AEOLIAN PROCESSES AND THEIR EFFECTS ON UNDERSTANDING THE CHRONOLOGY OF MARS

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Abstract. Aeolian (wind) processes can transport particles over large distances on Mars, leading to the modification or removal of surface features, formation of new landforms, and mantling or burial of surfaces. Erosion of mantling deposits by wind deflation can exhume older surfaces. These processes and their effects on the surface must be taken into account in using impact crater statistics to derive chronologies on Mars. In addition, mapping the locations, relative ages, and orientations of aeolian features can provide insight into Martian weather, climate, and climate history.

1. Introduction

Aeolian processes involve the interaction of the atmosphere and planetary surfaces (reviewed by Greeley and Iversen, 1985). Winds can erode and transport large quantities of fine particles and deposit them elsewhere on the surface. Consequently, existing landforms, such as craters, can be modified, erased, or buried, while new landforms, such as dunes, can be created. Aeolian processes operate on all scales, from wind-abraded grooves a millimeter across on rock faces, to rocks and kilometer-size hills sculpted by windblown sand, to dune fields tens of meters thick and covering thousands of square kilometers. These and other aeolian features have been found on Mars.

In the absence of liquid water on Mars and the lack of direct evidence for active volcanism and tectonic deformation, aeolian processes are probably the dominant agent of surface modification in the current geological regime (Wells and Zimbelman, 1989; Greeley *et al.*, 1992). High resolution views of Mars from the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) are showing the dominance of aeolian features on the surface, as reported by Edgett and Malin (2000). Aeolian processes are likely to have operated throughout much of Mars' history. Aeolian features such as wind streaks (Thomas *et al.*, 1981; see Figure 1) enable inferences to be drawn concerning the dominant wind directions at the time of their formation. Systematic mapping of these features through space and time on Mars' surface provides clues to current and past weather systems and climate. In this chapter, we outline the basics of aeolian processes, review the styles of potential resurfacing, and consider the consequences for understanding Martian chronology and history.

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Figure 1. High and low albedo patterns forming bright and dark streaks are seen in this high resolution view of the Medusae Fossae region of Mars. The prominent bright streak associated with the impact crater is typical of those seen on Mars at all scales up to tens of kilometers long. This and other *wind streaks* are inferred to represent the prominent wind direction at the time of their formation; in the case shown here, the wind would have been blowing from the lower left to the upper right. The area shown is about 500 m wide (*NASA MGS image M00-00534; Malin Space Sciences System*).

2. Aeolian Processes

Two factors are involved in aeolian processes, a dynamic atmosphere (i.e., wind) and a supply of small, loose particles. As reviewed by Zurek (1992), the Martian atmosphere is very dynamic, with near-surface winds measured by the Viking landers in excess of 28 m s^{-1}. General circulation models (GCMs) of the atmosphere (Pollack *et al.*, 1990) show systematic wind patterns as a function of season and location on the planet. For example, some of the strongest winds are modeled to occur in the southern highlands during the southern hemisphere summer, a season and location of frequent, observed dust storms. In many areas there is a direct correlation between the orientation of bright wind streaks and directions of strongest winds predicted by the GCM, suggesting that the streaks reflect the current wind system (Greeley *et al.*, 1993).

Most windblown particles are less than a few millimeters in diameter, both on Earth and Mars (Greeley and Iversen, 1985). Particles of this size are generated by a wide variety of geological processes, including chemical weathering, impact cratering, volcanism, tectonism, and other agents of gradation, such as running water, all of which have occurred on Mars.

As shown in Figure 2, winds transport particles in three basic modes: 1) *suspension* (typically involving grains $\lesssim 60\ \mu$ in diameter, or *dust*); 2) *saltation* (for grains ~ 60 to $2000\ \mu$ in diameter, or *sand*): and 3) surface *creep* for grains $\gtrsim 2000\ \mu$ across. *Threshold curves* define the minimum *wind friction velocity* (Bagnold,

