SOIL AND DUST ON MARS: LOCAL SOURCES, GLOBAL PROCESSES. J.F.Bell III; Cornell University, Department of Astronomy, Ithaca, NY 14853-6801 (jfb8@cornell.edu).

Introduction. This incredible decade of Mars exploration has seen major advances and paradigm shifts in our understanding of the finest-grained components of the martian surface. New information on the composition, mineralogy and physical properties of soil and dust on microscopic to orbital scales has revealed important new constraints on models of their origin and evolution.

Definitions. The term "soil" has become commonly used in planetary science to describe the fine-grained, porous, uppermost layers of a regolith, despite the common terrestrial soil science viewpoint that the term applies only to material formed by or in the presence of organic compounds [*e.g.,* 1,2]. A useful generic definition of soil is "unconsolidated mineral matter that may differ chemically, physically, morphologically, or biologically from the material from which it is derived" [3]. Martian soil in particular has been described as the excited "skin" of the part of the martian crust that is in direct contact with the (current or past) atmosphere [4-6], a description that also includes "soil" adhering to rock surfaces. In the grain-size scale used by soil scientists, modified from the originally-defined scheme of Wentworth [7], clay is the size fraction less than about 2 µm, silt is about 2 to 50 µm, and sand is about 50 µm to 2 mm. For Mars, planetary scientists typically define "dust" as the finest-grained component of the soil that can easily become airborne, and this component is known to be less than about 5 µm in diameter from Viking [8], Pathfinder [9,10], and Mars Exploration Rover (MER) [11,12] observations. For simplicity, typical usage of "sand" in the Mars context includes the sand size fraction used by soil scientists (50 µm to 2 mm) plus the 5-50 µm medium and coarse silt size fractions. Sand and dust that appear to have been concentrated into dunes, ripples, or other bedforms on the surface by the action of wind, but for which detailed physical properties and formation scenarios have not been (or could not be) derived, are often called "drift". Collectively, these definitions of "soil", "dust", "drift", and "sand" are often gathered together into the term "fine grained materials." Regardless of the formal definition or planet of interest, soils are formed by a combination of many influences, among them parent material composition and climate history. Thus, the soil can provide a window into the past lithologic and environmental history of a planetary surface.

Global-Scale Soil & Dust Formation Processes. Suspended and airfall dust on Mars was long assumed to be a highly altered, ferric-rich weathering product. However, MER Mössbauer and Magnetic Properties data [*e.g.,* 12-14] reveal that, volumetrically, each ~1 to 5 µm sized dust grain is magnetic, and each appears to be actually *dominated* by relatively unaltered, ferrous minerals, rather than ferric weathering products. The altered minerals in the dust that dominate its visible-wavelength spectral properties (giving the martian surface and sky their distinctive reddish color) are apparently only thin, geochemically minor coatings or rinds on what appear to be essentially pristine, basaltic particles that are compositionally and mineralogically similar to typical basaltic materials seen "under the dust" across the planet.

Alteration of dust to form ferric weathering products thus may be a global-scale process, as originally envisioned, but the degree of alteration involved may not be as extensive as once thought. In particular, slow, modest levels of surficial alteration on grain boundaries, perhaps catalyzed by atmospheric water vapor or transient/localized more water-rich environments (*e.g.,* volcanic eruptions, impact events), could have lead to the generation of weakly altered dust grains like those observed by MER. Regardless of the alteration scenario, low water:rock ratios are certainly inferred from the relatively low Fe^{3+}/Fe_{total} ratios observed in soils and dust [12,13].

MER Alpha Particle X-ray Spectrometer (APXS) data, Mars Global Surveoyr Thermal Emission Spectrometer (MGS/TES) mid-infrared spectra, Mars Express Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (MEx/OMEGA) near-infrared spectra, and other data sets provide other important new clues about martian soils and dust. For example, the dust appears to contain a small fraction of carbonate minerals [15]. The abundances may be consistent with simple global-scale water vapor-induced weathering reactions occurring on grain surfaces. Still, when considered globally, there may be enough carbonate to possibly represent a significant sink for early atmospheric CO_2. Soils at the MER sites appear to contain a small fraction of meteoritic material [16,17], perhaps enough to explain the observed Ni abundance at the surface and/or some of the observed surface magnetism [14,17]. Pathfinder and MER observations confirmed earlier Viking measurements that revealed high S and Cl in bright soils and dust [18-20], implicating regional or global-scale volcanic processes as contributors to the (apparently modest) alteration of fine-grained soil and dust precursor materials. OMEGA [21] and MER Mössbauer [*e.g.,* 12,13] spectra have confirmed and extended earlier telescopic [22] and

Phobos-2 ISM [23] measurements revealing the ubiquitous presence of poorly-crystalline or nanophase ferric oxides in the dust. Such "unripened" alteration minerals [24] may also represent weathering products formed by subaerial water vapor-basaltic grain interactions, also at relatively low water:rock ratios.

