Active aeolian processes on Mars: A regional study in Arabia and Meridiani Terrae

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[1] We present evidence of widespread aeolian activity in the Arabia Terra/Meridiani region (Mars), where different kinds of aeolian modifications have been detected and classified. Passing from the regional to the local scale, we describe one particular dune field in Meridiani Planum, where two ripple populations are distinguished by means of different migration rates. Moreover, a consistent change in the ripple pattern is accompanied by significant dune advancement (between 0.4–1 meter in one Martian year) that is locally triggered by large avalanche features. This suggests that dune advancement may be common throughout the Martian tropics. **Citation:** Silvestro, S., D. A. Vaz, L. K. Fenton, and P. E. Geissler (2011), Active aeolian processes on Mars: A regional study in Arabia and Meridiani Terrae, *Geophys. Res. Lett.*, *38*, L20201, doi:10.1029/2011GL048955.

1. Introduction and Study Area

[2] It has long been unclear whether the many fields of sand dunes on Mars are actively evolving in the present climatic era. Prior to the advent of the High Resolution Science Experiment (HiRISE) onboard the Mars Reconnaissance Orbiter (MRO), evidence of active sand movement on Mars was scarce and limited to few isolated areas [*Malin and Edgett.*, 2001; *Fenton et al.*, 2003; *Bridges et al.*, 2007; *Bourke et al.*, 2008; *Sullivan et al.*, 2008]. New images from the HiRISE camera have drastically changed our ability to study aeolian processes on Mars. Using such high resolution images (25 cm/pixel), *Silvestro et al.* [2010] provided orbital evidence of consistent (~2 meters) ripple migration on Mars, confirming previous hypotheses on the activity of the Martian dark dunes in the current atmospheric setting [*Fenton*, 2006]. Other clues of sand deflation and dune changes have been detected using HiRISE images in Meridiani Planum [*Chojnacki et al.*, 2011] and in the north polar area [*Bridges et al.*, 2011; *Hansen et al.*, 2011]. *Hansen et al.* [2011] in particular suggested that the activity of the dunes at these latitudes could be linked and enhanced by the seasonal melting of CO_2 frost over the dune slopes. Despite these works however, the possible activity of many dunes outside the polar regions remains largely unanalyzed.

[3] In this work, we focus our attention in Arabia Terra/Meridiani Planum (Figure 1). This region is spanned by strong winds as suggested by the presence of vast fields of wind streaks and yardangs. Most of the dune fields in this region were repeatedly targeted by the HiRISE camera, allowing us to search for signs of present-day aeolian activity.

2. Methods

[4] We conducted our regional analysis using different kinds of datasets. A global Viking color mosaic, together with 50 m/pixel THEMIS Infrared daytime mosaic were placed into an ArcGIS project to identify the dune fields. Then all the HiRISE pairs overlapping the dark dune fields were co-registered in ArcGIS using bedrock as a reference (1–2 pixels of accuracy), allowing us to detect evidence of aeolian changes. Where identified, such changes have been mapped and classified (Figure 1a and Table S1 in the auxiliary material).[1] Ripple migration, in particular, has been manually quantified in three sites (Table S2).

[5] Due to its distinctive features (see section 3.2) the Meridiani 2 site is investigated more thoroughly (see section 3.2). A detailed analysis was performed by automatically mapping the crest of all ripples over an entire dune in the image pair PSP_007018_1830 and ESP_016459_1830 (see Figure 3). These images were processed using the United States Geological-Survey ISIS (Integrated Software for Imagers and Spectrometers) software and present similar acquisition parameters (Table S3). In particular, they have been acquired at similar local times (14.35 and 14.55h, respectively) so that for both images illumination comes from the upper left. To minimize the albedo variations caused by the divergence in the solar incidence angle, we applied a basic photometric normalization using the "cosi" function in ISIS which divide each pixel of the image by the cosine of the incidence angle. The ripple mapping procedure consists of generating a ripple marker image (through the application of the self-complementary top-hat transform using line structuring elements), which is then binarized and vectorized using part of the methodology introduced by *Vaz* [2011]. This approach generates two sets of lineaments, which represent the location of the ripples in the two images. The ripple displacement is then estimated assuming a displacement perpendicular to the ripple traces (meaning that only an axial vector is obtained) and by computing the Euclidean distance between the two sets of mapped ripples. This methodology allows us to estimate the displacement over an entire dune instead of measuring it in individual ripples. The measured migration, however, represents the minimum distance between adjacent crests in the two datasets. This means that if a ripple migrated more than half of one crest wavelength, the calculated distance will be

