Geology of central Chryse Planitia and the Viking 1 landing site: Implications for the Mars Pathfinder mission

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Abstract. 1:500,000-scale geologic mapping in the central Chryse Planitia region of Mars was correlated with "ground-truth" data gathered by the Viking 1 lander. Materials within the Chryse basin can be subdivided into plains and channel units that are typically separated from one another by gradational contacts. Hesperian Ridged plains materials, unit 1 (Hr1) are the oldest materials mapped. Typically, these materials contain numerous fresh impact craters and have sharply defined, mare-like wrinkle ridges similar to those appearing on the lunar maria. These materials grade into Hesperian Ridged plains materials, unit 2 (Hr2), which are characterized by buried and eroded impact craters and subdued wrinkle ridges. From analyses of crater age dates and their associated geologic contacts, channel materials appear to have formed at the same time as Hr2 materials, and it is likely both units represent fluvial sediments. Measurements of buried craters contained in Hr2 materials suggest that in places this unit may be ~50 m thick, but crater size-frequency distribution curves suggest that the areal average may be closer to ~170 m. Based on these observations, our interpretation is that Hr2 materials were deposited into a standing body of water during channel formation. This interpretation implies that many of the rocks visible in the Viking 1 lander images were emplaced by fluvial processes. Possibly, finer-grained sediments remained in suspension and were subsequently transported out of Chryse Planitia and into the northern plains during draining of the ponded water. East-west trending surface undulations, visible in lander views toward the south, may represent aeolian dunes, lava flow fronts, or sediment waves formed at the bottom of the standing body of water. Broad physiographic units seen at the surface are not clearly visible in Viking orbiter images; however, they can be projected at the resolution of the orbiter images. These units show that concentrations of drift materials are oriented in a northwesterly direction, contrary to the strongest prevailing wind direction which is toward the northeast. These materials were probably deposited on Ridged plains materials, unit 2, during a period of time when aeolian processes were more active in the region. Both Earth-based radar and Viking thermal data suggest that the Mars Pathfinder landing site will be similar geologically to the Viking 1 site. If this is true, then the Mars Pathfinder mission provides the opportunity for building directly on results of the Viking program. Some of the outstanding questions that Mars Pathfinder may be able to address include determining the aeolian modification history of the Chryse Planitia region, the degree and possibly the relative rate of sediment induration, the fraction of rocks and boulders emplaced by impact processes, the possibility that some materials are the result of in situ weathering, and whether materials were emplaced by fluvial processes and the associated depositional environment.

Introduction

In July of 1997, the first in what will hopefully be a series of missions will end a long hiatus of direct exploration of the martian surface. The Mars Pathfinder spacecraft will provide stereo color imaging, multispectral analyses, direct measurements
of elemental composition of geologic material, atmospheric
information, and meteorology monitoring. The landing site for
the Mars Pathfinder spacecraft is scheduled to be in Chryse
Planitia near the mouth of Ares and Tiu Valles (19.5°N, 32.8°W).
Because this area is only ~850 km southeast of the Viking 1
landing site, examination of rocks and terrain features contained
near these channels may potentially allow us to build directly
upon the knowledge gained by the Viking 1 lander. In order to do
this, however, it is important to first place the geology of the
Viking landing site into a regional context that accounts for our
collective, post-Viking views of Mars.

During the Viking mission, orbiter-based geologic maps of
Chryse Planitia were produced literally within hours after
receiving the data. A synthesis of these geologic maps was
presented by Greeley et al. [1977]. Several other investigators
also made brief descriptions of the regional geology of Chryse
Planitia when discussing the observed geology of the landing site
[e.g., Binder et al., 1977]. However, despite its importance, a
detailed analysis of the regional geology in the vicinity of the
lander and an exact correlation between the orbiter and lander
data has not been made. A major part of the problem was
determining the precise position of Viking Lander 1 (VL-1) on
the surface of Chryse Planitia during the primary mission. Later,
however, the location of VL-1 was determined confidently to
within 50 m [Morris and Jones, 1980]. Also, additional high-
resolution photographic coverage of central Chryse Planitia was
obtained following the successful landing of VL-1 (i.e., Viking
orbiter frames 452B1-16).

