A terrestrial weathering and wind abrasion analog for mound and moat morphology of Gale crater, Mars

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Abstract

A striking feature of Gale crater is the 5.5 km high, central layered mound called Mount Sharp (Aeolis Mons)—the major exploration target for the Mars Science Laboratory rover, Curiosity. Within the 154 km diameter crater, low plains (Aeolis Palus) resemble a moat surrounding Mount Sharp. There is a similar terrestrial analog in the Jurassic Navajo Sandstone of southern Utah, USA, where a distinctive weathering pit 60 m wide by 20 m deep contains a central pillar/mound and moat. Strong regional and local winds are funneled to amplify their velocity and produce a Venturi effect that sculpts the pit via wind abrasion. Although the Navajo pit is orders of magnitude smaller than Gale crater, both show comparable morphologies accompanied by erosional wind features. The terrestrial example shows the impact of weathering and the ability of strong winds and vortices to shape lithified sedimentary rock over long periods of time.

1. Introduction

Recent NASA rover explorations by the Mars Science Laboratory Curiosity have revealed sculpted sedimentary rock exposures on Mars, with implications of surficial processes and the potential for records of extraterrestrial life. One of the thickest sedimentary sequences on Mars comprises a 5.5 km high layered mound known as Mount Sharp, Curiosity rover’s exploration target within Gale crater. Inside this 154 km diameter crater, low plains (e.g., Aeolis Palus) resemble a moat surrounding Mount Sharp (Figure 1). How did this moat-like morphology develop? Past studies suggest multiple working hypotheses [Borlina et al., 2015; Kite et al., 2013, 2016; Malin and Edgett, 2000] that call upon combinations of deposition, weathering, and differential erosion. Recent laboratory simulations and modeling studies propose a mechanism of wind erosion that carved the mound and moat inside of Gale crater [Day et al., 2016], but a true analog archetype demonstrating whether this is feasible in solid rock has not yet been previously documented.

The purpose of this paper is to demonstrate physical and surface process similarities of a Utah weathering pit as a terrestrial analog to the larger-scale geometry of Gale crater on Mars and the important role of eolian erosion by sand abrasion. Areas of southern Utah are favorable for terrestrial comparisons to Mars due to the exceptional sedimentary rock exposure, lack of vegetation, and weathering features in the desert climate [e.g., Chan et al., 2011]. Analog eolian depositional environments and diagenetic products of southern Utah also inform interpretations of Mars geology [e.g., Ormô et al., 2004; Chan et al., 2004, 2005a, 2011; Potter et al., 2011; Young and Chan, 2017]. The focus of this study is a large weathering pit in Grand Staircase Escalante National Monument of Utah (Figure 2), informally dubbed “inselberg pit,” German for “island mountain” [Netoff and Chan, 2008]. In the desert southwest of the U.S., the Colorado River and its tributaries have been key in shaping large geomorphic features, but weathering and wind are also effective sculptors of the landscape.

2. Mars Characteristics and Transport Models

Mars is a vast desert where wind is a dominant surficial landscape process. More than 30 Martian moats with intracrater central mounds are identified in the Noachian southern highland terrain [Bennett and Bell, 2016; Grotzinger and Milliken, 2012; Malin and Edgett, 2000]. A number of studies propose that the craters formed early and were filled in with numerous sedimentary layers. Some landscape evolution models call upon successive layers modified by slope winds, without complete fill of the crater [e.g., Kite et al., 2013, 2016]. Other studies suggest that these sedimentary formations were later shaped and carved out by wind to make the mound morphology over a long period of time that could extend back as far as the Noachian [Bennett and
Bell, 2016; Grotzinger and Milliken, 2012; Grotzinger et al., 2015]. The variance in mound morphologies could represent a spectrum of advancing stages of wind erosion of once filled craters [Malin and Edgett, 2000]. In the case of Gale crater, the thick sedimentary units preserve internal deposits of rim-derived material from ancient alluvial and fluvial environments, transitioning to wet-phase deposits of ancient lakes toward the center of the crater [e.g., Grotzinger et al., 2015; Williams et al., 2013; Wray, 2013]. Studies suggest that katabatic (cool, downward moving) winds from the north funnel and concentrate to make vortices that split and scour around the inner edges of the crater to shape a moat over time [Day and Kocurek, 2016]. To test this hypothesis, Day et al. [2016] detail small-scale wind tunnel experiments and numerical modeling of flow over a crater. Erosion of the interior first began just inside the crater rim where the contact between the bedrock and basin fill represented a preferential weakness. A shallow moat was created and deepened by turbulent wind vortices to make a channelizing pathway for flow and a retreating mound inside the crater. Over time, the streamlined mound retreated to the center until all side material was eroded away. Their wind tunnel experiments did produce morphologies similar to Gale crater, and their numerical modeling using large-eddy simulation further demonstrated a positive feedback between topographic focused flow along the crater rim and the wind erosion potential [Day et al., 2016].