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL048955.

underestimated (Figure S1). Furthermore, because in the study area high resolution HiRISE Digital Elevation Models (DTMs) are not available, our measurement suffers from geometric distortions that cannot be corrected at the present time. Another issue that may hinder estimates of ripple displacement from remote sensing data is the fact that ripple patterns can change in their entirety, making it impossible to establish a firm correlation between the ripples in both datasets; we assume that this has not occurred. Despite these potential limitations, the given vectors can still give some insight on the minimum magnitudes, trends and spatial distribution of the displacements.

3. Results

3.1. Regional Map of Aeolian Changes

[6] The results of our mapping are summarized in Figure 1a. In addition to the Endeavour crater dune changes [*Chojnacki et al.*, 2011], six other sites in this area present clear evidence of aeolian modifications: these include Becquerel (Figure 1b) and Trouvelot craters where ripples have been observed to migrate 0.6 to 1.5 meters downwind (Table S2) (30–80 cm/year). In both cases the dunes overlie bright mounds of sedimentary rock [*Malin and Edgett*, 2001; *Rossi et al.*, 2008] sculpted into yardangs by the saltating sand. Evidence of consistent (0.7–1 m/year) ripple migration is also found about 1000 km farther southeast in Meridiani Terra, inside an unnamed 50-km-diameter crater (Meridiani 1) (Figure 1a and Table S2). Sand movement is also evident in Pasteur Crater as reported by *Geissler et al.* [2011].

[7] A particular kind of aeolian modification was detected in the Arabia 4 site (Figure 1c). This intra-crater dune field consists of large (200 to 900 meters) barchan and barchanoid dunes with slopes that are grooved by several ripple sets. On the stoss side of the barchan of Figure 1c (see inset), three lee dunes [*Tsoar*, 2001] between 12 and 80 meters long elongate downwind from a bright outcrop of the underlying bedrock. These dunes display significant changes in their position across one Martian year, between T1 (April 2007, Ls = 217.1°) and T2 (March 2009, Ls = 217.1°). At T1, the crest of a lee dune changed its position and joined the closer dune crest into a Y junction (Figure 1c and Animation S1). This is the first time that these kinds of dunes, which are strongly topographically influenced, have been observed to move. Other major changes like large avalanches and consistent ripple migration have also been detected in this dune field. However, due to the low resolution of this image pair (50 cm/pixel, Table S1), we are unable to quantify these changes. Also in other zones (e.g., Firsoff crater, *Pondrelli et al.* [2011], Arabia 6 and Arabia 8) we observed evidence of sand movement and changes in slip face avalanche scars. However, significant differences in the acquisition parameters (Table S1) affect these image pairs, so these changes have been classified as "uncertain" (Figure 1a).

[8] Of the study sites, only one dune field in Meridiani Planum presents clear evidence of dune advancement accompanied by consistent apparent ripple migration: the Meridiani 2 site.