In this paper we present results from our 1:500,000-scale
mapping efforts of central Chryse Planitia and the Viking 1
landing site (Mars Transverse Mercator Maps 20047 and 25047;
Figure 1). Our objectives in attempting this large-scale map were
to: (1) correlate Viking orbiter images of central Chryse Planitia
with Viking lander "ground-truth" observations, (2) determine the
depositional and erosional history of the Chryse basin, (3)
determine how representative the surface materials observed by
the Viking lander are of the region and of plains units in general,
and (4) determine the extent of channel materials versus ridged
plains materials in the region. The results presented here are
important for understanding the observations and data obtained by
the Viking lander, understanding the mechanisms responsible for
rock formation and emplacement, determining the volatile history
of Mars and the mechanism of outflow channel formation, and
potentially in deciphering the relation between volcanism and
mapping efforts of central Chryse Planitia and the Viking 1
fluvial processes on Mars. Because the Pathfinder landing site is
~200-300 m lower in elevation than the Viking 1 landing site
and (4°-5°; [Haldemann et al., 1995]) or less than (4°-5°; [Haldemann et al., 1995])
the VL-1 site.

In addition to Earth-based radar measurements, Viking Infrared
Thermal Mapper (IRTM) data are also useful in assessing the
physical properties of martian surface materials. Particularly
useful is Christensen's [1986] block abundance model that
predicts the percentage of rocks on the surface from diurnal
variations in brightness temperatures. From these data, Edgett

Background

Chryse Planitia is an extensive, semicircular basin centered at
approximately 25°N, 40°W (Figure 2). At a maximum depth of
more than 3 km below the mean Martian datum, it is one of the
lowest regions on Mars (topography from the U.S. Geological
Survey [1976]), suggesting that it may be an ancient impact basin
[Schultz et al., 1982]. The boundary separating the southern
cratered highlands from the northern smooth plains borders most
of Chryse Planitia, but unlike other areas on Mars the transition
across the "dichotomy" boundary in this region is not marked by a
sharp change in elevation. The boundary has, however, been
incised by most of the large outflow channels, including Kasei
and Maja Valles to the west and Shabatana, Simud, Tiu, and Ares
Valles to the south.

Site Selection

On the morning of July 20, 1976, Viking 1 became the first
spacecraft to land successfully on the surface of Mars. From
Mariner 9 data Chryse Planitia had been selected as the primary
site for this first landing several years earlier; however, the actual
targeted site was not certified until the Viking 1 spacecraft had
been in orbit for several weeks. The preselected Chryse Planitia
landing site at 19.5°N, 34.0°W was rejected when Viking images
indicated that this area had been heavily eroded by both fluvial
processes and wind stripping and it also contained volcanic
terrain. All of these processes were thought to generate surface
features that could be hazardous to a safe landing [Masursky and
Crabill, 1981]. In addition, Earth-based radar data suggested that
the surface might be too rough [Tyler et al., 1976]. The landing
site was reselected for the central portion of the Chryse basin
(22.4°N, 47.5°W) 3 km below Mars datum where it was assumed
that the regional gradient caused deposition rather than erosion
from the large circum-Chryse outflow channel complex
[Masursky and Crabill, 1981]. Earth-based radar data, an
important consideration in the Viking landing site certification,
also showed reflectivity of 5-10%, which is close to the martian
average [Tyler et al., 1976]. These data strengthened the
interpretation that the selected site did not have unusually
abundant roughness at a scale not resolvable from orbit.

Ironically, the preselected, and subsequently rejected, Viking
landing site at 19.5°N, 34.0°W is now essentially the primary site
for Mars Pathfinder (19.5°N, 32.8°W). However, this site meets
both the elevation (<0 km) and the latitude constraints (0°N to
30°N) placed on the Pathfinder spacecraft. Golombek et al.
[1995a] also point out that only one Viking-era Earth-based radar
track actually has a subradar point within the Pathfinder landing
eclipse, and these data have a low signal to noise ratio [Downs et
al., 1978]. Additional Earth-based radar measurements were
made during the 1995 opposition in support of the Pathfinder
mission. These new data suggest that the Pathfinder landing site
is ~200-300 m lower in elevation than the Viking 1 landing site
[Haldemann et al., 1995; Harmon and Campbell, 1995] with an
RMS slope about equal to (~6°-7°; [Harmon and Campbell, 1995;
Slade et al., 1995]) or less than (4°-5°; [Haldemann et al., 1995])
the VL-1 site.
Figure 1. Photomosaic of Mars Transverse Mercator Maps 20047 and 25047. Area shown is between 17.5° and 27.5° latitude and between 45° and 50° longitude. Approximate location of the Viking 1 Lander is indicated by a cross.

