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Transverse Aeolian Ridges (TARs) on Mars II: Distributions, orientations, and ages

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ABSTRACT

Transverse Aeolian Ridges (TARs), 10 m scale, ripple-like aeolian bedforms with simple morphology, are widespread on Mars but it is unknown what role they play in Mars' wider sediment cycle. We present the results of a survey of all Mars Global Surveyor Narrow angle images in a pole-to-pole study area, 45° longitude wide.

Following on from the classification scheme and preliminary surveys of Balme et al. (Balme, M.R., Berman, D.C., Bourke, M.C., Zimbelman, J.R. [2008a]. Geomorphology 101, 703–720) and Wilson and Zimbelman (Wilson, S.A., Zimbelman, J.R. [2004]. J. Geophys. Res. 109 (E10). doi:10.1029/2004JE002247) we searched more than 10,000 images, and found that over 2000 reveal at least 5% areal cover by TARs. The mean TAR areal cover in the study area is about 7% (3% in the northern hemisphere and 11% in the southern hemisphere) but TARs are not homogenously distributed – they are concentrated in the mid-low latitudes and almost absent poleward of 35°N and 55°S. We found no clear correlation between TAR distribution and any of thermal inertia, kilometer-scale roughness, or elevation. We did find that TARs are less common at extremes of elevation.

We found that TARs are most common near the equator (especially in the vicinity of Meridiani Planum, in which area they have a distinctive "barchan-like" morphology) and in large southern-hemisphere impact craters. TARs in the equatorial band are usually associated with outcrops of layered terrain or steep slopes, hence their relative absence in the northern hemisphere. TARs in the southern hemisphere are most commonly associated with low albedo, intercrater dune fields. We speculate that the mid-latitude mantling terrain (e.g., Mustard, J.F., Cooper, C.D., Rifkin, M.K. [2001]. Nature 412, 411–414; Kreslavsky, M.A., Head, J.W. [2002]. J. Geophys. Res. 29 (15). doi:10.1029/2002GL015392) could also play a role in covering TARs or inhibiting saltation.

We compared TAR distribution with general circulation model (GCM) climate data for both surface wind shear stress and wind direction. We performed GCM runs at various obliquity values to simulate the effects of changing obliquity on recent Mars climate. We found good general agreement between TAR orientation and GCM wind directions from present day obliquity conditions in many cases, but found no good correlation between wind shear stress and TAR distribution.

We performed preliminary high resolution crater count studies of TARs in both equatorial and southern intracrater dunefield settings and compared these to superposition relationships between TARs and large dark dunes. Our results show that TARs near dunefield appear to be younger than TARs in the equatorial regions. We infer that active saltation from the large dunes keeps TARs active, but that TARs are not active under present day condition when distal to large dunes – perhaps supporting the interpretation that TARs are granule ripples.

We conclude that local geology, rather than wind strength, controls TAR distribution, but that their orientation matches present-day regional wind patterns in most cases. We suggest that TARs are likely most (perhaps only) active today when they are proximal to large dark dune fields.

1. Introduction

Mars' surface hosts a wide range of aeolian landforms including dunes, ripples, dust devil tracks, yardangs, and ventifacts. Large dune fields, characterized by low albedos and large duneform sizes, occur mainly around the north polar cap (Cutts et al., 1976; Tsoar et al., 1979) and in the southern mid-latitudes (Cutts and Smith, 1973; Thomas, 1981; Lancaster and Greeley, 1987) and were recognized in Mariner 9 images (McCauley et al., 1972). However, another morphologically and dimensionally distinct population of

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aeolian bedforms has also been noted from Viking (Zimbelman, 1987) and Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) (Thomas et al., 1999; Malin and Edgett, 2001) images. These are generally brighter than the surrounding terrain, are about an order of magnitude smaller than the large dark dunes (LDDs), have simple forms and crests that appear to form normal to local winds (Fig. 1). These bedforms have been designated 'Transverse Aeolian Ridges', or 'TARs' (Bourke et al., 2003), a term broadly independent of genetic inference given the current debate regarding their formation: researchers (e.g., Williams et al., 2002; Zimbelman and Wilson, 2002; Wilson et al., 2003) have compared TARs to large terrestrial ripples, or granule ripples (Sharp, 1963; Fryberger et al., 1992), and the latest data suggest that larger TARs might have formed as small reversing dunes (Zimbelman, 2010).

TARs are found in almost all geologic settings, from the highest volcanoes to the floor of the deepest impact basins (Dressing et al., 2006; Malin and Edgett, 2001), a nearly 30-km elevation range. TARs typically form in small fields of tens to thousands of individual bedforms and are characterized by their small size (usually of the order of 10 m wide and tens of meters along their crests) and generally "ripple-like" form. Lee and stoss slopes appear to be symmetric (Malin and Edgett, 2001; Wilson and Zimbelman, 2004; Zimbelman, 2010).

Despite their abundance, little has been known about what processes control the distribution and activity of TARs on the planet. For example, are TARs formed from local sediment, with their distribution reflecting the lithology of the source region, or are TARs sourced regionally, with their distribution reflecting regional wind patterns, rather than sediment supply? Also, when did TARs form, and are they still active? To answer some of these questions, we present the results of a survey of all high-resolution (~1–11 m/pixel) narrow-angle Mars Global Surveyor (MGS) Mars Orbiter Camera Narrow Angle (MOC NA) images (~10,000 images) in a pole-to-pole swath between 0 and 45°E longitude (Fig. 2). The aims of the project are to determine TAR distributions, orientations, morphologies and morphometries, possible sediment sources, and superposition relationships with LDDs. The approach involves comparing distribution and classification data with surface properties and climate model data. The results of the northern hemisphere part of this survey have been described by Balme et al. (2008a,b) although no comparisons with model data were presented in that work. The data presented here extend both this and the preliminary survey of Wilson and Zimbelman (2004) and, because that survey was conducted on the opposite site of the planet, provides a way of testing whether trends are replicated across the globe.

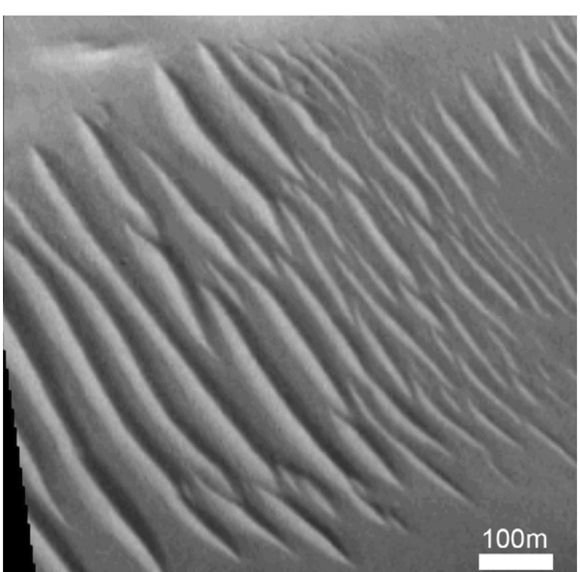

Fig. 1. Portion of MOC image M1104208, showing simple TAR forms. North is up. Image credit: NASA/JPL/MSSS.

2. Approach

2.1. Digitization of TARs from image data in a GIS

Every MOC NA image in the study area (>10,000) was examined at full resolution to search for TARs. The approximate percentage areal coverage of TARs in each MOC image was recorded together with the latitude and longitude of the image center (at the global scale, the 1–10 km maximum lengths of the images are inconsequential when plotting the data so it does not matter where in the image the TARs are concentrated). A GIS database was constructed to facilitate the comparison of various datasets with the survey results. We recorded data such as classification by morphology (e.g., simple, forked, sinuous, barchan-like, or networked), topographic influence (e.g., confined, controlled, influenced, or independent; see Balme et al., 2008a), and stratigraphic associations with LDDs. In addition, those images that contained >60% TARs and whose orientation appeared independent of topography were flagged in the database and their orientations digitized and recorded in the GIS.

Base maps added to the database include Viking MDIM 2.1, THEMIS IR daytime, and MGS MOC WA mosaics. Other raster layers added to the GIS include MOLA gridded elevation data, thermal inertia and kilometer-scale roughness maps. Shape data added include percent areal coverage for each MOC image, the Mars Digital Dunes Database (Hayward et al., 2006), a preliminary map of layered deposits identified in MOC NA images (Malin and Edgett, 2000), and locations of TARs from the Wilson and Zimbelman (2004) database, and any published regional and global geological maps.

2.2. Climate model data comparison

To investigate whether TAR orientations correlated with regional wind patterns or whether TAR abundance correlated with regional wind strengths, we obtained wind direction and wind shear model data from the NASA Ames General Circulation Model (GCM; Rafkin et al., 2001; Haberle et al., 2003; Kahre et al., 2006). Because it is unknown whether TARs formed under a climate similar to today's, or if they formed when climate conditions were different (most plausibly caused by cyclical variations in Mars's obliquity, e.g., Laskar et al., 2004; Haberle et al., 2003), we compared TAR orientations and distributions with climate data from several plausible martian obliquity values.

The GCM was used to predict the surface wind stress for obliquities ranging from 0° to 60° in 10° increments, plus the present day obliquity of 23.2° (referred to henceforth as the "control" obliquity). For consistency, all other constants and processes were identical in all simulations, including surface albedo and thermal inertia, and total system CO_2 mass. Atmospheric dust loading was prescribed as the zonally-averaged 9 μm dust opacity observed by the Thermal Emission Spectrometer (TES) aboard the Mars Global Surveyor (Smith, 2003). The model was configured with latitude by longitude spacing of 5° × 9°.

Care must be taken in interpreting model data in this study, because atmospheric numerical models necessarily are unable to simulate the influence of topographic features on scales smaller than roughly twice the model grid spacing. It is possible that TARs could result from localized circulations forced by sub-grid scale

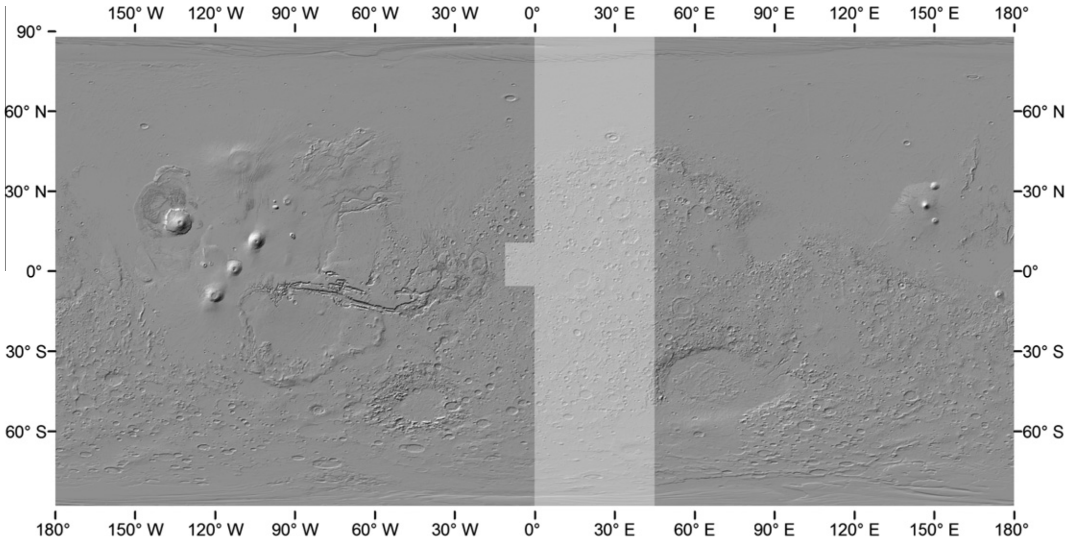

Fig. 2. Global 64 pixel/degree MOLA hillshade showing study region in light grey.

features, in which case a lack of correlation between TAR orientation and the GCM model might be expected. Consequently, it is important to also evaluate the local and regional topography in order to assess whether there is the potential to substantially perturb model-predicted large-scale flow, which is why we attempted to flag TARs in terms of their dependence on local topography. Mesoscale modeling studies that do simulate the effect of topography have consistently shown that the overwhelming influence of topography is to produce daytime upslope flows and nighttime downslope flows all of which are roughly parallel to the topographic gradient (e.g., Rafkin et al., 2001, 2003; Michaels and Rafkin, 2008). This holds for general topographic slopes as well as craters and channels.

The GCM output comprises instantaneous snapshots of the atmospheric state every 1/16 of a sol over a full martian year. The resolution used is relatively coarse, but sufficient for this application. The actual wind will be the sum of the large-scale circulation and the local/regional circulation. The $5^\circ \times 9^\circ$ is capable of providing the information on the large-scale. Simulations at $5^\circ \times 6^\circ$ are now regularly performed, but do not differ in any significant way for this application. The model is integrated with a time step of roughly 1 min. There is not much variability at the large-scale at higher frequencies, so there is little advantage to more frequent output. The archived model data were divided into 90° L_s bins centered on the cardinal seasons (i.e., $L_s = 0^\circ$ corresponds to data from $L_s = 335^\circ$ to 45°). Within these seasonal bins the maximum wind stress and corresponding wind direction were identified for each point and each time step. The annual maximum is simply the maximum value from the four seasons.

Although the maximum wind stress output from the GCM is expected to be associated with the greatest likelihood of aeolian activity, the single value alone is not necessarily representative of the actual rate or direction in which sediments will be transported (or the magnitude of the distance that bedforms migrate) during this time: aeolian transport potential depends upon a combination of the wind speed, the threshold shear stress of the particular sediment in its location and the length of time over which the winds act. Data on threshold wind speeds for the specific sediments at a given location are not globally available for Mars in any form other than theoretical parameterizations that proscribe the sediment char acteristics of the surface based on very low resolution remote sensing data. Therefore, we have not attempted to model sand transport potential of the winds, and present only statistics on the calculation of wind shear stresses themselves.

While it is true that we could derive an estimate of threshold wind speed for given particle sizes, the question arises as to what particle size to use and what particle density? We have little knowledge of whether TARs form from agglomerates, from basaltic material, and whether they are all granule ripples or if some are small dunes. This means we have little knowledge of the particle size or density. There are some very localized data on TAR particle size from the MER rover Opportunity, but they show a bimodal distribution. There are also some aeolian particle size estimates derived from thermal inertia, but they are normally only for LDDs, which are different to TARs in many ways.

Essentially any threshold expression is going to have some very arbitrary input values that are pretty much unconstrained, so in reality such a scheme would simply place a minimum cutoff point in the GCM wind speed data, rather than say anything meaningful about where/when particles are actually lifted. Hence our method is expressly arbitrary and seeks to provide only a very simple estimate of where winds are strong, and where they are not. We note that other people (e.g., Hayward et al., 2006) have used threshold expressions. However, given that LDDs are probably mostly unimodal in particle size and are large enough for good thermal inertia measurements to be made we argue that a threshold expression is more suited to studies of LDDs than TARs.

To account for the inability of a single peak windspeed datum to describe aeolian transport, we have also calculated the fraction of the year that the wind stress was within 10% of the maximum value to better gauge how often winds were at or near maximum aeolian transport potential at any given location. In extreme cases, it is possible that there were no data points within 10% of the maximum, indicating that the maximum value was rare, short-lived, and unlikely to result in large mass movement in a time-integrated sense. Therefore to further characterize the variability of the strongest winds, the average of the highest 10% of wind stress at a given location was calculated. This value provides insight into how much potential there is for aeolian activity integrated over time. While the use of the top 10% of the data is arbitrary, the advantage is that it provides a simple and internally consistent measure of the overall particle transport potential of the winds at a given point over a given time period.

One alternative, rather than gathering the top 10% of winds as described above, is to analyze the winds above a critical threshold. This methodology was considered but rejected, because the latter fails to measure the potential work (i.e., sufficient wind momentum integrated over time) that could be done by the wind. A strong wind will fail to create TARs if it is only present for a few short minutes every year. Furthermore, because a GCM has relatively coarse spatial resolution, a threshold speed is insufficient to account for the expected large spatial variability of wind speed within a grid cell. A grid cell in which the model wind speed is always below a given threshold does not necessarily indicate that aeolian activity is not possible. As documented in several mesoscale modeling studies (e.g., Rafkin and Michaels, 2003), the local wind speed and direction are composed of a sum of the large-scale circulation, as predicted by the GCM, and regional circulations forced primarily by topography. In contrast to thresholds, the upper 10% of the wind speed incorporates the time element required to perform meaningful work. Investigation of the magnitude of this upper 10% provides an indication of whether this upper end is of sufficient strength to do the work. Previous authors have also utilized this technique (cf., Arvidson et al., 1983; Parteli and Herrmann, 2007).

3. Results: distribution and associations

3.1. Geographical distribution

The geographic distribution of TARs is significantly non-random. TARs are more common in clusters at low- to mid-latitudes than in other regions. In the northern hemisphere, TARs are most commonly found between 0 and 35°N, and are especially common in the Terra Meridiani region. Six-hundred and sixty-nine MOC images in the northern hemisphere contain at least 5% areal coverage of TARs (Fig. 3a). In the southern hemisphere, TARs are almost exclusively found between 0 and 55°S. One-thousand five-hundred and sixty-one MOC images in the southern hemisphere had 5% or more areal coverage containing TARs (Fig. 3b). In the northern hemisphere, 11,767 km^2 of 398,466 km^2 contained TARs, an average of 3% areal cover. In the south, 19,817 km^2 of 365,812 km^2 had TARs, an average of 11% areal cover. The total areal cover by TARs was 31,585 km^2 out of 764,278 km^2 examined; an average of 7.1%.

Some of the highest densities of TARs were found within the Terra Meridiani region (Fig. 3a and b) and, for this reason, we extended the spatial extent of our survey to include a larger portion of the Meridiani region (0–10°W between 10°N and 5°S). TARs in this region were almost exclusively barchan-like in morphology (Fig. 4), whereas those in other regions were most often simple, forked, or networked (see Balme et al. (2008a) for a description of the morphological classifications).

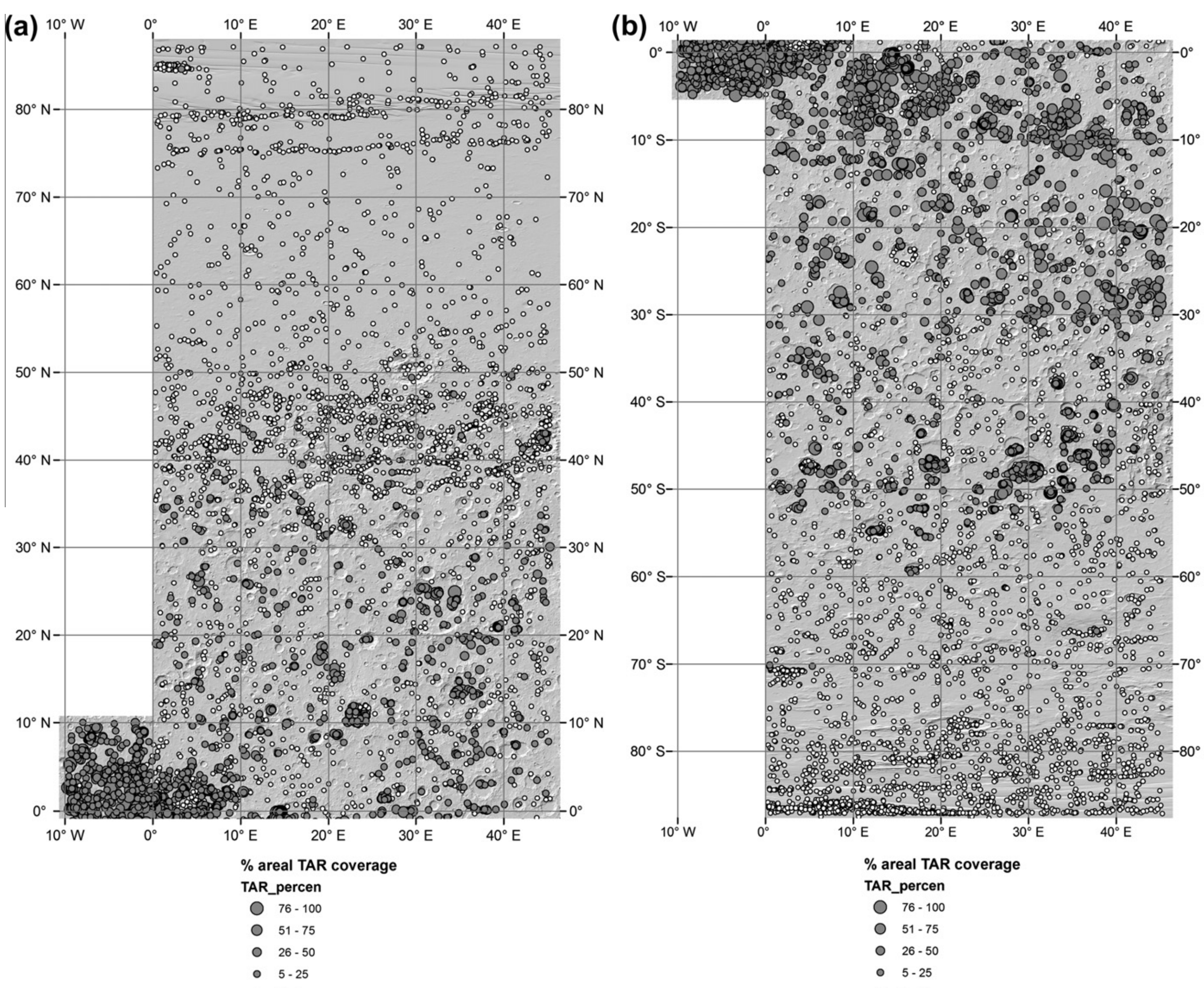

Fig. 3. Distribution of MOC images included in study with % areal TAR coverage designated by size of circles in (a) the northern hemisphere and (b) the southern hemisphere, with MOLA hillshade background.

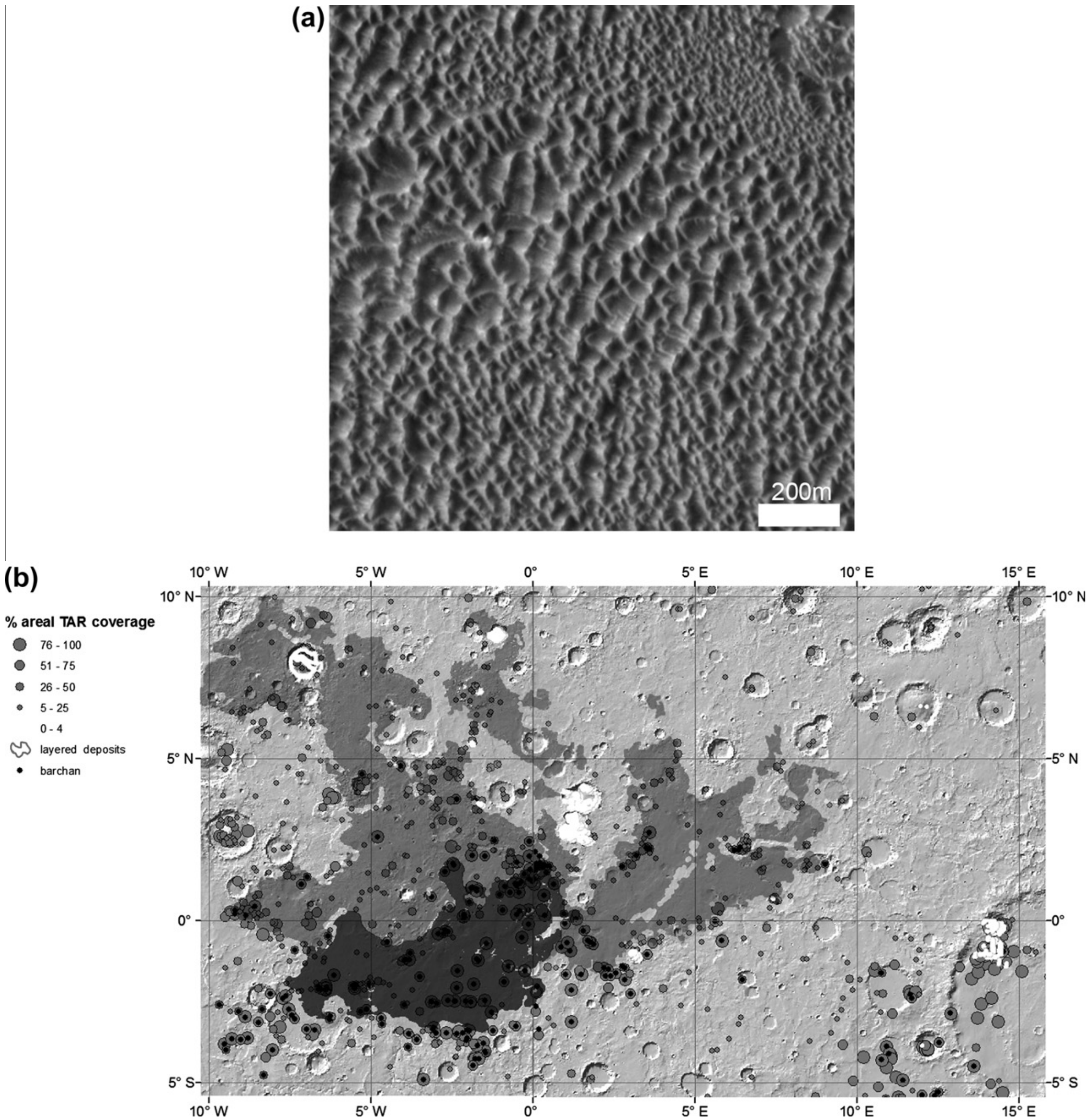

Fig. 4. (a) Portion of MOC image M1800277 showing barchan-like TARs in the Meridiani region. North is up. Image credit: NASA/JPL/MSSS; (b) spatial relations between barchan-like TARs and layered terrains from Malin and Edgett, 2000 and Hynek and Phillips, 2008.

3.2. Comparisons with roughness, thermal inertia, and elevation

The distribution of TARs was compared to gridded Thermal Inertia values as determined from the MGS Thermal Emission Spectrometer (TES; Mellon et al., 2000). The general principal of thermophysical sampling is that terrains that stay warmer at night are composed of larger particles, or have a larger fraction of bedrock, than materials that cool down quickly that are composed of fine sand or dust (Presley and Christensen, 1997a,b). Thus, thermal inertia can tell us about the size of particles in aeolian deposits. However, no obvious correlation was observed (Fig. 5a). Distributions were also compared with kilometer-scale roughness values, derived from MOLA data (Neumann et al., 2003), to see if kilometer-scale roughness might control TAR formation – rougher terrain being thought to have more steep slopes and perhaps more mass wasting. Again, no significant correlations were found (Fig. 5b).

MOC NA images with 0% areal TAR coverage were found across an elevation range of −6386 m to 4717 m, with a mean of −257.23 ± 2782.9 m. For those MOC NA images with 60% areal TAR coverage, the elevation range is −3850 m to 3245 m, with a mean of 429.4 ± 1187.6 m. For images with 100% areal TAR coverage, the elevation range is −1631 m to 2669 m, with a mean of −94.6 ± 1142.0 m (Fig. 6). This suggests that TARs are rarer at extremely high elevations and extremely low elevations.

3.3. Associations with regional geology

The MOC NA images with greatest TAR coverage are generally found in two distinct geographic distributions: equatorial and southern intracrater. In the equatorial regions, large numbers of TARs have been found near Terra Meridiani and Schiaparrelli Basin, both regions containing abundant outcrops of high albedo, layered

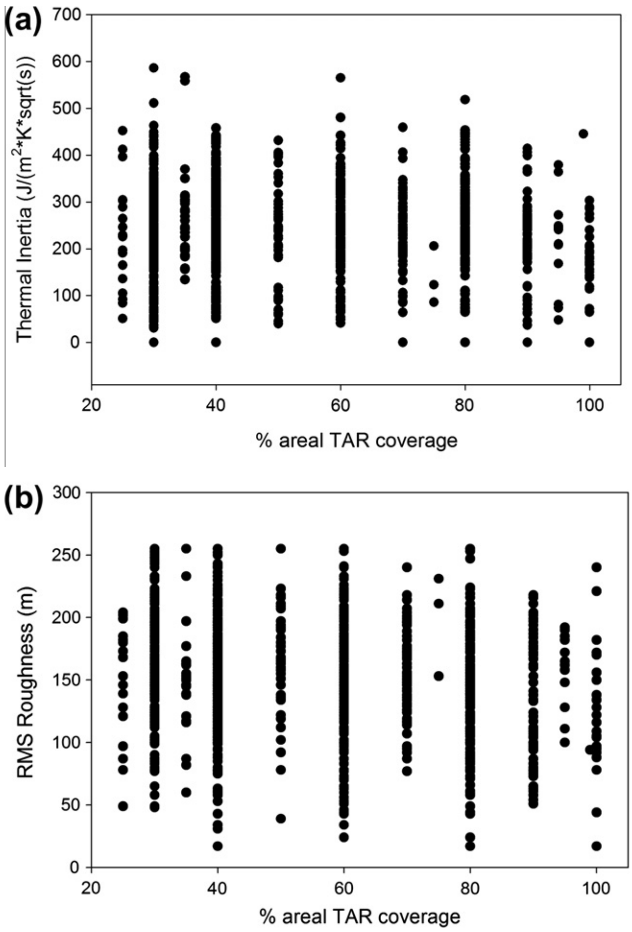

Fig. 5. Plots of (a) percent areal TAR coverage vs. thermal inertia; and (b) percent areal TAR coverage vs. roughness.

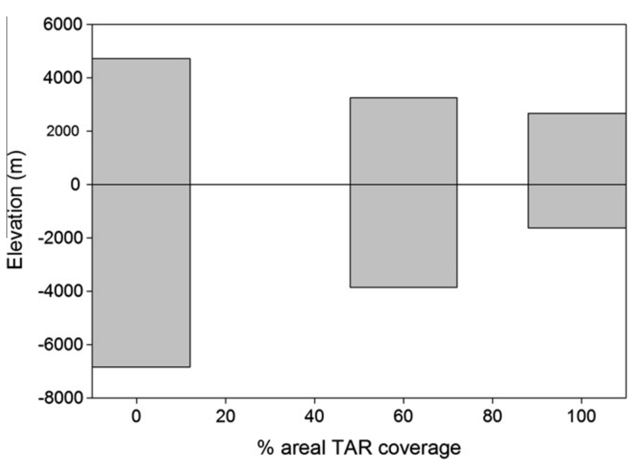

Fig. 6. Plot of elevation from MOLA vs. percent areal TAR coverage at 0%, 60%, and 100%.

materials (Malin and Edgett, 2000) that, at least in Terra Meridiani, have been investigated in situ by the *Opportunity* Mars Rover and found to be ancient sedimentary rocks of aeolian origin (Squyres et al., 2009). Fig. 7 shows the spatial association between TARs and layered mesas and outcrops.

The TARs in Meridiani are also proximal to one of the most prominent clusters of wind streaks in Arabia Terra (Fig. 8), which suggests that this area has a high degree of aeolian activity. Saltation of sand as wind streaks advance may be eroding sediments that are then fed into TARs. Interestingly, presumed wind streak-forming wind directions are perpendicular to both the GCM wind directions and presumed TAR-forming wind directions in the region. It is possible that the wind streaks are relicts and formed under different atmospheric conditions than the TARs.

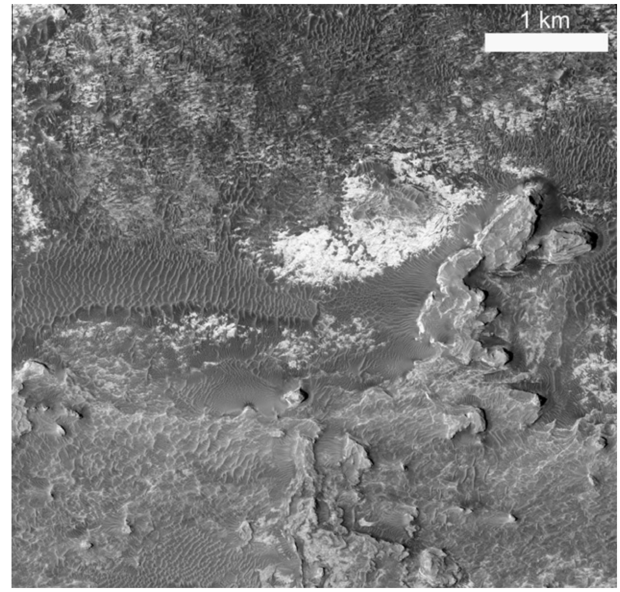

Fig. 7. Portion of HiRISE image PSP_006148_1820, showing influence of TAR orientations by local topography. North is up, image credit: NASA/JPL/MSSS.

Non-Meridiani TARs are most commonly found within craters of all sizes. Thus, the relative paucity of TARs in the northern hemisphere compared to the south could be related to the lack of morphologically pristine craters in the north. In addition, there appear to be many fewer outcrops of layered terrains in the north of the study area than in the southern equatorial regions.

3.4. Associations and superposition relations with large dark dunes

Many of the MOC NA images with >5% TARs also contain LDDs: 79 of 669 in the north and 260 of 1561 in the south contain LDDs as well as TARs. 74% (207 of 279) of MOC NA images within 10 km of LDD fields (as mapped by Hayward et al. (2006)) had ⩾5% TARs. Only 54% (599 of 1104) MOC NA images within 100 km of LDD fields had ⩾5% TARs. In the southern regions, TARs are most commonly found inside craters where there are also large dark dunes.

Malin and Edgett (2001) suggested that where dark dunes and bright TARs occur together, the dunes postdate the TARs. Wilson and Zimbelman (2004) suggested that in many cases TARs are indurated or lithified. Fenton et al. (2003) also suggested that TARs may be older than dark dunes, but note that in some cases TARs are destroyed by the dark dunes, only for new TARs to form in their wake. Fenton et al. (2003), Wilson and Zimbelman (2004), and Balme et al. (2008a,b) have all found examples of TARs superposing dark dunes.

Our data (Fig. 9a) show that in equatorial regions and the northern hemisphere, where the two landforms coexist LDDs in general superpose TARs (Fig. 9b), suggesting that TARs formed and then became immobile (perhaps becoming indurated?) before the LDDs formed. LDDs in these regions generally appear to be active given the lack of dust on their surfaces. In the southern intracrater regions however, TARs frequently superpose LDDs (Fig. 9c), and seem to be more active; the LDDs in these cases also appear to be inactive, being covered by bright dust. Fig. 9d shows coincidence of

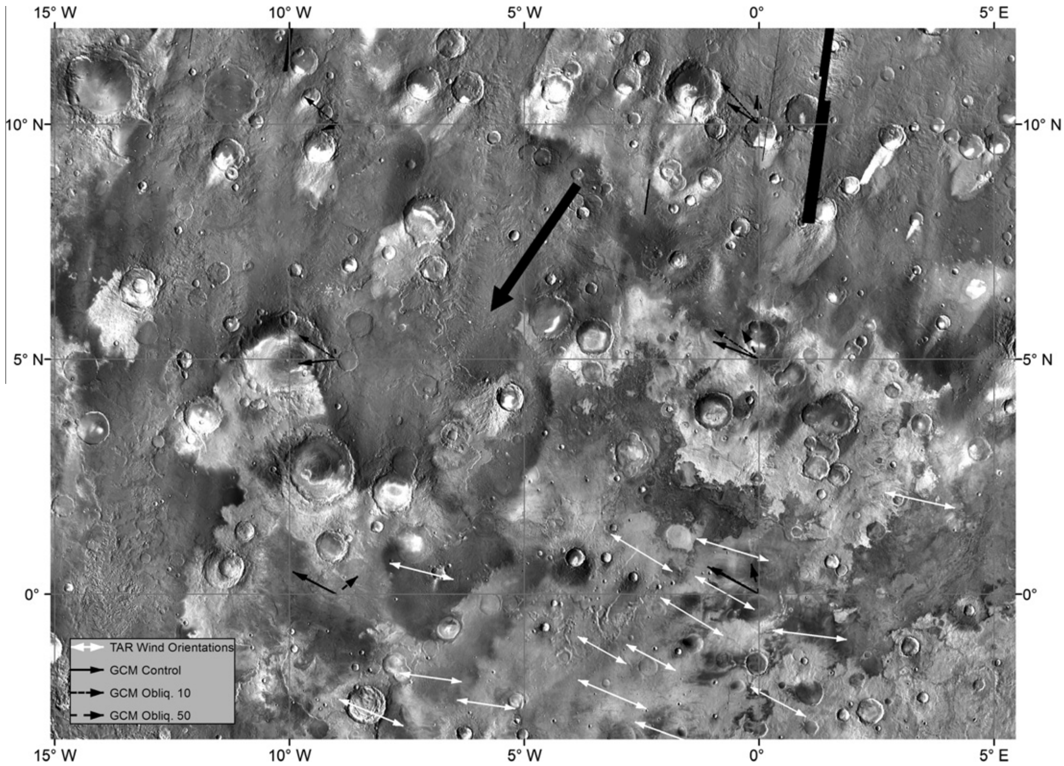

Fig. 8. Comparison of TAR, GCM, and wind streak orientations in Arabia Terra. Large black arrow indicates direction of wind streak-forming winds.

TARs and LDDs in southern intracrater region. Interestingly, many equatorial TARs contain visible impact craters, while southern intracrater TAR fields do not. This shows that the situation is more complicated than simply a linear progression from TAR activity to LDD activity in Mars' recent history.

3.5. TAR ages

Reiss et al. (2004) performed crater counts on TARs in Nirgal Vallis and found that, with a factor of two error, they ceased to be active 1.4–0.3 Ma before present. The challenge with using impact crater counts to measure when TARs were active is that almost all TARs are geologically very young, and so contain very few craters of any size, let alone craters larger enough to be visible in MOC NA images (generally only craters >10 m in diameter can be identified). We therefore used very high-resolution images from the Mars Reconnaissance Orbiter (MRO) High Resolution Imaging Stereo Experiment (HiRISE) camera to measure crater size-frequency distributions on candidate Meridiani and southern highlands TARs (Fig. 10). The aim of this work was to investigate whether impact crater statistics could be used to test the hypothesis suggested by the LDD superposition relationships: that TARs in the equatorial regions are "old" or lithified, while TARs in southern craters are younger, or still actively burying or erasing any impact craters that form.

We found that equatorial TARs have crater retention ages of ~1–3 Ma, while the southern intracrater TARs contain no craters >5–10 m in diameter at all. This indicates a crater retention age of less than 100 ka, which agrees with superposition relations.

4. Results: TAR orientations and comparisons with climate models

The presumed TAR-forming wind directions (orthogonal to TAR orientations) for TARs that were determined to be topographically independent (i.e., TARs whose orientations did not appear to be influenced by local topography on the MOC image scale) and which have >60% TAR coverage were compared to wind directions derived by the GCM at multiple obliquities (Fig. 11a–e). In general, TAR orientations tend to be approximately the same over large areas (several degrees), indicating TARs adopt orientations consistent with large-scale wind patterns and that the local topography is unlikely to perturb the large-scale circulation in a manner relevant for TAR formation. TAR-forming wind orientations in general match GCM wind orientations fairly well (Fig. 11a–e) – although there are some clear instances of noticeable disagreement – and in general orientations appear more consistent with data from model runs that use obliquities closest to the current Mars obliquity (~22°). Obliquities of 40° or 50° appear less consistent in general, suggesting that TAR formation occurred in recent geologic time. GCM wind direction data also generally match that of the Mars Digital Dunes Database (Hayward et al., 2006).

More specifically, in the Meridiani region (Fig. 11a), data for the control and 10° obliquities matched measured TAR orientations very well; the data from 50° obliquity runs do not match well in the Meridiani region. In non-Meridiani equatorial regions (Fig. 11b), all obliquities matched fairly well with TAR orientations. Fig. 11c shows orientations in a southern hemisphere region; the best matches were the control obliquity and the 50° obliquity, but the wind directions for 10° obliquity did not match. Orientations did not match well at any obliquity in the northern hemisphere (Fig. 11d). In this case, it is reasonable to assess whether local topography may play an important role. Circulations associated with the large crater in Fig. 11d would tend to be strongest near the crater rims and would be oriented in a radial direction. This circulation is inconsistent with the TAR orientations. Therefore, while the TAR orientations do not correlate with the large-scale wind, neither do they correlate with the expected local circulations. Turning back to Fig. 11b, two TAR orientations near the large crater are roughly perpendicular to the GCM winds but are

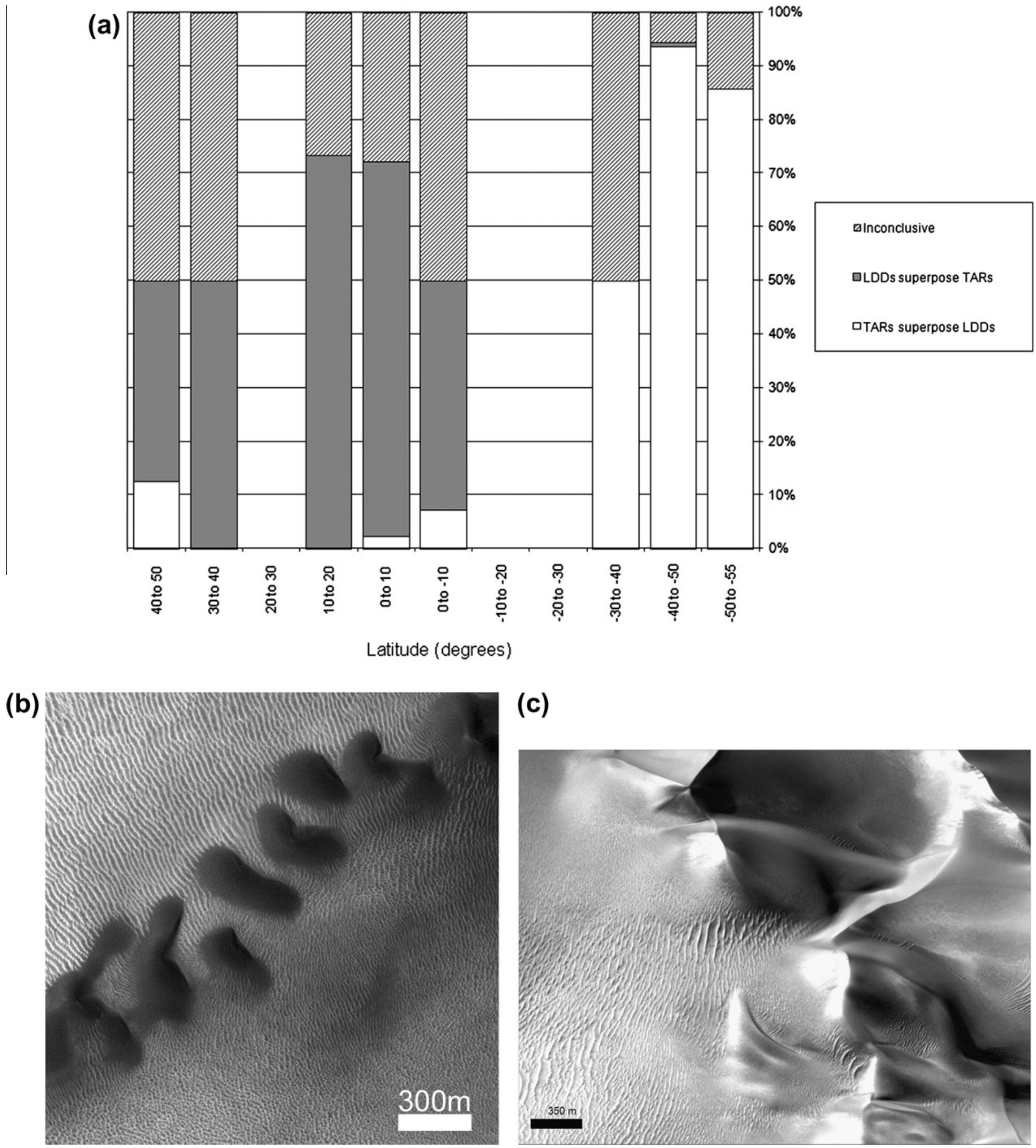

Fig. 9. (a) Chart of TAR/LDD superposition relationships by latitude; (b) portion of MOC image R0902119 showing LDDs superposed on TARs; TAR orientations are independent of LDDs. North is up, image credit: NASA/JPL/MSSS; (c) portion of MOC image E0200526 showing TARs superposed on LDDs in the southern hemisphere. TAR orientations are controlled by LDDs. North is up, image credit: NASA/JPL/MSSS; (d) map of southern region showing spatial relationship between intracrater TARs and LDD fields. Transparent white circles indication locations and percent areal coverage of TARs; black polygons indicate locations of LDDs, as mapped by Hayward et al. (2006). As white circles are transparent, they appear gray where they overlap the black polygons, where the two landforms coexist.

consistent with what might be expected from local circulations. So, in general TAR-forming wind directions are consistent with modern obliquity wind directions as shown by the GCM in the mid and southern latitudes, but are inconsistent with GCM wind directions at all obliquities in the northern latitudes. This may simply be indicative of the shortcomings of GCMs over mesoscale models, however.

Interestingly, the orientations of wind streaks in the equatorial regions indicate wind directions perpendicular to those indicated by TARs (Fig. 8). This suggests either that the wind streaks were formed under a different wind regime than the TARs, or that local circulations may be more important in the formation of either TARs or wind streaks.

Fig. 12 shows GCM shear stress for the entire study area at multiple obliquities. GCM estimations of wind shear stress in general show little correlation with the locations of TARs at any obliquity. We conclude that there is no evidence that the distribution of TARs is more related to the strength of the local winds, and that availability of material and effects of local topography are more likely controls.

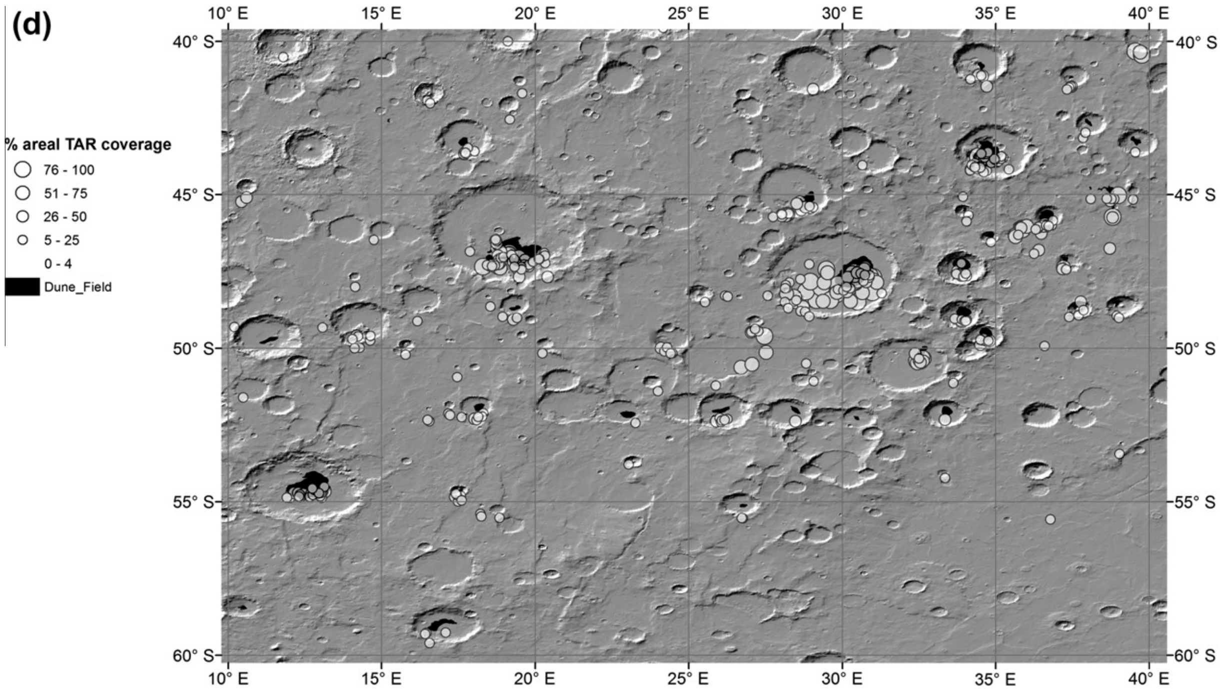

Fig. 9 (*continued*)

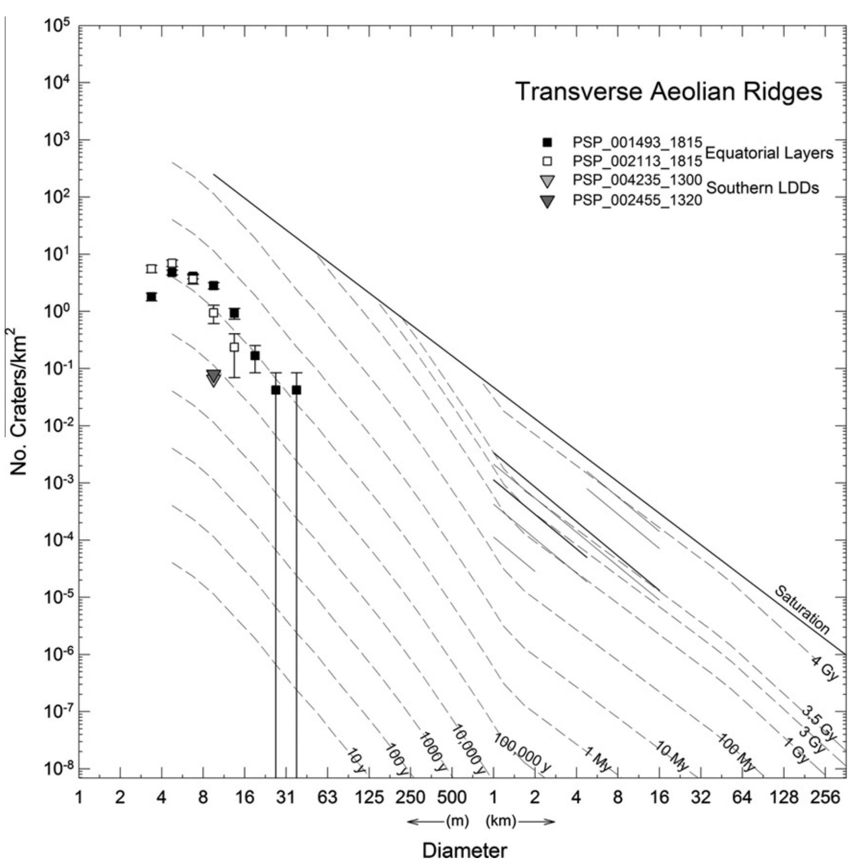

Fig. 10. Crater size-frequency distributions for HiRISE images PSP_001493_1815 and PSP_002113_1815 in the Meridiani region, and PSP_004235_1300 and PSP_002455_1320 in the southern intracrater region. Distributions for the Meridiani TARs give model ages of about 1–3 Myr. No images were found in the southern intracrater images, so they can be no older than about 100,000 years (which is what 1 crater would give for their area).

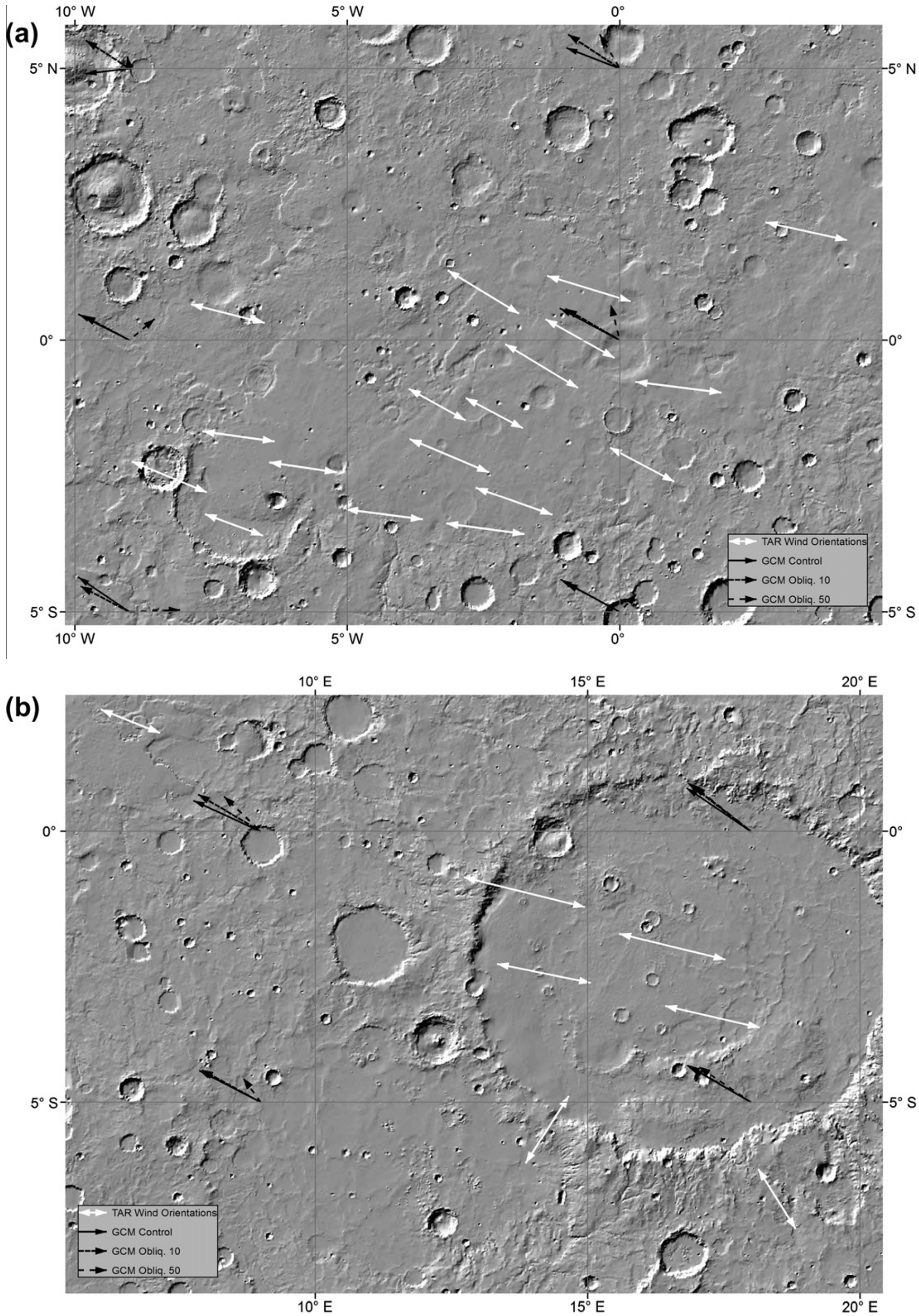

Fig. 11. Comparison of TAR and GCM orientations. Gray two-tailed arrows indicate presumed wind direction of TAR-forming winds (orthogonal to TAR orientation). Black arrows indicate GCM wind directions.

5. Discussion

5.1. TAR geographical distribution

TARs are not ubiquitous – some process appears to preclude their formation (or covers them up) at higher latitudes. Both this study and that of Wilson and Zimbelman (2004) on the other side of the planet find TARs are more common at low and mid-latitudes. Also, in a global survey of 500 randomly selected MOC images, Salvatore (2008) found a majority of TARs between 60°N and 60°S, although it is worth noting that there are many features poleward of ~35° that resemble TARs in MOC NA images, but are in fact other types of landforms, as described in Balme et al. (2008a). This global distribution of TARs must reflect a latitudinal control of one or

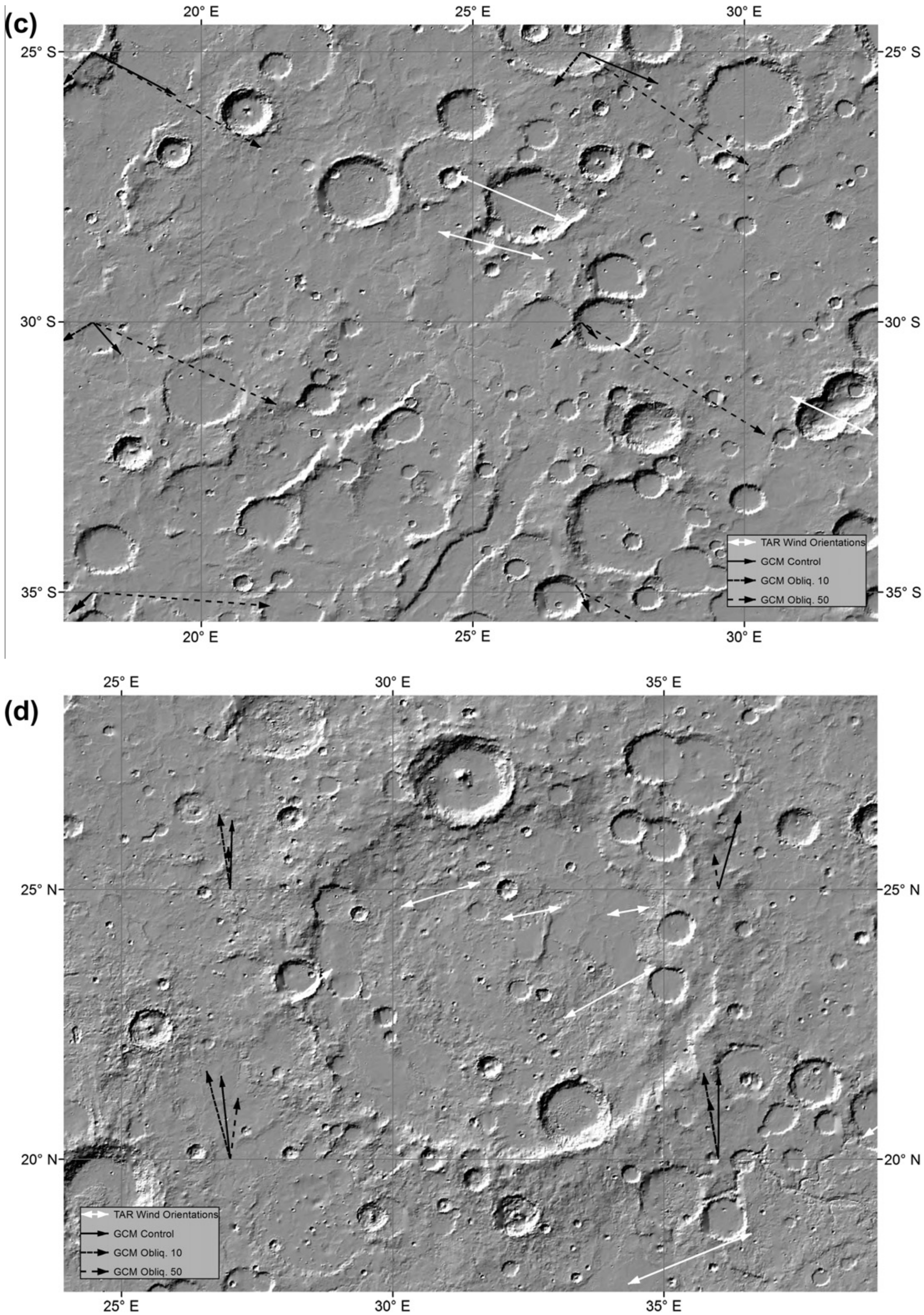

Fig. 11 (*continued*)

more of either (i) TAR formation processes, (ii) TAR migration controls, or (iii) TAR removal or burial processes. We now explore possible candidate mechanisms for such controls.

One possibility is that the presence of so-called mantling terrain, thought to be a mixture of dust and ice (e.g., Mustard et al., 2001; Kreslavsky and Head, 2002), which drapes the topography in both the north and southern hemispheres at mid- to high-latitudes, controls TAR distribution either through burial or by affecting the supply of TAR-forming sediment. Pre-existing TARs could either be covered by the mantle, or the presence of the mantle prevents significant erosion and transport of the aeolian materials that compose TARs. Alternatively, some authors have suggested that the equator-most extents of the mantle are currently degrading due to sublimation (Mustard et al., 2001); disaggregation of lag deposits of sediment from within the mantle could provide a source of sediment that is transported towards the equator.

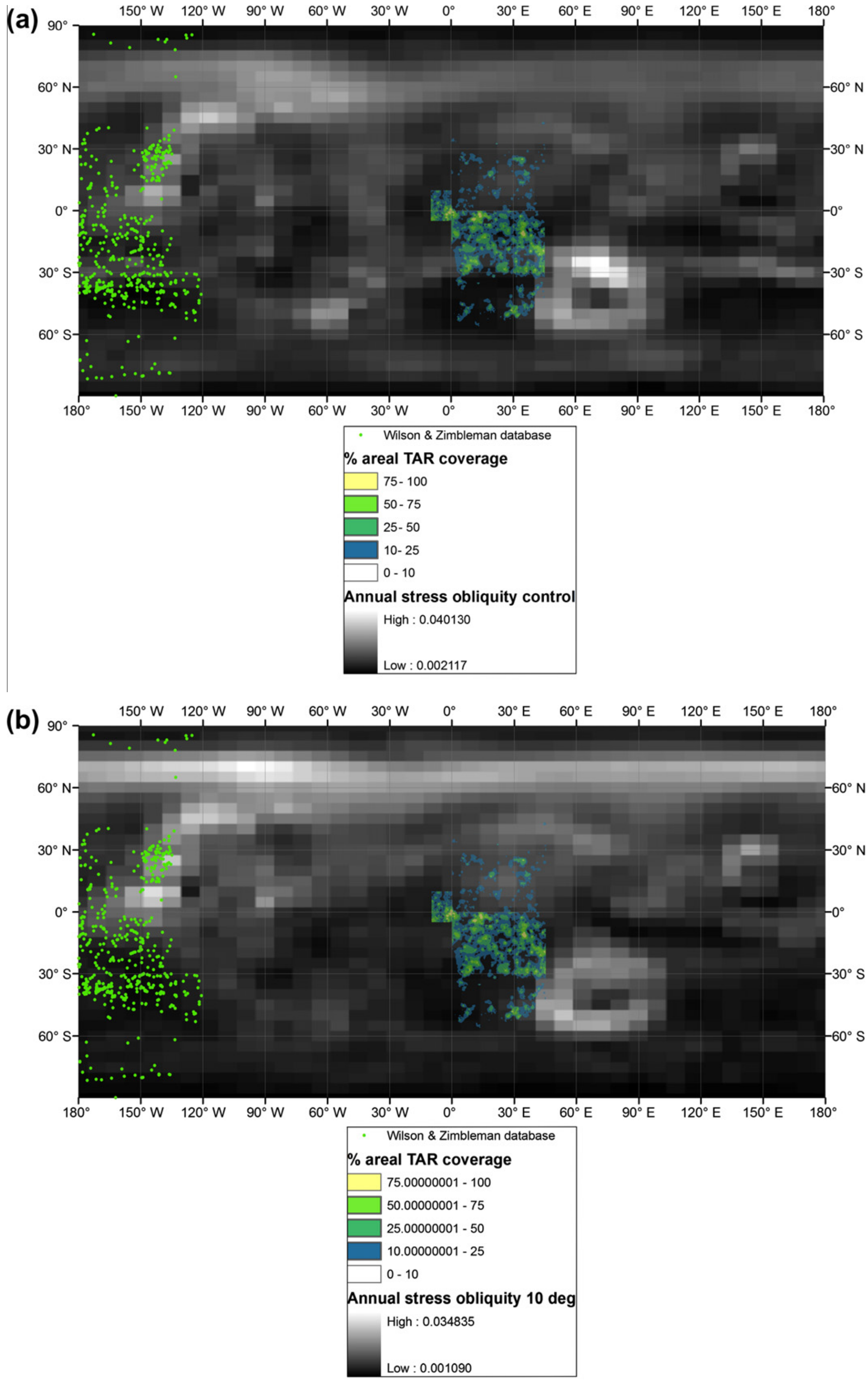

Fig. 12. GCM results for obliquities of (a) the control obliquity; (b) 10°; and (c) 50°; and plots of wind shear stress (N m^{-2}) vs. percent areal TAR coverage for obliquities of (d) the control obliquity, (e) 10°; and (f) 50°.

It does not appear that the degrading mantle is liberating sand-grade material that might form TARs, for we have found no evidence for TARs forming preferentially at the mantle boundaries, nor do our GCM results suggest that the winds are exclusively equatorward to transport sediment away from the mantle. Conversely, the presence of the mantle might very well inhibit

