the equatorial region probably offers a suitable site encompassing almost all the required parameters resulting in increased streak formation activities during certain months when the Martian surface temperatures are relatively higher. The entire study thus brings out strong evidences on the large-scale particulate supply, dust-lifting and dust-deposition phenomena, and thereby on the dynamic aeolian-driven atmosphere prevailing within this region. Present-day sand movement and aeolian developments are clearly visible. This study based on detailed morphological observations provides insights on the recent aeolian developments as well as modifications in the pre-existing morphologies.

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ACKNOWLEDGEMENT. We thank the Department of Space, Government of India for financial support.

Received 28 May 2015; revised accepted 14 September 2017

doi: 10.18520/cs/v114/i03/596-607