[1995] has determined that the thermal inertia within the Pathfinder landing site ranges from 9.8 to 12.9 x 10^{-3} \text{cal cm}^{-2} \text{s}^{-0.5} \text{K}^{-1} in comparison to the Viking 1 measurement of 8.5 x 10^{-3} \text{cal cm}^{-2} \text{s}^{-0.5} \text{K}^{-1} [Christensen and Kieffer, 1979]. He has also determined a rock abundance of 18 to 25\pm5\% within the Pathfinder landing ellipse, which is also slightly higher than the estimate of -15\pm5\% for Viking 1 [Christensen, 1982]. Although both radar and thermal data indicate that the Pathfinder landing site will be safe, they also suggest that the two landing sites will be geologically similar.

Previous Geologic Investigations

Mariner 9 based analysis of Chryse Planitia showed that surfaces within the basin are relatively smooth and sparsely cratered. These interior terranes were interpreted to be volcanic in origin [Milton, 1974], or possibly containing some fluvial sediments, especially in southern Chryse Planitia [Wilhelms, 1976]. This interpretation apparently changed little during evaluation of Viking orbiter data for certification of the VL-1 landing site: Greeley et al. [1977] report the smooth plains of
Chryse Planitia to be composed of a thin discontinuous veneer of sediments superposed on volcanically derived materials. Subsequently, other investigators have described the general region surrounding the Viking 1 landing site as resembling the lunar mare with a similar type of volcanic origin [Binder et al., 1977; Arvidson et al., 1989].

Interpretations of the geology of the Viking 1 landing site differ widely. It has been suggested that the blocks observed in VL-1 images (Plate 1; Figure 3) are the result of in situ weathering of basaltic materials [Mutch et al., 1976a; Binder et al., 1977; Garvin et al., 1981], ejecta emplaced by local impact craters [Garvin et al., 1981; Sharp and Malin, 1984; Arvidson et al., 1989], or possibly fluvial deposits from the circum-Chryse basin outflow channels [Mutch et al., 1976a; Mutch and Jones, 1978]. Although the VL-1 site was chosen as an area where fluvial deposition (as opposed to erosion) most likely occurred [Masursky and Crabill, 1976], this interpretation is not strongly advocated by most investigators. This is important to note because the Mars Pathfinder landing site has also been suggested as an area where fluvial deposition may have occurred as well [Kuzmin et al., 1994; Golombek et al., this issue]. Its value as a "grab-bag" site is reduced if the material near the mouth of Ares

Figure 2. Photomosaic of the Chryse Planitia region of Mars. Area presented in Figure 1 is outlined and the Mars Pathfinder landing ellipse (MPF) is marked. Note location of the outflow channels and their proximity to the area investigated.
Plate 1. Color photomosaic of the Drifts and Moderately rocky physiographic units shown in plan view in Figure 7. Figure 3 shows plate outline and provides labels to principal features and physiographic units (original digital mosaic courtesy of Mary Dale-Bannister).
Numerous geologic units were identified during the mapping; however, only those units essential to a discussion of the broad geologic history of Chryse Planitia are presented here. The oldest principal materials in the area are Hesperian in age. Noachian materials are not exposed, although degraded and buried impact craters may have excavated into underlying Noachian materials. Chryse Planitia is thought to be the result of a giant impact [Schultz et al., 1982], as is Acidalia Planitia immediately to the north [Schultz and Frey, 1990]. Presumably the Chryse and Acidalia basins formed during the early to middle Noachian near the peak of heavy bombardment on Mars (~4.0 Gyr; Tanaka [1986]). This suggests that all the units within the map area overlap highly fractured crustal rock.

The oldest exposed unit in the map area is the Hesperian ridged plains materials, unit 1 (Hr1). Hesperian ridged plains materials, unit 2 (Hr2) is the most extensive unit identified in the map area. Both units are characterized by numerous linear to sinuous wrinkle ridges collectively named Xanthe Dorsa. Ridged plains materials in Hesperia Planum, which have similar crater abundances (i.e., relative ages) and morphological characteristics as units Hr1 and Hr2, are the referent for the Hesperian period on Mars [Scott and Carr, 1978; Tanaka, 1986]. Unit Hr1 is distinguished from unit Hr2 by relative crater abundances (Figure 4; Table 1), frequency of ridges, and degree of modification to the ridges. The ridges on both units are morphologically similar to lunar mare-ridges and are interpreted to be the result of regional compressional strains in a competent, layered surface unit. The Xanthe Dorsa ridges trend predominantly north-south as opposed to being circumferential to the Chryse basin, which is in contrast to the occurrence of lunar mare-ridges. This suggests that basin subsidence was not the mechanism for Xanthe Dorsa formation, again in contrast to the origin suggested for most lunar ridges [Maxwell et al., 1975]. Phillips and Ivis [1979] and Phillips et al. [1990] demonstrated the possibility that compressional stresses in the Chryse Planitia region were caused by variations in the gravity and topography associated with the formation of Tharsis. Amazonian/Hesperian channel materials (AHeh) occur east of Kasei Maja Valles and are separated from ridged plains materials, unit 2 (Hr2) by a gradational contact hundreds of kilometers long. These units are distinguished by small (hundreds of meters), parallel channels that seem to have initiated at topographic highs and which anastomose around preexisting topography such as wrinkle ridges and impact crater rims. These units probably represent the late-stage erosional incision associated with the large-scale fluvial outwash into the topographic low of the Chryse basin. Hesperian channel materials (Heh) are characterized by arcuate, streamlined mounds located behind topographic features. These may represent large channel deposits or channel modification of high-standing ridges. A Hesperian age is inferred for this unit based on superposition relationships; they represent an area too small for accurate crater statistics.

