Comparison of Ventifact Orientations and Recent Wind Direction Indicators on the Floor of Jezero Crater, Mars

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Key Points:

- The orientations of linear wind abrasion features on ventifacts record the direction of ancient winds that formed them.
- Measurements of current and recent wind directions in Jezero crater differ significantly from the inferred direction of ancient winds.
- As observed at other locations on Mars, these differences suggest a change in the climate regime at these locations.

Abstract

Wind-abraded rocks and aeolian bedforms have been observed at the Mars 2020 *Perseverance* landing site, providing evidence for recent and older wind directions. This study reports orientations of aeolian features measured in *Perseverance* images to infer formative wind directions. It compares these measurements with orbital observations, climate model predictions, and wind data acquired by the Mars Environmental Dynamics Analyzer. Three-dimensional orientations of flute textures on rocks, regolith wind tails extending from behind obstacles, and other aeolian features were measured using Digital Terrain Models (DTMs) derived from Mastcam-Z and navigation camera (Navcam) stereo images. Orientations of rock flutes measured in images acquired through Sol (martian day) 400 yielded a mean azimuth of 94° ± 7° (wind from the west). However, similar measurements of regolith wind tails indicate that recent sand-driving winds have been blowing from the east-southeast, nearly the opposite direction (mean azimuth = 285° ± 15°). Atmospheric modeling generally predicts net annual sand transport from the east-southeast at present, consistent with *Perseverance*regolith wind tail and orbital observations. The orientation of ventifact flutes thus suggests that they were formed under a different climate regime. Differences in orientations of recent and paleo-wind indicators have been noted at other Mars landing sites and may result from major orbital/axial changes that can cause significant changes in atmospheric circulation. Orientation differences between modern and older wind direction indicators at Jezero are useful clues to the climate history of the region.

Plain Language Summary

Strong winds mobilize sand grains that can abrade rock surfaces to form lineated bedrock features. These wind abrasion textures record the direction of the sand-driving winds that created them. Wind abrasion textures were observed on rocks on the floor of Jezero crater traversed during the early part of the Mars 2020 mission. Orientations of these abrasion textures were measured using rover-acquired three-dimensional stereo image data. Results indicate that the sand-driving wind directions that abraded these rocks are very different—nearly opposite—from the current strongest wind directions indicated by orientations of sandy wind tails extending from behind obstacles, measured wind velocities, and climate model predictions for the area. Collectively, these results provide a record of changing atmospheric circulation patterns in the Jezero region.

1 Introduction

Ventifacts are rocks that have been abraded and shaped by wind-blown, sand-size particles. The abrasion process forms flutes, pits, and grooves that typically align along the flow direction of strong, sand-driving winds on both Earth and Mars (Bridges et al., 2004; Laity & Bridges, 2009). There is abundant evidence that aeolian abrasion modifies exposed rock surfaces on Mars, based on observations of ventifacts at previous landing sites (Bridges et al., 1999, 2014; Greeley et al., 2006, 2008; Thomson et al., 2008). Ventifacts also are present on the floor of Jezero crater, as observed by the*Perseverance* rover during the first 400 sols (martian days) of the Mars 2020 mission (Farley et al., 2020) and are thought to record the direction of the winds that formed them (Herkenhoff et al., 2021). This study reports orientation measurements of ventifact textures on the floor of Jezero and compares these with orientation measurements of recent wind direction features (regolith wind tails, i.e., sandy drifts behind obstacles). Similar comparisons of wind direction inferences at previous landing sites have shown significant differences in recent and paleo-wind indicators, suggesting significant changes in wind directions. The implications of our observations in Jezero crater for paleoclimatic variations are discussed along with similar results at other Martian landing sites. Atmospheric circulation modeling results are then presented and compared with the measured orientations.

2 Methods

Ventifacts and other wind-formed features were identified and measured in stereo data derived from images acquired by the Navcam (Maki et al., 2020; Maki, 2021) and Mastcam-Z (Bell et al., 2021; Hayes et al., 2021; Bell & Maki, 2021) cameras on the *Perseverance* rover. Navcam has a focal length of 19.1 mm and instantaneous field of view (IFOV) of 330 µrad/pixel, while Mastcam-Z's focal length ranges from 26 mm (IFOV of 283 µrad/pixel) to 110 mm (IFOV of 67.4 µrad/pixel) (Maki et al., 2020; Bell et al., 2021). At a typical range from the cameras of 3 m, Navcam and Mastcam-Z 110 mm focal length images have pixel scales of 1 and 0.2 mm, respectively. Mastcam-Z stereo mosaics acquired at 110 mm focal length allowed more detailed views supporting more accurate assessments of ventifact texture and orientations compared with shorter focal lengths and other onboard camera systems, so these were used heavily for ventifact orientation measurements in this study. All measured features were within 30 meters of the rover cameras when images were acquired. Care was taken to measure only aeolian abrasion textures with clearly expressed orientations; features that appeared to be aligned along bedding or other primary structures were not analyzed further.

Once linear abrasion features of interest were identified, their orientations were measured in digital ordered point cloud (OPC) datasets using the PRo3D software package (Barnes et al., 2018). The OPCs were produced by 3D vision processing of Mastcam-Z stereo pairs (Paar et al., 2022), georeferenced by the 20 to 50-cm-level-accurate rover localization (relative to HiRISE DTMs) provided by the Mapping Specialists on the Mars 2020 science team. At the maximum distance of measured features (30 m), the Mastcam-Z stereo range error is 7 cm. Each end of linear features, such as flutes, was selected manually and the bearing and slope of the line between them were recorded; an example is shown in Figure 1. Even at the maximum range of 30 m, feature measurements span multiple OPC grid points, so that the features are well resolved in the OPCs. Upwind points were picked first, followed by downwind points, to maintain a consistent dataset. Typically, the upwind ends of flutes are at a lower elevation than the downwind ends (Laity & Bridges, 2009), but an exception was found on the rock named "Rochette." As shown in Figure 2, Rochette does not appear to be in-place bedrock, and therefore may have tilted since the aeolian abrasion features were formed. In this one case, the downwind direction was reversed for comparison with other measurements, assuming that after most ventifact textures were formed on Rochette, the block tilted (counterclockwise about a ~horizontal axis in the mosaic view) slightly to place the downwind ends of the aeolian flutes at a lower elevation than the upwind ends. This assumption is supported by observations of linear features on larger rocks in the same Mastcam-Z mosaic, which show more typical flute orientations (e.g., Figure 1). Measurements of features that were questionable or poorly resolved in the OPC were not included in statistical analyses. Flutes on nearly vertical rock faces showed higher variability in azimuth, as expected because wind-driven particles are deflected laterally when impacting such rock faces (Laity & Bridges, 2009).

Figure 1. *Example measurements of flute orientations on ventifact. View toward south, approximate true color. (left) Part of Mastcam-Z image acquired on Sol 180 by sequence ZCAM08195. Three-dimensional (3D) downwind orientations of flutes indicated by yellow arrows were measured. (right) PRo3D visualization of ordered point cloud data derived from Mastcam-Z 110-mm stereo images acquired by same sequence. Endpoints of flutes were selected manually and are shown connected by blue lines. The highlighted line with red endpoints is 2 cm long. Context is shown in Movie S1.*

Figure 2*. Rochette ventifact. (top) Measurements of linear abrasion features on Rochette rock using PRo3D, shown as blue lines. Data at lower right for line highlighted with red dots at endpoints (length is 9.6 cm). (bottom) Part of enhanced-color Mastcam-Z mosaic ZCAM08195 acquired on Sol 180, showing Rochette rock and nearby terrain. View toward south-southeast.*

The orientations of regolith wind tails (drifts or sand shadows) extending from behind rocks were measured using Navcam and Mastcam-Z stereo data acquired through Sol 400. The three-dimensional (3D) locations of the upwind and downwind ends of each wind tail were measured using Mars 2020 flight operations ASTTRO software (Advanced Science Targeting Toolkit for Robotic Operations; Abercrombie et al., 2019), allowing slope and azimuth (clockwise from north) of each feature to be derived. An example downwind endpoint is shown in **Figure 3** . Similar to ventifact measurements, azimuths of regolith wind tails were calculated in the inferred downwind direction. An important qualitative criterion for feature selection was relative isolation in open ground away from adjacent large obstacles like outcrops, boulder clusters, and other features that might have blocked winds and/or wind-blown material from some azimuth ranges, or locally altered the wind direction.

Figure 3*. Screen capture of Mars 2020 ASTTRO visualization of part of Navcam image acquired on Sol 355, showing location of end of wind tail (length = 17.3 cm) at white cross. Other wind tails are visible near right side of frame and 3-D (XYZ) and other data shown at far right.*

3 Ventifact Orientation Results

Measurements of flutes using Mastcam-Z mosaics of the rock "Rochette" acquired on Sols 180 and 197 (after sample acquisition) differ by 7 degrees, reflecting the uncertainties inherent in our approach including manual point selection and variations in viewing geometry. Standard deviations of each sol's measurements are similar to this value (**Table 1**). Early in the mission, OPCs were generated in the rover coordinate frame, so that the rover heading had to be subtracted from measurements of features (corrections for tilt were not performed due to our focus on the azimuth of ventifact features). More recently, OPCs have been generated in the Mars local level coordinate frame. Measurements made using the new OPCs agree with measurements of the same features made using the old OPCs to within 4 degrees, reflecting errors in coordinate transformations and uncertainties in picking endpoints of linear features. The orientations of linear abrasion features seen in Navcam and Mastcam-Z stereo data acquired through Sol 57 were measured independently, and agree very well with the OPC measurements: the average downwind azimuth of features measured in terrain meshes generated at the Jet Propulsion Laboratory (JPL) using Navcam and Mastcam-Z images is 97° ± 6° while the average downwind azimuth of features measured in Mastcam-Z OPCs is 95° ± 4° (in both cases, the standard deviation in the measured azimuths is given rather than the uncertainty in the individual measurements). Similarly, the average downwind azimuth of all features measured in OPCs derived from Mastcam-Z stereo images acquired through Sol 400 is 94° ± 7°. Based on the comparisons summarized above, true variations in the orientations of linear features exceed the uncertainties in the measurements.

Table 1 . Sol number of image acquisitions for each set of aeolian abrasion features, number of orientation measurements (N), average downwind feature azimuth (clockwise from north, in degrees) and standard deviation for each sol.

Sol	*N*	*Average*	*Standard deviation*
3	21	103	9
22	7	89	12
53	17	93	11
54	3	94	3
64	8	96	7
66	6	108	6
74	9	97	10
112	2	93	0
125	4	101	6
129	4	93	7
159	6	94	13
180	20	90	7
197	2	78	13
238	4	99	11
240	19	101	7
254	10	89	11
279	7	99	9
281	2	97	26
341	11	96	11
353	7	81	7
362	6	91	9
Total:	175		
Global Average:	Global Average:	94	7

Figure 4 evaluates the potential effects of varying illumination angle on the azimuth measurements, comparing average azimuth for each sol (through Sol 238) and local true solar time of image acquisition. The Mastcam-Z mosaics that were analyzed typically required a few minutes to acquire, so the local true solar time of the midpoint of each mosaic acquisition was used for this analysis. While there is more scatter in the measurements when the sun was lower, there is no apparent systematic effect of illumination differences on the results. Potential systematic errors from viewing azimuth (measured clockwise from N, centered on Mastcam-Z) were also evaluated in ventifact orientations measured through Sol 238. **Figure 5** shows no apparent dependence of feature azimuth on viewing geometry either. We therefore conclude that neither illumination nor viewing geometry significantly affects our results.

Figure 4. Bearing (azimuth clockwise from north) of ventifact features on the floor of Jezero crater, averaged over measurements made in each Mastcam-Z panorama (acquisition sol indicated in boxes) through Sol 238.

Vertical bars show the standard deviation of each range of measurements. Three panoramas were acquired between 12:04 and 12:41 on Sol 180; the midpoint time of the second one is plotted here. The two bearing measurements of features seen in the Sol 112 panorama differ by only 0.1° so standard deviation is not visible for the Sol 112 data point. There is no significant correlation between time of day and ventifact orientation, indicating that illumination conditions do not affect these three-dimensional measurements.

Figure 5 . Bearing (azimuth clockwise from north) of ventifact features on the floor of Jezero crater vs. viewing azimuth for data acquired through Sol 238.

Overall, variations in ventifact orientations along the first 400 sols of the rover traverse are minor, as shown in **Figure 6** , perhaps because the area explored by the Mars 2020 rover over that period is only about 1 km across. Some of the variability in linear feature orientations is due to variations in the 3D geometry of the rock faces relative to the wind azimuth, as expected. It is also expected that local topography will deflect sand-transporting winds and that some of the observed variability may be caused by nearby topographic obstacles. To determine the significance of such effects on our measurements, individual ventifact azimuth measurements that differ from the global average by more than two standard deviations were examined.

Many of the >2-sigma variations in azimuth appear to be caused by the deflection of winds on more steeply inclined rock faces (e.g., on Sols 53, 254, 353, and 362). In these cases, differences between the normal to the abraded rock face and the direction of strong winds may cause the winds to be deflected horizontally. Such deflections have been observed on terrestrial ventifacts. To understand this, consider a hemispherical rock that is subjected to abrasion by saltating sand blowing from a single direction. The orientation of aeolian flutes will depend on the local surface normal at each grain impact site, resulting in variable flute orientations that radiate away from the upstream point on the rock. Lower-resolution topographic data on more distant features also contributed to uncertainty and more scatter in measured azimuths on some features. Evidence for large-scale wind deflections by upstream topography is limited, with possible cases observed on Sols 53 and 180. As described above, the Rochette float block may have moved slightly after the ventifact features were formed, contributing to differences in their orientations relative to other ventifacts.

Figure 6 . Locations of measurements of aeolian feature orientations (arrows) plotted on HiRISE color image (north up, illumination from left). White dots show rover locations, connected by grey traverse path with white arrows showing drive direction. Sols and average orientations of ventifact features shown by yellow arrows, average orientations of wind tails shown as green arrows. Wind tails were measured at multiple locations on Sols 340, 341, and 360; suffixes "a" and "b" were added to the sol numbers annotating these locations. Wind tail orientations measured later in the mission are not included, as the traverse extended to the north after Sol 379, beyond the area mapped.

4 Comparison with indicators of recent aeolian transport

Wind tail orientations, averaged over observations made at each rover location, are summarized in Table 2. These 101 downwind orientations were measured using Navcam stereo data in all cases except on Sols 34 and 52, when Mastcam-Z stereo images were analyzed. Sometimes images obtained at mid-drive pauses showed measurable features (i.e., in addition to features at the final, end-of-drive position). These instances are distinguished in Table 2 with letters appended to the sol number. Downwind azimuths that differ from the mean by more than two standard deviations were measured in images acquired on Sols 130, 137, 173, 199, 202, and 355. In all cases, topographic features near the measured wind tails are too small to have affected wind flow significantly, so the cause of the orientation differences is unclear. There is no evidence that differences in grain or feature size influenced susceptibility to recent wind modification.

Table 2. Sol number of image acquisition, number of measurements (N), average wind tail azimuth (clockwise from north, in degrees) and standard deviation. Measurements were made at multiple rover locations on Sols 32, 47, 340, 341, 355, and 360.

Sol	*N*	*Average*	*Standard deviation*
2	1	270	0

Sol	*N*	*Average*	*Standard deviation*
29	2	301	11
31	3	282	29
32a	1	312	0
32b	2	290	2
34	3	304	8
43	2	292	13
47a	1	280	0
47b	1	282	0
49	1	279	0
52	1	291	0
65	1	288	0
66	1	280	0
91	2	297	7
102	3	273	4
103	1	302	0
104	2	286	6
108	2	281	4
109	1	275	0
110	2	284	8
113	1	277	0
130	1	323	0
137	3	300	17
170	4	276	6
173	2	260	5
175	2	275	1
177	1	263	0
199	1	338	0
201	3	284	6
202	3	302	12
204	2	288	8
328	2	268	2
340a	2	276	6
340b	2	288	11
341a	1	266	0
341b	1	300	0
354	1	294	0
355a	1	286	0
355b	3	282	9
355c	7	273	12
358	5	292	3
360a	2	287	10
360b	4	283	6
380	3	282	14
383	7	280	11
386	2	286	15
387	1	277	0
389	1	285	0
Total:	101		
	Global Average:	285	15

The wind tail orientations indicate that they were formed by winds blowing toward the west-northwest (WNW) while the orientations of ventifact features suggest formative, sand-driving winds blowing toward the east, almost in the opposite direction (**Figure 7**). Note that the inferred direction of recent winds that formed the wind tails is consistent with the orientation of the dunes visible in**Figure 6** . These and other aeolian features were used by Day & Dorn (2019) to infer that they were formed by winds trending toward 263° ± 8°, very similar to the trend derived from the wind tail azimuths summarized in **Table 2** .

Figure 7.*Orientations of linear ventifact features (orange) and regolith wind tails (green) averaged over 15-degree azimuth bins. In both cases downwind azimuths are shown.*

The surface wind patterns in the tropical region of Mars reflect complex interactions between the large-scale circulation, which is dominated by Hadley cell flows, thermal tides and other planetary waves, and slope flows at regional and local scales (Rafkin et al., 2016; Newman et al., 2017; Viúdez-Moreiras et al., 2019). These flows can be affected by smaller-scale, complex topography. Jezero crater is located on the northwestern slopes of Isidis basin, a region that presents a steep slope, thus strong near-surface regional flows are expected in the region. Pre-landing mesoscale simulations using nine different models showed control by regional and local slope flows (Newman et al., 2021), which is consistent with Mars 2020 observations (Newman et al., 2022; Viúdez-Moreiras et al., 2022a). Chojnacki et al. (2018) found that sand ripples with 3-5 m wavelengths within the Mars 2020 landing ellipse in Jezero crater had moved ~0.2 m/yr toward the west-northwest based on HiRISE orbital observations, also consistent with the Mars 2020 observations.

The diurnal cycle of winds observed during the first 315 sols of the mission by *Perseverance* 's Mars Environmental Dynamics Analyzer (MEDA, Rodriguez-Manfredi et al., 2021; Rodriguez-Manfredi & de la Torre Juarez, 2021) instrument suite included part of northern spring and summer and presented two regimes (Viúdez-Moreiras et al., 2022a): (i) a daytime regime, from dawn to sunset, with average easterly (i.e., from the east) to southeasterly winds during which maximum wind speeds were measured, and (ii) a nighttime regime with a period of westerly and northwesterly downslope winds followed by a relatively calm period until sunrise. Maximum average wind speeds of ~7 ms^{-1} were measured during the afternoon, when winds were easterlies. Weibull models using high-frequency wind data show that winds exceed 8 ms^{-1} for about 20% of the afternoon period but for less than 0.2% of the nighttime period (Viúdez-Moreiras et al., 2022b), highlighting the strength and the convective activity involved in the easterly and southeasterly winds observed during the daytime. Although wind patterns have not been observed in northern autumn and winter, the strong effect of regional flows observed during spring and summer suggests that the aforementioned near-surface wind regimes at Jezero will be roughly maintained throughout the rest of the year, probably disturbed to a greater extent around the winter solstice due to the strength of the zonal-mean meridional circulation (cross-equatorial Hadley cell) in that season. In a pre-landing, multi-model intercomparison (Newman et al., 2021), most models predict in general the highest maximum and mean wind speeds in northern summer. This is also the period of generally highest wind stress and estimated sand flux for most models (see Figures 5 and 11 of Newman et al. 2021, respectively), despite atmospheric density reaching its annual minimum in late summer. Peak sand flux is predicted in the first half of the year by all models that resolve the crater. Hence the seasons already observed by Mars 2020 are expected to have included the period of maximum aeolian transport in Jezero, at least in the absence of major dust storm activity (the effects of which were not modeled).

The moderately strong wind speeds observed during the first part of the evening (the wind speed drops after midnight) are aligned with ventifact orientations but are rarely strong enough to drive sand and form the ventifacts observed by Mars 2020. In addition, ventifacts indicate a roughly opposite direction to the strong daytime winds observed by Mars 2020 under nominal conditions, which suggests that ventifacts were not produced under nominal wind patterns in the present-day Mars climate. Ventifact formation in the current era might occur only during anomalous weather conditions (e.g., rare strong, sand-driving wind events from atypical directions, associated with dust storms or other unusual weather phenomena). Alternatively, ventifact orientations might indicate a paleowind regime different from the current prevailing conditions (Newman et al., 2022; Bell et al., 2022), as discussed further in the next section.

4 Interpretation using atmospheric circulation models

Perseverance has yet to observe the circulation for northern autumn and winter, and damage to the MEDA wind sensors, likely due to flying debris on Sol 315 (Viúdez-Moreiras et al., 2022b), may preclude future observations of those seasons. However, winds measured to date show good agreement with the predictions of some atmospheric models that resolve the crater topography. Figure S1 of Newman et al. (2022) shows a mostly very good match between ~1.5 m altitude winds modeled by MarsWRF and those measured by MEDA for Sols 180-188, corresponding to the period around the northern summer solstice (areocentric solar longitude L_s ~90°). Figure 8 herein shows similarly good agreement for Sols 47-53, corresponding to the period around the northern fall equinox (L_s ~30°). Figure S1 also shows good agreement between the MarsWRF model and data acquired near L_s 150º. The agreement between model-predicted and 1-minute average observed wind speed is excellent at all times of sol, while the agreement with wind direction mainly diverges in the late afternoon when the model predicts southeasterly winds while observed winds are roughly easterly. These results lend greater confidence to MarsWRF predictions of how the circulation may differ at other seasons, as shown in Figures 2 and 8 (for L_s ~0° and 270°, respectively) of Newman et al. (2021) and in the high-resolution modeling results of Pla-Garcia et al. (2020). While there are subtle differences, those predictions show a lack of significant seasonal variation in diurnal wind patterns, except for a reduction in wind speeds at L_s ~270° compared to other seasons. Of course, the model may be incorrect, but it appears unlikely that seasonal changes can explain the difference between ventifact and wind tail orientations.

Figure 8. Comparison of minute-averaged MEDA wind data with WRF model results at every minute (black symbols) for L_s = 30°. Key for colors of various data shown in top panel.

As noted above, nighttime wind orientations (from the west-northwest) are quite consistent with ventifact orientations; the problem is that the nighttime wind speeds are typically very low compared to those during the day and thus unlikely to dominate sand transport and abrasion. However, the key variable here is the force on the surface, which is related to wind stress, rather than wind speed directly. The wind stress is given by air density times friction velocity (u*) squared, where we may estimate u* based upon the wind speed at 1.5 m above the surface by assuming a logarithmic wind profile and value of surface roughness, z_0, with $u(z) = u^* \ln(z/z_0)$ / kappa, where kappa is the Von Kármán constant (~0.4) and z=1.5 m. Air density is proportional to pressure and 1/temperature, hence increases at night when air temperature on Mars decreases significantly. This density effect means that if the daytime wind speed only slightly exceeds that at night, the nighttime wind stress may be greater. In the case of the rover's recent locations in Jezero crater, however, the daytime wind speed *far* exceeds that at night, hence the estimated nighttime wind stresses are also low compared to those during the daytime. Newman et al. (2022) used MarsWRF climate modeling to show that nighttime winds in the northwest quadrant of Jezero are likely dominated by the effect of the local crater rim to the northwest and west, on which strong, thermally-driven downslope flows are predicted to develop and intensify after sunset. For the first half of the night, these winds, from the west through the northwest, are predicted to penetrate well into the crater. Although strongest on the rim, they remain moderately strong by the time they reach the location of the rover. However, after ~02:30 local true solar time (LTST), modeled wind speeds drop rapidly at the rover's position, although they continue to intensify on the crater rim. The reason for this drop in nighttime wind speeds is not yet confirmed, but one possibility is that the mountain to the southeast of the crater generates strong downslope flows that induce an intra-crater circulation, which restricts the strong crater rim downslope flows closer to the rim as the night progresses.

Other than seasonal changes, there are two other possibilities for producing the observed ventifact orientations. One is that they are formed predominantly during dust storms, when winds could potentially be stronger and thus reflect the altered wind patterns during such events. Unfortunately, the MEDA wind sensor was damaged during the early part of the January 2022 regional dust storm, and although data from right beforehand does indicate a shift in the wind, it is difficult to determine whether storm winds are consistent with the observed ventifact orientations (Lemmon et al., 2022; Viudez-Moreiras et al., 2022a).