Local-Scale Soil & Dust Formation Processes. Despite the evidence for ubiquitous but global-scale soil and dust alteration processes, there is also significant evidence for local-scale soil alteration, indeed soil generation, processes. Figures 1-4 show representative Pancam images of local soil, dust, sand, and drift materials observed by the Spirit rover along its traverse in Gusev Crater, and Figure 5 shows examples of Pancam observations of similar materials observed along the Opportunity rover's traverse in Meridiani Planum.

For example, the Spirit rover has encountered several rover-wheel-excavated exposures of bright, whitish to yellowish, fine-grained, sulfur-rich soils since crossing the boundary from the plains to the Columbia Hills [25,26]. The soils exhibit spectral and compositional indicators of hydrated Mg- and Fe-bearing sulfates. While the origin of these enigmatic deposits is still the subject of debate and study (*e.g.,* are they volcanic fumarole/sulfatara deposits, evaporites from surface/subsurface water, weathering products from reactions between SO_2-rich volcanic aerosols and basaltic precursor rocks, or something else? [26]), their localized occurrence, at least along the Spirit rover traverse, suggests a local-scale rather than global-scale origin.

Other examples of possibly local-scale soil formation processes include the observation of small patches of light-toned "outcrop soil" at Meridiani Planum, in ripples at the bottom of Eagle crater and in a bright wind streak to the SE of Eagle's rim [27; Fig. 5c]. While this soil could be from globally-homogeneous aeolian dust settling out into temporary aeolian traps (the deposits were too small/thin to uniquely characterize with MER chemical instruments), their association with a source of similarly-colored, easily erodable material–the exposed Eagle crater outcrop–supports a hypothesis for their local origin.

In Gusev, some Columbia Hills rocks have been observed to have associated localized accumulations of "rock soil", similar to that observed in a few places at the Mars Pathfinder landing site [28]. Also, some Columbia Hills rocks (most notably, "Clovis", but ~10 others as well) exhibit evidence for goethite (α-FeOOH) in their Mössbauer spectra [12]. The very localized nature of these goethite occurrences, and the fact that liquid water must be involved in the formation of this mineral, imply the existence of local-scale conditions that could also lead to the formation of fine-grained, altered soil and dust.

Synthesis and Future Observations. The evidence for local-scale soil formation environments and processes at the MER sites provides insight into the potential importance of these processes globally. Specifically, localized generation/concentration of fine-grained sulfate salt deposits could be a major source of the high S and Cl in globally-homogenized dust deposits. One test of this hypothesis would be to find (or not find) significant occurrences elsewhere of concentrated sulfates like those found in Gusev. Indeed, some evidence of additional (scattered) sulfate exposures has already been reported from OMEGA data [21,29].

Similarly, processes that lead to the localized generation of crystalline ferric oxides/oxyhydroxides, such as has occurred on Clovis and some other Columbia Hills rocks in Gusev [12] and in the hematitic spherules found at Meridiani Planum [13], could represent extreme examples of "weaker" weathering/alteration processes that could generate the poorly-crystalline or nanophase ferric oxides/oxyhydroxides observed in typical high-albedo martian soils and dust. To test this hypothesis, a more extensive inventory of any significant occurrences of crystalline ferric oxides/oxyhydroxides (underway with OMEGA and MRO/CRISM observations) will need to be completed.