Crater size-frequency distribution curves (Figure 4; Table 1) for the Amazonian/Hesperian channel materials in the map area suggest that the formation of Maja Valles (south material) pre-dates the formation of Kasei Valles (north material). Crater counts of channel materials from Maja Valles indicate an age of N[2] = 690±218 (Upper Hesperian) versus 276±92 (Lower Amazonian) for Kasei Valles materials. Ridged plains materials, unit 2 (Hr2) have an age of N[2] = 466±79 (Upper Hesperian), which suggests that this unit was emplaced after the formation of Maja Valles but before the formation of Kasei Valles. However, the crater curve for the Kasei Valles materials also includes eroded or modified impact craters. It is therefore possible that the difference in age between the two groups of channel materials may actually be a reflection of the intensity of the channeling process (i.e., the formation of Maja Valles may have removed more impact craters in the map area through burial or erosion than the formation of Kasei Valles).
Carr et al. [1987] calculated that as much as $6.3 \times 10^6 \text{ km}^3$ of water may have been released into the Chryse basin during formation of the circum-Chryse outflow channel complex. This is equivalent to a global layer ~44 m deep [Carr, 1987]. The consequence of such a catastrophic discharge of water has recently led several investigators to speculate on the possibility of lacustrine basins [Scott et al., 1992] and even large oceans contained in the northern hemisphere of Mars [Parker et al., 1989, 1993; Baker et al., 1991]. Scott et al. [1992] state that the presence of channels within and peripheral to the basin, an etched basin floor, concentric ridges, polygonal outlines, and smooth,
Figure 4. Crater size-frequency distribution curves for principal units in the map area. The squares represent fresh lunar-like impact craters, triangles represent fresh rampart craters, and the circles represent eroded impact craters. Amazonian/Hesperian channel materials (AHch) are plotted separately to show age differences. According to the crater density boundaries designated by Tanaka [1986], Kasei Valles materials (AHch, north) are Amazonian in age, and Maja Valles materials (AHch, south) are Hesperian in age (Table 1). Mapped as the same unit based on physiographic similarities, the two are thus considered Amazonian/Hesperian in age.

Table 1. Relative Ages of Geologic Materials in the Central Chryse Planitia Region

<table>
<thead>
<tr>
<th>Unit</th>
<th>N(2)</th>
<th>N(5)</th>
<th>N(16)</th>
<th>Area, km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ridged plains materials, unit 1 (Hr₁)</td>
<td>1004±157</td>
<td>244±77</td>
<td>-60</td>
<td>40,833</td>
</tr>
<tr>
<td>Ridged plains materials, unit 2 (Hr₂)</td>
<td>466±79</td>
<td>-160</td>
<td>-13</td>
<td>75,133</td>
</tr>
<tr>
<td>Amazonian/Hesperian channel materials (AHch), north (Kasei Valles)</td>
<td>276±92</td>
<td>-</td>
<td>-</td>
<td>32,629</td>
</tr>
<tr>
<td>Amazonian/Hesperian channel materials (AHch), south (Maja Valles)</td>
<td>690±218</td>
<td>-</td>
<td>-</td>
<td>15,932</td>
</tr>
</tbody>
</table>

