INSIGHTS INTO MARTIAN AEOLIAN PROCESSES FROM MARS EXPLORATION ROVERS *SPIRIT* AND *OPPORTUNITY*.

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Introduction: Redistribution of fine particles by wind affects atmospheric opacity, changes the martian global system of surface markings, and has created dunes, ripples, and drifts. Yardangs indicate wind/surface interactions erode rock and strip off surface units to exhume older terrains. The importance of wind affecting the martian landscape, currently and in the past, has been recognized and appreciated mostly from orbital observations. The twin Mars Exploration Rover (MER) vehicles *Spirit* and *Opportunity* have been exploring Gusev crater (>7 km traverse) and Meridiani Planum (>10 km traverse) since early 2004[1,2]. These long MER traverses, across two very different, widely separated landing sites, have provided a two-orders-of-magnitude increase in terrain observed directly from the ground compared with previous landed missions, with proportional increases in opportunities for understanding martian aeolian processes. Just as significantly, the MER vehicles' Microscopic Imagers (MIs) have allowed far superior observations of grain sizes in aeolian deposits than were possible with the Viking Landers and Pathfinder[3]. Unfortunately, neither MER vehicle can measure wind velocities, although unusually strong wind events have sometimes been recognized from sudden increases in solar panel efficiency (due to cleared dust), and/or from observed sudden wind-related changes to local surroundings. Here we briefly summarize the MER landing sites from an aeolian point of view, then discuss five MER results that carry implications with wider application across the martian surface.

MER Site Overviews: The two MER landing sites are geomorphologically quite different. *Spirit's* site on the floor of Gusev Crater consists of dusty basalt plains with kipukas of older material (e.g. Columbia Hills). Deflation rates there seem to have been very low for much of martian history, preserving gross geomorphological features of great antiquity[4]. The effects of aeolian processes are seen in the sparse scattering of large ripples (some more recently active than others), ventifacted rock surfaces, wind tails of regolith associated with some rocks, and dust devils redistributing ongoing dusty air fall that thinly coats most rock and regolith surfaces[5,6].

In contrast, the geomorphology of *Opportunity's* landing site is completely dominated by the effects of wind. Relatively friable sulfate-enriched bedrock is mostly covered by dark, mafic regolith worked into ripples everywhere by wind. Where bedrock is exposed, commonly it has been planed off or otherwise affected by abrasion from wind-blown particles[7,8].

MER Spirit's traverse at Gusev crater. MOC and HiRISE images show that the mostly dust-covered landscape is marked with darker, time-variable dust devil tracks[5,6,9]. *Spirit* began its traverse within one of these tracks, but soon drove into dustier terrain on its way to Bonneville crater, en-route to the Columbia Hills. Along the way, *Spirit* encountered scattered low bedforms and ventifacts. These bedforms (including those observed on the floor of Bonneville) had no obvious slipfaces and were coated with bright dust. A detailed view, provided by wheel disturbances into one of these bedforms, revealed a coarse sand monolayer overlying a finer-grained, less sorted interior; surface dust and soil cohesion indicated bedform inactivity[5,6]. Many other examples of similar, dusty

Fig. 1. Asol073 false color Pancam view of wheel scuff into a light-toned ripple near the rim of Bonneville crater. Undisturbed surface is dust covered. Rim of scuff displays slightly cohesive overhang. Ripple interior is poorly sorted.

(inactive) ripples have been observed along *Spirit's* traverse to and into the Columbia Hills. Several lines of evidence are consistent with NW winds affecting the plains in this part of Gusev crater: (1) plains ripples are oriented NE/SW, with slightly steeper SE faces that are also dustier; (2) facets, flutes, and grooves on rocks interpreted as ventifacts are more abundant on NW exposures; and (3) asymmetric debris piles from Rock Abrasion Tool grinding extend to the SE. This evidence is consistent with afternoon WNW winds predicted in the area by mesoscale climate models[5,6,9].

