**MARS EXPLORATION ROVER OBSERVATIONS OF SAND SALTATION AND SAND-SIZED DUST AGGREGATES.**

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**Introduction:** Evidence for current sand movement on Mars is rare, compared with routine and regular dust lifting [1-8]. More examples of sand movement should be expected as the temporal span of our highest resolution observations continues to increase, but the overall picture likely will remain that downwind migration of dune crests is rare compared with dust raising [9]. However, wind tunnel experiments show that wind should initiate movement of sand-sized grains more easily than dust [10,11], so it has been paradoxical that winds routinely raising dust hardly seem to affect bedforms of more easily moved sand-sized grains. We address this issue by combining MER in situ evidence for sand saltation (including ripple migrations), observations revealing airfall dust as fragile sand-sized aggregates, observations of pervasive regolith cohesion (under mantles of loose dust aggregates where present), and histories of dust accumulation and clearing at both MER landing sites.

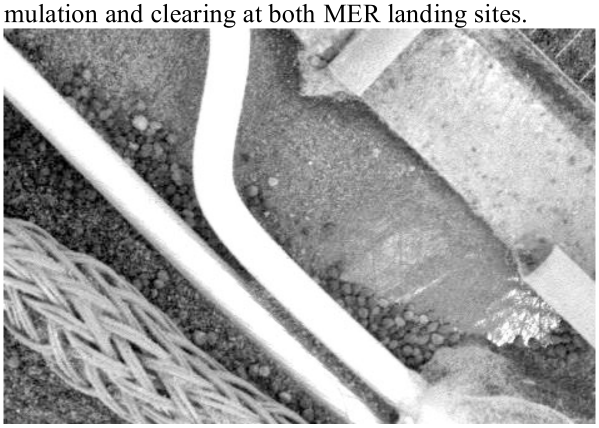

Figure 1. Spirit MI image of rover deck taken in shadow, showing sand grains up to 0.3 mm diameter. Area shown is 1 cm high.

**MER Observations of Active Sand and Dust:** Both rovers have observed evidence of sand mobility. Sand grains up to 0.3 mm diameter were recognized in MER Microscopic Imager (MI) views of the Spirit rover deck (Fig. 1), indicating saltation heights of at least 0.7 m [9,12]. Opportunity's pause at a dark wind streak outside Victoria crater revealed changes in drifts of ~0.1 micron sand [13]. Repeated imaging of Gusev soils during strong wind events associated with the 2007 dust storm showed ripple migration (Fig. 2)[9], redistribution of sand around rocks, and obliteration of sandy tracks nearby. Opportunity MI images acquired on sols 551 and 552 show movement of sand grains. Indirect evidence for recent saltation in the current surface environment is indicated by: (1) ripples of clean mafic sand on the floor of Eagle crater that are misaligned with indurated plains ripples outside the crater, but aligned with (i.e., perpendicular to) the transient wind streak extending from the crater's rim; and (2) the ripple field El Dorado at Gusev crater consists of sands with almost no cohesion which have remained considerably less dusty than surrounding terrain.

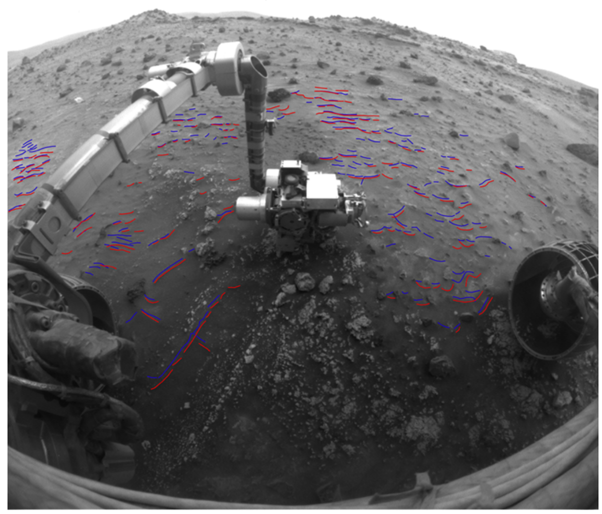

Figure 2. Front hazcam view showing 2 cm of ripple migration between sols 1260 (blue crests) and 1265 (red crests) at Gusev crater (image acquired sol 1265).

