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Ventifacts on Earth and Mars: Analytical, field, and laboratory studies supporting sand abrasion and windward feature development

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A B S T R A C T

Terrestrial ventifacts – rocks that have been abraded by windblown particles – are found in desert, periglacial, and coastal environments. On Mars, their abundance suggests that aeolian abrasion is one of the most significant erosional processes on the planet. There are several conflicting viewpoints concerning the efficacy of potential abrasive agents, principally sand and dust, and the relationships between wind direction and ventifact form. Our research, supported by a review of the literature, shows that sand, rather than dust or other materials, is the principle abrasive agent on Earth and Mars. Relative to dust, sand delivers about 1000× the energy onto rock surfaces on a per particle basis. Even multiple dust collisions will do little or no damage because the stress field from the impact is much smaller than the spacing of microflaws in the rock. The abrasion profiles of terrestrial ventifacts are consistent with a kinetic energy flux due to saltating sand, not airborne dust. Furthermore, Scanning Electron Microscope images reveal surfaces that are fractured and cleaved by sand grain impact. With respect to their distribution, ventifacts are found in regions that contain sand or did so in the past, but are not found where only dust activity occurs. Contrary to some published reports, our evidence from field studies, analytical models, and wind tunnel and other experiments indicates that windward, not leeward, abrasion is responsible for facet development and feature formation (pits, flutes, and grooves). Leeward abrasion is confined to fluvial conditions, in which the high viscosity and density of water are able to entrain sand-size material in vortices. Therefore, ventifacts and abraded terrain provide an unambiguous proxy for the direction of the highest velocity winds, and can be used to reconstruct palaeowind flow.

1. Introduction

Ventifacts are rocks abraded by windblown particles, characterized by their distinctive morphology and texture (Laity, 1994). Many show one or more facets, separated by sharp keels that form through progressive planation by impacting particles. A facet is a relatively planar surface cut at right angles to the wind, regardless of the original shape of the stone (Fig. 1e–g). The term ‘face’ is used to describe the original surface of the rock. Facets often join along a sharp ridge or keel (Fig. 1g). Multiple facets may develop on a rock, related not only to winds from different directions but also to the shifting and overturning of small ventifacts. Large boulders, which cannot be moved, are the best indicators of regional wind direction.

The ventifact shape and associated surface features depend on rock size, density and hardness, primary texture, and abrasion maturity. Hard, fine-grained rocks become faceted, with little roughness or feature variation. Heterogeneous, coarse-grained, or initially rough-textured rocks are more likely to develop pits, flutes, or grooves. On Earth, ventifacts develop in vegetation-free areas subject to frequent, high-speed, sand-laden winds. Ventifacts on Mars are well developed and widespread as shown in images from the Mars Exploration Rover (MER) and earlier surface missions (McCauley et al., 1979; Bridges et al., 1999; Greeley et al., 2002, 2006; Sullivan et al., 2005; Thomson et al., 2008) (Fig. 1). They provide invaluable markers of ancient winds and provide insight into climate and landscape modification.

The interpretation of Martian ventifacts is based on terrestrial field studies and wind tunnel simulations (Bridges et al., 1999, 2004; Greeley et al., 2002). On Mars, ventifacts are one of the most important long-term records of aeolian activity. They provide critical information on past and present climates, weathering rates, local wind direction and intensity, global circulation, and aeolian modification of the surface. Thus, it is critical that ventifact formation be well understood, so that consistent hypotheses can be formulated. To correctly interpret ventifacts requires an understanding of the abrasive agent and process. Mars is a planet with abundant dust and sand. The dust is mobilized by localized vortices (dust devils) and regional to planet-wide storms (dust storms). Seen from orbit, bedforms interpreted as

