NASA-CR-204689

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. E2, PAGES 4219-4229, FEBRUARY 25, 1997

Near-surface geologic units exposed along Ares Vallis and in adjacent areas: A potential source of sediment at the Mars Pathfinder landing site

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Abstract. A sequence of layers, bright and dark, is exposed on the walls of canyons, impact craters and mesas throughout the Ares Vallis region, Chryse Planitia, and Xanthe Terra, Mars. Four layers can be seen: two pairs of alternating dark and bright albedo. The upper dark layer forms the top surface of many walls and mesas. The upper dark-bright pair was stripped as a unit from many streamlined mesas and from the walls of Ares Valles, leaving a bench at the top of the lower dark layer, ~250 m below the highland surface on streamlined islands and on the walls of Ares Vallis itself. Along Ares Vallis, the scarp between the highlands surface and this bench is commonly angular in plan view (not smoothly curving), suggesting that erosion of the upper dark-bright pair of layers controlled by planes of weakness, like fractures or joints. These near-surface layers in the Ares Vallis area have similar thicknesses, colors, and resistances to erosion to layers exposed near the tops of walls in Valles Marineris [*Treiman et al.*, 1995] and may represent the same pedogenic hardpan units. From this correlation, and from analogies with hardpans on Earth, the light-color layers may be cemented by calcite or gypsum. The dark layers are likely cemented by an iron-bearing mineral. Mars Pathfinder instruments should permit recognition and useful analyses of hardpan fragments, provided that clean uncoated surfaces are accessible. Even in hardpan-cemented materials, it should be possible to determine the broad types of lithologies in the Martian highlands. However, detailed geochemical modeling of highland rocks and soils may be compromised by the presence of hardpan cement minerals.

Introduction

A major scientific goal of the Mars Pathfinder mission is to obtain chemical and lithologic data on rocks of the martian highlands, and the Mars Pathfinder landing site was chosen specifically to permit sampling of highlands lithologies [*Golombek*, this issue; *Golombek et al.*, this issue]. Although the highlands encompass more than half of Mars' surface, our knowledge of their bulk compositions and lithologies is minimal. Most data suggest that basalt is present in the highlands [e.g., *Singer and McSween*, 1993; *Mustard and Sunshine*, 1995; *Treiman*, 1995a], but it is unclear if other materials are also abundant. Thus additional clues to the nature of the highlands crust will be critically important to the overall understanding of Mars and its geologic history.

In this paper, I will describe geologic units and boundaries in the near-subsurface of the Martian highlands, as exposed on cliffs, scarps, and crater walls in Ares Vallis and surrounding areas. Highlands surfaces near Ares Valles are underlain by a consistent sequence of flat-lying layers, assumed to represent lithologic units. The layers are recognized by variations in albedo and resistance to erosion, and form characteristic "dark-light-dark-light" sequences, in which the tops of the dark layers commonly form benches or erosional surfaces. The layers were eroded during the Ares Vallis floods and are likely contributors to the fluvial sediments of the Mars Pathfinder landing site [*Treiman*, 1995b]. This layer sequence can be recognized from Iani Chaos, a source of Ares Vallis, to streamlined islands at the mouth of Ares Vallis (northeast of the Mars Pathfinder landing site), a distance of ~1500 km.

These near-surface lithologic layers in the Ares Vallis region are essentially identical in color, sequence, and stratigraphic position to layers described by *Treiman et al.* [1995] throughout the entire Valles Marineris region. Following *Treiman et al.* [1995], it seems reasonable to hypothesize that, like that in Valles Marineris, the layer sequence in the Ares Vallis region represents a regionally extensive hardpan sequence.

Paper number 96JE02437.
0148-0227/97/96JE-02437$09.00

Method

This work assumes that Ares Vallis and adjacent channels were carved by a catastrophic flood or floods, that sedimentary deposits from these floods underlie the Mars Pathfinder landing area, and that these sedimentary deposits are exposed at the present ground surface [*Kuzmin and Greeley*, 1995; *Tanaka*, 1995; *Komatsu and Baker*, this issue; *Rice and Edgett*, this issue]. Further, its seems likely that these sedimentary deposits include clasts and fragments eroded from the walls of Ares Vallis and from islands in the path(s) of the Ares Vallis flood(s). Thus the source materials for some sediments in the Mars

Pathfinder landing site can be examined in situ on the walls of Ares Vallis, streamlined islands, and nearby outflow channels, and also on the walls of fresh impact craters near Ares Vallis.

To investigate geologic relations exposed on cliffs and walls in the Ares Vallis area, I relied on Viking Orbiter (VO) images, both as prints and in digital format from the U.S Geological Survey compact disk series. Images presented here were processed through "level 1" of the PICS system of computer programs, which includes despeckling, removal of reseaus, and radiometric calibrations [*U.S. Geological Survey (USGS)*, 1990]. Images were not corrected for viewing angle and orientation ("level 2" of PICS). Further enhancements were done with commercial image processing packages. Available images are mostly through clear filters.

Lithologic features on cliffs and walls can be consistently resolved only on images with spatial resolutions better than 100 m/pixel; lithologic features are rarely visible on images with poorer resolution if slope directions and lighting are optimal. There is complete coverage of the Ares Vallis outwash fan (the Mars Pathfinder landing site area) at spatial resolutions <100 m/pixel, but very limited coverage of Ares Vallis itself, its surroundings, and its sources. Thus the lack of evidence for lithologic features in walls outside these limited regions (Figure 1) reflects the lack of high-resolution imagery, and not necessarily an absence of lithologic features. To interpret thicknesses of lithologic features in walls, the heights of walls were calculated from shadow lengths. Thicknesses of lithologic features were then calculated as proportions of total wall heights.