N(x) = number of craters ≥x km diameter per 10⁶ km².
infilled crater floors suggest that water was contained as a lake within the Chryse basin. Parker et al. [1993] also cite numerous lines of evidence suggesting standing water within Chryse. They present evidence for backfilling and slack-water deposition within the Chryse basin and surrounding outflow channels: features interpreted as streamlined hills and channel banks appear smooth and rounded, suggesting that water overtopped these structures and "drowned" them; lobate, high-albedo deposits superficially resemble terrestrial turbidite fan lobes; and channel fissures (i.e., polygonal outlines) in northern Chryse and central Acidalia Planitiae suggest subsequent desiccation of water-rich sedimentary deposits. The scenario they present is one where the catastrophic release of water into Chryse Planitia quickly exceeded the rate at which water could flow into the northern plains. The water level rose quickly, causing a headward transgression of the base level and locus of sediment deposition. Presumably, preexisting but inactive channels would have also been partially inundated. Such a scenario would not have allowed a depositional center to remain steady for a long period, thus explaining the lack of obvious deltaic deposits associated with any of the large outflow channels.

Smooth, rounded hills and terraces exist in the map area (Figure 1), as well as in the Mars Pathfinder landing site area [Golombek et al., 1995b]. Such features also suggest a similar "drowning" effect from channel waters. The large crater Guaymas (20 km in diameter; 26.2°N, 44.8°W) also appears to have been affected by fluvial processes. The southern edge of its ejecta blanket has been heavily eroded (Figure 5). Providing the local slope increases toward the north near the crater, then a standing body of water ~100 m deep would be sufficient to partially erode this crater's ejecta given its diameter. Because this crater is superposed on Ridged plains materials, unit 2 and is only partially eroded there appears to have been multiple episodes of channel deposition and flooding within the Chryse basin, which is a likely scenario based on crater counts of the circum-Chryse channels [Rotto and Tanaka, 1991; Rotto, 1992; Tanaka, 1995]. Multiple flooding events may also help explain the apparent lack of shoreline features observed elsewhere along the martian dichotomy boundary [Parker et al., 1989, 1993]. A base level would have oscillated with the intensity of the flooding event, and deposition during high-intensity events would have buried shorelines which may have formed during low-intensity events. Because they are so fragile, any remaining shorelines were probably eroded by later aeolian processes (discussed below).

Greeley et al. [1977] described additional, partially eroded craters in western Chryse Planitia, which support multiple channel-
forming episodes for the Lunae Planum outflow channel complex (i.e., Vedra, Maumee, Bahram, and Maja Valles). These particular craters, along with erosional features from the Lunae Planum outflow channels in western Chryse Planitia, may have been preserved because they are at an elevation that is too high (greater than -1 km elevation; Plate 3) to have been affected by even the most intense late channel-forming event.

A Case for Basin Sedimentary Deposits

Martian wrinkle ridges are morphologically similar to lunar mare ridges. Numerous investigators have suggested that, like the units in which the lunar mare ridges occur, the ridged plains material in central Chryse Planitia (Hr1 and Hr2) are also volcanic in origin [Mutch et al., 1976a; Binder et al., 1977; Carr et al., 1976; Greeley et al., 1977; Mutch and Jones, 1978; Theilig and Greeley, 1979; Arvidson et al., 1989]. However, despite the high resolution of available images (<10 m/pixel), primary volcanic features such as flow fronts or vents have not been observed. As an answer, Binder et al. [1977] suggested a very low viscosity lava incapable of forming a flow front observable from orbit or, alternatively, the original relief became degraded. However, the interpretation of the ridged plains in Chryse as volcanic in origin cannot be supported without additional geologic evidence. As pointed out by Watters [1988] wrinkle ridges can also form in sedimentary materials, thus the presence of lunar mare-like ridges does not preclude the possibility of extensive fluvial deposits within central Chryse Planitia.

Materials in Chryse Planitia are located at one of the lowest elevations on the planet (approximately -2.5 km below Mars datum; topography from the U.S. Geological Survey [1977, 1992]) and are surrounded by a large outflow channel complex. Chryse Planitia was certified as the Viking I landing site based on the reasoning that some channel materials (presumably smooth) were in the Chryse basin [Masursky and Crabill, 1981]. Carr et al. [1987] calculated that 5.89x10^6 km^3 of material was eroded from the circum-Chryse highlands during channel formation, which suggests that a fluvial deposit ~4 km thick should be present throughout Chryse Planitia (assuming a radius of Chryse Planitia of ~700 km). They estimated that over 36.9 x 10^4 km^3 of material was removed by the formation of Kasei Valles alone. Available digital topographic data [U.S. Geological Survey, 1992] show a topographically high lobe of material (i.e., a blue "tongue" in Plate 3) extending from the mouth of Kasei Valles into Chryse Planitia. In addition, other investigators have suggested that large volumes of standing water were contained in Chryse Planitia during the Hesperian [Carr, 1986; