Interactions between boulders and aeolian ridges on Mars

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1 | INTRODUCTION

1.1 | Aeolian ridges on Mars

Transverse aeolian ridges (TARs) are bright linear aeolian bedforms first observed and detected in Mars Orbiter Camera (MOC) (Malin & Edgett, 2001) images (Balme et al., 2008; Berman et al., 2011; Wilson & Zimbelman, 2004). Thought to be relict features, TARs are widespread on Mars but their role in Martian sedimentary cycles is poorly understood, and their origins remain unclear (Balme et al., 2008; Berman et al., 2011; Bridges et al., 2012; Chojnacki et al., 2015; Geissler, 2014; Geissler & Wilgus, 2017). Although the overwhelming majority of the literature suggests most TARs are immobile (Berman et al., 2018; Bridges et al., 2013; Fenton et al., 2003; Reis et al., 2004), a recent study found that some TARs are active over multi-year periods (Silvestro et al., 2020).

TARs can be morphometrically similar to both ripples and dunes. Most TARs are nearly symmetrical in profile, comparable to large ripples or very small reversing dunes (Shockey & Zimbelman, 2013; Zimbelman & Williams, 2007). TARs similarly occupy a middle ground between ripples and dunes in terms of wavelength. They are typically on the order of tens of metres; larger than impact ripples on Mars or Earth (typically decimetres but smaller than dunes (high decimetres to hundreds of metres when fully developed) (Bourke et al., 2006; Lapotre et al., 2016; Leeder, 1982; Milana, 2009; Williams, 2002; Wilson, 2003). Further, TARs can be observed in locations prohibitive to reversing wind patterns (e.g. TARs within large fields of asymmetrical dunes as in this study). Many studies have identified TAR proxies on Earth: gravel megaripples in Argentina (de Silva et al., 2013; Hugenholtz et al., 2015), megaripples in Iran and Libya (Foroutan & Zimbelman, 2016; Foroutan et al., 2019; Gough et al., 2020; Hugenholtz & Barchyn, 2017), and reversing dunes in Idaho (Zimbelman & Scheidt, 2014), but a definitive terrestrial analogue has not been determined.

Martian aeolian features lie on a continuum that does not lend itself to easy discrimination between classes. There is strong and growing evidence of overlapping amplitude and wavelength characteristics between various types of aeolian features on Mars (Lapotre et al., 2016). For example, such overlap occurs between active ripples and inactive course-grained ripples (Silvestro et al., 2010; Sullivan et al., 2008), between large ripples and TARs (Geissler & Wilgus, 2017; Hugenholtz et al., 2017), and between active megaripples and TARs (Chojnacki et al., 2019; Fenton et al., 2021; Silvestro et al., 2020). For this study, we draw a distinction between apparently inactive bright-toned ridges with wavelengths of ~10 m (referred to here as TARs) and smaller inactive dark-toned ridges with wavelengths of <10 m (inferred to be ripples based on this study).

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Crater counting is currently the best method for calculating surface ages on planetary bodies (Benedix et al., 2020; Hartmann, 2005; Hartmann & Daubar, 2017; Hartmann & Neukum, 2001; Shoemaker, 1961; Shoemaker & Hackman, 1962). A study of TARs using Mars Orbiter Camera data found sparse cratering on the large TARs in Nirgal Vallis, concluding that the TARs were 300 ka–1.4 Ma in age (Reiss et al., 2004). A survey of uncratered TAR fields (those with no craters 5–10 m in diameter) versus cratered TAR fields estimated that the uncratered fields were ~100 ka old, while the cratered fields were 1–3 Ma old (Berman et al., 2011). Similarly, in-situ studies by the Opportunity Rover of cratering in large ripples found that even relatively small aeolian bedforms could be preserved for tens or even a few hundred thousand years (Golombek et al., 2010). No craters have been identified in well-documented dune fields, but crater-retention estimates and superpositioning over Amazonian surface puts the age of most Martian dune fields at 100–8 Ma in the southern highlands and 3 Ga–8 Ma at higher latitudes (Fenton & Hayward, 2010).

The lengthy duration of these aeolian features on the Martian surface offers an opportunity to examine the atmospheric past to different degrees (Fenton et al., 2003, 2005). Given a much slower resurfacing rate as compared to Earth, even small Martian bedforms offer insight that extends one to two orders of magnitude further back into the past than can be found on Earth, where our observations are limited to dune fields dating approximately to the Last Glacial Maximum (31–16 kya) (Beveridge et al., 2006; Kocurek, 1991; Lancaster et al., 2003; Wolfe et al., 2004).

Here we document previously undescribed patterns in small aeolian features in three boulder fields in and around the Proctor Crater region on Mars and use comparative analyses to analyse similar areas on Mars. While absolute dating is unavailable for the features in this area, by inferring the corresponding past flow regimes in the boulder fields we can deduce and interpret some of the governing flow during ridge development. These findings are promising examples of how studies of aeolian features present on Mars today can be used to infer some of the flow conditions that shaped the target features.

In the remainder of this Introduction, we give a brief overview of surface roughness dynamics and lee-side topographic features. In our Methods section we describe how we extracted boulder and ridge characteristics. In our Results section, we (1) summarize the ridge characteristics of the study sites, (2) compare the boulder distributions between the sites, (3) compare the ridge orientations and spacings interior and exterior to the boulder fields, and (4) describe and illustrate unusual fan-like downflow features on some of the ridges. In our discussion, we explore inferences about the formative conditions for each of the study sites, outline the novelty of the fan features, and finally confirm that the ridges were inactive in our study sites.

1.1.1 | Roughness density

We observe the effects of locally varying roughness density (λ) on aeolian ridges by comparing ridges in boulder fields to adjacent ridges without boulders. We can thus infer the flow regime that may have dominated when the ridges were still active in the past, and hypothesize some of the formative mechanisms at work. A change in roughness density affects aerodynamic roughness length (z0): the length scale at which a wind speed profile can be accurately approximated by a logarithmic function (Charru et al., 2013; Raupach, 1992; Raupach et al., 1993). We examine these effects through the lens of three possible flow regimes depending on the roughness density (Lee & Soliman, 1977; Wolfe & Nickling, 1993): (1) isolated roughness flow, where individual turbulent airflow wakes are shed from roughness elements and do not impinge on advancing elements; (2) wake interference flow, where airflow wakes overlap and interfere with each other; and (3) skimming flow, where wake regions completely overlap across the surface, creating stable vortices between the roughness elements, causing the wind to seemingly pass smoothly above the roughness elements (Lee & Soliman, 1977; Raupach, 1992; Raupach et al., 1993).

The three flow regimes can be characterized by the ratio of z0 to roughness element height (z0/h) (Raupach, 1992; Raupach et al., 1993), hereafter referred to as Λ. Isolated roughness flow

FIGURE 1  Simplified diagrams of well-documented lee-side features (red) downflow of obstacles (yellow). Left: An isolated obstacle such as a shrub or rock. Right: A linear feature such as a dune. Note that the lee-side features have a single central crest and come to one point [Color figure can be viewed at wileyonlinelibrary.com]
occurs when $\Lambda$ is relatively low. As roughness element density increases, $\Lambda$ increases to higher values distinctive of wake interference flow. As roughness elements become even more tightly packed, initiating the formation of a new surface, $\Lambda$ decreases to a stable intermediate value typical of the new skimming flow regime (Charru et al., 2013; Raupach, 1992; Raupach et al., 1993).

1.1.2 Lee-side topographic features

Here we also document unusual ‘wakes’ in ripples downwind of some boulders in Proctor Crater. These wakes have multiple tails, a pattern we believe has not been documented either on Earth or in simulations of aeolian or fluvial flows. While significant research has been conducted relative to features formed downflow of obstructions due to horizontal and/or vertical flow separation, the findings of these studies can be difficult to correlate across spatial and temporal scales. This is primarily due to changes in terminology: ‘umbracer dunes’ (Melton, 1940), ‘micro-dunes’ (Pidgeon, 1940), ‘embryo dunes’ (Salisbury, 1952), ‘tongue hills’ (Cooper, 1958), ‘shadow dunes’ (Hesp, 1981; Hesp & Hyde, 1978), and others (Hesp & Smyth, 2017; McKenna Neuman & Bédard, 2015; McKenna Neuman et al., 2013). These studies universally document either elongate pyramidal bedforms or single-tail flow patterns behind various obstacles.

![Figure 2](https://example.com/figure2.png)  
*Figure 2*  HiRISE observations for study site details; north is up in all images. Basemap: Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) digital elevation model 463 m v2 data and Mars nomenclature via USGS. All HiRISE images © NASA/JPL/University of Arizona [Color figure can be viewed at wileyonlinelibrary.com]
under stable conditions (Figure 1). Both the bedform and the flow pattern are generated by the reconvergence of the flow after separation by the obstruction (Hesp, 1981; Hesp & Smyth, 2017; Hesp et al., 2015; McKenna Neuman & Bédard, 2015; McKenna Neuman et al., 2013). This phenomenon has been documented in a variety of environments and flows: in numerical simulations (Kuo et al., 2007; Rapaport & Clementi, 1986), in aqueous flow around boulders (Tritico & Hotchkiss, 2005), in stranded ice blocks (Russell, 1993), porous obstructions (Chen et al., 2012; Zong & Nepf, 2012), vegetation (Tanaka & Yagisawa, 2010; Tsujimoto, 1999), and other solid obstacles (Sousa, 2002), and in aeolian flow around vegetation (Hesp, 1981; Mayaud et al., 2016; Yang et al., 2019), over dunes (Gunatilaka & Mwango, 1989), hills (Xiao et al., 2015), and even ripples (Swanson et al., 2018). The wake morphology documented in the aforementioned literature does not follow the general morphology documented in this study, as illustrated in Figure 1.

2 | METHODS

We documented surface features with observations made at three sites: two fields in Proctor Crater and a field in an unnamed area to the northeast of Proctor Crater (Figure 2, Table 1). Georeferenced High-Resolution Imaging Science Experiment (HiRISE) images (McEwen et al., 2007) were analysed in ArcGIS Pro (ESRI, 2020). A sub-area from each image was selected for closer examination (Figure 2). Each study area contains large dark dunes that have been well documented and described in the literature (Fenton & Mellon, 2006; Fenton et al., 2003, 2005; Jackson et al., 2015; Taniguchi & Endo, 2007). These dune fields contain a range of TAR morphologies, and extensive boulder fields (Figure 3). TAR wavelength, ridge–crest length, and width were extracted using the distance measurement tool in ArcGIS Pro (ESRI, 2020). Using standards defined in Balme et al. (2008), width is measured as the total linear distance of a ridge; measured end-to-end along the average orientation of the ridge, length is the maximum distance perpendicular from toe to toe across a given ridge crest; wavelength is the spacing between ridge crests as measured perpendicular from the centre of the ridge (Figure 4).

### Extracting boulder sizes

Measurements were also taken of the boulder fields in the study areas. Clasts larger than 0.5 m² in diameter were extracted using an approach developed by Nagle-McNaughton et al. (2020), where boulders can be digitized by thresholding brightness values in HiRISE images (Nagle-McNaughton et al., 2020). This method is feasible because boulders are typically brighter in HiRISE imagery than their surroundings. Boulder dimensions (length, width, area) can be found by isolating the pixel values that are almost exclusively produced by boulder reflection, and then generating outlines for bright groups of pixels (convex-hulled polygons in this case) (Nagle-McNaughton et al., 2020). Smaller detections are ambiguous, so all detections with an area of 0.5 m² or smaller were masked out of the database. We note that shadows have helped detect boulders previously (Golombek et al., 2009, 2012; Matthies et al., 2007; Nagle-McNaughton et al., 2020), but the boulders in our study areas can be buried such that they do not cast useful shadows (Figure 5).

The HiRISE images in this study had 10-bit radiometric resolutions corresponding to pixel values ranging from 0 to 1,023. Using our approach (Nagle-McNaughton et al., 2020), a range of threshold values were iteratively tested for each location, emphasizing false-negative detections over false-positive detections. Due to minor differences in the lighting in the source HiRISE images, the final thresholds were 650 for Site 1, 625 for Site 2, and 600 for Site 3 (Figure 5).
3 | RESULTS

3.1 | Characteristics of the three study areas

Site 1 exhibits the smallest and most regular ridges, likely impact ripples based on their size and spacing (Table 2, Figure 6). TAR lengths at Site 2 were highly irregular, likely the result of sand in-fill of the area (Table 2, Figure 7) (Fenton et al., 2003). Sites 2 and 3 exhibit similar TAR wavelengths and lengths, but different widths (Table 2). However, the TARs at Site 3 are highly sinuous (Figure 8), with bends approximately every 3–6 m, and have notably greater amplitudes than those at Sites 1 or 2 and are usually taller and larger than the boulders based on shadow length comparisons. Ridges in all three study areas had prominent and well-developed secondary ridges; smaller crests that form near perpendicular to main ridges (Lapotre et al., 2016). Secondary ridges extend crest to crest throughout Sites 1 and 2 (Figures 6 and 7), and in most locations at Site 3 (Figure 8).

3.2 | Boulder distributions

The three study areas required different thresholds for effective extraction of boulder pixels given the slightly different lighting conditions in each scene. Rare cases of false-positive detections of bright ridge crests occurred and were especially evident at Site 2 (Figure 9). However, these false positives are greatly outnumbered by the false-negative detections of boulders, and the overall undercount of boulder pixels throughout the images (Figure 9). The boulder areas were likely systematically underestimated in each area, but this bias should not affect relative comparisons across the regions. Further, the boulder count frequency plots shown in Figure 10 should thus be considered minimum values.

Sites 1 and 2 contained similar boulder morphologies in terms of their typical widths, lengths, and areas, while Site 3 generally contained smaller and less elongate boulders (Table 3, Figure 10).

It is useful to compare Site 2 to the other two study sites: Site 2 contains boulders that are similar to those found at Site 1, and TARs that are similar in size and wavelength to those found at Site 3 (Figure 10, Table 3). Thus, both variables (ridge size and boulder field) can be observed; different ridge sizes can be examined with similar boulder fields (Site 1 vs. Site 2), and different boulder fields can be examined with similar ridges (Site 2 vs. Site 3).
3.3 | Ridge geometry

The orientations of the TARs at Sites 2 and 3 were consistent within a small range (340°–350° and 350°–10°, respectively), regardless of the presence or absence of boulders. Ridge orientations in Site 1 were substantially more difficult to measure as many of the crests formed long arcs. Because of this variability, we can only characterize an orientation range from 330° to 25° in the western area of Site 1.

Site 1 appeared to be affected by the presence of roughness elements (boulders). The wavelengths within the boulder field at Site 1 were 1.3 m shorter than those to the west where no boulders were present (Table 4, Figure 6). This is a difference of ~30%, or more than six standard deviations different from the exterior field. The wavelengths interior to the boulder field were also less regular, with a standard deviation seven times larger than those exterior to the boulder field. The shortened wavelengths suggest that drag from the boulders decreased the local wind velocity, and the greater variability in wavelengths inside the boulder field is indicative of increased turbulence. In contrast, the TARs at Site 3 were not affected by the roughness of the boulder field: wavelengths differed by less than 3% between the boulder-free area and the boulder field (Table 4).

3.4 | Unusual ‘wakes’ behind boulders

At Site 1, within the boulder field, the ridges formed multi-armed fan-shaped wakes to the east–northeast of large boulders, opposite the inferred wind direction (Figure 11). Outside the boulder field the ridges form long, continuous, slightly arcing crests. The divergent wakes are typically ~10 m long and deviate from the prevailing local ridge orientation by up to 90° (Figure 12).

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**Table 2** The wavelengths, lengths, and widths for n samples in each study area. Mean and median statistics are presented for each characteristic. Note that the ridges in Site 1 are much smaller by every metric.

| Site | Mean wavelength (m) | Median wavelength (m) | Mean width (m) | Median width (m) | Mean length (m) | Median length (m) |
|------|---------------------|-----------------------|----------------|------------------|-----------------|------------------|
| 1    | 4.1                 | 4.1                   | 41             | 37               | 1.2             | 1.1              |
|      | n = 110             |                       |                |                  |                 |                  |
| 2    | 13.8                | 13.6                  | 78             | 69               | 4.4             | 3.9              |
|      | n = 117             |                       |                |                  |                 |                  |
| 3    | 12.6                | 12.6                  | 97             | 78               | 7.9             | 7.8              |
|      | n = 128             |                       |                |                  |                 |                  |
FIGURE 7  (a) Site 2. Characterized by forked TARs with highly variable widths (i.e. the cross-crest distance west–southwest to east–northeast). Note the dark sand mantling secondary ridges and general absence of boulder shadows that are likely due to sand in-fill. (b) Detailed ridge morphology. Note the larger wavelength and ridge length compared to Site 1. An example of the primary ridge crest is in red, and a secondary crest in yellow (PSP_004077_1325) [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 8  (a) Site 3. The boulder field is to the right (east) of the purple line. Note the high degree of TAR sinuosity. The blue extent indicator marks the TAR annotated in Figure 4. (b) Detailed ridge morphology. Note the steep ridge flanks and greater amplitude than those at Site 2. An example of the primary ridge crest is in red, and a secondary crest in yellow (ESP_011909_1320) [Color figure can be viewed at wileyonlinelibrary.com]
4.1 Morphological responses to changes in roughness density

The boulders at Site 1 likely disrupted the local airflow by changing the roughness density within the boulder field, causing the wakes and more broadly, less uniform bedform orientations. Based on their size and observed changes, the boulders themselves are likely responsible for altering the aerodynamic roughness length. Ridges within the boulder field at Site 1 likely formed under a wake interference flow regime. \( z_0 \) peaks when roughness elements (in this case, boulders) are spaced approximately twice their diameter apart (Greeley & Iversen, 1987), and the boulders at Site 1 are separated by two to three times the average boulder length of \( \sim 3 \) m (Table 3). Further, many of the boulder wakes can be observed overlapping and interfering, a characteristic of wake interference flow (Wolfe & Nickling, 1993).

Although a combination of conditions likely plays a role, based on our observations, flow separation and deceleration caused by the boulder field likely caused the decrease in wavelength at Site 1. This is

| Site | Total number of boulders | Mean boulder area (m²) | Median boulder area (m²) | Mean boulder length (m) | Median boulder length (m) | Mean boulder width (m) | Median boulder width (m) |
|------|---------------------------|------------------------|--------------------------|-------------------------|--------------------------|-----------------------|------------------------|
| 1    | 1947                      | 6.33                   | 3.38                     | 3.37                    | 2.83                     | 1.97                  | 1.50                   |
| 2    | 1955                      | 6.25                   | 3.16                     | 3.26                    | 2.65                     | 1.92                  | 1.50                   |
| 3    | 4090                      | 2.88                   | 1.86                     | 2.37                    | 2.12                     | 1.40                  | 1.00                   |

| Site | Median wavelength | Standard deviation | Interior to boulder field (m) | Standard deviation | Change |
|------|-------------------|---------------------|-------------------------------|-------------------|--------|
| 1    | 4.1 (n = 110)     | 0.2                 | 2.8 (n = 89)                  | 1.4               | 32%    |
| 2    | N/A               |                     | 13.6 (n = 117)               | 4.4               | N/A    |
| 3    | 12.6 (n = 128)    | 2.1                 | 12.3 (n = 102)               | 4.3               | 2.4%   |
consistent with the longstanding observation that wind speed and ripple spacing are proportional (Anderson, 1987; Goossens, 1991; Nishimori & Ouchi, 1993; Sharp, 1963). Further, the spatially rapid change in wavelength over short spatial scales at Site 1 is characteristic of saltation, the principle formative mechanism of ripples. Other sediment transport mechanisms such as suspension, which operate over longer distances, are unlikely to alter bedform wavelengths by 30% over a span of just a few wavelengths. We thus
interpret this deceleration as evidence that the ridges are large ripples formed via saltation within the lower boundary layer.

Unlike Site 1, the wavelengths at Site 3 did not meaningfully change between the barren area and the boulder field. The Site 3 TARs likely developed under a skimming flow regime where the more tightly packed boulders and the TARs themselves contributed to an already high roughness density. Given that the TARs at Site 3 do not appear to respond to changes in the roughness density caused by the boulder field, the TARs could be (1) too large relative to the boulders to be affected by changes in boulder distribution and/or (2) unaffected by the processes that decreased the saltation length that generated shorter ripple wavelengths in Site 1.

4.2 Implications of the ‘wakes’

At present, Site 1 is the only area where wakes have been well documented. However, more comprehensive surveys looking for this type of feature may be fruitful, particularly in areas with ongoing sediment transport (i.e. proximal to sand dunes) and with boulders or other obstacles. Several similar morphologies from other locations are shown in Figure 13.

The multi-armed wakes downwind of boulders are extremely unusual surficial features with no analogue in the literature to the authors’ knowledge. As described above, an obstacle in steady flow near universally results in single-pointed features as the flow converges or reattaches behind the obstacle (Cooper, 1958; Hesp, 1981; Hesp & Hyde, 1978; McKenna Neuman & Bédard, 2015; McKenna Neuman et al., 2013; Melton, 1940; Pidgeon, 1940; Salisbury, 1952). The wakes suggest that there is an interruption to this convergence of the flow. We hypothesize that an interaction between pre-existing ridges and the flow separation around the obstacles interrupted the convergence of the flow, and generated the boulder wakes (Figure 14). Why this process would be undocumented on Earth or in numerical simulations remains unclear and warrants further study.

We interpret the wakes at Site 1 as further evidence that the features are ripples. The small length scale of these interactions, just a metre or two, is highly suggestive of ripple-like dynamics. Further, given our proposed formation process, the rapid temporal response of ripples to changes in flow conditions is more plausible than a dune-like formation.

4.3 No detected TAR activation

Recent research has suggested that some TARs may still be active on Mars, with migration rates of ~0.13 m/year as measured over 8–10 Earth years (Silvestro et al., 2020). Active TARs are likely to be found in areas with moving dunes, where dune-sourced saltating grains have been hypothesized as enabling TAR activation and migration via impact creep (Anderson, 1987; Berman et al., 2011; Kok et al., 2012; Mladenoff et al., 1997; Swet et al., 2019).

Change-detection methods similar to those of Silvestro et al. (2020) can be applied to the three boulder sites in this study.

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**Figure 13** Examples of possible wake-like morphologies. Yellow arrows mark the wake-initiating object and indicate the inferred flow direction. (a) Examples of boulder wakes interrupting the regular ridge crests elsewhere in Proctor Crater (PSP_006806_1,365). (b) Boulder generating a multi-armed wake in field TARs that is quickly recaptured by the downflow crests (ESP_016036_1370). (c) Partially buried boulder (top arrow) generates a wake, while a clearly protruding boulder creates a smaller one (bottom arrow) (ESP_029500_1330). (d) A large outcrop generates a very faint potential wake in typical Martian ripples (ESP_067135_1275). Coordinates mark the centre of each image [Color figure can be viewed at wileyonlinelibrary.com]
to establish the activity or inactivity of TARs. Within the images, the boulders themselves are useful anchor points for detecting any relative movement, as well as potential ongoing boulder–wake interactions. A preliminary visual test of the available elevation-corrected ortho images of the area (PSP_003800_1325) did not reveal any changes in the TARs. There is a slight increase in TAR albedo over the 11 and 13-year periods, likely due to increased dust mantling.

Previous work has concluded that Proctor Crater experienced significant aeolian erosion in the past, and continues to be shaped by aeolian processes (Fenton et al., 2003). The visibility of the fractured boulders in the TAR fields at Sites 2 and 3 indicates that several hundred metres of sediment were likely eroded from these sites, and ongoing dune and ripple movement illustrates the ongoing evolution in these areas (Fenton et al., 2003, 2005; Jackson et al., 2015). Both Sites 2 and 3 are excellent candidates for more rigorous change-detection studies as they have already been imaged repeatedly. Site 2 has eight images taken over 11 years (2007–2018), and Site 3 has 22 images taken over 13 years (2007–2020). Sites 2 and 3 would thus be ideal for further study because ongoing saltation and sediment transport are likely a requirement for TAR activation (Berman et al., 2011; Silvestro et al., 2020), and the TARs in these two sites are surrounded by active dunes.

5 | CONCLUSION

Here we observed TARs and ripples in three locations in and near Proctor Crater with boulder fields to infer some properties of their formative flow regimes. Characteristics of the boulder fields and aeolian forms at each of the sites were documented and analysed. Site 1 contained ripples, while Sites 2 and 3 contained TARs. Sites 1 and 2 had similar boulder distributions, and Sites 2 and 3 had similar TARs. The ripples at Site 1 decreased in wavelength by ~30% within the boulder field, indicating that the ripples likely formed under a wake interference flow regime as the boulders disrupted the local wind. Conversely, the larger TARs at Site 3 did not have any systematic difference within or exterior to the boulder field, suggesting a flow regime that skimmed over the combined roughness elements of the boulders and TARs themselves. None of the aeolian features observed in our study locations showed any movement during the course of this study, we also documented unusual multi-armed ‘wakes’ at Site 1 that have no analogue on Earth. The exact formative process of these downflow forms should be explored in future theoretical and empirical studies.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All data are publicly available imagery. Thanks to NASA/JPL/University of Arizona.

FIGURE 14 A conceptual model for wake formation. (a) Standard flow lines similar to those in Figure 1 (thick black arrows) around an obstacle (yellow) and subsequence arch vortex generation (dashed black arrows) (Pattenden et al., 2005). (b) Transverse flow moves the bedforms (crests in red) downflow (red arrows). (c) Erosion in the area exposes an obstacle (yellow) and the flow is diverted around the obstacle. The horseshoe and arch vortices are deflected by the downflow ridge (blue dashed arrows), and the ridge is pulled upflow behind the obstacle and downflow to either side by the deflected flow. (d) The ridge is bent into the V shape more characteristic of the observed wakes (e.g. see Figure 13D). The deflected flow still does not converge and a similar downflow push and central upflow pull affects the next ridge. Over time, small asymmetries in the ridges or the obstacle might cause wake arms to move at different rates, merge, and create the irregular fan shapes observed in Figure 12. [Color figure can be viewed at wileyonlinelibrary.com]
REFERENCES

Anderson, R.S. (1987) A theoretical model for aeolian impact ripples. Sedimentology, 34, 943–956.

Balme, M., Berman, D.C., Bourke, M.C. & Zimbelman, J.R. (2008) Transverse aeolian ridges (TARs) on Mars. Geomorphology, 101, 703–720. https://doi.org/10.1016/j.geomorph.2008.03.011

Benedix, G.K., Lagain, A., Chai, K., Meka, S., Anderson, S., Norman, C., et al. (2020) Deriving surface ages on Mars using automated crater counting. Earth and Space Science, 7, e2019EA001005. https://doi.org/10.1029/2019EA001005

Berman, D.C., Balme, M.R., Michaels, J.R., Clark, S.C. & Joseph, E.C.S. (2011) Transverse aeolian ridges on Mars: Morphology, aeolian inactivity, and climate change. Geomorphology, 121(1–2), 98–121. https://doi.org/10.1016/j.geomorph.2009.11.006

Fenton, L.K. & Mellon, M.T. (2006) Thermal properties of sand from Thermal Emission Spectrometer (TES) and Thermal Emission Imaging System (THEMIS): Spatial variations within the Proctor Crater dune field on Mars. Journal of Geophysical Research E: Planets, 111(E6), 1–7. https://doi.org/10.1029/2004JE002363

Fenton, L.K., Silvestro, S. & Kocurek, G. (2021) Transverse aeolian ridge growth mechanisms and pattern evolution in Scandia Cavi, Mars. Frontiers in Earth Science, 8, 1–17. https://doi.org/10.3389/feart.2020.619704

Fenton, L.K., Toigo, A.D. & Richardson, M.J. (2005) Aeolian processes in Proctor Crater on Mars: Mesoscale modeling of dune-forming winds. Journal of Geophysical Research E: Planets, 110(E6), 1–18. https://doi.org/10.1029/2004JE002309

Foroutan, M., Steinnett, G., Zimbelman, J.R. & Duguay, C.R. (2019) Megaripples at Wau-an-Namus, Libya: A new analog for similar features on Mars. Icarus, 319, 840–851. https://doi.org/10.1016/j.icarus.2018.10.021

Foroutan, M. & Zimbelman, J.R. (2016) Mega-ripples in Iran: A new analog for transverse aeolian ridges on Mars. Icarus, 274, 99–105. https://doi.org/10.1016/j.icarus.2016.03.025

Geisler, P.E. (2014) The birth and death of transverse aeolian ridges on Mars. Journal of Geophysical Research Planets, 119, 2583–2599. https://doi.org/10.1002/2014JE004633

Geisler, P.E. & Wilgus, J.T. (2017) The morphology of transverse aeolian ridges on Mars. Aeolian Research, 26, 63–71. https://doi.org/10.1016/j.aegeo.2016.08.008

Golombok, M., Huertas, A., Kipp, D. & Calef, F. (2012) Detection and characterization of rocks and rock size–frequency distributions at the final four Mars Science Laboratory landing sites. Mars, 7, 1–22. https://doi.org/10.1555/mars.2012.0001

Golombok, M., Robinson, K., McEwen, A., Bridges, N., Ivanov, B., Tornabene, L. & Sullivan, R. (2010) Constraints on ripple migration at Meridiani Planum from opportunity and HiRISE observations of fresh craters. Journal of Geophysical Research E: Planets, 115, 1–34. https://doi.org/10.1029/2010JE003628

Golombok, M.P., Huertas, A., Marlow, J., McGrane, B., Klein, C., Martinez, M., et al. (2009) Size–frequency distributions of rocks on the northern plains of Mars with special reference to Phoenix landing surfaces. Journal of Geophysical Research E: Planets, 114, https://doi.org/10.1029/2007JE003065

Goossens, D. (1991) Aeolian dust ripples: Their occurrence, morphometrical characteristics, dynamics and origin. Catena, 18(3–4), 379–407. https://doi.org/10.1016/0341-8162(91)90033-T

Gough, T., Hugenholtz, C. & Barchyn, T. (2020) Eolian megaripple stripes. Geology, 48(11), 1067–1071. https://doi.org/10.1130/G47460.1

Greeley, R. & Iversen, J.D. (1987) Wind as a geological process: On Earth, Mars, Venus and Titan. Cambridge: Cambridge University Press.

Gunatiaka, A. & Mwango, S.B. (1989) Flow separation and the internal structure of shadow dunes. Water Resources Research, 48, 1–12. https://doi.org/10.1029/2012WR012224

Chojnacki, M., Banks, M.E., Fenton, L.K. & Urso, A.C. (2019) Boundary condition controls on the high-sand-flux regions of Mars. Geology, 47, 427–430. https://doi.org/10.1130/G45795.1

Chojnacki, M., Hargitai, H., & Kereszturi, (2015) Encyclopedia of Planetary Landforms. Springer: New York: 1–6. https://doi.org/10.1007/978-1-4614-9213-9

Cooper, W.S. (1958) Coastal Sand Dunes of Oregon and Washington. New York: Geological Society of America: Boulder, CO.

de Silva, S.L., Spagnuolo, M.G., Bridges, N.T. & Zimbelman, J.R. (2013) Gravel-mantled megaripples of the Argentinian Puna: A model for their origin and growth with implications for Mars. Bulletin of the Geological Society of America, 125(11–12), 1912–1929. https://doi.org/10.1130/B30916.1

ESRI. (2020) ArcGIS Pro 2.7. Environmental Systems Research Institute ArcGIS desktop.

Fenton, L.K., Bandfield, J.L. & Ward, A.W. (2003) Aeolian processes in Proctor Crater on Mars: Sedimentary history as analyzed from multiple data sets. Journal of Geophysical Research E: Planets, 108(E12), 3–1. https://doi.org/10.1029/2002JE002015

Fenton, L.K. & Hayward, R.K. (2010) Southern high latitude dune fields on Mars: Morphology, aeolian inactivity, and climate change. Geomorphology, 121(1–2), 98–121. https://doi.org/10.1016/j.geomorph.2009.11.006

Fenton, L.K. & Mellon, M.T. (2006) Thermal properties of sand from Thermal Emission Spectrometer (TES) and Thermal Emission Imaging System (THEMIS): Spatial variations within the Proctor Crater dune field on Mars. Journal of Geophysical Research E: Planets, 111(E6), 1–7. https://doi.org/10.1029/2004JE002363

Hartmann, W.K. (2005) Martian cratering 8: Isochron refinement and the chronology of Mars. Icarus, 174(2), 294–320. https://doi.org/10.1016/j.icarus.2004.11.023

Hartmann, W.K. & Daubar, I.J. (2017) Martian cratering 11. Utilizing decameter scale crater populations to study Martian history. Meteoritics and Planetary Science, 52(03), 493–510. https://doi.org/10.1111/maps.12807

Hartmann, W.K. & Neukum, G. (2001) Cratering chronology and the evolution of Mars. Meteoritics and Planetary Science, 36, 9–22. https://doi.org/10.1111/1367-945X.00314

Hesp, P.A. (1981) The formation of dune fields. Journal of Sedimentary Research, 51, 101–112. https://doi.org/10.1002/12127F718-2B24-11D7-8648000102C1865D

Hesp PA, Hyde R. 1978. Sand trapping ability of two pioneer sand dune plants, Ammophila arenaria and Festucia littorialis – a preliminary investigation. In Fourth Australian Conference on Coastal and Ocean Engineering, Preprints; 69–72.
Exploration Rover observations at “El Dorado” and surroundings at Gusev Crater. *Journal of Geophysical Research* 113: 1–70. https://doi.org/10.1029/2008je003101

Swanson, T., Mohrig, D., Kocurek, G., Perillo, M. & Venditti, J. (2018) Bedform spurs: A result of a trailing helical vortex wake. *Sedimentology*, 65, 191–208. https://doi.org/10.1111/sed.12383

Swet, N., Elperin, T., Kok, J.F., Martin, R.L., Yagisawa, H. & Katra, L. (2019) Can active sands generate dust particles by wind-induced processes? *Earth and Planetary Science Letters*, 506, 371–380. https://doi.org/10.1016/j.epsl.2018.11.013

Tanaka, N. & Yagisawa, J. (2010) Flow structures and sedimentation characteristics around clump-type vegetation. *Journal of Hydro-environment Research*, 4, 15–25. https://doi.org/10.1016/j.jher.2009.11.002

Taniguchi, K. & Endo, N. (2007) Deformed barchans under alternating flows: Flume experiments and comparison with barchan dunes within Proctor Crater, Mars. *Geomorphology*, 90, 91–100. https://doi.org/10.1016/j.geomorph.2007.01.010

Trétil, H.M. & Hotchkiss, R.H. (2005) Unobstructed and obstructed turbulent flow in gravel bed rivers. *Journal of Hydraulic Engineering*, 131, 635–645. https://doi.org/10.1061/(ASCE)0733-9429(2005)131:8(635)

Tsujimoto, T. (1999) Fluvial processes in streams with vegetation. *Journal of Hydraulic Research*, 37, 789–803. https://doi.org/10.1080/00221689909498512

Williams, S. (2002) Large Ripples on Earth and Mars. In *Proceedings of the 33rd Annual Lunar and Planetary Science Conference*

Wilson, S. (2003) Large Aeolian Ripples: Extrapolations From Earth To Mars. In *Proceedings of the 34th Annual Lunar and Planetary Science Conference*: 1–2.

Wilson, S.A. & Zimbelman, J.R. (2004) Latitude-dependent nature and physical characteristics of transverse aeolian ridges on Mars. *Journal of Geophysical Research E: Planets*, 109, 1–12. https://doi.org/10.1029/2004JE002247

Wolfe, S.A., Huntley, D.J. & Ollerhead, J. (2004) Relict late Wisconsinan dune fields of the northern Great Plains, Canada. *Geographie Physique et Quaternaire*, 58, 323–336. https://doi.org/10.7202/013146ar

Wolfe, S.A. & Nickling, W.G. (1993) The protective role of sparse vegetation in wind erosion. *Progress in Physical Geography*, 17, 50–68.

Xiao, J.H., Qu, J.J., Yao, Z.Y., Pang, Y.J. & Zhang, K.C. (2015) Morphology and formation mechanism of sand shadow dunes on the Qinghai-Tibet Plateau. *Journal of Arid Land*, 7, 10–26. https://doi.org/10.1007/s40333-014-0074-9

Yang, Y.Y., Liu, L.Y., Shi, P.J., Zhao, M.D., Dai, J.D., Lyu, Y.L., et al. (2019) Converging effects of shrubs on shadow dune formation and sand trapping. *Journal of Geophysical Research: Earth Surface*, 124(7), 1835–1853. https://doi.org/10.1029/2018JE004695

Zimbelman, J.R. & Scheidt, S.P. (2014) Precision topography of a reversing sand dune at Bruneau Dunes, Idaho, as an analog for transverse aeolian ridges on Mars. *Icarus*, 230, 29–37. https://doi.org/10.1016/j.icarus.2013.08.004

Zimbelman, J.R., & Williams, S.H. (2007) Dunes versus ripples: Topographic profiling across terrestrial examples, with application to the interpretation of features on Mars. *Eos Transactions of the American Geophysical Union* 88

Zong, L. & Nepf, H. (2012) Vortex development behind a finite porous obstruction in a channel. *Journal of Fluid Mechanics*, 691, 368–391. https://doi.org/10.1017/jfm.2011.479

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