NATURE AND ORIGIN OF MARTIAN SURFACE MATERIALS. J. F. Bell III[1], [1]Cornell University, Department of Astronomy, Ithaca NY 14853; jfb8@cornell.edu.

Introduction: The nature and origin of Martian surface materials can be assessed from a mineralogic and compositional standpoint using the available data from telescopic and orbiting spacecraft imaging and spectroscopy, as well as landed *in situ* imaging, spectroscopic, compositional, and magnetic studies. These studies are designed to answer important questions about Martian surface materials that constrain not only their present physical or compositional properties, but also the present and past environmental conditions that have lead to the formation of the presently-observed materials (Table 1).

Here I briefly describe some of the most recent observational data and interpretations that bear on the question of the nature and origin of Martian surface materials, focusing mostly on the composition and mineralogy of the ubiquitous soils and dust as derived from *in situ* (Viking and Pathfinder) studies, but also describing recent results on the chemistry and mineralogy of rocks. Many of the results and interpretations outlined here are described in much more detail in recent papers based on Pathfinder results on Martian rocks [1] and soils [2].

Table 1. Some Important Questions About the Nature and Origin of Martian Surface Materials.

• What is the chemical composition of the rocks and soils?

• What is the mineralogy of the rocks and soils?

• What are the physical properties (*e.g.*, magnetism, grain size, texture, stratigraphy) of the rocks and soils?

• Are there differences in chemistry, mineralogy, or morphology among rocks and soils studied closely at the Viking and Pathfinder landing sites?

• Is there a genetic connection between soils and rocks at the Viking or Pathfinder landing sites?

• Can the observed composition and mineralogy of the soils and rocks be used to constrain specific weathering environments or alteration scenarios?

Previous Measurements. Classically, the Martian surface has been observed to consist of bright and dark regions that have changed little in large-scale form during more than 350 years of telescopic observations [3]. Telescopic spectroscopy at visible to near-IR wavelength since the 1960s have revealed that mineralogic differences are correlated (at large scales) with this albedo difference: the spectral properties of classical bright regions are dominated by heavily-oxidized Fe^{3+}-bearing (ferric) minerals, and the spectral

properties of dark regions include this ferric component, but also show evidence for the unoxidized Fe^{2+}-bearing (ferrous) mineral pyroxene [4]. More recent spacecraft visible and near-IR observations at higher spatial resolution (Viking, Phobos-2, HST) have revealed more subtle differences in spectral properties at finer scales, that often do not correlate simply with albedo [5-7]. Spectroscopic observations by MGS/TES in the thermal infrared are also consistent with this finding [8]. Higher spatial resolution does not always imply increased spectral heterogeneity, however, as evidenced by the relative lack of spectral contrast observed by the Viking Landers [9] and at the Mars Pathfinder landing site [10].

Chemically, the Viking landers studied the composition of soils at widely-separated landing sites. The soils sampled by the Viking Lander XRF investigation exhibited high iron contents (ranging from 16% to 19% Fe as Fe_2O_3) as well as high sulfur and chlorine abundances. The soil composition was interpreted using normative calculations and compositional mixing models as secondary weathering products of mafic igneous rocks, possibly resulting from palagonitization. In particular, the models yielding the best fits to the data included iron-bearing smectite (nontronite) and/or iron oxides (hematite, maghemite, magnetite) as the major iron-bearing minerals [11]. The high abundance of sulfur in the Viking soils was interpreted as evidence for cementing salts or duricrust, responsible for the hardpan appearance of some regions near the landers. This result was also consistent with soil mechanics results indicating the presence of crusty and cloddy deposits at both Viking landing sites [12].

Viking also revealed that the soils are highly magnetic, possibly resulting from 1-7 wt.% of a strongly magnetic component like maghemite (- Fe_2O_3) dispersed as a pigment throughout the surface particles [13].

Pathfinder Observations. Mars Pathfinder observations bearing on the question of the nature of the surface materials included multispectral imaging and magnetic properties studies by the Imager for Mars Pathfinder (IMP); elemental chemistry measurements by the Alpha Proton X-Ray Spectrometer (APXS), including the first elemental chemistry measurements of rocks on Mars; and soil and rock textural and physical properties measurements (imaging and soil mechanics) by the Sojourner rover [14].