A second possibility is that they formed during a different orbital epoch, such as one with a different obliquity compared to the present day (˜25°) or a different seasonal timing of perihelion. Newman et al. (2022) offer a hypothesis that involves strengthening of the winter-solstice Hadley circulation–in which the zonal-mean flow near the surface blows from north to south–at higher obliquities, with this increase due to the latitudinal shift in solar forcing (e.g., Haberle et al., 2003; Newman et al., 2005). The idea is then that stronger background northerlies might enhance and/or push nighttime downslope winds from the northwest/west-northwest deeper into the crater, which might result in stronger wind speeds from this direction at the rover's location. While a thorough exploration of a range of orbital changes is beyond the scope of this paper, Figure 9 shows the predicted change in sand flux and sand transport direction predicted by MarsWRF if the orbital obliquity is increased to 45°, which may last have been the case ˜5 Myr ago (Laskar et al., 2004). Here the present-day simulations are the same nested mesoscale (crater-resolving, grid spacing ˜1.4 km) MarsWRF simulations shown in Newman et al. (2021), while the 45° obliquity simulations use the same model setup but with an obliquity of 45°. While it is possible that higher obliquity periods resulted in stronger global circulations and greater dust lifting (e.g., Newman et al., 2005), it is also possible that dust was rapidly depleted from most source regions and dust loading was reduced. In the absence of a clear answer, these simulations use the same prescribed atmospheric dust distribution, based on observed years with no major dust storms, as described by Newman et al. (2021), for both the present day and the past climate epoch. Note that MarsWRF includes a CO_2 cycle that parameterizes surface-atmosphere exchange of CO_2 and redistributes the CO_2 ice cover with the seasons. However, while the seasonal variation of CO_2 ice cover changes for the higher obliquity simulation, this produces only a small change in the surface pressure cycle compared to the present-day simulation, and we do not explore more significant changes that might have resulted from the proposed buried CO_2 release. All simulations were conducted for 9 sols at L_s ˜0° and L_s ˜270°, with the first two sols (in which the model may still be adjusting to its initialization) not used, and the global domain in which they were embedded had first been run for at least one Mars year before the nested simulation start time, again to allow the model to adjust and reach a quasi-seasonally-repeatable state.

The main result shown in Figure 9 is that, at both seasons examined, the high-obliquity simulations generally predict a balance between daytime and nighttime sand flux magnitudes similar to that found for the present day. The exception is at L_s ˜270° in the high obliquity simulation, in which the peak flux across all sols at ˜23:00 LTST is comparable to the peak mid-sol. However, the sand transport direction in that particular sol (at ˜23:00) is from the northeast. Further, peak fluxes during this simulation are lower than those predicted during the daytime for the present-day L_s ˜270° simulation, and are *much* lower than those predicted in the late afternoon at L_s ˜0° for both the present-day and 45° obliquity simulations, during all of which times the predicted sand transport is from between the east and southeast. These preliminary results do not support the idea that higher obliquities could explain the observed ventifact orientations. However, far more study is needed of other seasons, including the idea that at L_s˜270° at higher obliquity the atmosphere might have much greater dust content due to feedback between winds and dust lifting, driving a stronger zonal mean circulation, although this may not occur if the dust supply is limited. This preliminary investigation barely scratches the surface of exploring past orbital configurations; further modeling could be beneficial.

Figure 9. Predicted sand flux (left) and direction from which the sand blows (right) assuming the Lettau and Lettau (1978) sand flux equation and a threshold of 0, using output from the MarsWRF model every five minutes, for (a) present-day orbital settings at L_s ˜0°, (b) same season as (a) but for an orbital obliquity of 45°, (c) present-day orbital settings at L_s ˜270°, (d) same season as (c) but for an orbital obliquity of 45°. As in Figure 8, colors indicate different sols, with 7 sols shown for each seasonal period.

We conclude this section by noting that Newman et al. (2021) used the output from eight Mars atmospheric model simulations (involving six different models) to estimate the net sand transport direction as a function of season at the center of the landing ellipse in Jezero crater (77.43°E, 18.47°N), which is close to the rover's true location during this period. Fig. 11 of that paper presents the results, which show the expected sand transport direction to be toward the west or north-west in all seasons for most simulations and choices of sand motion threshold, consistent with observations of regolith wind tails in the crater and with the estimated net sand transport direction based on MEDA winds and air densities measured over the first 216 sols (see above). The exception is at zero sand motion threshold, where there is greater spread (sand transport also toward the south-west, south, or even south-east) in some simulations and seasons. Even then, however, the season of peak sand flux still coincides with transport toward the west or north-west, again consistent with wind tail observations in Jezero.

4 Discussion

The distribution of measured ventifacts (Figure 6) does not suggest correlations of ventifact susceptibility with various rock units. Rocks with measurable ventifact orientations were found locally among rocks that displayed less or no obvious ventifact textures. This suggests that the susceptibility to aeolian abrasion of source bedrock now weathering at the surface varies across relatively short length scales, and/or that the current population of rocks exposed along the rover traverse also includes an important fraction of “erratics” different from local source bedrock, contributed either as impact ejecta from elsewhere and/or as resistant remnants lowered into place by erosion of stratigraphically younger/higher materials (e.g., mixed delta deposits that once covered the rover traverse) to the current level of the crater floor. Figure 6 indicates that ventifact orientations do not vary significantly along the rover traverse through Sol 379, so most likely they record strong sand transport from a narrow range of directions in a different past climate regime.

Evidence for changes in strong wind directions has been noted at other locations on Mars. Bridges et al. (1999) concluded that ventifacts at the *Mars Pathfinder* landing site have orientations that are significantly different from recent wind directions indicated by the orientations of wind tails and local wind streaks, strongly suggesting a change in local circulation patterns since the ventifacts were formed. At the MER *Opportunity* site at Meridiani Planum, orientation differences between aeolian features of different relative ages indicate that strong wind events have changed direction by about 40° over time (Sullivan et al., 2005). Fenton et al. (2018) modeled changes in atmospheric circulation over the past 400,000 years to infer that the ripples on Meridiani Planum observed by *Opportunity* were likely formed by strong winds during the most recent obliquity maximum (between 26° and 27°) about 100,000 years ago when the atmospheric pressure was ~25% higher than today. Evidence for abrasion from periodically sustained paleo-winds was observed in the sculpted surfaces of iron-nickel meteorites by *Opportunity* at Meridiani Planum (Ashley et al., 2011; 2022). Microscopic Imager mosaics and their respective 0.09 mm/post DTMs show oriented hollows and fluted oxide coatings on Meridiani meteorites, as well as patterns in coating occurrence with respect to topography (e.g., wind shadows), and possibly even gross meteorite morphology in at least one instance. However, these patterns do not appear to be consistent with either recent wind streak orientations (Sullivan et al., 2005) or the most recent aeolian bedform migration directions (Golombek et al., 2010). Similarly, orientations differ between recent and paleo-wind direction indicators at Gale crater, based on observations of ventifacts near the Mars Science Laboratory landing site (Bridges et al., 2014). Measured orientations of thousands of aeolian bedforms and Periodic Bedrock Ridges (PBRs) at Oxia Planum, the intended landing site for the ExoMars Rosalind Franklin rover, indicate changes in the direction of formative winds with time (Favaro et al., 2021). In addition, Favaro et al. (2021) found that modeled contemporary wind directions and strengths are not consistent with the orientations of either the aeolian bedforms or PBRs. Hence, the differences between Jezero floor ventifact feature orientations and models or other indicators of current wind directions in Jezero crater are not atypical for Mars, because such differences have been observed at other landing sites (e.g., Greeley et al., 2000). Collectively, all of these examples indicate the potential of aeolian abrasion textures to preserve records of past wind conditions for relatively long surface exposure times under arid martian conditions.

5 Conclusions

The capabilities of *Perseverance* ’s Mastcam-Z and Navcam stereo instruments and their data products and visualization assets allow statistically significant 3D measurement and analysis of ventifacts observed on the floor of Jezero crater during the first 400 sols of the landed mission. These measurements of features located within ~1 km of the landing site show that strong winds forming the ventifacts blew from the west (toward azimuth 94 $\pm$ 7°), nearly the opposite direction of the winds that formed more recent aeolian features (toward azimuth 285 $\pm$ 15°). Therefore, a major change in the direction of strong winds in Jezero crater is recorded by surface features of different ages. In the past, sand-driving winds consistently from the WNW prevailed long enough to establish ventifact textures on rock exposures throughout the study area, but the strongest winds of the current wind regime have not prevailed long enough, with whatever sand supply exists upwind, to leave a comparable ventifact record. Current nighttime wind directions are similar to the paleowind direction inferred from the ventifact orientations, so a past wind regime that causes nighttime wind speeds to increase and dominate over daytime winds may explain the formation of the ventifacts. Further work is needed to determine what changes in global orbital/axial parameters might cause such a wind regime.

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Open Research

The data and associated metadata used in this study are available at the Geosciences node of the PDS: https://pds-geosciences.wustl.edu/missions/mars2020/.Navcam products are included in the Engineering Camera Bundle (https://doi.org/10.17189/1522847), while Mastcam-Z*(* https://doi.org/10.17189/1522843) and MEDA (https://doi.org/10.17189/1522849) data are archived in separate bundles. MEDA wind data may also be found at https://atmos.nmsu.edu/PDS/data/PDS4/Mars2020/mars2020_meda/data_derived_-env/.

Tables of ventifact feature and wind tail orientation measurements, and MarsWRF model results are available on the USGS ScienceBase site: https://www.sciencebase.gov/catalog/item/637509e2d34ed907bf6ceafd (doi:10.5066/P9NAGUG1). Ordered Point Clouds (OPCs) processed by PRoViP from all PDS-released Mastcam-Z stereo and monoscopic data sets are available from sftp://PRoViP-Mastcam-Z-PDS-Released@digsftp.joanneum.at:2200 – with user *PRoViP-Mastcam-Z-PDS-Released* and password*MQRr63hJdUzVFHYc!* .

Software Availability Statement

The MarsWRF model contains over 300,000 lines of code and is not straightforward to implement without a substantial investment of training time and documentation by the development team, hence public release of the model used to generate these results is not possible at this time. However, the present day Jezero crater atmospheric simulations used in this work are fully described in Newman et al. (2021) and results from the same set of simulations were also described and shown in Newman et al. (2022).

The Planetary Robotics 3D Viewer, in short PRo3D (PRo3D, 2022), is an open-source interactive 3D visualization tool that allows members of the Mars 2020 Science and Operations teams to work with high-resolution 3D reconstructions of the Martian surface: PRo3D (2022). Planetary Robotics 3D Viewer GitHub page [Software]. https://github.com/pro3d-space/PRo3D.

Mars 2020 custom mission operations software applications, such as ASTTRO, are not available to the public.

References

Abercrombie, S. P., Menzies, A., Abarca, H. E., Luo, V. X., Samochina, S., Trautman, M., et al. (2019). Multi-platform immersive visualization of planetary, asteroid, and terrestrial analog terrain. *Lunar Planet Sci., L* , Abstract #2268. https://www.hou.usra.edu/meetings/lpsc2019/pdf/2268.pdf

Ashley, J. W., Golombek, M. P., Christensen, P. R., Squyres, S. W., McCoy, T. J., Schröder, C., et al.

(2011). Evidence for mechanical and chemical alteration of iron-nickel meteorites on Mars: Process insights for Meridiani Planum, *J. Geophys. Res.* ,*116* , E00F20, doi:10.1029/2010JE003672.

Ashley J. W., Herkenhoff, K. E., Schröder, C., Golombek, M. P., Curtis, A. G., Johnson, J. R., et al. (2022). Topometric analysis of iron meteorite surfaces and their oxide coatings using microscopic imager digital elevation models at Meridiani Planum Mars — Support for recent equatorial mineral-water interaction and persistant paleo-wind direction. *Lunar Planet Sci., LIII* , Abstract 1387.

Barnes, R., Gupta, S., Traxler, C., Ortner, T., Bauer, A., Hesina, G., et al. (2018). Geological analysis of Martian rover-derived digital outcrop models using the 3-D visualization tool, Planetary Robotics 3-D Viewer—PRo3D. *Earth and Space Science* , *5* (7), 285-307. https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2018EA000374.

Bell, J. F. & Maki, J., Mars 2020 Mast Camera Zoom Data Bundle (2021), Planetary Data System, doi:10.17189/1522843.

Bell III, J. F., Maki, J. N. Alwmark, S., Ehlmann, B. L., Fagents, S. A., Grotzinger, J. P., et al. (2022). Geological and meteorological imaging results from the Mars 2020 *Perseverance* rover in Jezero crater. *Sci. Adv* . 8, eabo4856, https://doi.org/10.1126/sciadv.abo4856.

Bell III, J. F., Maki, J. N., Mehall, G. L., Ravine, M. A., Caplinger, M. A., Bailey, Z. J., et al. (2021). The Mars 2020 *Perseverance*rover mast camera zoom (Mastcam-Z) multispectral, stereoscopic imaging investigation. *Space Sci. Rev* . *217* , doi:10.1007/s11214-020-00755-x.

Bridges, N. T., Calef, F. J., Hallet, B., Herkenhoff, K. E., Lanza, N. L., Le Mouelic, S., et al. (2014), The rock abrasion record at Gale Crater: Mars Science Laboratory results from Bradbury Landing to Rocknest, *J. Geophys. Res. Planets, 119,* 1374– 1389*, doi:* 10.1002/2013JE004579.

Bridges, N. T., Greeley, R., Haldemann, A. F. C., Herkenhoff, K. E., Kraft, M., Parker, T. J., & Ward A. W. (1999). Ventifacts at the Pathfinder landing site. *J. Geophys. Res., 104* , 8595.

Bridges, N. T., Laity, J. E., Greeley, R., Phoreman, J., & Eddlemon, E. E. (2004). Mechanisms of rock abrasion and ventifact formation from laboratory and field analog studies with applications to Mars,*Planet. Space Sci., 52* , 199-213.

Chojnacki, M., Banks, M., & Urso, A. (2018). Wind-driven erosion and exposure potential at Mars 2020 Rover candidate-landing sites. *J. Geophys. Res. Planets* , *123* , 468–488. https://doi.org/10.1002/2017JE005460.

Day, M. & Dorn, T. (2019). Wind in Jezero crater, Mars. *Geophys. Res. Lett* ., *46* , doi:10.1029/2019GL-82218.

Farley, K. A., Williford, K. H., Stack, K. M., Bhartia, R., Chen, A., de la Torre, M., et al. (2020). Mars 2020 mission overview. *Space Science Reviews* , *216* , 142.

Favaro, E. A., Balme, M. R., Davis, J. M., Grindrod, P. M., Fawdon, P., Barrett, A. M., & Lewis, S. R. (2021). The aeolian environment of the landing site for the ExoMars Rosalind Franklin rover in Oxia Planum, Mars. *J. Geophys. Res. Planets* , *126* , e2020JE006723, https://doi.org/10.1029/2020JE006723.

Fenton, L. K., Carson, H. C., & Michaels, T. I. (2018). Climate forcing of ripple migration and crest alignment in the last 400 kyr in Meridiani Planum, Mars, *J. Geophys. Res. Planets* , *123,* 849-863. https://doi.org/10.1002/2017JE005503.

Golombek, 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, *J. Geophys. Res. Planets* , *115* , E00F08, doi:10.1029/2010JE003628.

Greeley, R., Arvidson, R. E., Bartlett, P. W., Blaney, D., Cabrol, N. A., Christensen, P. R. et al. (2006), Gusev crater: Wind related features and processes observed by the Mars Exploration Rover Spirit.,*J. Geophys.*

Res. Planets, 111 , doi:10.1029/ 2005JE002491.

Greeley, R., Kraft, M. D., Kuzmin, R. O., & Bridges, N. T. (2000). Mars Pathfinder landing site: Evidence for a change in wind regime from lander and orbiter data, *J. Geophys. Res. Planets* , *105* (E1), 1829– 1840, doi:10.1029/1999JE001072.

Greeley, R., Whelley, P. L., Neakrase, L. D. V., Arvidson, R. E., Bridges, N. T., Cabrol, N. A. et al. (2008), Columbia Hills, Mars: Aeolian features seen from the ground and orbit. *J. Geophys. Res. Planets, 113* , doi:10.1029/2007JE002971.

Haberle, R. M., Murphy, J. R. & Schaeffer, J. (2003). Orbital change experiments with a Mars general circulation model. *Icarus, 161* , 66-89.

Hayes, A. G., Corlies, P., Tate, C., Barrington, M., Bell III, J. F., Maki, J. N. et al. (2021). Pre-flight calibration of the Mars 2020 Rover Mastcam Zoom (Mastcam-Z) multispectral, stereoscopic imager. *Space Sci. Rev. 217* , doi:10.1007/s11214-021-00795-x.

Herkenhoff, K., Sullivan, R., Newman, C. E. & Baker, M. (2021). Comparison of ventifact orientations and recent wind direction indicators near the Mars 2020 Octavia E. Butler landing site on Mars, Geological Society of America Abstracts with Programs, Vol. 53, No. 6, doi: 10.1130/abs/2021AM-367128.

Laity, J. E. & Bridges, N. T. (2009). Ventifacts on Earth and Mars: Analytical, field, and laboratory studies supporting sand abrasion and windward feature development, *Geomorphology* , doi:10.1016/j.geomorph.2008.09.014.

Laskar, J., Correia, A.C.M., Gastineau, M., Joutel, F., Levrard, B., & Robutel, P. (2004). Long term evolution and chaotic diffusion of the insolation quantities of Mars, *Icarus* , *170* , 343–364.

Lemmon, M. T., Smith, M. D., Viudez-Moreiras, D., de la Torre-Juarez, M., Vicente-Retortillo, A., Munguira, A. et al. (2022). Dust, sand, and winds within an active Martian storm in Jezero crater. *Geophys. Res. Lett., 49* , e2022GL100126. https://doi.org/10.1029/2022GL100126

Lettau, K. & H.H. Lettau (1978). Experimental and micro-meteorological field studies of dune migration, in H.H. Lettau and K. Lettau, eds., Exploring the world's driest climate, *University of Wisconsin-Madison, Institute for Environmental studies, IES report* ,*101* , 110-147.

Maki, J. M. (2021). Calibrated data products for the Mars 2020 Perseverance rover navigation cameras. *PDS Imaging Node* . https://doi.org/10.17189/yvkm-rx37

Maki, J. N., Gruel, D., McKinney, C., Ravine, M. A., Morales, M., Lee, D. (2020). The Mars 2020 Engineering Cameras and Microphone on the Perseverance Rover: A next-generation imaging system for Mars Exploration. *Space Sci. Rev* . *216* , doi:10.1007/s11214-020-00765-9.

Newman, C. E., de la Torre Juarez, M., Pla-Garcia, J., Wilson, R. J., Lewis, S. R., Neary, L., Kahre, M. A., Forget, F., Spiga, A., Richardson, M. I., Daerden, F., Bertrand, T., Viudez-Moreiras, D., Sullivan, R., Sanchez-Lavega, A., Chide, B., & Rodriguez-Manfredi, J. A. (2021). Multi-model meteorological and aeolian predictions for Mars 2020 and the Jezero crater region. *Space Science Reviews* ,*217* , 20, https://doi.org/10.1007/s11214-020-00788-2.

Newman, C. E., Gomez-Elvira, J., Marin, M., Navarro, S., Torres, J., Richardson, M. I., Battalio, J. M., Guzewich, S. D., Sullivan, R., de la Torre-Juarez, M., Vasavada, A.R. & Bridges, N.T. (2017). Winds measured by the Rover Environmental Monitoring Station (REMS) during the Mars Science Laboratory (MSL) rover's Bagnold Dunes campaign and comparison with numerical modeling using MarsWRF. *Icarus* , *291* , 203-231.