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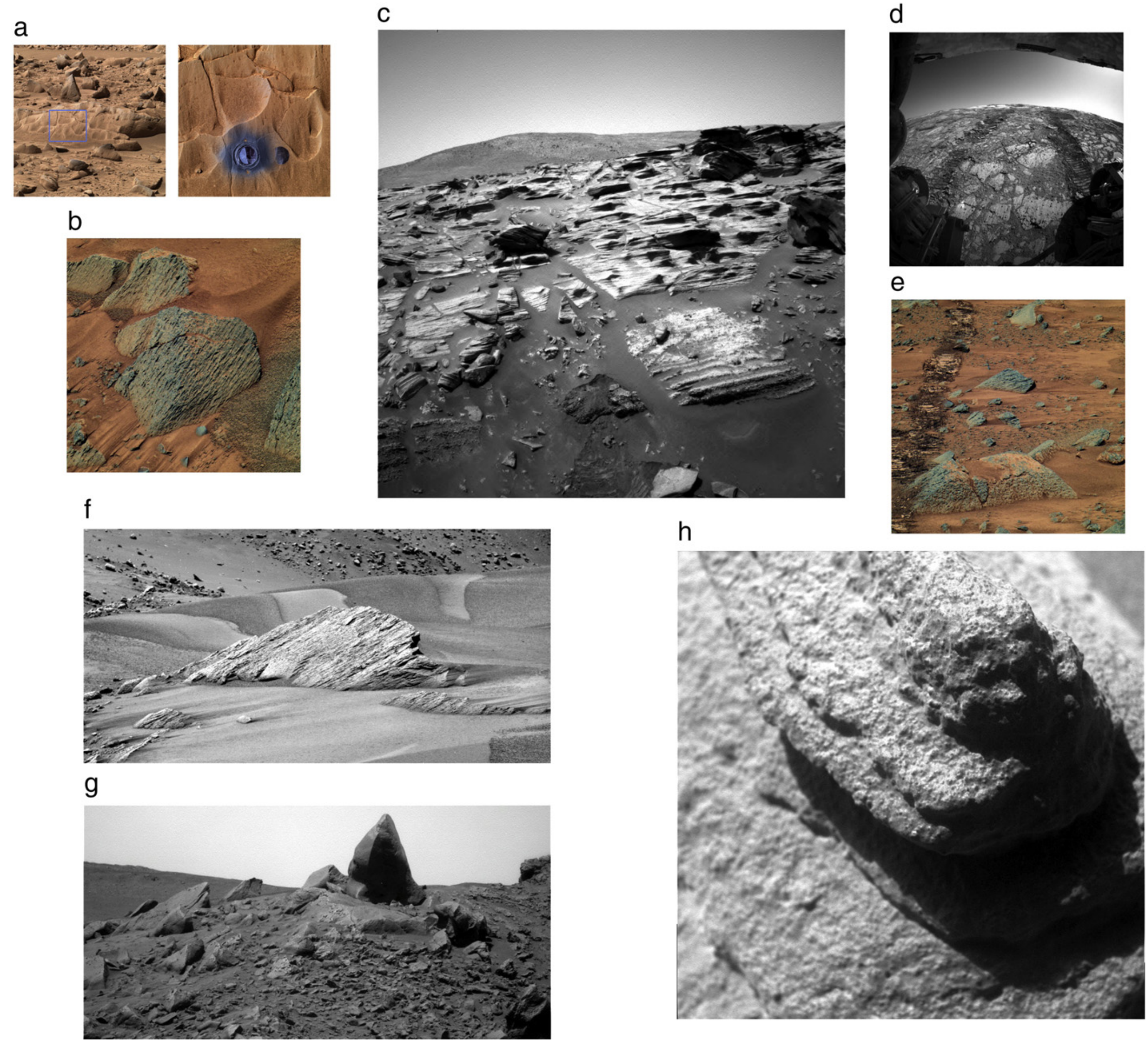

Fig. 1. Ventifacts and abrasion textures on Mars: (a) The fluted rock "Mazatzal" at the *Spirit* site (Pancam composite color). (b) Fluted rocks at the *Spirit* site (Pancam composite color, Sol 584). (c) Bedded rocks that have preferentially abraded along weak layers, Columbia Hills, *Spirit* site (Pancam, Sol 754). (d) "Tails" in the lee of resistant nodules within sulfate-rich soft rock at the *Opportunity* site (Hazcam, Sol 142). (e) Faceted and fluted rocks at the *Spirit* site (Pancam, Sol 585). (f) Faceted rocks near bedforms at the *Spirit* site (Pancam, Sol 620). (g) Faceted rocks at summit in Columbia Hills, *Spirit* site (Pancam, Sol 1344). h) Microscopic image of rock texture in vicinity of (c) (image width is 3 cm, Sol 753).

dunes and ripples, sand sheets, and ergs imply that sand is widespread (Greeley et al., 1992). Surface landers and rovers reveal smaller scale bedforms (Greeley et al., 1999, 2006; Sullivan et al., 2005), with microscopic images showing dark sand (Herkenhoff et al., 2004; Sullivan et al., 2005). Although sand is prevalent, the low atmospheric density makes it difficult to initiate saltation (White, 1979). Nevertheless, some sand is moved in the current Martian environment. Sand on the deck of the rover *Spirit* may have been deposited by dust devils with high vortical friction speeds or by strong wind gusts (Greeley et al., 2006). Fresh craters have meter-scale bedforms within them, implying rapid modification of unconsolidated impact debris (Bridges et al., 2007). However, orbital images since 1971, and 6 years of observation by Viking Lander (VL) 1, suggest that aeolian landscapes are largely static, with no migration of bedforms, changes in wind tails, or landform abrasion apparent (although the disappearance of two dome dunes and a shrinkage of another over a Mars year has been documented (Bourke et al., 2007)). Much of the sand is concentrated in topographic lows, indicating that winds are generally of insufficient strength to move it out of these traps (Breed et al., 1979; Golombek and Bridges, 2000; Golombek et al., 2006). This is consistent with the theoretical difficulty of saltation on Mars. Our understanding of Martian ventifacts is directly tied to this issue: if dust is an important abradant, it suggests that ventifact formation is active; however, if sand is the dominant abrasion agent, by implication most erosional modification either occurred in the past (under a higher density atmosphere?) or is only episodically active over long time periods during conditions of unusually strong wind gusts.

The terrestrial ventifact literature includes several radically conflicting theories as to the process of ventifact formation, the nature of the abradant, and the interpretation of various surface features, such as