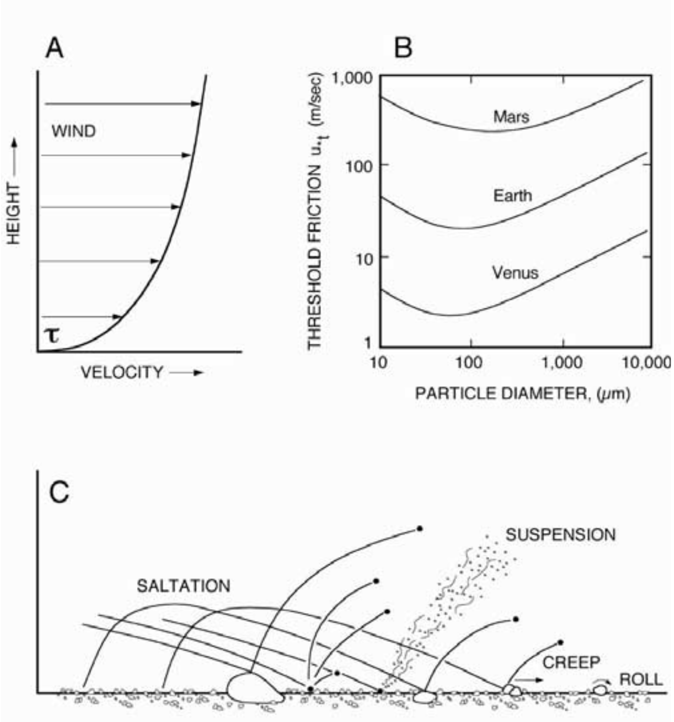

Figure 2. A) typical wind velocity profile above the surface though the boundary layer; friction along the surface generates a *shear stress* (τ) which lifts particles into the atmosphere; B) threshold curve for Mars showing the *threshold wind friction velocities* (U_{*t}, which is a function of the shear stress exerted by the wind) for particles of different sizes; differences among Mars, Earth, and Venus result from the differences in atmospheric densities (Greeley and Iversen, 1985); C) diagram showing the three modes of particle transport by the wind; although suspension and surface creep/roll can occur independently, these modes are often initiated or enhanced by saltation impact.

1954) needed to set grains into motion as a function of diameter. Extrapolation to the low-density, carbon dioxide atmosphere of Mars shows that minimum frictional velocities to set sand into saltation are about 10 times greater than on Earth, depending on the surface roughness (Greeley *et al.*, 1980). It should be noted that friction velocities are related to the shear stress exerted by the wind boundary layer above the surface, and are not equal to the wind speeds that one would experience standing on the surface. Grains $\sim 100\ \mu$ in diameter (fine sand) have the lowest threshold friction velocity, with both smaller (e.g., dust) and larger grains requiring higher velocities for movement due to interparticle forces and aerodynamic effects for the smaller grains and the higher mass of the larger grains. In addition to simple wind shear, more complicated vortical atmospheric motions, termed *dust devils*, are effective in setting grains into motion. First discovered on Mars in Viking orbiter images (Thomas and Gierasch, 1985), numerous dust devils have been observed in Mars Pathfinder data (Smith and Lemmon, 1998; Renno *et al.*, 2000) and Mars

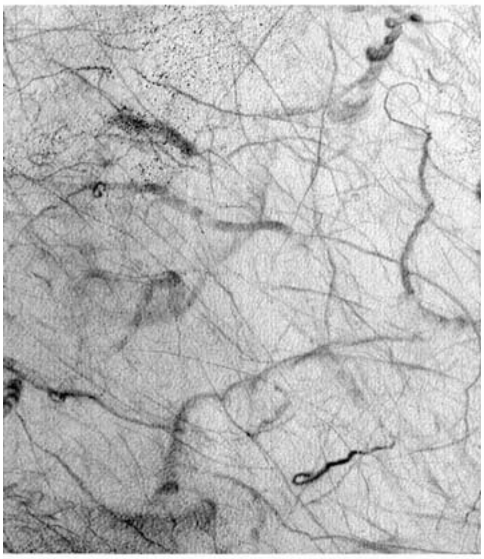

Figure 3. These dark meandering and looping patterns on the surface of Mars are inferred to be the trails left by dust devils which lifted fine particles into the atmosphere, exposing a darker substrate. The area shown is about 2 by 2.4 km (*NASA PIA02377; Malin Space Sciences System*)

Global Surveyor images (Malin *et al.*, 1998), including traces of inferred dust devil tracks (Figure 3).

