The microstructure of the martian surface

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Abstract:

We propose an increased emphasis on microanalysis in future Mars surface exploration. The dust component of the soil on Mars offers a microcosm of the mineralogical history of the planet, and it exerts a primary influence on atmospheric, geological, and periglacial properties. The Phoenix mission offered first glimpses of the diversity of soil particle properties that encourage future in situ investigation. Beyond robotic exploration, a soil sample offers a particularly simple and potentially globally representative target for sample return.

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Preamble

Surface features on Mars are sculpted from rocks, ices, and a blanket of sand-, silt-, and clay- sized regolith particles that we collectively refer to as "soil" (following the usage of Banin et al. 1992). Airborne dust particles are a component of this soil. Recent microscopic imagery from the Phoenix Lander drew attention to the complexity and heterogeneity of this soil. On August 27, 2009, a Workshop on the Microstructure of the Martian Surface was convened at the Niels Bohr Institute in Copenhagen to discuss the implication of these and related results. This White Paper summarizes the conclusions and recommendations of that workshop.

In the larger context of Mars science, why should we care about soil, and why should we devote resources to its study? We suggest two broad reasons. The first derives from the influence of soil and dust on surface and atmospheric processes, the second from the window that soil provides on geology present and past.

- Soil plays a central role in nearly every martian surface process. It presents an enormous surface area that dominates the absorption and release of volatiles (including water), insolation, and other types of radiation, as well as hosting surface chemical reactions. It is the most accessible abode for any aspiring martian biology and offers a mechanism to disperse prebiotic and biotic material. Wind activated, soil particles sandblast rocks, modifying surface texture and promoting erosion (e.g. Greeley et al., 1992, Bridges et al., 1999). In the atmosphere, dust modulates and disperses sunlight, profoundly affecting surface temperature and climate, and it provides nucleation sites for precipitation (e.g. Zurek et al. 1992). On the surface, soil regulates albedo (e.g. McCord and Adams, 1969; Singer, 1982), further influencing climate, and provides an effective thermal blanket that determines the form of subsurface processes ranging from polygon formation at high latitudes (Mellon et al. 2008) to thin layers of liquid water formation (Farmer 1976).

- Particle size distributions, spectroscopic properties, and surface textures of the soil bear witness to the erosion and subsequent alteration of surface materials across the planet and throughout time. The apparent spectroscopic uniformity of dust across the surface of the planet suggests that a single sample could provide a global insight into the history of Mars. Studies of the microstructure of the soil at a range of sites across the planet will help quantify this uniformity. If it can be confirmed that the dust and soil are globally representative, it will greatly enhance the relevance of any analysis of such a sample returned to Earth.

Accordingly, we recommend a program of geological and atmospheric investigations of the planet Mars, focused on fine particles and supplemented by laboratory and theoretical study.

1. Major questions and investigations

Results from the Phoenix microscopy experiments suggest that even a single soil sample reflects the diversity of source material on Mars, and may hold clues to the global geological and atmospheric history of the planet. The soil is primarily basaltic in character (e.g. Bell et al. 2000; Goetz et al. 2005; Madsen et al. 2009) though nanophase iron oxides are believed to be responsible for the characteristic reddish color (e.g. Morris et al. 2006). Under a microscope, it was found to contain a bimodal distribution of particles, with various small sand-sized particles dispersed in a matrix of clay and silt-sized red powder (Figure 1 from Goetz et al. 2009a). Workshop attendees whimsically settled on the acronym URD (Ubiquitous Red Dust) to refer to the fine supporting matrix, and we will follow that practice here. Most of the larger particles were subrounded and frosted, with varying degrees of roughness, suggesting transport by saltation. Blacks and browns dominate the coloring, with the latter tending to be glassy, translucent and less magnetic. The remainder was white flaky material, possibly salts. The atomic force microscope revealed that at least some of the red fines are platy and reminiscent of phyllosilicates, though angular and spheroidal particles were also seen.