These transport-based models have difficulty scaling upward and cannot represent the true model of conditions of Mars. In support of an eolian-dominated landscape, observations of ventifacts, yardangs, dunes, and wind streaks in Gale crater [e.g., Bridges et al., 2014; Day et al., 2016; Day and Kocurek, 2016] are indeed reliable indicators of wind direction that agree with model results. However, the inselberg pit and pillar described here is a valuable intermediate bridge between the meter to decameter scales between the 30 cm and 60 cm
bench top models and the 154 km diameter of Gale crater. In addition, the Utah field example shows physical evidence of weathering by mass wasting and erosion by sand abrasion, similar to Gale crater features.

3. Utah Inselberg Pit Analysis

Weathering pits are shallow-to-deep, surficial, meter-scale, bedrock depressions that can occur on multiple types of substrates [Goudie, 1991]. These pits typically collect precipitation from their small catchments, and each can be its own miniecosystem with complex connections and feedbacks between the host rock, meteoric water, and organisms. In the arid southwest across much of the Colorado Plateau, weathering pits number from tens to hundreds at individual sites. They commonly form on relatively flat, porous sandstone surfaces that are susceptible to weathering and erosion. The pits are highly variable in shape, size (decameter scales up to decameter scales), depth, relations to tectonic elements, and ability to retain water [Netoff and Shroba, 1993; Netoff et al., 1995; Chan et al., 2005b, 2010; Netoff and Chan, 2008]. The pit types of southern Utah include pans, bowls, cylinders, breached cylinders, and elongate joint-controlled pits [Netoff and Shroba, 1993; Netoff et al., 1995] (supporting information). Studies in the Middle Jurassic Entrada Sandstone near Lake Powell, Utah, document a concentrated area containing 122 decameter-scale pits [Netoff and Shroba, 1993; Netoff et al., 1995] (supporting information). However, none of these other large Entrada Sandstone pits possess an internal pillar or mound.
Inselberg pit (Figure 2) is an unusually large weathering pit within a cluster of depressions that sit atop a NE-SW elongate barren sandstone dome 160 m high in Grand Staircase Escalante National Monument of southern Utah [Weir and Beard, 1990] (supporting information). Here alignment of drainage suggests modification of joint (or fault?)-controlled topography by strong southwesterly winds [Netoff and Chan, 2008]. The impressive expression of the pit is accentuated by its open 360° view position on the dome and the striking color contrasts of the bleached white pit walls contrasting with the red dune sand (diagenetic iron oxide-coated grains) inside. Inselberg pit has dimensions of 60 m wide by 20 m deep, with an interior cylindrical pillar/mound of 10 m height. The pit is carved into the quartz-rich, fine-grained, cross-bedded eolian Jurassic Navajo Sandstone bedrock. The feature that is distinctive for inselberg pit besides its size is an interior, central pillar or mound that rises up above the pit floor. The interior mound contains some deformed cross bedding from soft-sediment deformation, and it is likely that the textural differences of the deformed sandstone contributed to how the weathering pit developed.

Although there are subtle textural differences in internal cross bed sets and laminae, the Navajo Sandstone is a relatively homogenous and isotropic unit with relatively high porosity (typically ~20–25%) [Lindquist, 1988; Nielsen et al., 2009; Schultz et al., 2010] compared to other strongly layered rock units with more inherent anisotropy (e.g., fluvial or marine sandstones and shales). There are no obvious water features or pour offs indicating water erosion on the sandstone surfaces. Instead, there is a large, prominent, smooth, fluted groove 5 m wide by 29 m long, which funnels southwesterly wind directly into the pit (Figure 3a). Inside the groove is a deflationary lag of iron oxide-cemented concretionary (cemented) pieces (Figure 3b), with dozens of asymmetrical erosional step-like marks up to tens of centimeters long from wind abrasion (Figure 3c). These step-like marks have a SW–NE alignment parallel to the long axis of the groove.

Inside the pit, walls show wind-blasted outcrop with characteristic centimeter-scale features of small streamlined, roughly horizontal, wind-parallel ridges and elongate stalks and ridges behind diagenetic concretionary forms (Figures 3d and 3e). These fluted erosional features are most common and pronounced on the northeast wall and in the lower 3–5 m along the wall. The streamlined walls of the pit show subtle wind etching of the sandstone that result in ribs of better cemented laminae. The smoothed nature of the walls is interrupted in places where recent rockfalls or spalls from mass wasting occurred (Figure 3f). As the interior deposit erodes, the mass of sand grains that can be mobilized around the deposit increases, allowing for more abrasion. The pillar mound inside the pit is surrounded by active fine-grained dune sand (up to 8 m high) that seasonally shifts. Unlike some shallow weathering pits of southern Utah that can retain water during significant parts of the year [Chan et al., 2005b], inselberg pit generally lacks standing water, perhaps due to the strong wind action and water absorption by dune sand.