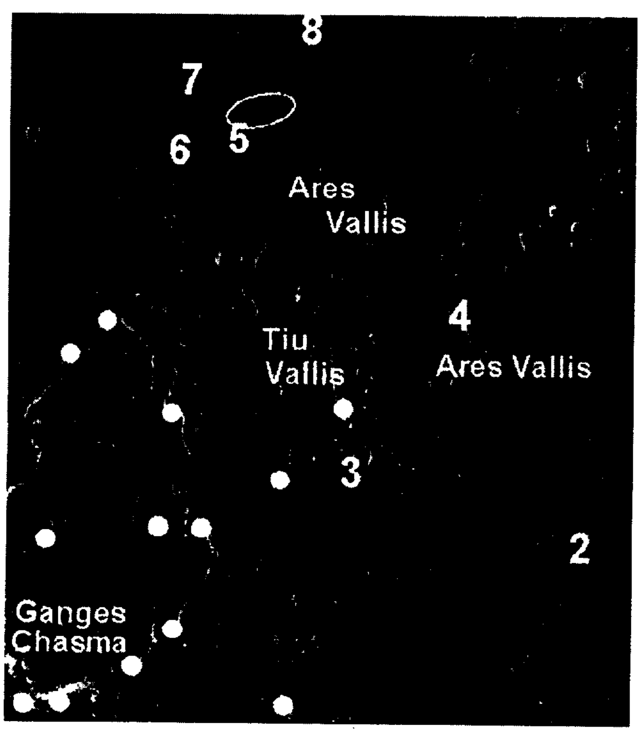

Figure 1. Mars Digital Image Model scene of the Ares Vallis area, Mars: 10°S - 25°N, 15-50°W. The ellipse is the Mars Pathfinder landing target on the outflow fan of Ares and Tiu Valles. Numbers correspond to locations of the images in Figures 2 through 8. White circles show other exposures of the near-surface layering visible on Viking Orbiter images.

Near-Surface Stratigraphy

This section reports on near-surface geologic units exposed throughout the Ares Vallis region, moving south to north. Cliffs, channel walls, and crater walls all exhibit a common near-surface stratigraphic sequence: alternating dark and bright layers, with the darker layers more resistant to erosion. These layers are all parallel to the ground surface before formation of Ares Vallis, collapse features, and chaoses. Equally surprising, the layer sequence appears essentially identical over the full length of Ares Vallis, ~1500 km, and under surface units of Noachian and Hesperian ages.

The geology of the Ares Vallis region has been described in detail [*Greeley et al.*, 1977; *Scott and Tanaka*, 1986; *Tanaka*, 1986, 1995; *Komatsu and Baker*, this issue; *Rice and Edgett*, this issue]. Ares Vallis originates in the collapsed terrane of Iani Chaos (Figures 1 and 2), with smaller valleys feeding in from Aram Chaos and Margaritifer Chaos. A significant portion of the Ares Vallis flow came from Hydaspis Chaos through a NE trending drainage into the main Ares channel (Figures 1 and 3). Hydaspis Chaos is also a source for flow into the Tiu Vallis drainage, immediately west of Ares Vallis. The Mars Pathfinder landing site includes portions of the outflow systems (both erosional and depositional) of both Ares and Tiu Valles.

Ares Vallis itself is of Hesperian age and was incised into Noachian and Hesperian units [*Scott and Tanaka*, 1986]. Surfaces adjacent to the Ares and Tiu Valles channels are mostly cratered plains of Noachian age in various stages of degradation. East of Ares Vallis, Hesperian-aged ridged plains surfaces are common, and the eastern walls of the lower reaches of Ares Vallis are in these ridged plains [*Scott and Tanaka*, 1986].

The southernmost high-resolution images of the Ares Vallis system are of a small portion of Iani Chaos, which is surrounded by Noachian-age cratered plains. High-resolution VO coverage of Iani Chaos is very limited (only the VO 405B series); spatial resolution is excellent at ~30 m/pixel, but the images are hazy

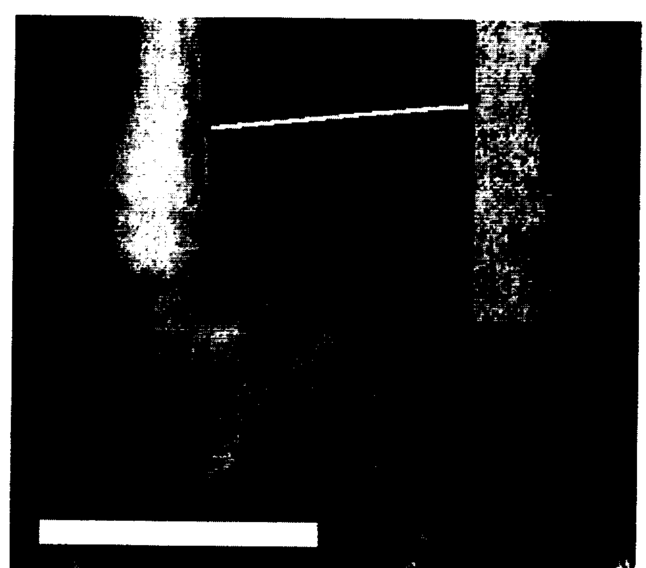

Figure 2. Mesas in Iani Chaos 1.8°S 18.5°W (from VO 405B13). Minus-blue filter, north is vertical, scale bar 5 km. Albedo layering visible on several mesa walls. Inset is enhanced 2× enlargement of mesa wall, ~1.25 km tall; note dark-bright-dark-bright layering from rim down.

Figure 3. Hydaspis Chaos, 1.6°N 29.4°W (from VO 083A34). Clear filter, north is 3° counterclockwise from vertical, scale bar 5 km. Insets are enhanced 3× enlargements; upper left inset shows the wall of a mesa within the Chaos, lower inset is of the scalloped southern wall of the Chaos, right inset is of eastern wall of this portion of the Chaos. In all insets, note dark layer part way down the wall, and darkness at the wall top.

(taken through the MBL (minus-blue) filter) and have extremely low contrast (valid data numbers range from 0 to 50 out of a possible range of 0 to 255). Figure 2 shows an enhanced enlargement of a portion of one such frame, showing a mesa within Iani Chaos; mesas in this area are ~1.3 km tall. This mesa has distinct albedo layering in its upper slopes: the mesa top is dark and is underlain by bright, dark, and bright layers. The lower dark layer is approximately 250 m beneath the mesa top. While the layering shown in Figure 2 is the most photogenic available for Iani Chaos, a similar sequence is present on other mesas in the Chaos.

Hydaspis Chaos, another of the many collapsed chaotic terranes in the Ares region, was an important flood source for both Ares and Tiu Valles (Figures 1 and 3). Hydaspis Chaos was developed in Noachian-age cratered plains, drained northwest directly into Tiu Vallis, and drained northeast into Ares Vallis. The southern wall of Hydaspis Chaos shows alternating dark and bright layers, parallel to the ground surface (Figure 3). The insets on Figure 3 show enhanced close-ups of these brightness variations. On walls with oblique illumination, the dark layers (especially the uppermost) appear to support steeper slopes than the bright layers, thus suggesting that the darker layers are more resistant to erosion. The height of the Hydaspis walls is approximately 1 km [*USGS*, 1991], and the lower dark layer is ~ 250 m below the ground surface.