References: [1] Johnson, D.L., *Science, 160,* 1258, 1968; [2] Markewitz, D., *Nature, 389,* 435, 1997; [3] Soil Science Society of America, *Glossary of Soil Science Terms,* 1984; [4] Nikiforoff, C.C., *Science, 129,* 186-196, 1959; [5] Retallack, G.J., *Nature, 391,* 12, 1998; [6] Bell III, J.F. *et al., JGR, 105,* 1721-1755, 2000; [7] Wentworth, C.K., *J. Geology, 30,* 377-392, 1922; [8] Pollack, J.B. *et al., JGR, 84,* 2929-2945, 1979; [9] Markiewicz, W.J. *et al., JGR, 104,* 9009-9017, 1999; [10] Morris, R.V. *et al., JGR, 106,* 5057-5083, 2001; [11] Lemmon, M. *et al*., *Science, 306,* 1753-1756, 2004; [12] Morris, R.V. *et al., JGR, 111,* E02S13, 2006; [13] Morris, R.V. *et al., JGR, 111,* E12S15, 2006; [14] Goetz, W. *et al., Nature, 436,* 62-65, 2005; [15] Bandfield, J.L. *et al., Science, 301,* 1084-1087, 2003; [16] Yen, A.S. *et al., Nature, 436,* 49-54, 2005. [17] Yen, A.S. *et al., JGR, 111,* E12S11, 2006; [18] Rieder, R. *et al., Science, 278,* 1771-1774, 1997; [19] Gellert, R. *et al., Science, 305,* 829-832, 2004; [20] Reider, R. *et al., Science, 306,* 1746-1749, 2004; [21] Bibring, J.-P. *et al., Science, 312*, 400-404, 2006; [22] Bell III, J.F. *et al., JGR,95,* 14447-14461, 1990; [23] Murchie, S.M. *et al., Icarus, 105,* 454-468, 1993; [24] Banin, A., *Science, 309,* 888-890; [25] Wang, A. *et al., LPSC 38,* Abstract #1338, 2007; [26] Johnson, J.R. *et al.*, submitted to *Geophys. Res. Lett.,* 2007; [27] Sullivan, R. *et al., Nature, 436,* 58-61, 2005. [28] Bell III, J.F. *et al., Icarus, 158,* 56-71, 2002; [29] Gendrin, A., *Science, 307,* 1587-1591, 2005.

Figure 1. Part of the Spirit "Legacy" panorama, showing the large albedo and color contrast between the rover's tracks (albedo around 0.20) and the surrounding bright, dusty soils (albedo around 0.30) along the traverse from the landing site to the rim of Bonneville crater. This is an approximate true color rendering generated using Pancam's 753 nm, 535 nm, and 480 nm filters from *Spirit* sols 59-61 Pancam sequences P2211 through P2216.

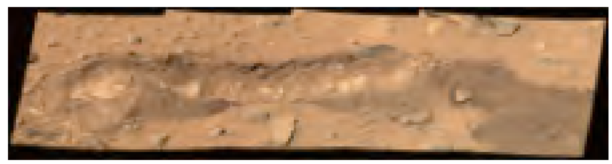

Figure 2. Pancam mosaic of "Big Hole Trench", an approximately 50 cm wide by 9 cm deep furrow excavated by one of the rover's wheels in Gusev crater plains materials between Bonneville crater and the Columbia Hills. This is an approximate true color rendering generated using Pancam's 753 nm, 535 nm, and 480 nm filters from *Spirit* sol 116 Pancam sequence P2404.

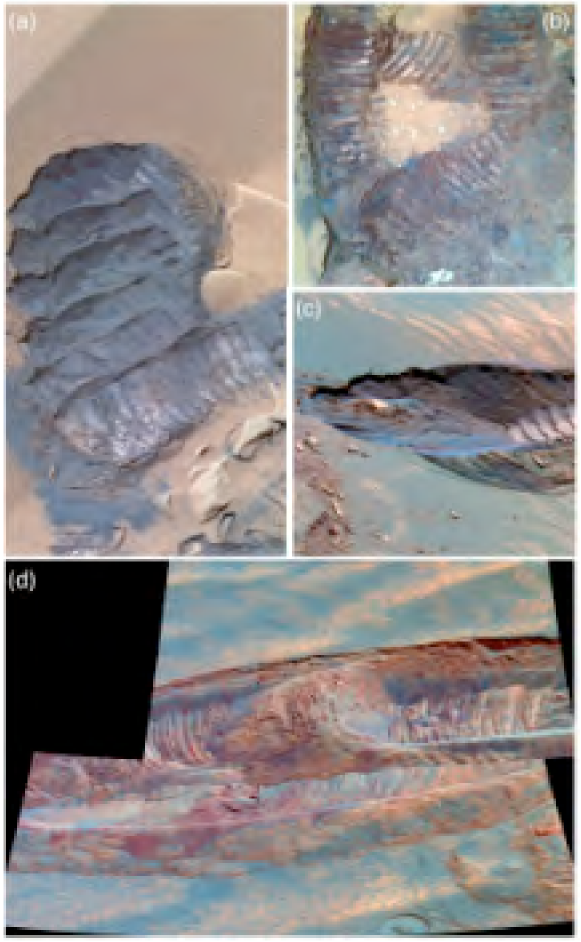

Figure 3. MER/Pancam false color images showing examples of subsurface color variations in soil at Gusev crater. (a) Sol 72 sequence P2352 view of a rover wheel scuff mark into an aeolian bedform near the rim of Bonneville crater. Field of view ~72 cm; (b) Sol 332 sequence P2440 view of rover tracks in West Spur soils. Field of view ~85 cm; (c) Sol 498 sequence P2541 view of rover wheel scuff into an aeolian drift deposit along the "Larry's Lookout" outcrop, visited while ascending Husband Hill. Field of view ~79 cm; (d) Sol 711 sequences P2535 and P2536 mosaic of rover wheel trench dug into the "El Dorado" dune field on the southern flanks of Husband Hill. Different color units appear to have been excavated by the interaction of the rover wheels and the dune sands. Field of view ~83 cm.

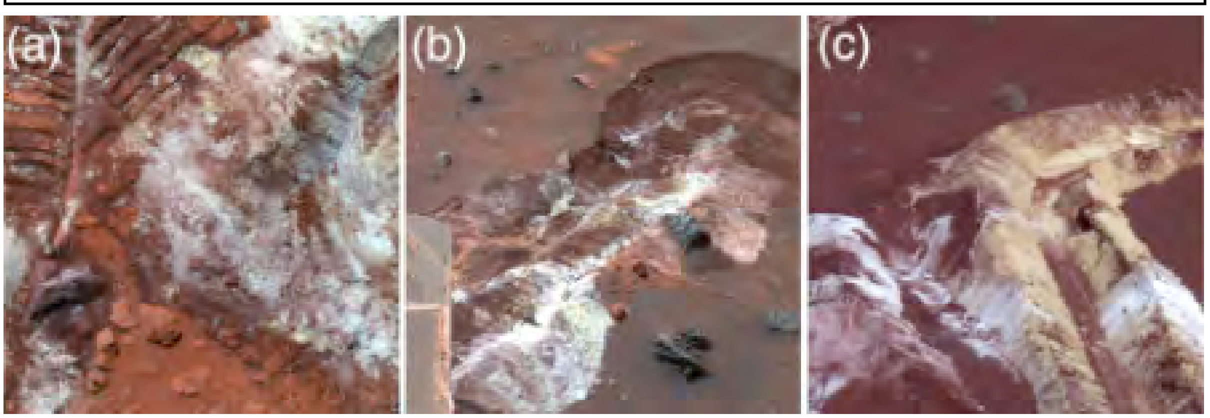

Figure 4. False-color RGB (754nm, 535 nm, 432 nm) images of showing the bright, sulfur-rich soils uncovered by the Spirit rover wheels in Gusev crater [26]. (*a*) Paso Robles (Sol 400, P2551), encountered during the ascent of the west side of Husband Hill; (*b*) Arad (Sol 721, P2538), encountered in the southern basin after the rover descended Husband Hill; and (*c*) Tyrone (Sol 790, P2531), encountered near Home Plate in the southern basin. Tracks are ~16 cm wide.

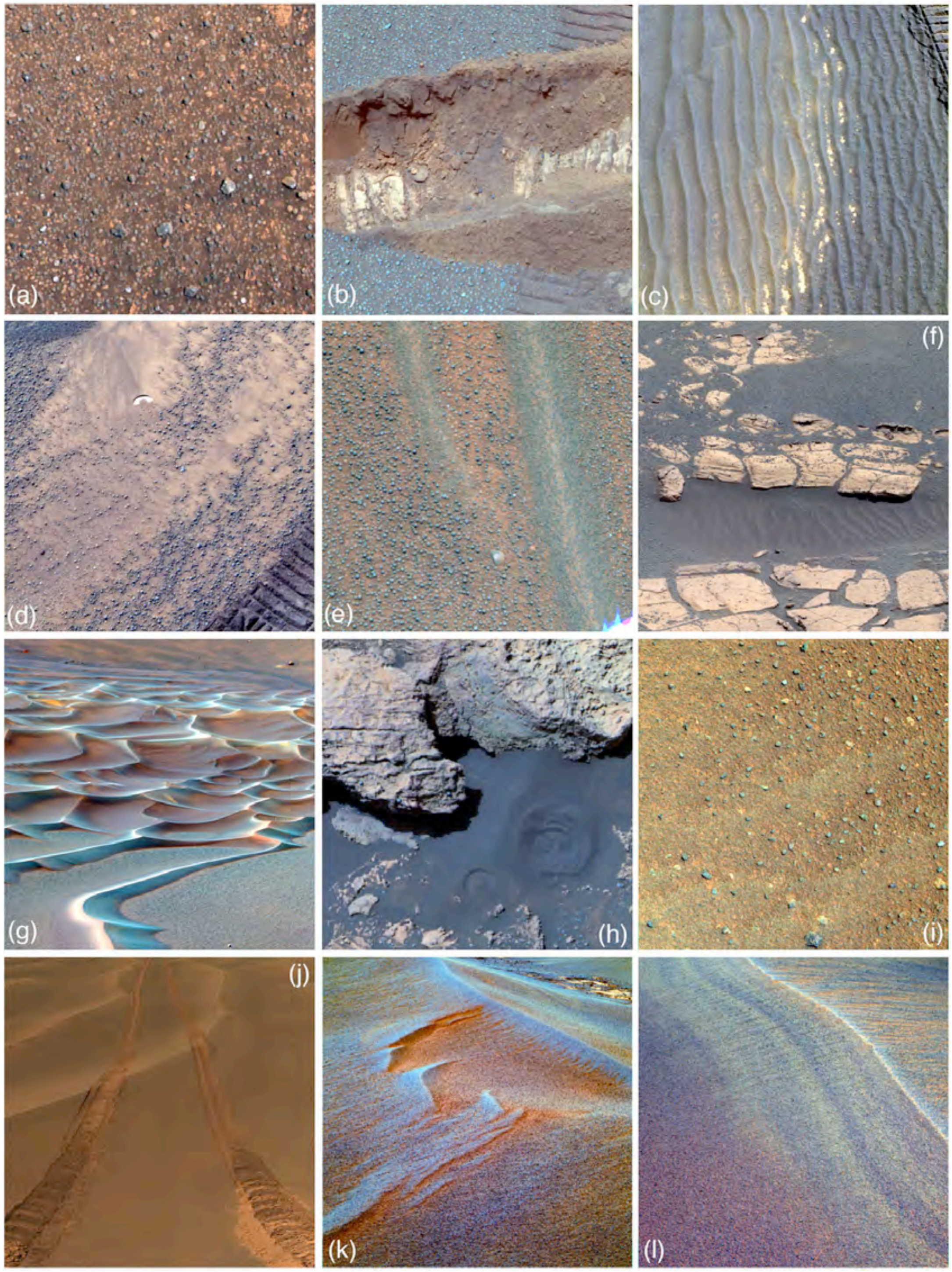

Figure 5. Pancam examples of soil morphologies at Meridiani Planum. (a) Sol 20 sequence P2564 natural color view of "clean" and "dusty" blueberries, clasts, outcrop fragments, and soil. Field of view (FOV) is ~34 cm; (b) Sol 26/P2385 false color image of trench in Eagle crater. FOV ~65 cm; (c) Sol 54/P2540 false color view of sandy ripples and aeolian/outcrop dust in Eagle. FOV ~54 cm; (d) Sol 61/P2559 false color view of dust, sand, & blueberries in the bright Eagle wind streak. FOV ~59 cm; (e) Sol 73/P2589 false color view of ripple crests and troughs on the plains between Eagle and Endurance. FOV ~52 cm; (f) Sol 81/P2422 false color view of sandy drift and outcrop deposits within a rift/crack in the plains between Eagle and Endurance. FOV ~192 cm; (g) Sol 211/P2424 false color view of megaripples in the center of Endurance. FOV ~30 m; (h) Sol 237/P2588 false color view of dark sand drift next to outcrop blocks within Endurance. FOV ~58 cm; (i) Sol 414/P2583 false color view of cobble-rich, berry-poor surface in the plains north of Viking crater. FOV ~45 cm; (j) Part of sols 456-464/P2260 to P2270 natural color mosaic of plains ripples from "Purgatory" ripple. Wheel treads are ~120 cm apart; (k) Sol 749/P2546 false color view showing air fall dust in the lees of plains ripples near Erebus. FOV ~210 cm; (l) Sol 798/P2393 false color view of banded ripple structure in the brighter plains materials NW of Victoria. FOV ~3 m.