Prefrontal winds across southern Utah are typically out of the southwest and then shift to the west and northwest after frontal passage (Figure 2b) [Helm and Breed, 1999]. Utah’s regional and local winds in the study area accelerate by passage over topographic highs, funneled by wind-parallel valleys. Spring cold front winds >100 km/h (supporting information) can persist for several hours and may be topographically enhanced by 200–300% to provide southwesterly winds capable of producing the pit, groove, moat, and other abrasional features [Netoff and Chan, 2008]. Wind gusts can be strong but are short lived [Cooley et al., 1969] (supporting information). In another large weathering pit near Dance Hall Rock (Figure 2a) located 41 km to the southeast of the inselberg pit, a Venturi effect with enhanced wind speed due to funneling showed a large vortex that rotated on a roughly vertical axis, with dozens of smaller turbulent eddies up along the pit walls (observed with confetti; see supporting information). The consistent pattern of focused wind and its complex eddies help carve the decameter-scale Utah sandstone pits and leave behind wind abrasion proxies.

Our observations of hundreds of weathering pits across southern Utah (see supporting information) indicate that inselberg pit is unique with its central pillar, possibly because it is large with an inherently different deformed sandstone lithology, it is positioned at the top of a dome, and it has a focused groove that may facilitate stronger vortices compared to other pits.

4. Discussion and Implications

The physical comparisons of Gale crater and Utah’s inselberg pit are strikingly similar and compelling (Table 1). Each is a large example in a class of other similar deep depressions in a desert regime, showing a qualitatively
similar spectrum of morphology. Both possess a central layered pillar mound that was once more extensive but was subsequently eroded and reduced by wind over time to leave a moat surrounding the mound. Turbulent vortices trap and transport sand, abrading the central deposit and causing it to become a reduced mound that retreats to the center until all material is eroded away. The homogenous nature of the Jurassic Navajo Sandstone comprising inselberg pit means that focused wind erosion can be effective in this weakly cemented host rock. A local area of deformed sandstone could have caused anisotropies that facilitated erosion around a pillar form toward the center of the pit. This terrestrial example is likely

**Figure 3.** Wind-abraded features of inselberg pit in the Jurassic Navajo Sandstone. (a) A giant, abrasional/erosional groove funnels wind and sand into the pit in the direction of the yellow arrows. Person for scale in groove near the center of the image. (b) The fluted groove (29 m long × 5 m wide) is scoured from southwesterly winds. The prevalent wind is in the direction of the yellow arrow toward the pit, with some concretionary iron oxide lag along the bottom of the groove. View is toward the southwest, with the Straight Cliffs on horizon. Seated person for scale in groove near the center of the image. (c) Step-like, asymmetrical marks inside the giant groove are formed by wind erosion in the direction of the yellow arrow. This image is located close to the yellow arrowhead in Figure 3b. (d and e) Wind abrasion produces horizontal-oriented, elongate wind-parallel ridges or “tails” in the shadow/protected lee side of concretions along the lower sides of the pit walls. Yellow arrows show direction of dominant wind movement. (f) Inside of pit, blocks of sandstone erode from the wind-etched pit wall, likely due to changes in insolation (rockfall ~1996–1997). Largest block ~5 m across. Red, fine-grained dune sand is blown in and accumulates and shifts within the pit. Figures 3a, 3c, and 3f are modified from figures in Netoff and Chan [2008].
Table 1. Comparative Features of Gale Crater on Mars and Inselberg Pit in Utah

| Comparative Features          | Mars—Gale Crater and Others With Intracrater Mounds                                      | Earth—Utah’s Inselberg Pit                                                                 |
|------------------------------|------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| Geomorphology                | Crater with resistant rim and “moat” with interior dome-shaped mound of sedimentary layers (multiple formations) | Weathering pit in cross-bedded quartz sandstone, interior subvertical mound/pillar of deformed sandstone (Jurassic Navajo Sandstone) |
| Depth:diameter               | 1:10 for 15 km crater, 1:30 for 150 km crater [Robbins and Hynek, 2012]                  | 1:3 for 60 m pit                                                                             |
| Weathering processes         | Physical breakup of rock from impact bombardment, thermal cycling, and mass wasting [Day and Kocurek, 2016; Viles et al., 2010] | Physical breakup of rock from joints, fractures, cracks, thermal cycling, and mass wasting, with assistance of ice, water, and moisture [Chan et al., 2008] |
| Eolian processes             | Inferred from wind tunnel experiments, numerical models [Day et al., 2016], and katabatic (cool, downward moving) winds | Observations and physical measurements of wind regimes, topographic enhancement, and Venturi effect [Netoff and Chan, 2008] |
| Eolian abrasion evidence     | Yardangs, dunes, and wind streaks [Day and Kocurek, 2016], ventifacts [Bridges et al., 2014, polished bedrock surfaces [Day and Kocurek, 2016], and streamlined bedrock nodules and inferred concretions [Stack et al., 2014] with tapered elongate ridge tails in the lee side of nodules [Day and Kocurek, 2016] | Moving fine-grained dune sand, deflation surfaces, abraded grooves, bedrock valleys, flutes, and streamlined and tapered ridge tails in the lee side of fingers/stalks topped with concretions [Netoff and Chan, 2008] |
| Age                          | Old-Noachian, global desiccation? [Day et al., 2016]                                      | Young (tens to hundreds of thousands of years) [Chan et al., 2010]                           |