Moving north, imagery at ~70 m/pixel is available for a portion of the middle reach of Ares Vallis (Figures 1 and 4) where it cuts cratered plains of Noachian age [*Scott and Tanaka*, 1986]. Near-surface geology is exposed on the walls of collapse depressions, impact craters, and Ares Vallis itself. Inset A of

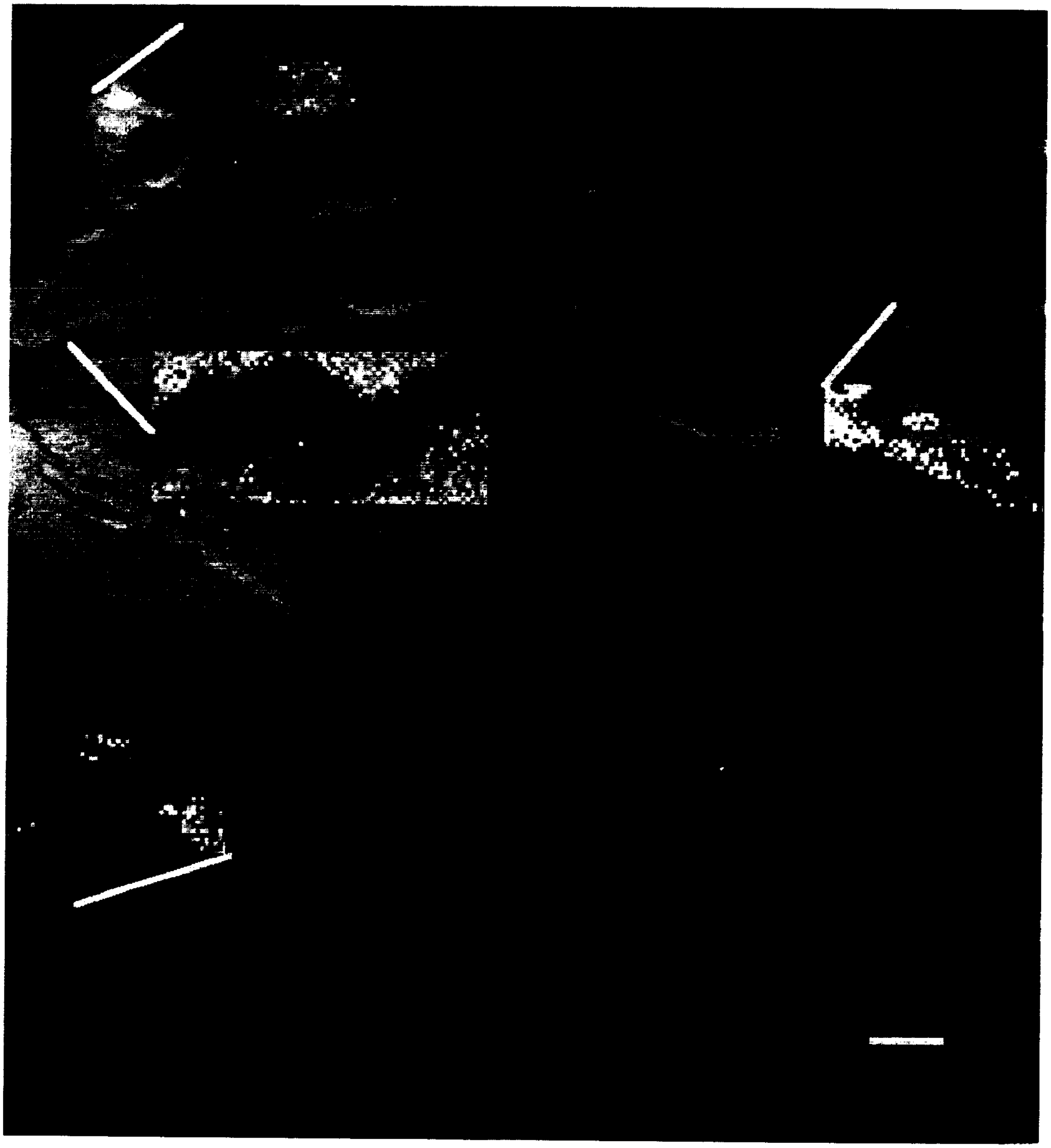

Figure 4. Ares Vallis, 9.6°N 23.8°W (from VO 083A49). Clear filter, north is 7° counterclockwise from vertical, scale bar 5 km. Insets are enhanced 4× enlargements of main frame. The insets are, clockwise starting at the image top: the southern wall of a fresh impact crater (from VO083A50) with a dark layer halfway down the wall; the degraded southern wall of a large impact crater, showing a dark layer part way down the wall; a portion of the SW wall of Ares Vallis, with an exposed dark layer part way down the wall; and a portion of the N wall of Ares Valles, showing the angular plan of the bounding cliff, the base of the cliff is a broad bench at the same elevation as the dark layer on the SW wall of Ares Vallis.

Figure 4 shows a small relatively fresh crater, just north of the Ares channel. On the south wall of the crater a dark layer is exposed. Similarly, a dark layer is apparent on the southern wall of the impact crater/collapse basin shown as inset B. Inset C shows a portion of the south wall of the Ares Vallis channel; which is ~500 m deep in this section [*Komatsu and Baker*, this issue]. On that wall, a dark layer can be observed (in favorable orientations only) at ~250 m below the wall top. Finally, inset D shows a portion of the north wall of the channel, emphasizing the cliff at the wall top and the bench beneath it. The cliff here is about half the depth of the full Ares channel, or ~250 m tall; this estimate places the bench beneath the cliff at approximately the same elevation as the dark layer exposed in inset C.

Farther north, the walls of the Ares channel break apart into isolated mesas, most of which have been carved into streamlined forms by the floods. The mesa of Figure 5 is at the mouth of

Figure 5. Streamlined mesa, ~600 m tall, near the mouth of Ares Vallis, 18.1°N, 34.1°W (from VO 003A51). Clear filter, north is 18° counterclockwise from vertical, scale bar 5 km. From mesa top, note dark-bright-dark-bright layers down to base of mesa. The layering is visible on all illuminated slopes. Flood flow direction to north. This mesa and its layers are also visible on VO 004A23, 004A38, 004A64, 004A66, 004A81, and 004A83.