3.2. Meridiani 2

[9] In Figure 2 we show the Meridiani 2 site and its regional context (Figure 2a). This dune field lies in a 30-km-diameter crater and is subject to dominant winds from the NE, as inferred by the orientation of the optically dark (bright in the THEMIS daytime infrared mosaic in Figure 2a) wind streaks associated with many impact craters in the area [*Edgett*, 2002]. The dune field consists of large barchans (up to 500 meters in width) that overlie a bright toned mound of sedimentary rock (Figure 2b). The local wind regime is inferred by mapping the dune slip face orientations (results plotted on the rose diagram on top left of Figure 2b) suggesting that the dunes are primarily shaped by winds from the NE. However, the morphology of the dunes seems to reflect a more complicated wind pattern. The eastern horns of several barchans are elongated toward the SE suggesting that at least one other wind locally shaped these dunes. Following the model of *Bagnold* [1941, p. 223, Figure 78d] this secondary wind should blow parallel to the elongated horn (red arrow in Figure 2c) from the NW. This more complex wind situation is confirmed by the morphology of the wind ripples that could be distinguished in two classes (Figure 2c). The population 1 has a wavelength of 2.5 meters while the population 2 has a higher average wavelength of 5.6 meters and consists of much brighter megaripples. In both populations the crests are oriented perpendicular to the two dominant winds represented in Figure 2c. The ripples 1 in particular, are arranged in two orthogonal sets (Figure 2d) while a close-up on the ripple 2, shows a complex "star-like" morphology (Figure 2e). In Figures 2e and 2f we show a clear stratigraphic contact between the two populations (Figure 2f), with the ripple 1 being superposed on the ripple 2. We also note how the ripple 2 tends to lag behind the margin of the dunes (Figure S2). To calculate the migration of the ripples we automatically mapped their crests on the two images at T1 and T2 (Figure 3a) and we plot the length-weighted azimuths in the rose diagram (see inset). The two main orientations previously recognized (see Figure 2d) are obvious in the rose diagram that presents two modes ~N45°E and N150°E. While the 2008 modes present approximately the same frequency, for the 2010 case a higher proportion of ripples trending N45°E is observed. This is indicative of a differential evolution of the two main sets of ripples and suggests that between 2008 and 2010, the N150°E pattern has been reworked by winds from the NW.

[10] The minimum distance between the ripples (see method section) was then computed (Figure 3b). Two different areas can be distinguished: areas presenting higher displacements (1), and areas with lower displacements (2) that correspond to the two ripple populations discussed above. The population 2 shows no movement (we considered values of migrations between 0–30 centimeters as zero because they are close to the image resolution, Table S3). In contrast, population 1 migrated consistently, at a rate of 0.5 meters/year on average with maximum peak migration >2 meters. A displacement weighted circular diagram is shown in the upper right corner. The main axis of displacement corresponds to a NW-SE trend but some NE-SW minor displacements are also recognizable. This shows that the main displacement occurred along the NW-SE axis, which is consistent with the higher proportion of observed N45°E ripples at T2. Considering the regional orientation of the wind streaks and the whole dune morphology at this site, we infer a downwind sense of migration to both ripple trends toward the SW and the SE, with the SE migration being dominant (i.e., more frequent) during the time