Pathfinder Results. A recent study of the multispectral, elemental, and physical properties of soils and dust at the Mars Pathfinder landing site [2]
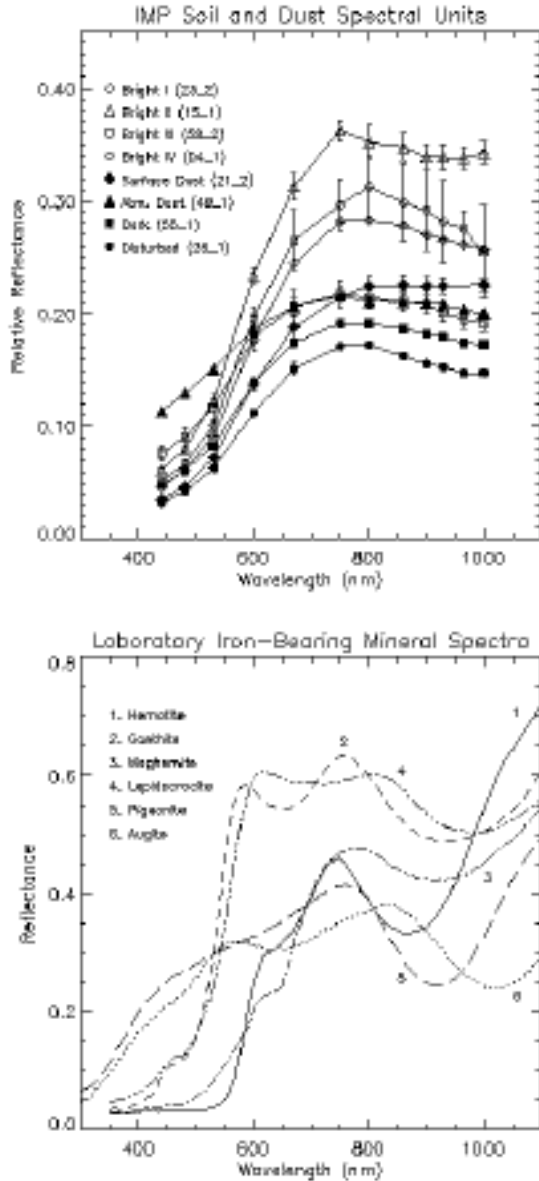
Figure 1. (Top Panel) Direct comparison of the eight Pathfinder soil and dust spectral units defined in [2]. (Bottom Panel) Laboratory spectra of ferric- and ferrous-bearing analog minerals. The iron oxides/oxyhydroxides hematite (HMS3), goethite (GTS2), maghemite (MHS4) and lepidocrocite (LPS2) are from [15,16]; the pyroxenes pigeonite (EAC042) and augite (WS592) are from [17].

has revealed that at least eight soil spectral units can be defined based on uncompressed and fully spectrally-sampled IMP Multispectral Spot data parameterized by reflectivity, red/blue ratio, and near-IR spectral slope and band strength (Figure 1). The IMP soil spectra are consistent with the presence of poorly crystalline or nanophase ferric oxide(s) in the soil, sometimes mixed with a small and variable component

of well-crystalline ferric or ferrous phases. Leading candidates for the ferric phase include nanophase goethite and maghemite, and akaganeite and schwertmannite cannot be entirely ruled out. The Fe-Ti spinels titanomaghemite and titanomagnetite could also be present, as they may be consistent with the IMP magnetic properties experiment results and (because they are spectrally neutral) they would likely not be uniquely identifiable in IMP spectra. Candidates for the ferrous phase are difficult to constrain from IMP data, but based on previous laboratory and telescopic spectroscopic studies these include high-Ca pyroxene and olivine.

These Pathfinder soil spectral properties results can be compared to the IMP-derived spectral properties of rocks at the site reported by McSween *et al.* [1]. Four spectral classes of rock surfaces were identified: Gray and Red surfaces were found to commonly occur on the same rocks, with Gray portions on the upwind sides or at eroded edges and Red portions on downwind surfaces. Several Pink rocks were found to occur as tabular rock-like masses, probably soil crusts (analogous to the pinkish "Bright I" soils in [2]). Maroon rocks were identified as mostly large, rounded boulders in the far field. Correlated spectral parameters allow the rocks to be assigned to two spectral trends: rocks of the primary spectral trend, which share a reflectance peak at 750 nm, include most materials (both rocks and soils) in the optical surface. Only Maroon rocks and spectrally similar Disturbed soils are assigned to the secondary spectral trend, defined by reflectance peaks at longer wavelengths. The spatial pattern of spectral variations in rocks and their relationship to wind direction suggested that the source of spectral heterogeneity (*i.e.,* the primary spectral trend) is primarily thin ferric coatings of red aeolian dust on dark rocks. The ferric phase in primary trend coatings is ambiguous due to lack of a diagnostic spectral signature. The secondary spectral trend apparently requires coating by a different ferric mineral with distinct spectral properties (possibly maghemite or ferrihydrite).

APXS elemental chemistry observations at the six Pathfinder soil sites indicate that the differences in elemental chemistry between soils at the Pathfinder site are much smaller than the differences in multispectral properties. This suggests that many of the characteristics that make the soils appear different in IMP data may be related to physical or mechanical differences, rather than mineralogic variations. For example, Dark and Disturbed soils may be coarser grained or compressed versions of Bright soil units. Some Bright soils, like Scooby Doo, which does not exhibit significant chemical differences from the other soils sampled, may be spectrally different because they are cemented or indurated. Nonetheless, Pathfinder IMP data do reveal some rarer soil units that exhibit spectral characteristics, like near-IR band depth

variations, that may truly indicate soil mineralogic diversity.

Despite broad general similarity in elemental composition, Pathfinder and Viking soils do exhibit significant differences. Specifically, Pathfinder soils exhibit significantly lower S and Cl and higher Si than Viking soils, and do not show the correlation between Ti and Fe evident in Viking soils. APXS soil elemental chemistry may suggest the presence of two geochemical components in the soil, like Viking soils, but the correlations are not as strong as in Viking data. In addition, Pathfinder data do not appear to show any statistically significant linear correlations between IMP-derived spectral parameters and APXS-derived elemental chemistry for the six APXS soil measurement sites. And finally, attempts to recast the APXS soil elemental chemistry data in terms of a normative suite of minerals [2] yielded high residual sums and no unique or acceptable solutions. The best (poor) fits are consistent with soils composed mostly of smectites, but this result is not well supported by available remote sensing observations.

Preliminary APXS analyses reported by McSween *et al.* [1] of most elements in rocks plot as nearly linear arrays, interpreted as mixing lines between a single rock composition and adhering dust. This interpretation is supported by a strong correlation between rock sulfur contents and red/blue spectral ratios measured at the same spots. Extrapolations of regression lines to zero sulfur give the approximate composition of a presumed igneous rock, which has a chemistry corresponding to an andesitic volcanic rock.

Origin of Martian Soils. Can the observed spectral and compositional properties of Martian soils and rocks be related through reasonable weathering or alteration scenarios? Numerous formation mechanisms that might explain the chemical composition and multispectral and magnetic properties of Martian soils and dust have been suggested, including meteoritic mixing, impact volatilization, freeze-dried precipitation of iron-rich solutions, oxidation of volcanic aerosols, magmatic or impact-induced hydrothermal alteration, palagonitization, and acid fog reactions [reviewed in 2]. However, none of the models examined for the origin of soils and dust were found by [2] to provide unique fits to the observed Pathfinder data. Palagonitization may provide the best fit to the observed elemental trends and multispectral signatures, but the soils and rocks at the Pathfinder site cannot be linked by this process. This may simply reflect the globally-mixed nature of Martian fines and the resultant muting of unique geochemical weathering signatures (the "decoupling" of Martian soil and bedrock). However, similar calculations by [16] with data derived for palagonitization under relatively dry (subarael) conditions on the upper slopes of Mauna Kea volcano have also indicated that Pathfinder rocks and soils cannot be related by hydrolytic or sulfatetic alteration processes.

The search for a link between the soils, dust, and rocks on Mars is thus not straightforward, and likely involves weathering or alteration scenarios that are unique to the Martian environment (with no simple terrestrial analogs) and that are difficult to simulate in the laboratory. However, the database of observed spectral and compositional properties, especially at localized (lander-based) scales, is still quite small. We should not forget, then, that in many ways we are still in a relatively early "data gathering" stage, during which time our estimates of the compositional and mineralogic diversity of the Martian surface will likely increase because of increased sampling of geologically diverse sites. Perhaps this additional sampling will reveal endmember compositions or mineralogies that will allow us to more firmly establish the complex link between soils and rocks on Mars.

References: [1] McSween *et al.* (1999) *JGR,* in press. [2] Bell *et al.* (1999) *JGR,* submitted. [3] Martin *et al.* (1992) in *Mars* (U. Arizona Press), pp. 34-70. [4] Soderblom (1992) *Ibid,* pp. 557-593. [5] Bell (1996) in *Geochem. Soc. Spec. Pub. 5.,* pp. 359-380. [6] Mustard *et al.* (1993) *JGR, 98,* 3387-3400*.* [7] Murchie *et al.* (1993) *Icarus, 105,* 454-468*.* [8] *e.g.,* Lane *et al.* (1999) LPSC 30th, Abstract #1469. [9] Adams *et al.* (1986) *JGR, 91,* 8098-8112. [10] Smith *et al.* (1997) *Science, 278,* 1758-1765. [11] Toulmin *et al.* (1977) *82,* 4625-4634. [12] Moore *et al.* (1979) *84,* 8365-8377. [13] Hargraves *et al.* (1979) *84,* 8379-8384. [14] Golombek (1999) *JGR,* in press. [15] Morris *et al.* (1985) *90,* 3126-3144. [16] Morris *et al.* (1999) *JGR,* in press. [17] Clark *et al.* (1993) U.S. Geol. Surv. Open File Report 93-592.