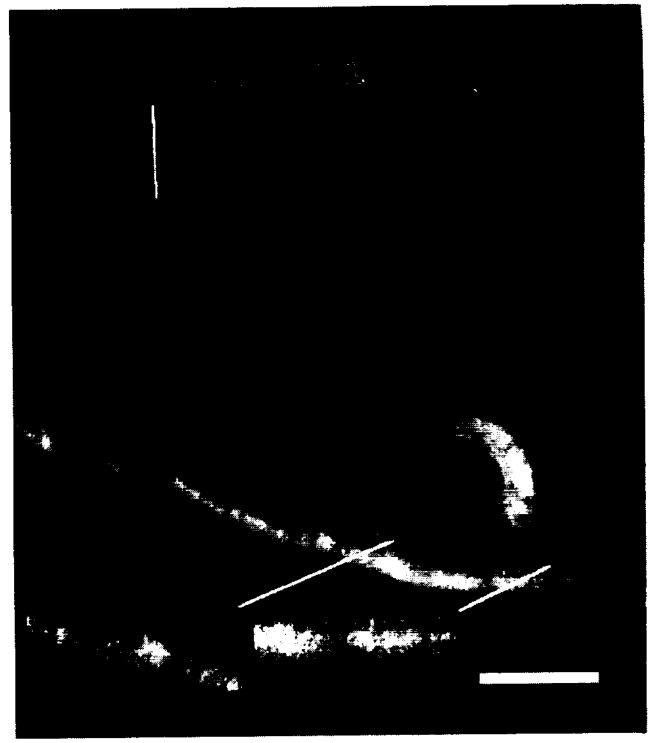

Figure 6. Streamlined mesa, ~500 m tall, at the mouth of Tiu Vallis, 17.8°N 36.8°W (from VO 004A57). Clear filter, scale bar 5 km, north is 54° counterclockwise from vertical. Note that the mesa has been stripped layer by layer into a series of benches along the SE-NW channel that crosses the mesa. Top inset is enhanced 2× close-up of the NE of the channel, showing its dark-bright-dark-bright layers; note that the lower dark layer appears to form a discontinuous bench. Bottom insets are enhanced 2× close-ups of portions of the mesa's southwest wall; note again the dark layer partway down the wall.

Ares Vallis, only 25 km SW of the Mars Pathfinder landing ellipse (Figure 1). The mesa is ~600 m tall and shows an uppermost dark unit, underlain successively by bright, dark, and bright units. The existence of an uppermost dark unit seems clearest on the eastern wall of the small channel cutting N–S across the mesa. There, the uppermost slope below the mesa top is darker than the mesa top itself. The dark layer on the mesa slopes is ~200 m below the mesa top.

To understand the origins of near-surface stratigraphy and lithologies in the Ares Vallis region, it is important to document exposures surrounding the Mars Pathfinder landing site. To this end, I document three exposures near the landing site, either in the adjacent drainage, or in the Ares Vallis drainage downstream from the landing site.

First, near-surface lithologic layering is evident on a beautifully streamlined mesa in the Tiu Vallis outflow, ~280 km WSW of the center of the Mars Pathfinder landing ellipse (Figures 1 and 6). The southernmost end of the mesa is supported by an impact crater, north of which the mesa is divided by a SE–NW trending channel. The mesa surface in that area has been stripped layer-by-layer (lit-par-lit) to yield a series of benches on a slope from the crater to the channel floor. Northeast of the channel, shadow lengths imply that the mesa is ~500 m tall. Layers marked by albedo, dark-light-dark-light from the mesa top, are clearly exposed on the northeastern wall of the channel and less clearly on the southern wall of the whole mesa (Figure 6, insets). The top of the middle dark layer is ~200 m below the mesa top. Note also that the bench levels along the subsidiary channel correspond to the dark layers exposed along the wall.

Second, the streamlined mesa shown in Figure 7 is ~250 km WNW of the center of the Mars Pathfinder landing ellipse, and ~200 km due north of the mesa in Figure 6 (Figure 1). It also is in the Tiu Vallis outflow, although it is possible that some Ares outflows traveled that direction. This mesa, as with the others above, shows layers of different albedos on its slopes, dark-light-dark-light from the top down.

And finally, Figure 8 shows the wall of a sinuous channel cut into Hesperian ridged plains materials ~300 km NE of the center of the landing ellipse (Figure 1). A dark layer is apparent on the channel wall. The inset shows that the uppermost slope beneath the mesa top is darker than the top, suggesting (as above) the presence of a dark layer at the wall top. The whole wall is slightly less than a kilometer tall, so the dark layer in the middle of the walls is ~300 m below the mesa top.

Where visible, the walls of canyons, mesas, and craters in the Ares Vallis region (~1500 km N to S) display essentially the same near-surface stratigraphic section: a dark unit at the land surface, underlain successively by light, dark, and light units. The units are at the same position relative to the land surface throughout the area, a dark unit on top and the second dark unit at ~250 m depth, although the elevation of the ground surface ranges from ~0 km (relative to the datum) in the south to approximately -2 km in the north [*USGS*, 1991]. For the most part, the ground surface above these layers is of Noachian age cratered plains, although layers are also exposed beneath Hesperian age ridged plains.

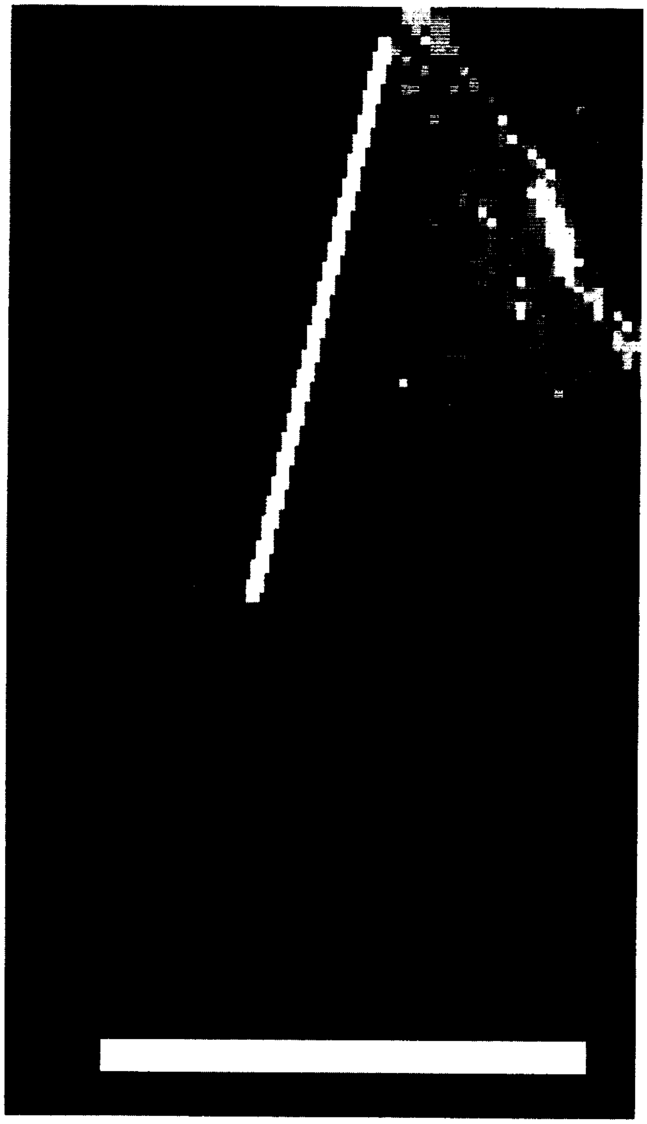

Figure 7. Streamlined mesa in distal fan of Ares Vallis, 21.1°N 36.0°W (from VO 034A78). Clear filter, north is 18° counterclockwise from vertical, scale bar 5 km. Inset is enhanced 2× close-up of mesa wall; note dark-bright-dark-bright layers extending to base of mesa.

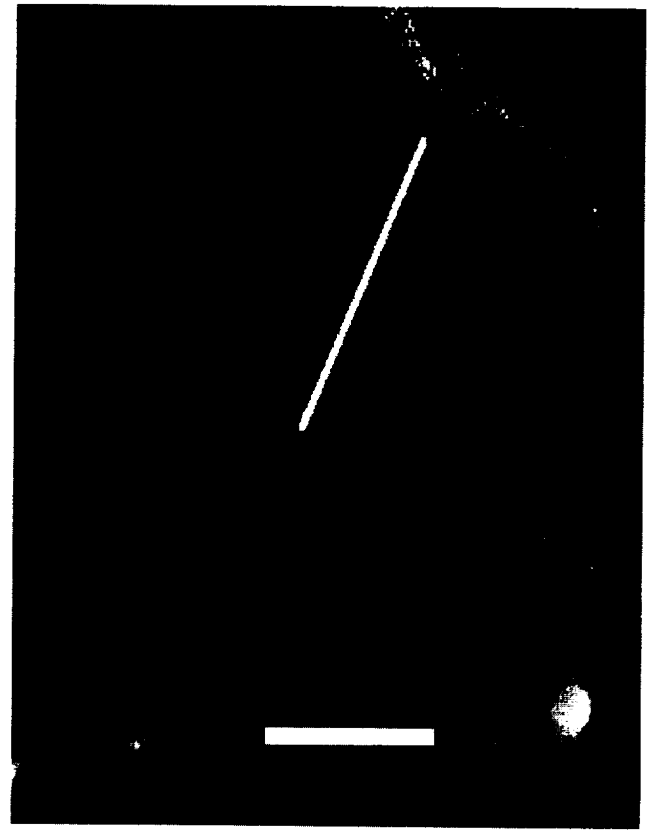

Figure 8. Edge of sinuous channel at NE-most outlet of from the Ares Vallis fan area, 23.9°N 30.5°W (from VO 003A13). Clear filter, north is 50° counterclockwise from vertical, scale bar 5 km. Inset is enhanced 2× close-up of channel wall; note dark-bright-dark-bright layers extending to channel floor.

Interpretation

Based on the limited exposures in the Ares Vallis region, it would seem premature to speculate on the origins and compositions of the consistent, dark-light-dark-light layering present in the near subsurface. It is tempting to correlate the layers observed at one site with those at another, but image coverage in the Ares Valles region is too spotty to require such a correlation. Even so, it seems significant that layers with similar appearances are present at sites separated by ~1500 km in distance, > 2 km in elevation, and beneath surfaces of different ages.

Many scenarios can be suggested to explain the observed near-surface layers. In one view, all known exposures of the layers (Figures 2-8) could all represent spatially isolated views of a single, laterally extensive, depositional sequence. In this case, the depositional sequence must be time-transgressive (as it appears under surfaces of different ages), and transgress surface morphology (as it appears under heavily cratered and volcanic plains units). In another view, the exposures in Figures 2-8 might not be strictly correlative, but represent isolated sections within an extensive depositional package. In this case, the depositional package must be very extensive (>1500 km in length), thick (equivalent of ~2 km of strata), and time-transgressive. These requirements are not impossible; for instance, one could imagine a prograding delta sequence (like that of the Mississippi River) having comparable length, apparent thickness, and layer alternations; it is not clear how this scenario could be reconciled with the different surface morphologies in the region (heavily cratered units and volcanic plains units). In yet another view, each exposure might represent an isolated depositional environment (e.g., a lake), and the layers visible at one exposure are not related to those at another exposure. This scenario, however, does not explain the presence of similar layers beneath different surface morphologic units.

A different scenario is favored here: the layers formed in place through chemical diagenetic or pedogenic processes. In other words, they represent hardpan horizons formed in place by chemical action on preexisting regolith and rock. This explanation is suggested by the geologic relations of similar near-surface layers throughout the Valles Marineris region

[*Treiman et al.*, 1995] and, as will be shown, is consistent with the properties of the layers in the Ares Vallis region.

Hardpan

Hardpan is a generic word for regolith or rock cemented in place near the ground surface to form physically strong, coherent layers or horizons. Hardpans are common in arid regions on Earth [*Petrov*, 1976; *Watson*, 1989]. Carbonate minerals, especially calcium carbonates, are the most common cementing agents on Earth. Other hardpan cements include Ca-sulfate, silica, clays, iron and aluminum oxides and hydroxides, and soluble ionic salts (halides, sulfates, nitrates) [*Petrov*, 1976; *Watson*, 1989]. Hardpan cements can displace or replace the host sediment, and leave deposits of 70-95% cementing mineral. A typical calcium carbonate hardpan layer (i.e., calcrete) in Washington state is shown in Figure 9, and thicker carbonate hardpans are shown in Figures 234 and 235 of *Shelton* [1966] and Figure 3.1A of *Watson* [1989]. A gypsum hardpan (i.e., gypcrete) with columnar jointing, approximately 10 m thick, is shown in Figure 3.2 of *Watson* [1989]. A silica-rich hardpan supports the surface of the Gilf Kebir plateau in southwestern Egypt, a region with landforms analogous to many on Mars [*Breed et al.*, 1982; *El-Baz and Maxwell*, 1982]. The regional geomorphic importance of hardpans is beautifully shown in Figure 152 of *Shelton* [1966] and Figure 3.1B of *Watson* [1989].

Many lines of evidence suggest that hardpan or duricrust is common on Mars. Both Viking landers encountered crusty, cloddy, and blocky solid materials that are inferred to be cemented dust [*Christensen and Moore*, 1992]. *Fuller and Hargraves* [1978] noted that the shapes of some rocks at the Viking 1 lander site resembled eroded hardpan (a suggestive, but not compelling, argument). Thermal inertia measurements suggest that much of the Martian surface is hardened (indurated) [*Jakosky and Christensen*, 1986; *Christensen and Moore*, 1992]. Photogeologic analyses of some regions on Mars, notably Oxia Palus and Valles Marineris (east and west of Ares Vallis, respectively), suggest the presence of extensive hardpan horizons [*Presley and Arvidson*, 1988; *Treiman et al.*, 1995].

Hardpan in Valles Marineris

Layers similar to those in the Area Vallis region are present throughout the Valles Marineris region, an area of ~4000 × ~800 km immediately west of the Ares Vallis drainage, and were interpreted as hardpan layers by *Treiman et al.* [1995]. The easternmost exposure of these layers documented by *Treiman et al.* [1995] is ~600 km east of Iani Chaos (Figure 2), and similar layers are exposed in canyon and crater walls between Ares Vallis and Valles Marineris (Figure 1). *Treiman et al.* [1995] found that the tops of canyon walls throughout the Valles Marineris were underlain by a relatively uniform packet of

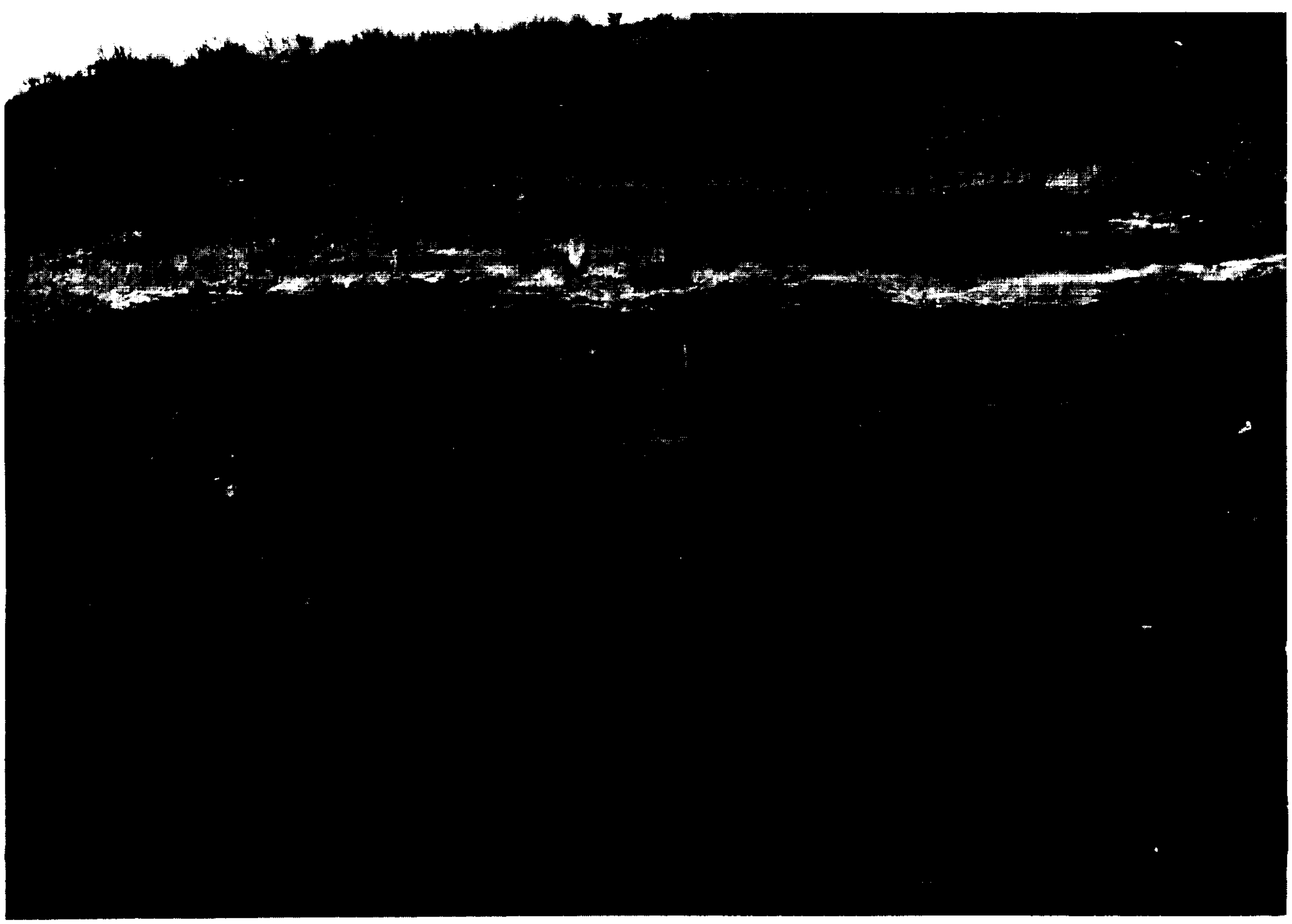

Figure 9. Hardpan layers developed in loess in the channeled scablands area of western Washington state; image taken during a field trip accompanying the Mars Pathfinder II Workshop. Hillside view is ~5 m tall. Light-colored and more resistant layers near the cliff top, each approximately 1 m thick, are soils indurated (hardened) by calcium carbonate.

physically resistant layers (Figure 10), consisting of alternating layers of differing albedo: dark, bright, and dark. In some reaches of canyon wall (with adequate imagery), the layer sequence could be followed continuously for 200-300 km. The total thickness of the layers range from 250 to 750 m, and the depth to the second dark layer (where visible) varies from about 200 to 400 m. The uppermost dark layer remains within 50 m of the land surface, even though the age of that surface ranges from Noachian in the east to mid-Hesperian in the west, and even though the surface elevation varies from +10 km to 0 km. In addition, the layers continue uninterrupted beneath at least one impact crater.

Considering the extent and continuity of the near-surface layer sequence, its constant topographic position, and its transgression of structural and time-stratigraphic markers, *Treiman et al.* [1995] concluded that the layer packet must have formed in place. The most likely mechanism for its formation in place was by cementation of preexisting rock and regolith, i.e., the layers are pedogenic hardpan horizons.

Hardpan in Ares Vallis

It seems reasonable, or at least permissible, to suggest that the near-surface layers exposed in the Ares Vallis region are a continuation of those exposed in the Valles Marineris. This inference relies on two observations: the near-identity of the near-surface layering exposed in Ares Vallis and in the Valles Marineris; and the fact that seemingly identical layering is exposed on cliff walls between Ares Vallis and Valles Marineris. It could well seem outrageous to correlate near-surface geologic units from the Valles Marineris to Ares Vallis, a distance of at least 800 km. Yet, the upper wall layer sequence in the Valles Marineris is exposed nearly continuously for ~4000 km E-W (Noctis Labyrinthus through Eos Chasma) [*Treiman et al.*, 1995]; at this scale, another 800 km extent seems small.