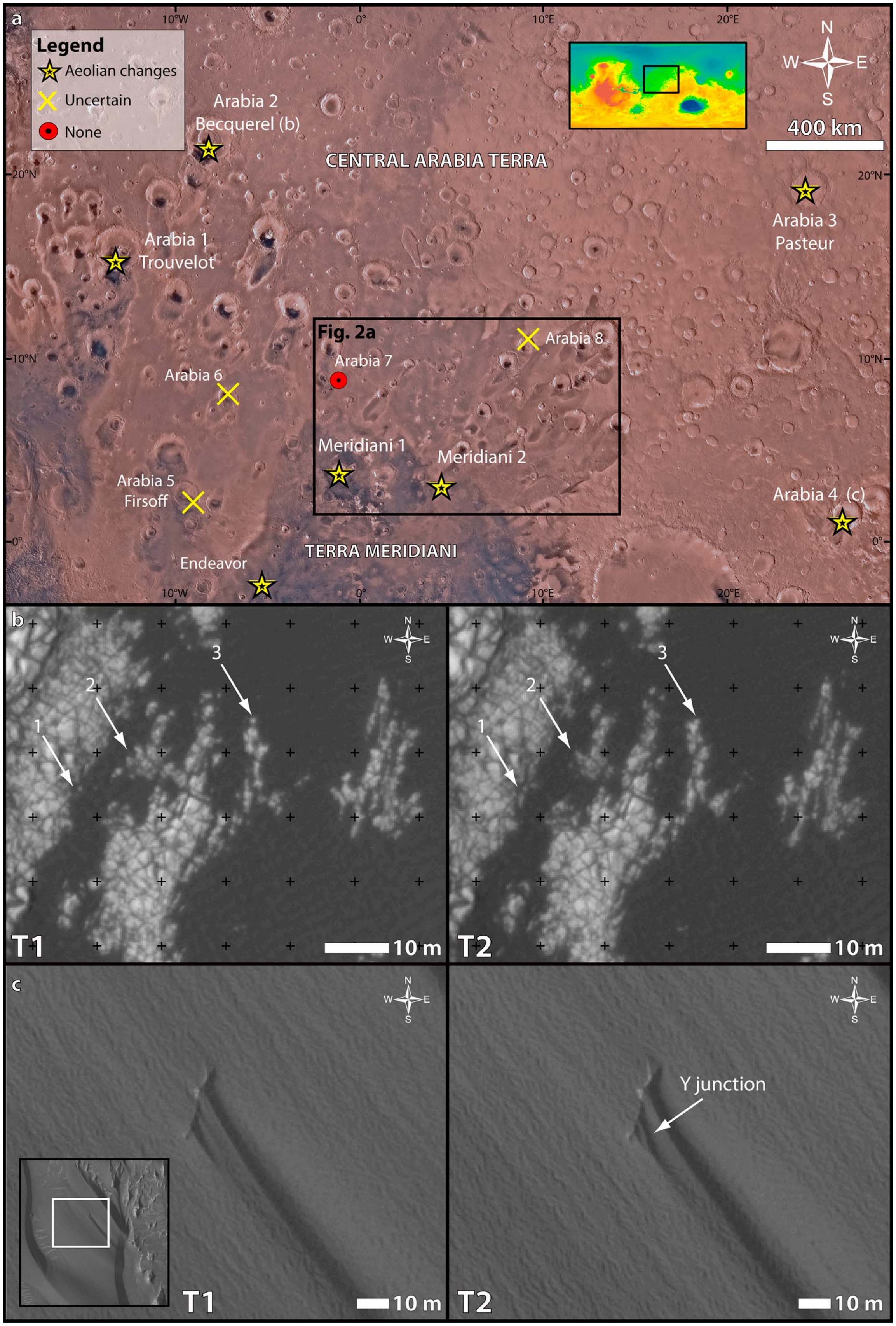

Figure 1. (a) Location map of the study area and detected aeolian changes (MOLA gridded topography, Viking color mosaic). (b) Sand movement in Becquerel Crater (HiRISE PSP_001546_2015; ESP_019268_2015). (c) Lee dune changes in Arabia 4 (HiRISE PSP_003312_1810; ESP_01299_1810).

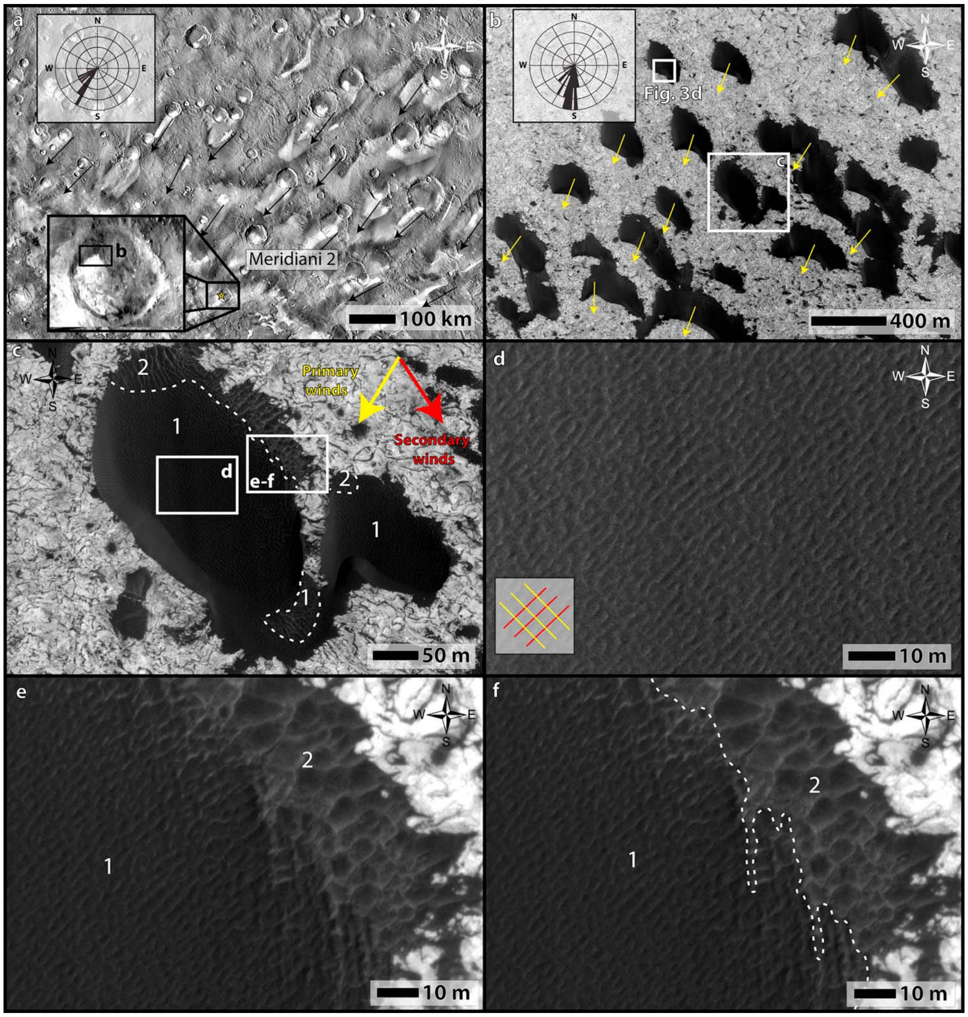

Figure 2. (a) Regional context of the Meridiani 2 site; wind streak orientations are plotted on the rose diagram on the top left (see Figure 1a for location) (THEMIS IR Daytime mosaic). (b) Meridiani 2 barchans (inferred wind directions -yellow arrows- are plotted on the rose diagram on top left in a downwind direction). (c) Selected dune in Meridiani 2, the orientation of the main crest and the elongation of the eastern horn suggest two main wind directions (yellow and red arrows on top right). Two main ripple populations (pop. 1 and 2) are also distinguished by means of different albedo and wavelengths. (d) Ripple pop. 1, two orthogonal trends (see inset on the bottom left). (e, f) Stratigraphic contact between the two ripple populations (Figures 2b, 2c, and 2d, HiRISE ESP_016459_1830).

between the acquisition of the two images. The formation of the ripples trending N45°E on the toe of the lee face of the study dune (Figure 3c) and the reworking of the N150°E pattern at T1 (highlighted by the red circles in Figure 3c), confirm the results of our automatic mapping. Similar changes have not been observed within the ripple 2 population.

[11] Of the study dune field, the Meridiani 2 site is the only one that, together with the migration of the ripples, shows a consistent advancement of slip faces. We highlighted these movements in Figure 3d (see Figure 2b for location) where the dune toe advancement is triggered by an unusually large (620 m^2) avalanche feature (Figure 3d, right). Several grainflow scars are also visible in both images, providing further indication of dune activity at this site. A migration rate of 1.1 meters/year has been calculated computing the distance between the lee margins at T1 and T2 for the dune of Figure 3d. Four other dunes in this dune field have been analyzed in this way, producing migration rates ranging from 0.4 to 1 meter/year. The stoss sides of the study dunes have been observed to advance and retreat, confirming the wind directional variability at a local scale.

4. Discussion and Conclusions

[12] Most of the study sites in Arabia and Meridiani Terrae present clear evidence of aeolian activity, suggesting that winds above the threshold for sand movement often occur on the Martian surface. However, results from wind tunnel simulations [*Merrison et al.*, 2007] and atmospheric models [*Hayward et al.*, 2009], show that such strong wind events should be rare in the current Martian atmospheric setting. This suggests that, conversely from what happens on Earth where wind gusts give a small contribution to dune modification [*McKenna Neuman et al.*, 2000], the effect of daytime turbulence-induced wind gusts should play a key role in initiating sand movement and dune modification on Mars [*Fenton and Michaels*, 2010]. Once saltation has been