MER Opportunity's traverse at Meridiani Planum. Wind/surface interactions have largely shaped this landscape, a level plain of dark-toned regolith overlying friable, sulfate-enriched bedrock. Regolith is a mixture of basaltic ~100 μm sand, coarser particles (hematite concretions, meteorite fragments, and other, unidentified, clasts), and minor air fall dust (much less dust than at Gusev)[10,11]. Wheel trenches show the coarser regolith grains are concentrated in surface lags, and that with some notable exceptions, the regolith is slightly cohesive[10,12,13]. The aeolian geomorphology of this site constitutes an unusual weathering/erosion system in which ripple surfaces lagged with durable, hematite-enriched concretions are more stable than friable bedrock exposures[8]. A key component of this system currently is a minor fraction of the basaltic ~100 μm sand that is loose or very loosely bound, sparsely distributed across the plains, that currently is mobilized periodically by wind. This mobile portion of the sand population moves slowly through traps such as pits, troughs, and impact crater floors, forming ripples that are misaligned with the more stable, less recently active ripples outside of the traps encrusted with much coarser-grained (and potentially denser) hematite-concretions[5,8,14,15] (Fig. 2).

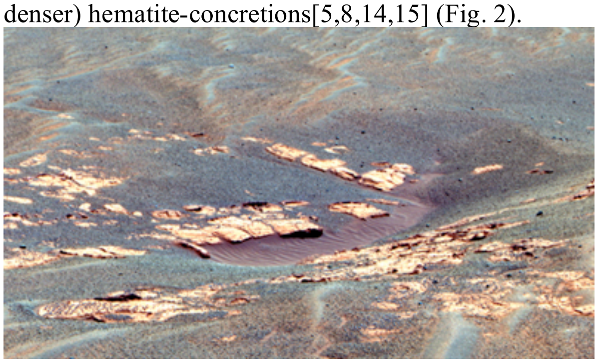

Fig. 2. Bsol081 view of rippled basaltic sand deposit (purple in the center of this false-color Pancam view) on floor of the Anatolia trough system. Note contrast in color and morphology with larger plains ripples elsewhere in view.

The flatness of the Meridiani plains, defined by the underlying bedrock, likely is due to planation of bedrock by more durable regolith components driven by wind[8].

Aeolian ripples ~1 cm high dominate the dark plains in the northern part of *Opportunity's* traverse (Eagle crater, Anatolia, Fram, Endurance, heat shield impact site) (Fig. 3). Ripple surfaces are covered with well-sorted, 1-2 mm hematite-enriched concretions; inter-ripple flats have fewer of these grains, and are instead dominated by much smaller ~100 μm basaltic sand. Intact spherules (full "blueberries") are found scattered only on the inter-ripple flats. Mössbauer contact plate impressions reveal weak cohesion out on the plains, on ripple crests as well as on inter-ripple flats. On the plains, much of the ~100 μm μm sand (and therefore all larger particles) evidently has remained inactive long enough for slight cohesion to form between grains by some unknown process. Plains ripples seem not to have been active as recently as other bedforms described below[8,14]. Ripples in depressions serving as particle traps generally have different, continuous profiles, and are composed of basalt sand only. The Eagle floor ripples are aligned with the crater's transient bright wind streak, were trenched more easily by the rover wheel than any other material, and appear especially clean in MI images. Mafic sand in these bedforms (and in other mafic sand ripples and drifts seen along the traverse but investigated less intensively) probably are also mobilized regularly by current winds[5,8,14,15,16].

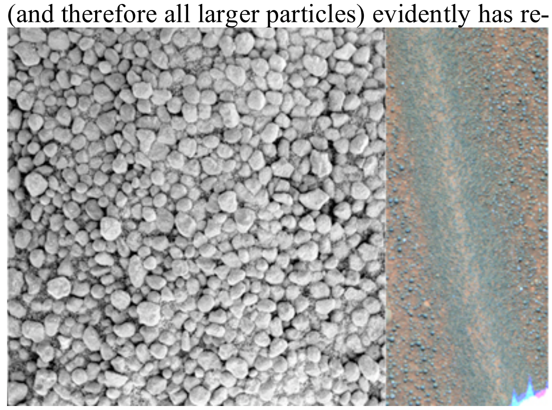

Fig. 3. Bsol072 coarse-grained ripple, mantled with resistant hematite concretions. MI view ~31 mm across; same ripple, ~10 cm across, is seen in Pancam false color view.

As *Opportunity* drove south of the heat shield impact site, ripple morphology changed. The system of low, cm-high ripples with intervening flats seems to have been disrupted by increasingly common, finally coalescing, blowouts, evolving into fields of ripples with heights of up to 40 cm high. Much smaller secondary bedforms found along trough floors, oriented at right angles to trough lines, indicate these larger ripples channel near-surface winds, controlling particle movement down trough axes[8].