Grains in saltation "hop" along the surface; as the grains impact, they can inject smaller particles into suspension and push larger grains along the surface in creep (Figure 2c). Thus, saltating sand is critical in the aeolian regime because it is 1) the grain size moved by lowest winds and, thus, will be the most common material moved (provided they are available), 2) capable of setting dust and larger grains into motion under wind conditions otherwise too low for threshold, and 3) the size commonly forming dunes, ripples, and wind-abraded rocks.

3. Aeolian Resurfacing

Resurfacing of Mars by aeolian processes includes erosion, burial or mantling, and exhumation of older surfaces which have been mantled by deposits of aeolian, fluvial, or volcanic origins.

3.1. WIND EROSION

Wind erosion occurs in two principal forms, *deflation* and *abrasion.* In deflation, relatively loose materials are picked up by the wind and removed. Such material can be unconsolidated sediments, including previously wind-transported deposits, or grains weathered free from consolidated or crystalline parent rocks. Landforms on Earth resulting from deflation include wind-stripped surfaces and depressions (commonly called *blowouts*) ranging in size from a few meters across to basins hundreds of kilometers across, as reviewed by Cooke *et al.* (1993).

Various areas on Mars have been attributed to wind deflation, as first noted by McCauley (1973) in the analyses of Mariner 9 images. These include surfaces surrounding *pedestal craters* which were assumed to have been lowered by wind erosion. The "pedestals" coincide approximately with the ejecta zone and was assumed to have been left high-standing because it was rockier than the surrounding plains, forming a type of armor-plating less subject to wind erosion. The crater shown in Figure 1 is one type of pedestal crater, although its "pedestal" has a more serrated outer boundary than typical forms. If pedestal craters do reflect deflational areas, then their presence would signal significant amounts of material removed by the wind, and lowering of the surfaces by tens of meters (the heights of the pedestals). Such deflation might be capable of removing or substantially eroding craters <100 m. On the other hand, if pedestal craters are remnants from wind erosion, one would expect the outline of the pedestal to be asymmetric in response to prevailing wind directions, as is the case with other aeolian features observed on Mars. Such asymmetry, however, is not seen around pedestal craters and their formation is open to question.

Abrasion occurs when windblown grains strike surfaces, rocks, or other grains and cause fragmentation. On the scale of millimeters to centimeters, *pits*, *flutes*, and *grooves* can be cut into rock, while on scales of centimeters to meters, rocks can be faceted and eroded into distinctive shapes called *ventifacts.* On scales of meters to kilometers, wind-sculpted hills, called *yardangs*, can be developed by a combination of abrasion and deflation. These features have been identified in images of Mars in many areas (Binder *et al.*, 1977; Mutch *et al.*, 1977; Ward, 1979; Bridges *et al.*, 1999).

It is difficult to determine the amounts and rates of wind erosion on Mars. Arvidson *et al.* (1979) estimated the age of the surface around the Viking 1 landing site from the preservation of small craters and extrapolation from lunar crater chronologies. They estimated the rates of erosion by all processes, including wind, to be relatively low. Similarly, Golombek and Bridges (2000) estimated the rate of erosion at the Pathfinder site to be 0.01 to 0.04 nm/yr. On the other hand, theoretical considerations by Sagan (1973) suggested that rates of wind abrasion should be very high on Mars because of the high wind speeds needed for particle entrainment. Laboratory experiments by Greeley *et al.* (1982) showed that the low rates of erosion could be explained if there were a paucity of effective agents of abrasion (such as holocrystalline sand grains) on Mars. They also showed that, while wind speeds are high on Mars in comparison to Earth, particles reach a smaller percentage of the wind speed on Mars because there is less effective "coupling" of the wind to the grains.

There is a fundamental consideration which must be taken into account in assessing wind erosion. Very little work has been done on the rates of landform

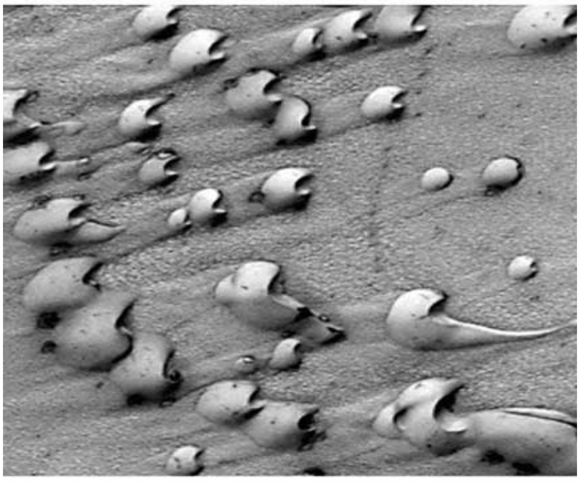

Figure 4. High resolution image of sand dunes in the Martian north polar area (*Borealis Chasma*) showing classic *slip faces* (the steeper, right-hand sides of the dunes) the orientations of which indicate that the prevailing wind direction at the time of their formation was from the left to the right. When this image was taken (September 1998) most of the area was covered with bright frost, including the dunes. Area shown is about 1.4 by 1.8 km (*NASA PIA02069; Malin Space Sciences Systems*).

erosion by the wind on the scale of hundreds of meters and larger, and extrapolation of wind abrasion from smaller features, such as rocks, probably is not appropriate. Thus, rates of wind erosion and eventual “erasure” of large landforms such as impact craters is poorly constrained on Earth and Mars.

3.2. WIND DEPOSITION

There appears to be abundant windblown material on Mars, as evidenced by the frequent dust storms and widespread occurrence of sand dunes. Viking orbiter images reveal extensive dune fields, the most prominent of which is in the north polar area (Cutts *et al.*, 1976; Tsoar *et al.*, 1979). More recently, Edgett and Malin (2000) document sand dunes in many parts of Mars imaged in high resolution, including the north polar area (Figure 4). Although few estimates of the thickness of the dune deposits have been made, one study suggests that parts of the north polar dune field have an “equivalent sediment thickness” (the thickness of all the material if it were spread out as a uniform layer) ranging from 0.5 to 6.1 m, with an average of 1.8 m (Lancaster and Greeley, 1990). Although this thickness of material could bury craters tens of meters in diameter, it is unlikely to mask larger craters. On the other hand, this estimate applies only to the dunes on the surface and does not take into account the possibility of older dune deposits which could exist below the observed dune field.

In addition to windblown materials organized into dunes, sand sheets could also occur on Mars and be unrecognized in images from orbit. For example, Viking infrared thermal mapping (IRTM) data suggest the presence of sand-size deposits in many areas (Edgett and Christensen, 1994) where obvious dunes are not seen at available orbital image resolution. In addition, most of the duneforms seen at the Pathfinder site are at the limit of detection by MOC, yet this surface suggests the presence of sand-size material in the MGS Thermal Emission Spectrometer data.

Perhaps the greatest volume of windblown material is in bright and dark dust deposits. For example, Soderblom *et al.* (1973) noted that large areas of Mars have a subdued appearance and suggested that mantling deposits were derived by wind erosion in the polar areas and were transported to lower latitudes, burying smaller craters ($<$1200 m in diameter) and subduing larger craters. This material was likely to be dust carried by suspension. Viking IRTM data suggest mantles of dust in many areas, including the southern highlands (Christensen, 1986), but it is not possible to determine the thickness of the deposits.

Low albedo dust is also probably present, as reviewed briefly by Edgett and Malin (2000). They show MGS MOC images supporting earlier suggestions by Dollfus *et al.* (1993) that some low albedo zones, such as Mare Erythraeum, include coarse dust which might have been emplaced in short-term suspension. Other low albedo areas probably include this type of dust which is fixed within duricrust and is immobile to transport, and sand-size particles of dark minerals.

3.3. EXHUMATION

Some areas show evidence for exhumation of older surfaces by wind erosion. For example, in Figure 5 a series of craters is seen in the Amazonis Planitia region (Greeley *et al.*, 1985); crater 1 appears to be mantled, crater 2 appears to be half mantled and half exhumed, and crater 3 is superposed on the mantle. As the material is stripped, linear streamlined hills, or yardangs, are left behind. Nearby, small dunes found along the margin of the exhumation boundary suggest that sand-size material is being stripped from the mantle. Were these relationships not seen in this area, it is doubtful that crater 2 would be recognized as being formerly buried. The pristine morphology of the exhumed part gives little evidence of the extensive deflation that must have taken place, and is very similar to the ejecta morphology of crater 3.

4. Wind Regime, Past and Present

Several lines of evidence suggest that the wind regime on Mars has been variable through time in terms of wind and windblown particles. For example, Edgett and Malin (2000) analyzed MGS MOC images and showed evidence for both active and inactive dunes, suggesting that aeolian processes might have been more vigorous (or at least variable) in the past.

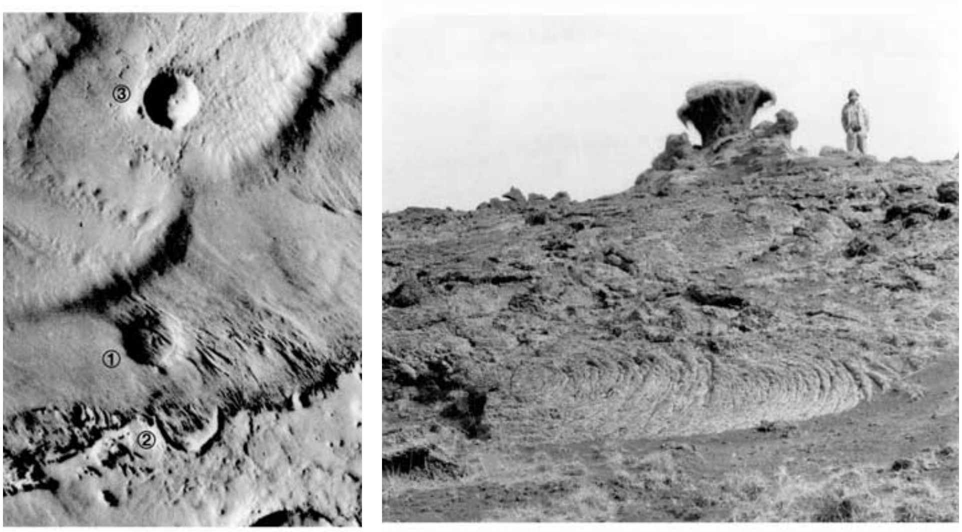

Figure 5. a) Viking Orbiter image of the Medusae Fossae area showing deposits (top 3/4 of the image) which mantle cratered terrain. Crater 1 is mostly mantled, crater 2 is half- mantled and half-exhumed, and crater 3 is superposed on the mantle deposits. Without seeing the relationships portrayed here, it is doubtful that the cratered terrain in the lower part of the image would have been recognized as formerly buried, as evidenced by the similar appearance of the ejecta for crater 3 and the exhumed part of crater 2. Area shown is about 52 by 75 km. (Greeley *et al.*, 1985; *NASA Viking Orbiter image 438S01*). b) Photograph of an exhumed basaltic surface north of Askja, Iceland, showing the well-preserved surface features, such as pahoehoe "ropes" seen in the foreground; in the background (near the figure) is the remnant of the ~1.5-m-thick deposit of silt and clay which covered the entire area, but is being stripped by wind deflation. This is a smaller version of the case illustrated on Mars in a) (photograph by R. Greeley, August 1980).

The geometry of most aeolian features, including wind streaks, drift deposits, yardangs, and many duneforms, indicates the prevailing wind direction at the time of their formation. Comparing the orientations of these features with meteorological data taken from landers on the surface and predictions from GCM simulations gives insight into the aeolian regime on Mars. In addition, comparing the orientations of wind features which might reflect paleowind regimes can provide clues to changes in climate and Martian history in general. Bright wind streaks correlate well with GCM predictions for strongest winds in most parts of Mars, including the Viking 1 site where there is also a correlation with measured strongest winds. Dark wind streaks do not correlate very well with GCM runs, and it was suggested that these features result from local winds influenced by topography, which is not modeled in the GCM (Greeley *et al.*, 1993).

A wide variety of aeolian features are seen at the Pathfinder site in images taken from orbit and the surface (Greeley *et al.*, 1999, 2000), including bright wind streaks, wind tails (oriented drift deposits associate with rocks), duneforms, wind-modified craters, and wind-abraded rocks (Bridges *et al.*, 1999). Greeley *et* *al.* (1999) analyzed the orientations of these features for comparisons with GCM runs. Results show excellent correlations among the bright wind streaks, the wind tails, and the duneforms (seen both from orbit and the surface) with the strongest winds predicted by the GCM. The wind-abraded rocks and the wind-eroded parts of small craters, however, do not correlate with these features, suggesting that they represent a paleowind regime (Greeley *et al.*, 2000). GCM runs for all Martian seasons under current conditions and for changes in Mars' obliquity cannot account for the inferred orientation of the paleowind regime suggested by the anomalous aeolian features. This leads to the suggestion that either there are anomalous meteorological patterns not modeled by the GCM, or that Mars' spin axis was at a different geographic position than it is at present (Kuzmin *et al.*, 2000).