Similar to the wind tunnel experiments that also employed a homogeneous and erodible substrate. However, it is still unclear how this would compare to a Mars crater with a resistant rim and a more erodible interior fill. The contrast between the host rock rim and the sedimentary infill would be a likely zone of weakness for differential wind abrasion.

Both examples are proportionally wider than they are deep, with the Gale crater example approximating a 1:30 depth to diameter ratio [Robbins and Hynek, 2012]. The Gale crater dimension, and by extension its moat, would be predetermined by the size of the impact crater. The Gale crater landscape and its fill further evolved by physical weathering from impact bombardment, thermal cycling, and gravity-driven mass wasting to fracture and break up the bedrock [Day and Kocurek, 2016; Viles et al., 2010]. The physical proxy evidence for wind erosion and abrasion at Gale crater consists of yardangs, ventifacts, dune sand, wind streaks, and streamlined bedrock nodules with elongate tails in the lee side of the nodules [Bridges et al., 2014; Day and Kocurek, 2016; Stack et al., 2014].

Although there is not significant evidence of modern surface water erosion at inselberg pit, rainwater and moisture still contribute to the physical weathering in this desert regime along with thermal/insolation changes in the rock and mass wasting [Chan et al., 2008]. The large terrestrial size of inselberg pit may be influenced by inherent rock and textural properties, as well as the local focusing and funneling of wind. The physical proxy evidence for wind erosion at inselberg pit consists of dune sand, deflation surfaces with lags, abraded grooves, bedrock valleys, flutes, and streamlined tails in the lee side of finger-shaped stalks topped with concretions [Netoff and Chan, 2008]. One of the reasons the proxy evidence between the two cases differs is that many of the Gale crater characteristics are observed from orbiter remote images, although streamlined and exhumed bedrock nodules [Day and Kocurek, 2016] and features are likely to be observed more by the rover as it continues its future journeys. In the inselberg pit example, it is accessible for close outcrop study where centimeter- to meter-scale features are observed firsthand.

An unresolved question is how much time is required to make a moat and mound morphology? Farley et al. [2014] report wind-driven scarp retreat rates of ~1 m/Myr over the last ~80 Myr, for units of the Yellowknife Bay formation within Gale crater. Current winds on Mars are very strong and powerful and would be expected to be very effective erosional agents but possibly episodic. Day et al. [2016] propose that the erosion goes back to the Noachian desiccation event. In contrast, inselberg pit is a young feature, formed after uplift on the Colorado Plateau and downcutting of the Colorado River. Attempts at cosmogenic dating of small weathering pits and exposure surfaces on southern Utah weak-cemented sandstones suggest ages on the order of tens to hundreds of thousands of years or more [Chan et al., 2010].

Weathering and wind abrasion in southern Utah’s desert can yield terrestrial analogs to understand the moat-like landscape at Gale crater. Although the natural Navajo Sandstone inselberg weathering pit is still
considerably smaller than Gale crater by about 3 orders of magnitude, it nevertheless demonstrates how the physical processes can happen and supports theoretical modeling while comprising an intermediate-scale example between the orders of magnitude smaller 30 and 60 cm scale substrates for wind tunnel experiments and a physical 154 km diameter crater. The inselberg pit documents the importance of local landscape morphology that can focus and enhance wind erosion. The natural Navajo analogy suggests that strong, dynamic, focused winds on Mars were capable of carving deeply into sedimentary layers to generate Mount Sharp, surrounded by the low, eroded plains within Gale crater.

5. Methods

Field studies, measurements, videos, and observations were conducted across multiple areas of the Jurassic Navajo Sandstone of southern Utah and northern Arizona in years ~1994–2010, with focus on weathering pits in the Grand Staircase Escalante National Monument and Glen Canyon National Recreation Area of southern Utah.

Comparisons in this paper to Martian features are based on published interpretations of data relevant to Mars.

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