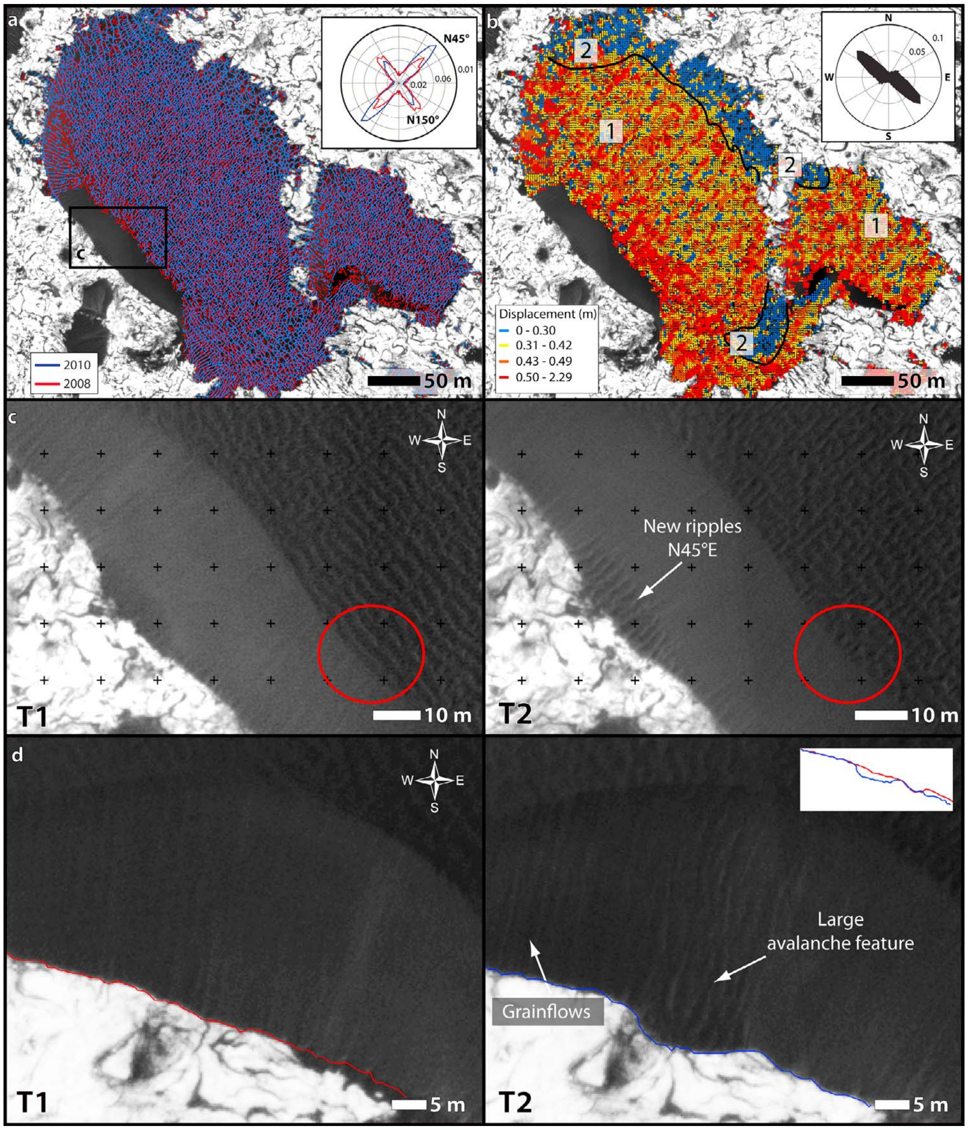

Figure 3. (a) 2008 and 2010 automatically mapped ripples. The rose diagram in the upper right corner shows polar histograms of the ripples' crestlines for the two datasets. Both distributions present two modes, N45°E and N150°E. In the 2010 case (in blue), a higher proportion of ripples trending N45°E can be observed. (b) Minimum distance vectors between the ripple traces in 2008 and 2010. Two different areas can be distinguished: areas presenting higher displacements – population 1, and areas with lower displacements - population 2. The polar histogram in the upper right corner show the two main trends of the axial displacement (NW-SE and NE-SW) suggesting that the main displacement occurred along the NW-SE axis. (c) New ripples trending N45°E formed at T2 (2010) on the foot of the dune and close to the dune brink (red circle), confirming the re-working of the N150°E pattern. (d) Grainflow scars and lee foot advancement triggered by a large avalanche features (see Figure 2b for location) (HiRISE PSP_007018_1830; ESP_016459_1830).

initiated, it could then be maintained for a long time by relatively low speed winds as suggested by *Kok* [2010].

[13] The direction of the ripple migrations in the study areas match with the regional and local wind pattern extracted from wind streaks and dune morphology, suggesting that regional winds play an important role in causing the observed changes. However, local flows seem to be important especially in the Meridiani 2 site; here two ripple populations have been identified and distinguished by means of different wavelength, albedo and migration rate. Ripple population 2 are interpreted as coarser-grained megaripples, with activations requiring stronger and (presumably) less frequent wind events than those activating ripple population 1, explaining why these bedforms tend to lag behind the dune. Their higher albedo could reflect a different grain size and/or composition, or it could be caused by a thin veneer of dust. In this latter scenario, the population 2 could be considered an intermediate stage between active and fossil mega-ripples (the so-called Transverse Aeolian Ridges - TARs). They could be immobile for a sufficient time, becoming covered by a thin layer of dust, but they may be more active than the crusted bright bedforms on the plains imaged by *Spirit* at Gusev [*Sullivan et al.*, 2008]. Ripples population 1 are frequently kept active by the two winds shaping the dunes, from the NE and the NW. For this reason a complex pattern emerges. The winds

coming from the NW were probably the latest that shaped the dunes as suggested by the reworking of the N150°E ripples (Figures 3a–3c).

[14] Both winds could act together in modifying the main dune shapes, causing the downwind migration of the dunes at this site. The Meridiani 2 dune field represents the only case in the region where dunes are observed to advance consistently (between 0.4 to 1 meter/year). This is further indication of how the local winds should be considered in order to explain the observed activity. Such activity is triggered by large avalanche features that cannot be attributed to the seasonal frost coverage as suggested for the North Polar dunes [*Hansen et al.*, 2011]. This means that seasonal processes like CO_2 ice sublimation may be important, but is not necessary, for initiating sediment transport.

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