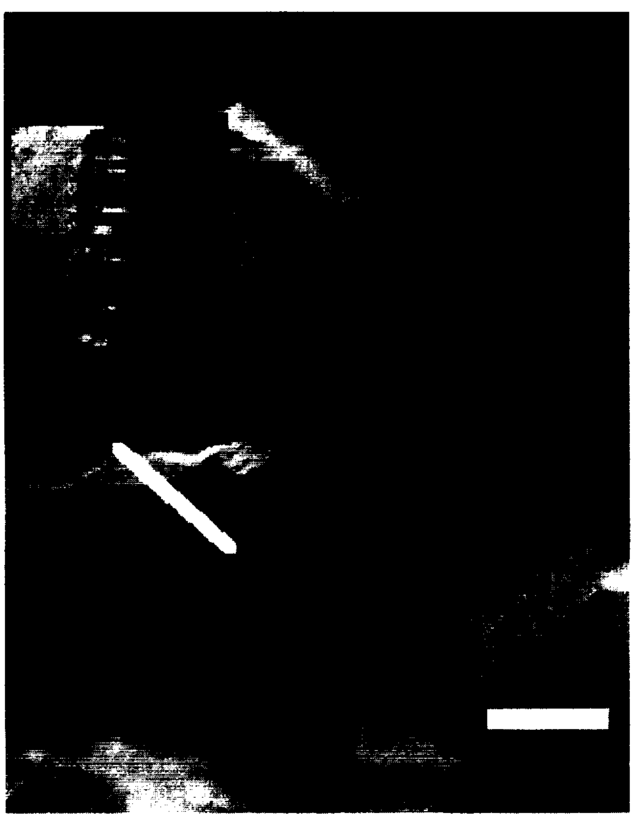

Figure 10. Near-surface layering in Valles Marineris, exposed in a collapse pit (~1.25 km deep) in western Noctis Labyrinthus, 15.9°S 104.7°W (from VO 915A06). Clear filter, north is up, scale bar 10 km. Inset is enhanced 2× enlargement of pit wall; note dark-bright-dark layers extending to channel floor. Top of lower dark layer is ~400 m below plateau surface.

First, the near-surface lithologic layering exposed in the Ares Vallis region is nearly identical to that exposed on the walls of the Valles Marineris. In both sequences, a dark layer is at (or nearly at) the ground surface, the surface dark layer is underlain by a bright layer and another dark layer, the lower dark layer is ~250 m below the ground surface, the layers are everywhere parallel to the ground surface, the layers appear to form steeper slopes than underlying units, and the layers cut across the time-stratigraphic boundary between Noachian and Hesperian age surface units. Of course, documentation of the layers is much better for the Valles Marineris than for Ares Vallis; high-resolution coverage of the Valles Marineris is superb and nearly complete.

Second, the near-surface layer sequence is exposed in many walls between the Valles Marineris and Ares Vallis (Figure 1). Although not figured here, horizontal near-surface layers, alternating dark and bright, of the same thickness and depth beneath the surface, are exposed in Ravi Vallis (VO 014A67), Shalbatana Vallis (VO 897A61), Simud Vallis (VO 897A85), and Hydraotes Chaos (VO 014A54, 083A04). Considering these exposures, the longest gap in coverage without exposures of the upper wall layers is ~400 km (between the sites of Figures 4 and 5). Compared to the 4000+ km extent of the upper wall layers in the Valles Marineris, this 400 km gap seems minor.

It remains only to consider the origin of the Ares Vallis layering in comparison to that exposed in the Valles Marineris. I have shown that the near-surface layering in the Ares Vallis region is nearly identical to that in the Valles Marineris, and have shown that layers like those in Valles Marineris are exposed between the Valles Marineris and Ares Vallis. It thus seems reasonable to consider the near-surface layers in Ares Vallis as an extension of those exposed in the Valles Marineris. In this case, one might infer a similar origin for the near-surface layering in the two areas, and so infer that the near-surface layers exposed in and near Ares Valles (as with those in the Valles Marineris) represent hardpan surfaces.

Implications for Mars Pathfinder

Material from the near-surface layers in the Ares Vallis region is likely to be a significant contributor to the rocks and soils that Mars Pathfinder will image and analyze. First, the near-surface layers are present throughout the Ares Vallis catchment (Figure 1), the source of fluvial sediment at the landing site. Second, the layers have been eroded from the walls of Ares Vallis and the streamlined islands, and must have been entrained in the flood(s) and transported (Figures 2-5). Third, the horizons are physically stronger than much of its surrounding materials; being stronger, they are more likely to be preserved as coherent fragments and coarse sediment in the landing site area.

In discussing the chemical composition of the near-surface layers and their implications for Mars Pathfinder, I will assume that the layers represent hardpan horizons, diagenetically formed in place from preexisting rock. It must be recognized here that diagenesis, including hardpan formation, requires the mobility of at least some chemical components, and the most likely mobilizing agent is liquid water. Thus *Treiman et al.* [1995] hypothesized that Martian climate must have been warm and humid enough at some time since the Hesperian to permit liquid water in the soil.

Understanding the chemical constitution of the hardpan cements is critical in interpreting them, should they be discovered among the sediments at the Mars Pathfinder landing site. Because so little is known about the compositions of surface units on Mars or about the average composition of the Martian highlands, the following discussion of the chemistry of the Ares Vallis hardpans relies heavily on analogy with terrestrial hardpans.

Light-Colored Hardpan

The mineralogy of the light-colored hardpan layers cannot be constrained tightly. On Earth, a wide range of light-colored or colorless minerals can be the primary cements in hardpans, and many of these minerals are found as weathering or alteration products in the Martian meteorites. Given the known abundances and availability of elements at the Martian surface, carbonates and/or sulfates of alkaline earth elements are the most likely cements in the light-colored hardpans.

Most desert hardpan horizons on Earth are cemented by alkaline earth carbonate minerals, principally calcium carbonate [*Petrov*, 1976; *Watson*, 1989]. Dolomite and magnesite hardpans are relatively uncommon. Carbonate hardpans are reasonable for Mars because carbon dioxide is available from the atmosphere, and alkaline earth carbonates are among the most abundant alteration minerals in the Martian meteorites. Calcite is present in the Martian alteration materials of most Martian meteorites [*Gooding*, 1992]; magnesite is also present in the Chassigny meteorite [*Wentworth and Gooding*, 1994]. ALH84001 contains percent levels of carbonates, including calcite, ferroan dolomite, ferroan magnesite, and nearly pure magnesite [*Mittlefehldt*, 1994; *Treiman*, 1995a; *Harvey and McSween*, 1995].