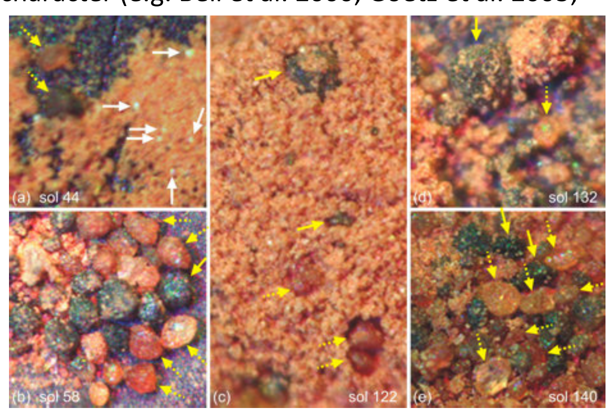

Figure 1: Different types of Phoenix soil particles. All images are at the same scale (500 µm wide). Yellow arrows specify silt- to sand-sized grains (dotted arrows: class b, solid arrows: class c) White arrows specify white fines (class d). The red fines have a low bulk density and are not specifically marked, as they are pervasive (see especially a and c). The grains make up ~ 80 wt% of the soil.

Striking among the Phoenix results was the finding that the Martian soil is highly deficient in fine particles compared to terrestrial soils (Pike et al. 2009; Smith et al. 2009; Goetz et al. 2009b), including Mars analogues such as JSC-Mars 1, even allowing for the formation of agglomerates. The sub-5-µm dust seen in the Martian atmosphere represents less than 0.5% of the Phoenix soil composition. The URD ranged up to 7 µm in size, some ten times *larger* than the fines commonly seen in terrestrial soils. These reddish particles have the same spectral signature as that of the Martian dust observed from orbit. They comprise about 20% by mass of the soil. The morphology and coloration is suggestive of chemical weathering, consistent with palagonitization (e.g. Allen et al. 1981; Morris et al. 1993; Schiffman et al., 2002; Bishop et al. 2007).

While the URD dominates the soil spectroscopically, a mineralogically distinct population of larger grains accounted for 80% of the dust by mass, with a median particle size by cumulative mass of 90±10 µm. These grains have a range of colorations, and textures that vary from rough and dark to translucent and smooth as shown in Figure 1. These are similar to soil particles observed by the Mars Exploration Rover (MER) microscopic imager (MI) at Gusev (Herkenhoff et al., 2004). The morphology is suggestive of aeolian weathering, probably through saltation. Moreover, a break in the cumulative mass plot suggests that the formation processes of the two populations did not occur at the same place and time, as shown in Figure 2 (Pike et al. 2009). A plausible conclusion is that aoelian processes are ongoing, while palagonitization is an earlier process.

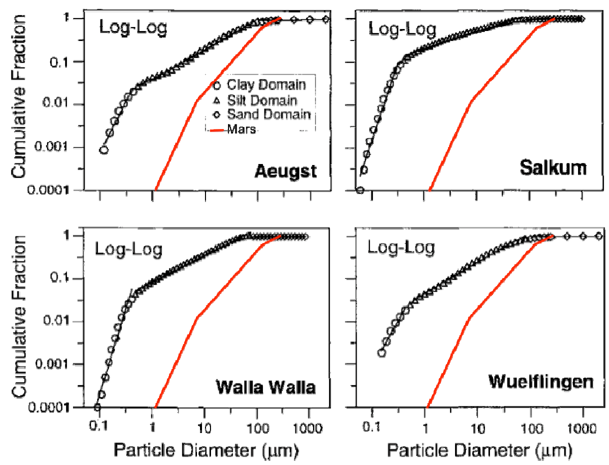

Figure 2: Particle size distribution from Phoenix optical and atomic force micrographs compared to various terrestrial samples (from Bittelli et al 1999). The Phoenix sample is deficient in fines (Pike et al 2009).

For clay-sized particles in general, Phoenix found less than < 0.1% by mass of that generally seen on Earth. This result constrains the contact with liquid water to an upper limit of 10,000 years, assuming the fastest terrestrial rates of clay formation, a result consistent with previous dust analyses (Goetz et al. 2005) and the hypothesis of Bibring et al. (2006) that such material formed in the "siderikian" epoch of anhydrous ferric oxide formation.

With this information in hand, workshop participants posed the following questions:

Question 1: What is the relationship between the airborne dust, surface soil, and the present-day rock mineralogy, on Mars in general and at particular sites?

Question 2: What weathering and alteration processes are occurring presently? What is the contribution of aqueously altered material to the soil?

Question 3: What does the microstructure of soil tell us about the spatial extent and time scale of water activity?

Question 4: How local or global is the material observed in the regolith? What is the spatial distribution? What is the capacity for transportation of sediment, and how might it have changed with time?

Question 5: What are the dynamics of the upper meter or two of regolith? What is the exposure age of the surface? The exposure history of the subsurface?

2. Suggested approach to surface investigation

To address the above questions, workshop participants suggested the following types of surface investigations.

