MINERALOGY, COMPOSITION, AND ORIGIN OF SOIL AND DUST AT THE MARS PATHFINDER LANDING SITE.

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Summary. Data obtained from the Mars Pathfinder mission are being used to determine the spectroscopic, photometric, compositional, and magnetic properties of the fines at the landing site, and thus to constrain their origin and weathering history. The measurements have been obtained from IMP camera multispectral images [1,2], APXS chemical composition measurements [3,4], and the Magnetic Properties experiment [1,5]. Results to date reveal that the dust is composed of micron-sized silicate particles composed in part of at least two distinct and poorly crystalline ferric minerals (one of which may be maghemite, .-Fe_2O_3), and that the soils, while likely containing a substantial and variable dust component, also may be coarser grained and/or contain a greater abundance of a less heavily oxidized component, like ferrous-bearing pyroxene. Several models for the formation of Martian soils and dust have been proposed based on Pathfinder and previous data sets, but analyses performed to date have not provided a unique solution to the complex question of the origin of Martian fines.

Background. The chemistry and mineralogy of Martian surface fines provide a window into physical and chemical weathering processes at work in the present and past Martian environment(s). These fines can be divided into two broad classes of materials: "soil", meaning the primarily locally-derived unconsolidated particulate material that is originated and influenced by genetic and environmental factors like climate, host rock mineralogy, and topography, and "dust", meaning the most fine-grained component of the soil, which is able to be easily transported locally and globally by aeolian processes.

The Mars Pathfinder mission was designed to address a number of specific goals in the study of Martian soil and dust. These included: determination of the mineralogy and chemical composition of the fines; characterization of variations in soils and dust around the landing site and between this landing site, the Viking landing sites, and other areas of the planet studied by remote sensing; searching for a genetic relationship between the rocks and the fines at the landing site; and using the observed composition and mineralogy of the soils to constrain specific pedogenic scenarios.

The data used to achieve these goals includes: (a) multispectral (440 to 1000 nm) imaging from the IMP camera [2], composed of highly compressed 3- and 5-color panoramas, uncompressed 64,64 pixel 12-color "multispectral spots", and a nearly uncompressed 12-color panorama ("Super Pan") of 80% of the landing site; (b) results from the magnetic properties experiment [5], composed of constraints on the magnetic properties of airborne dust particles and on its particle size and spectral properties; and (c) APXS chemical analysis results from 6 soil or soil-like regions [4]. Calibration of the IMP data relies upon onboard calibration targets and preflight instrument characterization and is preliminarily estimated to be accurate to within 10-15% absolute and 2-4% relative for most images [2,6]. Known sources of calibration uncertainty include photometric variability of the calibration targets [7] and the influence of strongly colored diffuse sky illumination on the scene [8,9]. The latter is much less of a concern for analyses of soil data because, like the calibration targets, most soil surfaces are relatively flat and unshadowed. Preliminary calibration of the magnetic and APXS data use preflight laboratory characterizations [1,5].

Multispectral Imaging. Analysis of IMP multispectral images relies upon a number of spectral parameters that can be related to the presence of specific iron-bearing minerals and/or to the particle size or degree of crystallinity of the surface mineralogy. The parameters employed in our initial analyses include the reflectance (R^*, measured relative to an onboard calibration target observed at the same time of day), red/blue and red/near-IR color ratios, spectral curvature in the ferric absorption edge, and the presence, strength, and center of any 800-1000 nm absorption features.

Table 1 presents a preliminary classification of soil and dust spectral units based on the IMP images. At least six spectral units can be identified (based on reasonable assumptions about spectral unit boundaries), including the material adhering to the magnetic properties experiment surface. The primary spectral units are bright red dust, dark gray soil, and dark red soil. Possible interpretations for the mineralogy and/or particle size of these units are listed in Table 1.

Interestingly, no evidence has been found to date for unambiguous, well-crystalline hematite absorption features like those seen in remote sensing spectra of other regions of the planet [10,11]. As well, no unambiguous evidence for an absorption resulting from pyroxene centered in the 900 to 1000 nm region has been identified in IMP spectra of dark soils or rocks, in contrast to clear evidence for the presence of this mineral in remote sensing spectra of classical dark regions [12,13]. There is evidence for a weak absorption centered near 900 nm in a small fraction of the soils classified at the landing site, primarily near and apparently associated with the rock called Lamb. If this feature is real, its position and apparent width are consistent with either a very fine-grained ferric oxide/oxyhydroxide phase (such as maghemite, goethite, or ferrihydrite [14,15]), or a mixture of minor amounts of crystalline hematite and pyroxene [27].

Rather than well-crystalline phases, the IMP spectra of soils and dust appear to indicate that poorly crystalline or nanophase ferric-bearing materials dominate the visible to near-IR spectral properties of this site. This result is broadly consistent with spectral unit mapping of this and similar regions of the planet from Earthbased telescopic remote sensing measurements [*e.g.,* 16,17].

Chemical Composition. APXS data reveal that the soils are enhanced in Fe, Mg, Ti, and S and are depleted in Si, Al, and K relative to the rocks [4]. The overall chemical compositions of the soils analyzed are similar to those measured by the Viking XRF experiments [18], and element correlations indicate that the soil is likely composed of two primary geochemical components, like the Viking soils [19], with a few significant exceptions (*e.g.,* Fe and Ti in Pathfinder soils are in the other component from Viking soils) [20]. The most noticeable difference between the Viking and Pathfinder soils is that the former have significantly higher Cl and S. Normative calculations using these chemical analyses yield ambiguous results regarding the soil mineralogy [20], indicating that the soils (like the Viking soils) are probably complex mixtures of fine-grained weathering products.

Magnetic Properties. The results of the Pathfinder magnetic properties experiment indicate the presence of a fine-grained, ferric-rich, and magnetic material in the airborne dust, interpreted as clay-size composite silicate particles composed at least partly of maghemite (.-Fe_2O_3) and/or titanomagnetite [5]. The measured level of saturation magnetization of the dust combined with the average APXS Fe content of the fines suggests, however, that this magnetic component likely accounts for only around one-third of the iron-bearing minerals in the fines, and thus other perhaps spectrally-active components are also present.

Soil Origins. There are clear chemical and multispectral differences between rocks and fines at the Pathfinder landing site, and some of the trends observed in either chemical correlations or spectral properties are consistent with weathering of the observed rocks to produce certain aspects of the observed soils [20,21]. Several models for the formation of soils and dust have been proposed for Mars, based on terrestrial analogies or attempts to reproduce results from Viking Lander *in situ* experiments. These include palagonitization [22,23], acidic or acid-sulfate weathering [24,25,28], and direct precipitation from aqueous solution [5,26]. All of these processes can lead to the formation of extremely fine-grained ferric-rich minerals from initially what is assumed to be primarily basaltic igneous host rock or glassy material. Specific tests that will constrain the soil formation mechanisms on Mars include an expanded comparison of APXS data to geochemical correlations in natural weathering processes, continued efforts to derive mineralogic parameters from calibrated IMP images and terrestrial analog materials, and estimates from other geologic or morphologic data sets of the abundance and duration of liquid water interacting with surface or subsurface materials.

References: [1] Smith, P. *et al.* (1997) *JGR, 102,* 4003. [2] Smith, P. *et al.* (1997) *Science, 278,* 1758. [3] Rieder, R. *et al.* (1997) *JGR, 102,* 4027. [4] Rieder, R. *et al.* (1997) *Science, 278,* 1771. [5] Hviid, S. *et al.* (1997) *Science, 278,* 1768. [6] Reid, R. *et al.,* (1997) *Eos, 78,* F402. [7] Arnold, G. *et al.* (1997) *Eos, 78,* F403. [8] Keller, U. *et al.* (1997) *Eos, 78,* F395. [9] Wuttke, M.W. *et al.* (1997) *Eos, 78,* F402. [10] Morris, R.V. *et al.* (1989) *JGR, 94,* 2760. [11] Bell, J.F. III *et al.* (1990) *JGR, 90,* 14447. [12] Singer, R.B. *et al.* (1979) *JGR, 84,* 8415.[13] Mustard, J.F. *et al.* (1993) *JGR, 98,* 3387. [14] Morris, R.V. *et al.* (1985) *JGR, 90,* 3126. [15] Bishop, J.L. *et al.* (1993) *Geochim. Cosmochim. Acta, 57,* 4583. [16] Bell, J.F. III *et al.* (1997) *JGR, 102,* 9109. [17] Merényi, E. *et al.* (1996) *Icarus, 124,* 296-307. [18] Clark, B.C. *et al.* (1982) *JGR, 87,* 10059. [19] Clark, B.C. (1993) *Geochim. Cosmochim. Acta, 57,* 4575. [20] Ghosh, A. *et al.* (1998) this volume. [21] Bridges, N. *et al.* (1998) this volume. [22] Gooding, J.L. and K. Keil (1978) *GRL, 5,* 727. [23] Morris, R.V. *et al.* (1993) *Geochim. Cosmochim. Acta, 57,* 4597. [24] Clark, B.C. and A.K. Baird (1979) *JGR, 84,* 8397. [25] Banin, A. *et al.* (1997) *JGR, 102,* 13341. [26] Burns, R.G. (1993) *Geochim. Cosmochim. Acta, 57,* 4555. [27] Morris, R.V. *et al.* (1995) *JGR, 100,* 5319. [28] Morris, R.V. *et al.* (1996) in *Mineral Specroscopy, A Tribute to Roger G.. Burns* (Geochem. Soc. Special Publ. #5), 327.

Table 1. Preliminary Pathfinder Landing Site Soil Spectral Units

Unit	R^* @ 750 nm	670/ 440 nm	750/ 965 nm	800 to 1000 nm Band	Preliminary Interpretation
Bright Red Dust	> 20%	> 4.0	< 1.05	< 5%	Poorly crystalline, fine-grained and highly altered Fe-rich dust or drift; very minor mafic signature (based on near-IR slope)?
Dark Gray Soil	< 20%	< 4.0	1.05 to 1.12	< 5%	Coarser-grained and/or less altered ferric-rich soil, slightly stronger mafic signature?
Dark Red Soil	< 20%	> 4.0	1.05 to 1.13	< 5%	Coarser-grained, compacted, or higher Fe^{2+} content Bright Red soil, and/or a mixture of Bright Red, Dark Gray
Lamb Soil	> 20%	> 4.0	1.05 to 1.20	> 5%	(Rare) Highly altered soil but more crystalline or "riper"? Band center . Fe oxide or oxyhydroxide, and not pyroxene
Bright Gray Soil	> 20%	< 4.0	1.03 to 1.08	< 5%	(Rare) Coating or Dusting of Bright Red soil over Dark Gray soil? *cf.* Pink Rock [2]?
Magnetic Dust	> 20%	> 4.0	0.95 to 1.00	< 1%	Magnetic properties . .-Fe_2O_3; Spectral properties . nanophase Fe oxide with little/no mafic signature