Dust particles suspended in the martian atmosphere typically are <4 μm in diameter [14,15], much smaller than MI resolution of ~31 μm/pixel. However, MI views show that dust mantling the surface commonly occurs as fragile, sand-sized aggregates of irregular shape, superficially resembling tiny popped corn (Fig. 3). The large size and low density of these aggregates should make them much easier to entrain than either <4 μm air fall dust, or hard (saltation-capable) sand-sized grains [9]. We have proposed that dust aggregates like those seen in MI views are widespread across dusty regions of Mars, and that they are the primary means—the "low-hanging fruit"—for wind to raise dust directly into the atmosphere [9]. Implicit in these ideas is that once the dust aggregates are entrained, they contribute to the suspended dust load by shedding suspendable smaller grains, perhaps breaking up completely into their <4 μm constituent particles.

The impressions of fragility in MI images suggest that these aggregates partially or totally disaggregate back into their clay-sized constituent grains during the violence of entrainment by a passing dust devil or a strong wind event (including disintegration from high-speed impacts with the ground). Tensile strengths of martian dust aggregates likely are much less than even the tiny magnitudes of the compressive pressures of MER Mössbauer touches, which easily crush and re-mold the aggregates into extremely high-fidelity castings [9, 16-17]. We therefore suggest that dust devils seen by Spirit—and by analogy dust devils elsewhere on Mars—must be raising a substantial fraction of their dust opacity by the relatively easy raising and rupturing of these fragile dust aggregates [9].

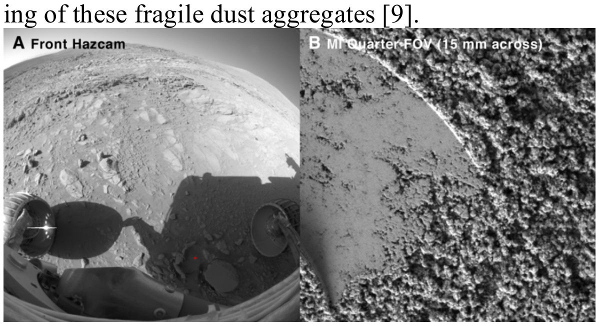


Figure 3. Mössbauer contact plate impression into dust mantle at Gusev crater. (A) front hazcam with red dot showing MI image location; (B) quarter-frame excerpt of MI image, ~15 mm across. Large, well-developed dust aggregates blanket the regolith. MI view shows where the Mössbauer contact ring touched the ground with ~1 N of force, completely and easily crushing the aggregates into ultrafine, unresolved particles that allow a high-fidelity casting of the smooth metal surface of the contact plate. (After Fig. 20 of [9])

**A Dust Particle Cycle On Mars:** The MER observations suggest that a dust particle cycle operates on Mars, in which <4 μm dust grains alternate between suspension as individual grains, and as components within very loosely-bound, much larger aggregates at the surface. How might individual dust grains migrate between these two states? Aggregate growth has been observed in wind tunnel experiments involving dust "rolling up" across the surface downwind [Rod Leach, personal comm., 1980s], and similar behavior has been observed on the MER Spirit rover deck [12]. On Mars it is unclear whether aggregate growth might initiate earlier, between <4 μm particles "colliding" while still suspended, due to electrostatic attractions (perhaps affecting fall-out rate). Some circumstantial evidence for this comes from wind tunnel experiments in which dust aggregates were observed to form from suspended dust in a martian environmental wind tunnel [18]. We speculate that dust aggregate growth would continue on the ground, facilitated by "jostling" of the growing aggregates by minor wind turbulence that is otherwise too weak to move the dust aggregates enough to destroy them. This scenario suggests that on the ground, the maximum dust aggregate size at any given place and time would be a function of: (1) local dust fall-out rate; (2) time interval between disturbances (e.g., between dust devil passages, and/or regional wind events); and (3) very local aerodynamic protection characteristics of the setting (e.g., exposed, sloping rock surfaces vs. small ground patches sheltered by surrounding rocks). At the surface, then, dust aggregate size and growth rate might change with time and overall size, perhaps approaching a limiting maximum diameter governed by inherent electrostatic bond fragility and the local conditions of dust abundance (functions, in turn, of local fall-out rate and time interval since the last major wind disturbance).

**Conclusions:** On a planet where hard sand grains are found at the surface along with fragile sand-sized dust aggregates, we should expect winds to be more successful mobilizing the dust (in its weakly aggregated form) than moving the sand. This is consistent with what has been observed repeatedly from orbit (lots of dust raised, not many dune movements).

Dust raising therefore seems much easier than suggested by the classic Iversen & White relationships [10] that have been applied to hard <4 μm dust particles, or to indirect raising of these dust grains by saltation of hard, sand-size grains. If the appropriate grain characteristics (sand-sized diameters and very low densities) are applied, however, the Iversen and White relationships and their successors predict much lower dust threshold-of-motion wind speeds.

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