- **Microanalysis:** Using standard laboratory microanalytical techniques, go beyond optical imaging and further characterize morphology, mineralogy, and chemistry of dust. The specific methods are discussed in Section 3 below. In addition to new techniques, however, it is important to retrieve a comparative dataset to Phoenix and other missions. *Understanding that dedicated microanalysis surface missions are unlikely, we suggest incorporation of increasingly ambitious microanalytical campaigns into future surface mobility missions.*

- **Diversity**: Examine local differences in soils from a mobile platform. Examine global diversity by landing in multiple locations. Attempt to distinguish globally mixed material from globally similar genetic and alteration processes (“the same but different”). In particular, go to higher and older surfaces to study differences in chemical processes.

- **Subsurface access**: With modest subsurface access (of order 1-2 m. as specified for the ExoMars mission), study differences in soil due to surface/atmosphere interactions, radiation effects, thermal stresses, water exposure, etc. At higher latitudes, study effects of cryoturbation and other periglacial processes.

- **Sample return.** The study of dust and soil is particularly well suited to a “grab and go” sample return architecture. Phoenix results suggest that any given sample will contain particles of a variety of ages and origins, with both chemical and mineralogical diversity. A particularly important objective of such a mission would be dating of individual grains as a means of testing theories of chemical evolution over the history of the planet.

3. Microscopy and microanalysis

Microanalysis on Mars will enable us to understand the transport of dust in air, mediated by liquid water, or through solid phase processes such as cryoturbation; the possibility of finding evidence of surface chemical reactivity on soil particles, and understanding the role of such reactivity in determining microstructure; and the opportunity to study *rock* surface microstructure with the aim of determining the relationship between rocks and soil.

Microscopy: While atomic force microscopy (AFM) was sufficient to obtain an initial glimpse of submicron features, the preferred tool for such analysis will ultimately be scanning electron microscopy (SEM), which can potentially be implemented on Mars in the form of Environmental SEM (ESEM) without the need to introduce samples into a vacuum system. A practical performance target is 10 nm resolution from 1-20 KeV.

Compositional Microanalysis: The most straightforward method to mineralogically characterize individual soil particles is with energy dispersive x-ray spectroscopy (EDX), a popular enhancement to SEM that requires the addition of a solid state detector of the type already flown on Pathfinder, Spirit and Opportunity. EDX provides elemental composition much like APXS, but on a microscopic scale.

Structural Microanalysis: At micron scales, the same electron beam used for ESEM and EDX can be used for electron diffraction to characterize the mineral structure of individual particles.

Contextual (macro) analysis: Any microanalysis requires a contextual understanding of the target, beginning with orbital data. Such analysis emphasizes particle surface properties (preferably as a function of temperature). The central measurement is optical and near infrared microscopy, such as provided by the µ-OMEGA instrument developed for ExoMars. Additional mineralogical information can be provided by Raman spectroscopy, Mossbauer spectroscopy, and x-ray diffraction (XRD), while surface chemical information is best provided by x-ray photoelectron spectroscopy (XPS), Auger spectroscopy, or secondary ion mass spectroscopy (SIMS). Surface textural information is easily provided by the BET (Brunauer, Emmett, Teller) technique, which was utilized on the Viking landers. The BET method measures effective surface area with saturation and subsequent desorption of an inert gas.

Summary and conclusions

NASA's strategy for orbital imagery has, sensibly, been a gradual progression from a global survey to high resolution imaging, culminating in the HiRISE dataset. Similarly, we have pursued a well reasoned strategy with respect to surface imagery: First capturing landforms and rocks; then meso-scale structures such as hematite concretions; and most recently, microscopically examining the structure of the dust itself as part of the Phoenix mission.

The high science yield of the Phoenix microscopy experiments (in the words of William Blake, we began "to see a world in a grain of sand") encourages us to weave a soil microanalysis campaign into the fabric of the Mars surface exploration program, moving beyond microscopy to chemical and mineralogical analysis of individual soil particles. In particular, we hope to test the long-held hypothesis that martian soils are largely homogeneous, representing a mantle of globally-distributed material.

In support of an *in situ* campaign we require the development of instruments such as SEM, EDX, and XPS. Laboratory and field investigations of potential Mars analogue materials are needed, including analysis of particle size, color, shape, mineralogy, and surface chemistry. We further require laboratory experiments to help us understand the importance of surface reactivity as a determinant of microstructure under martian conditions.

Finally, to the extent that the dust component of the soil proves to be uniformly distributed, sample return from any site will address many outstanding science questions concerning the planet as a whole, including the suitability of martian soil to support life.

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