Regolith Induration vs. Wind: Bedform activity at the MER sites (and likely elsewhere on Mars) is controlled by competition between ongoing soil induration, and the frequency of induration resets caused by strong wind events. Bedform activity is not a function solely of wind frequency. These principles are most easily appreciated at Gusev. At Gusev crater, dust falling from the atmosphere obscures somewhat darker materials everywhere, causing dust devil tracks to gradually fade (brighten). However, a few persistent dark-toned areas within the Columbia Hills are exceptions where air fall dust is less stable on substrate. *Spirit* visited one of these dark patches, a 170 m-wide field of dark ripples termed "El Dorado" (Fig. 4). MI, APXS, and Mössbauer data show the dark El Dorado ripples are dominated by well-rounded 200-300 μm basaltic sand that is only very slightly cohesive[17].

Lighter-toned, dust-covered transverse ripples are common along *Spirit*'s traverse, and happen to also occur immediately adjacent to the El Dorado dark ripples, interfingering along the edges of the El Dorado deposits but with different orientations. These light toned (dustier) ripples seem not to have been active as recently as El Dorado's dark-toned ripples. Proximity implies different wind directions cannot be responsible for differences in orientation between the darker and lighter ripple sets. Instead, the main factors influencing activity seem to be (1) particle size, (2) the rate of the indurating process, and (3) the strength-frequency of wind events. In this scenario, if bedform surfaces are left undisturbed by strong wind events for sufficient lengths of time, induration develops so that an increasingly strong (therefore unlikely) wind event is required to overcome increasing surface cohesion and reactivate the bedform, resetting the induration process. Light-toned transverse ripples at Gusev, which seem to have well-developed cohesive crusts with relatively coarse grains, cannot currently be easily reactivated. By contrast, the dark ripples at El Dorado have finer surface grains more easily mobilized by lesser, more common wind events, allowing induration to proceed much less between such wind events[17].

Fig 4. Spirit approaches the dark, active ripples of El Dorado on Asol699 in this false color Pancam view.

Saltation/Suspension Transition: Well-formed ripples in 100 μm mafic sand on the floor of Eagle crater and elsewhere at Meridiani Planum indicate that the transition between saltation and suspension occurs at unexpectedly small particle sizes (<<100 μm), compared with pre-MER predictions of ~200 μm. The unexpectedly small transition particle size probably is due to poor coupling between grains and turbulent eddies in the martian atmosphere[14,18], a factor not fully accounted for in previous work.

Dust Devil Observations: Ground observations of dust devil activity by *Spirit's* cameras (including dramatic time-lapse "movies") have captured >500 active dust devils. Dust devils have been observed from around 0930 to 1630, most commonly in the early afternoon. Activity peaked during southern late spring (around L_s 250°). Dust devil migration speeds ranged from near stationary to 21 m/s. Modeling from image analysis suggested ~19 kg/km^2/sol of dust is contributed (at least locally) by dust devils to the atmospheric dust load across the landing site[6,19].

Effective Dust Particle Threshold-of-Motion: Wind tunnel experiments have shown that initiating movement of dust-sized particles requires stronger winds than for sand[20]. It has therefore been a long-standing challenge to explain how martian winds could be so regularly successful at mobilizing dust across the martian surface into dust storms. However, MI views at Gusev show that dust grains appear to self-organize into weak, irregularly-shaped clumps large enough to be resolved by the MI. Wind lifting (and disaggregating) these fragile clumps should be significantly easier than for much smaller individual (non-aggregated and unresolvable) dust-sized particles. MER observations suggest, therefore, that entraining dust into the martian atmosphere may in many cases involve the relatively easy lifting and disaggregation of irregular, fragile, transient clumps of dust, rather than mobilization of individual dust particles.

Wind Streak Ground Observations: In situ explorations of bright and dark wind streaks representative of numerous time-variable features seen widely across the planet from orbit have provided insights into the nature of these features, how they form, and the characteristics of the grains and small-scale surface roughness involved. A bright wind streak was investigated by *Opportunity* outside Eagle crater. Minor amounts of bright air fall dust lingering in lees of small surface roughness (in this case, pre-existing 1 cm-high ripples formed from coarser material) were responsible for the appearance of the bright streak seen from orbit[14]. A dark streak extending from Victoria crater was investigated later in *Opportunity's* traverse, and was found to consist of an abundance of basaltic sand sourced from deposits just beneath the rim of Victoria crater; in this case the absence of significant surface roughness exterior to the crater enhanced distribution of mafic sand grains downwind.

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