Hardpans cemented by sulfate minerals are fairly common on Earth, particularly in the most arid deserts [*Petrov*, 1976]. The most common hardpan sulfate is gypsum, but alkali and magnesium sulfate crusts occur rarely in evaporite basins. Sulfate hardpans seem reasonable for Mars because sulfur is abundant in the Martian dust [*Clark et al.*, 1982; *Banin et al.*, 1992] and because the dust clods at the Viking landing sites appear to have been cemented by a magnesium sulfate [*Clark and van Hart*, 1981]. Calcium sulfate is present in the Martian alteration materials of most Martian meteorites, and a magnesium sulfate is also present in the Nakhla meteorite [*Gooding*, 1992].

Other light-colored hardpan cements on Earth include silica, halides, and nitrates. Of these, only silica hardpans are widely distributed; the other minerals are too soluble to be retained long in any but the most arid deserts. Halides are inferred to be present in the martian dust [*Clark and van Hart*, 1981] and are also present sparingly in the Martian meteorites [*Gooding*, 1992]. Silica has also been reported from the ALH84001 Martian meteorite [*Harvey and McSween*, 1995], but has not been suggested as an independent geochemical component in the Martian soils [*Clark et al.*, 1982; *Banin et al.*, 1992].

Dark Hardpan

Iron-bearing minerals seem to be the only reasonable cements for the dark hardpan layers. Organic materials (which can accumulate in terrestrial soils) seem unlikely for Mars, and manganese minerals are probably not sufficiently abundant. Hematite has been suggested and a duricrust constituent in at least two areas on Mars, Lunae Planum and western Arabia, both relatively near the Ares Vallis region [*Presley and Arvidson*, 1988; *Christensen and Moore*, 1992; *Murchie and Mustard*, 1994; *Kirkland and Murchie*, 1995]. Iron-bearing minerals are also moderately common in the Martian alterations in the Martian meteorites. Magnetite, ferrihydrite, and ferroan clays are common in the nakhlite meteorites, iron-bearing "illitic" clay is found in EETA79001, siderite (iron carbonate) is present in the nakhlites, and Mg-Fe-Ca carbonates are relatively common in ALH84001 [*Gooding*, 1992; *Treiman et al.*, 1993; *Mittlefehldt*, 1994; *Harvey and McSween*, 1995; *Treiman*, 1995a].

However, most iron-rich hardpans (i.e., ferricretes) on Earth are residual soils, leached of most rock-forming elements by "...weathering and pedogenesis under humid, tropical conditions .... The ferricretes ... occurring in arid and semi-arid environments are relict" [*Watson*, 1989]. This model is probably not applicable to Mars. A possible scenario for dark hardpans on Mars is chemical reaction between Fe^{2+}-bearing groundwater and oxidized gas species diffusing from the surface. The reaction products might include ferrihydrite or other poorly crystalline ferric phase, which could then dehydrate to hematite [vis., *Carson and Schwertmann*, 1981; *Burns and Fisher*, 1993]. Another possible scenario is reaction of Fe^{2+}-bearing groundwater with atmospheric carbon dioxide to precipitate siderite. Subsequent reaction with oxidizing gas species could yield hematite. If the groundwater in the latter scenario also carried Mg^{2+}, the precipitated carbonates could be siderite-magnesite solid solutions, as are present in the Martian meteorite ALH84001 [*Mittlefehldt*, 1994; *Harvey and McSween*, 1995; *Treiman*, 1995a].

Recognizing Hardpan Lithologies

Hardpans rich in cementing minerals should be relatively easy to recognize with the Mars Pathfinder scientific instruments, if clean rock surfaces are visible and accessible. On uncoated surfaces, the albedo differences between different hardpans (Figures 2-8) should be obvious with the IMP camera on the lander [*Smith et al.*, 1995]. The cationic constituents of the cements should be readily detected by the X ray analyzer portion of the alpha proton X ray (APX) instrument on the rover [*Rieder et al.*, 1994]. Anionic constituents should be recognizable from both the X ray and backscattered α particle analyzers. Using the visible and near-IR spectral bands of the IMP camera, it should be possible to distinguish among many of the possible iron minerals in dark hardpans. Hardpans rich in cementing materials could likely be confused only with chemical sediments, like limestone or evaporitic gypsum deposits.

For hardpans containing relatively little cementing material, it should be equally easy to recognize the approximate composition of the cemented soil. For instance anorthositic, granitic, and basaltic (or palagonitic) soils could be readily distinguished by their abundances and/or abundance ratios of SiO_2, Al_2O_3, TiO_2, MgO, Na_2O, and K_2O; abundances of CaO and FeO are the most likely to be affected by hardpan cements. If analyses of a range of samples can be obtained, it may be possible to "unmix" the analyses into a soil contribution and a hardpan cement contribution.

However, detailed geochemical modeling of highland materials may be compromised by the presence of hardpan cements. For example, hematite cement in a basalt, if unaccounted for during interpretation of an APX analysis, would increase the basalt's apparent Fe/(Fe+Mg) ratio and decrease its apparent level of silica saturation. In concert, these effects will tend to suggest that the basalt is more primitive (less fractionated) than it actually is, and that its source mantle is more ferroan than it actually is. If a magnesian cement (e.g., magnesite or magnesium sulfate) were unaccounted for, the basalt will appear more primitive than in reality, and its source mantle will appear more magnesian. In either case, one might infer an incorrect mantle composition and thereby an incorrect size for the Martian core, etc. If a calcic cement (e.g., calcite or gypsum) in a basalt were not recognized, the basalt would appear to contain excess clinopyroxene and olivine, and perhaps be misclassified (e.g., as a nakhlite-related basalt rather than a shergottite-related basalt) [vis., *Longhi and Pan*, 1989; *Treiman*, 1993; *McSween*, 1994]. Misintepretations like these could lead to significant errors in understanding the highlands crust of Mars.

Acknowledgments. This work, first presented at the Mars Pathfinder II workshop in Spokane, Washington, builds on research by K. Fuks during a summer internship at the Lunar and Planetary Institute. I have been assisted by D. Reub, B. Fessler, K. Fuks, C. Howard, and R. Hurd. The Viking Orbiter Image Database from Malin Space Science Systems was particularly useful as a reference for image selections. Careful, thorough reviews by S. Clifford, P. Schenk, and two anonymous colleagues are greatly appreciated. Dedicated to the memory of Dannan Norman. Lunar and Planetary Institute contribution 893.

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(Received March 12, 1996; revised July 1, 1996; accepted August 1, 1996.)