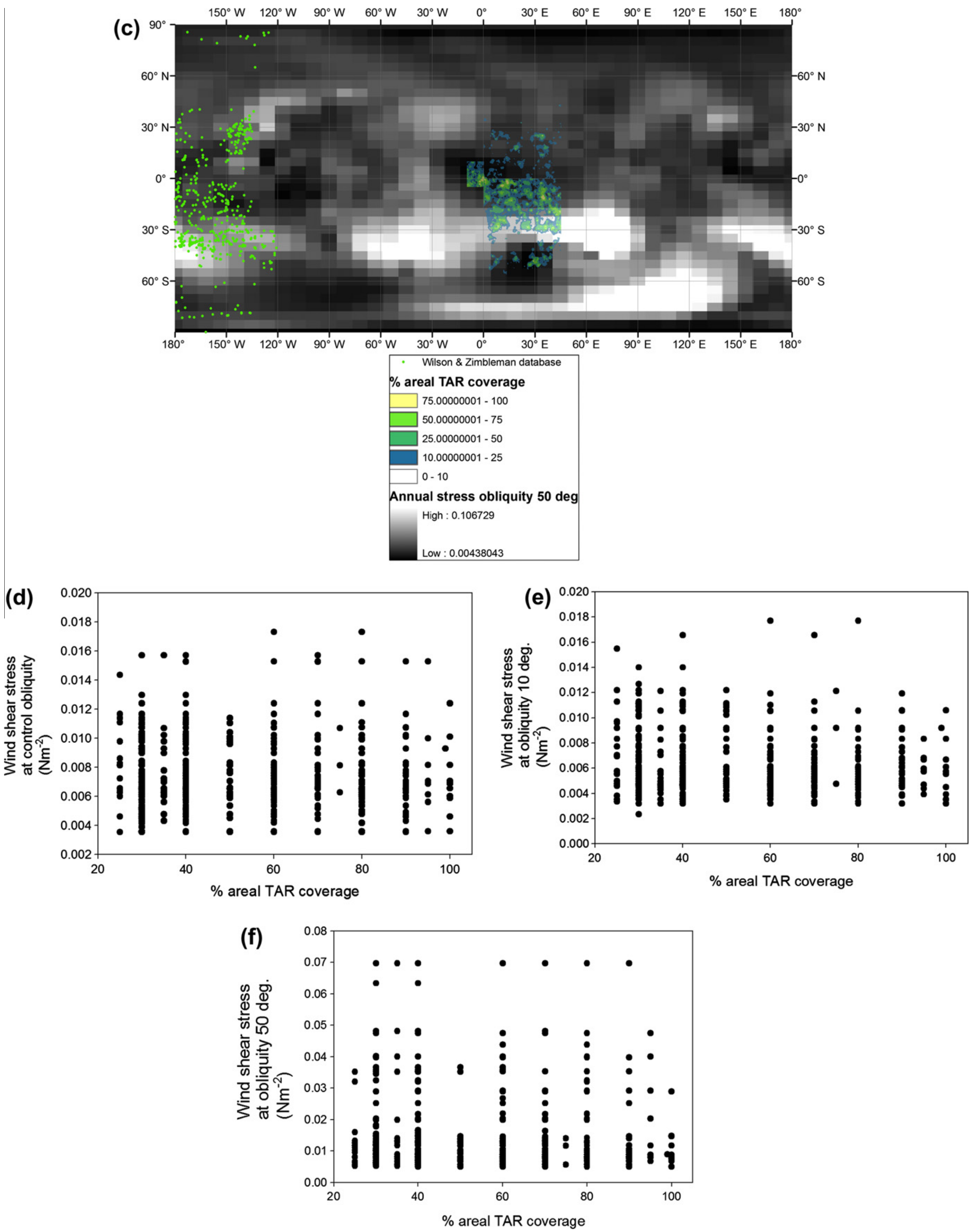

Fig. 12 (*continued*)

TAR formation: if the mantle is mainly composed of dust and ice, then liberated surface sediments would not tend to move in saltation, could not then form bedforms like TARs, and instead would either gather as a lag or be removed by wind and transported great distances in suspension. Finally, we note that most TARs appear to be geologically very young, as does the mantling material (perhaps associated with the most recent obliquity variations; Kreslavsky and Head, 2002), so it is plausible that mid-to high latitude TARs have simply been buried by the mantle, and few TARs have since formed within it or migrated onto it.

A second possibility is that TAR distribution simply reflects the lithology of the underlying geology and the availability of suitable sediments. TARs tend to be found on crater floors, adjacent to steep slopes, and in regions containing layered terrains (Fig. 4a and b). This implies that weathering or erosion of steep, layered terrains is the main source of TAR materials and that TARs are associated with local geology and have not moved great distances from their sediment sources. In areas with substantial layered terrains (e.g., Meridiani, Schiaparreli) TARs seem to be forming in situ: the source of the TAR sediments is the underlying layered rock. We note that the observations of large ripple-like landforms in the MER Opportunity site are consistent with our remote sensing observations – TARs have formed here in such great numbers because the local substrate is an aeolian sedimentary deposit that is liberating sand-grade materials as it is eroded (Squyres et al., 2009). Further, because we find that in the mid-latitudes TARs are generally found at the level of 5–10% areal cover anywhere where there are local steep slopes, we speculate that mass wasting deposits from steep slopes provides enough material for this "background" TAR distribution. We further suggest that the lack of TARs in the northern hemisphere reflects the paucity of steep slopes here due to the lack of large impact craters. This would have two effects: (i) because craters are more subdued in the north, they provide less of a sink for TAR sediments to accumulate in, (ii) the lack of steep slopes means fewer mass wasting events and a reduced availability of debris deposits that could be reworked to form TARs.

A third possibility is that TARs can only form where wind shears are appropriate and that it is the regional wind regime that controls the distribution of TARs, rather than the lithology or sediment supply. This is not borne out by our results. TAR distribution did not match well with modeled wind stress values at any obliquity, although we found good correlation between TAR orientations and regional wind directions. This suggests that the strength of the winds is not a primary control on the global distribution of TARs.

5.2. TAR age/activity

The associations with, and superposition relationships between, LDDs in the southern highland craters suggest that, in this setting, there is either a common sediment source for the two landforms, or that the TARs form from pre-existing LDD deposits. The TAR/LDDs superposition results and derived ages from crater counts suggest that TARs are only young (or active) when associated with large dune fields. This is consistent with an interpretation that TARs are granule ripples (Balme et al., 2008a) that are only active if they have a constant supply of high energy saltating material that can mobilize the granules; i.e., active TARs require the presence of LDDs. The granule ripple hypothesis is also consistent with morphologic observations of TARs, as they are generally symmetrical, lack a steep slipface, and are relatively small. MER observations of a granule coating on TAR-like forms are also consistent with the idea that they are granule ripples (Sullivan et al., 2005, 2007). Zimbelman (2010) also concluded that TARs < 0.5 m in height are most likely granule ripples, based on topographic profiles measured from photoclinometry in HiRISE images, although Zimbelman does suggest that larger TARs could be reversing dunes.

5.3. Controls on TAR formation

TAR-forming wind orientations match the GCM directions better in the equatorial and southern regions than in the northern region. Possible explanations for this include: (1) the GCM is inaccurate in the North; (2) measured TAR orientations were not as topographically independent as they might have been; (3) TARs in the north respond more to regional or non-dominant winds that cannot be resolved in the coarse GCM; and/or (4) TARs in the north are paleofeatures that do not reflect any of the recent wind regimes we have modeled. Higher resolution mesoscale atmospheric models would be useful for constraining the effects of local topography.

TAR-producing winds appear to match most closely with present day obliquity conditions. From this we conclude that TARs formed under wind conditions similar to today's, and that local geological factors rather than regional wind conditions determine the distribution of TARs on Mars (although the regional wind regime does appear to control the orientation in which TARs form and thus their local direction of migration). In addition, TAR-producing sediments appear to be derived locally, either from nearby layered terrains, or from large dark dunes. To summarize, the TAR distribution appears to be sediment supply controlled, rather than wind-controlled.

6. Conclusions

(1) TARs are widespread on Mars and are found at low to mid-latitudes in the northern and southern hemispheres. There is no clear correlation between TAR distribution and any of thermal inertia, km-scale roughness, or elevation (although TARs generally are not found at extremes of elevation).
(2) TARs in the equatorial band are usually associated with layered terrain. TARs in the southern hemisphere are associated with LDDs in craters. Distinct barchan-like TAR forms in Meridiani and in other equatorial regions may indicate a specifics source lithology (ancient aeolian sandstones).
(3) TARs are older than large dark dunes in the north, but younger in the south. Equatorial TARs often appear to be old or inactive. We conclude that TARs form over geologic history.
(4) TARs appear only to be active when associated with large dunefields. This is consistent with an interpretation that at least some TARs may be granule ripples that are only active if they have a constant supply of saltating material
(5) There is no evidence that TAR distribution correlates with GCM wind shear stress data. There are, however, good correlations with TAR orientations for current obliquity.
(6) TAR deposits are formed from locally derived sediments and have not travelled great distances from discrete regional sources (see also Thomas et al., 1999).

7. Future work

We would like to go deeper in our comparison of TARs with climate through the use of mesoscale, rather than global, atmospheric models, and in comparison of TARs with regional rather than global datasets such as topography, thermal inertia, etc. The use of very high resolution datasets could also help advance our understanding of TARs. Zimbelman (2010) used photometric methods and new HiRISE images to obtain such data, finding that TARs are most similar in profile shape to terrestrial granule ripples but much taller with respect to wavelength. We propose to use HiRISE data to explore these issues further, especially in terms of comparing profiles of TARs with terrestrial data for small dunes and large ripples.

Suggested future avenues of research include:

(1) *Determine better what factors control the morphology and morphometry of TARs*. Local to regional studies of sediment sources, climate, and local topography/geology as potential factors are required, including a limited number of meso-scale circulations to test the influence of local topographic features on wind stress and wind direction in relation to TAR orientation. This will help to constrain potential formation mechanisms.
(2) *Determine the composition (and explore the variability in composition) of the materials that compose TARs*. High-resolution thermal spectrometry to investigate the composition of TARs appears to be the best methodology to do this. In particular, links between composition and sediment source should be studied, and the variability of TAR composition as a function of different morphologies and geological settings investigated.
(3) *Investigate formation ages of TARs and TAR fields, and how they move and evolve over time*. We have begun to ask whether TARs are forming under current climate conditions, or if they are indurated/cemented and thus indicators of past climates. We suggest that two approaches could be used to explore the mobility of TARs: first, to explore how TARs evolve under the current climate regime, time series high-resolution images could be studied to search for changes in morphology and position of TARs with time (similar work has been successful in finding movement of sub-TAR scale ripples on the back of LDDs; Silvestro et al., 2010). Second, many more crater counts investigations are required to determine when TARs and TAR fields were last active.
(4) *Explore the links between TARs and large dark dunes (LDDs)*. The compositions, crater count ages and morphologies of both TARs that are proximal to and TARs that are distal to LDDs should be compared. The hypothesis that LDDs provide a sediment source (or that the two are linked by a single source) for TARs could then be tested. Thermal spectroscopy data of TARs and LDD should be used to investigate whether they are composed of the same materials.

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