Newman, C. E., Hueso, R., Lemmon, M. T., Munguira, A., Vicente-Retortillo, A., Apestigue, V., Martinez, G., Carrasco, D. T., Sullivan, R., Herkenhoff, K., de la Torre Juarez, M., Richardson, M. I., Stott, A., Murdoch, N., Sanchez-Lavega, A., Wolff, M., Rodriguez, I. A., Martinez, E. S., Navarro, S., Gomez-Elvira, J., Tamppari, L., Viudez-Moreiras, D., Hari, A.-M., Genzer, M., Hieta, M., Lorenz, R. D., Conrad, P., Gomez, F. G., McConnochie, T., Mimoun, D., Tate, C., Bertrand, T., Bell, J., Maki, J., Rodriguez Manfredi, J. A., Wiens, R., Chide, B., Maurice, S., Zorzano, M.-P., Mora, L., Baker, M., Banfield, D., Pla-Garcia, J., Beyssac, O., Brown, A., Clark, B., Lepinette, A., Montmessin, F., Fischer, E., Patel, P., del Rio-Gaztelurrutia, T., Fouchet, T., Francis, R., Guzewich, S., and the Mars 2020 Atmospheric Science Working Group (2022). The dynamic atmospheric and aeolian environment of Jezero crater, Mars, *Science Advances* , *8* , 21, https://www.science.org/doi/10.1126/sciadv.abn3783.

Newman, C. E., Lewis, S. R., & Read, P. L. (2005). The atmospheric circulation and dust activity in different orbital epochs on Mars.*Icarus, 174* , 135-160.

Paar, G., T. Ortner, C. Traxler, R. Barnes, M. Balme, C. Schroeder, S.G. Banham (2022). Preparing 3D vision & visualization for ExoMars. Proc. ASTRA 2022 - 16th Symposium on Advanced Space Technologies in Robotics and Automation, ESA/ESTEC, Noordwijk, The Netherlands, June 1-2, 2022. https://www.vrvis.at/publications/PB-VRVis-2022-017.

Pla-Garcia, J., Rafkin, S. C. R., Martinez, G. M., Vicente-Retortillo, A., Newman, C. E., Savijarvi, H., et al. (2020). Meteorological predictions for Mars 2020 Perseverance rover landing site at Jezero crater. *Space Sci. Rev* . *216* , https://doi.org/10.1007/s11214-020-00763-x.

Rafkin, S. C., Pla-Garcia, J., Kahre, M., Gomez-Elvira, J., Hamilton, V. E., Marin, M., et al. (2016), The meteorology of Gale Crater as determined from Rover Environmental Monitoring Station observations and numerical modeling. Part II: Interpretation, *Icarus, 280* , 114-138.

Rodriguez-Manfredi, J. A., & de la Torre Juarez, M. (2021). Mars 2020 Perseverance rover Mars Environmental Dynamics Analyzer (MEDA) experiment data record (EDR) and reduced data record (RDR) data products archive bundle. *PDS Atmospheres Node* . https://doi.org/10.17189/1522849

Rodriguez-Manfredi, J. A., de la Torre Juarez, M., Alonso, A., Apestigue, V., Arruego, I., Atienza, T., Banfield, D., Boland, J., Carrera, M. A., Castaner, L., Ceballos, J., Chen-Chen, H., Cobos, A., Conrad, P., Cordoba, E., del Rio-Gaztelurrutia, T., de Vicente-Retortillo, A., Dominguez-Pumar, M., Espejo, S., Fairen, A., Fernandez-Palma, A., Ferrandiz, R., Ferri, F., Fischer, E., Garcia-Manchado, A., Garcia-Villadangos, M., Genzer, M., Gimenez, S., Gomez-Elvira, J., Gomez, F., Guzewich, S. D., Harri, A.-M., Hernandez, C. D., Hieta, M., Hueso, R., Jaakonaho, I., Jimenez, J. J., Jimenez, V., Larman, A., Leiter, R., Lepinette, A., Lemmon, M., Lopez, G., Madsen, S., Makinen, T., Marin, M., Martin-Soler, J., Martinez, G., Molina, A., Mora-Sotomayor, L., Moreno-Alvarez, J. F., Navarro, S., Newman, C. E., Ortega, C., Parrondo, M. C., Peinado, V., Pena, A., Perez-Grande, I., Perez-Hoyos, S., Pla-Garcia, J., Polkko, J., Postigo, M., Prieto-Ballesteros, O., Rafkin, S., Ramos, M., Richardson, M. I., Romeral, J., Romero, C., Runyon, K., Saiz-Lopez, A., Sanchez-Lavega, A., Sard, I., Schofield, J. T., Sebastian, E., Smith, M. D., Sullivan, R. J., Tamppari, L. K., Thompson, A., Toledo, D., Torrero, F., Torres, J., Urqui, R., Velasco, T., Viudez-Moreiras, D., Zurita, S., & the MEDA team (2021). The Mars Environmental Dynamics Analyzer, MEDA. A suite of environmental sensors for the Mars 2020 mission, *Space Science Reviews* , *217* , 48. https://doi.org/10.1007/s11214-021-00816-9.

Sullivan, R., Banfield, D., Bell, J. F., Calvin, W., Fike, D., Golombek, M., et al. (2005). Aeolian processes at the Mars Exploration Rover Meridiani Planum landing site. *Nature, 436* , 58–61, https://doi.org/10.1038/nature03641.

Thomson, B. J., Bridges, N. T., & Greeley, R. (2008), Rock abrasion features in the Columbia Hills, Mars, *J. Geophys. Res., 113* , E08010, doi:10.1029/2007JE003018.

Viudez-Moreiras, D., Gomez-Elvira, J., Newman, C.E, Navarro, S., Marin, M., Torres, J., et al. (2019). Gale surface wind characterization based on the Mars Science Laboratory REMS dataset. Part I: Wind retrieval and Gale's wind speeds and directions. *Icarus* , *319* , 909-925. https://doi.org/10.1016/j.icarus.2018.10.011.

Viudez-Moreiras, D., de la Torre, M., Gomez-Elvira, J., Lorenz, R. D., Apestigue, V., Guzewich, S., et al.

(2022b). Winds at the Mars 2020 landing site. Part 2: Wind variability and turbulence, *J. Geophys. Res. Planets* , *127* , doi:10.1029/2022JE007523.

Viudez-Moreiras, D., Lemmon, M., Newman, C. E., Guzewich, S., Mischna, M., Gomez-Elvira, J. et al. (2022a). Winds at the Mars 2020 landing site. Part 1: Near-surface wind patterns at Jezero crater, *J. Geophys. Res. Planets* , *127* , doi.org/10.1029/2022JE007522.