5. Summary Implications for Chronology and History

Aeolian processes are probably the current primary agent of surface modification on Mars today and are likely to have operated throughout much of the evolution of the surface. Landforms are both destroyed and created by these processes, as shown in Figure 6, leading to resurfacing through erosion, deposition and exhumation of older surfaces. Unfortunately, rates of resurfacing are poorly constrained because "absolute" Martian chronologies are poorly known and because the techniques for extrapolating wind abrasion rates from scales of < a few meters to larger landforms are not well developed, even on Earth.

Aeolian processes can have a significant influence on the record of impact cratering. Unlike the Moon, the Martian surface is subjected to erosion and redistribution of materials by wind and water, leading to degradation, removal, or burial of impact craters. If such modifications are not recognized, then crater statistics for the areas under study will be compromised; for the most part, age determinations based on crater counts would be underestimates. High resolution images, however, might reveal such modifications and perhaps some future technique could be developed to adjust the estimated ages.

Surfaces which have been exhumed, however, might pose a more difficult problem for obtaining impact crater statistics. Such surfaces, in effect, would have been removed from the impact crater regime for an unknown period of time corresponding to the burial. Moreover, as shown in Figure 5, it might not be possible to recognize a completely exhumed surface because small features can be perfectly preserved, even when viewed at extremely high resolution from the surface. For example, one could imagine a lava flow which has emplaced early in Mars' history, then buried by sediments before very many impacts occurred on its surface, yielding erroneously young dates. Although this scenario is conceivable, careful analysis of geological relations of all the units in the immediate area and in the regional context would likely reveal the anomaly.

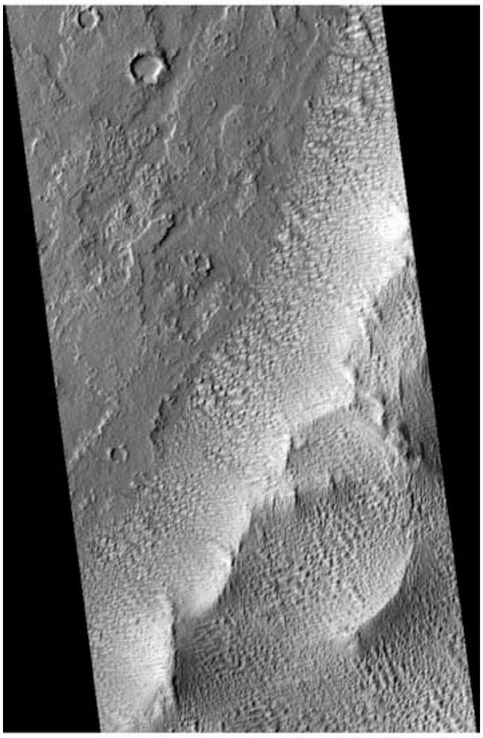

Figure 6. This high resolution MOC image illustrates the complex interplay of volcanic, impact, and aeolian processes on Mars. These lava flows northwest of the volcano, *Pavonis Mons*, show a record of impact cratering, but most of the craters are degraded. The complex sand dune field to the right includes both large dunes (the prominent ridges) and smaller duneforms which appear to encroach the lava flows. Although parts of the flow margins are clearly visible, the crater morphologies suggest partial mantling and degradation, possibly by windblown sand (*MOC image M0003198-part Malin Space Sciences System*; courtesy of W. Hartmann).

Future work should focus on quantifying rates of erosion, burial, and exhumation of large landforms by aeolian processes on Mars, drawing on terrestrial analogs to the extent reasonable to validate the approaches and to provide a means for extrapolation to Mars. Concurrently, studies should be undertaken to quantify the potential influence of aeolian processes on chronologies derived from impact crater statistics, beyond the qualitative assessment outlined here.

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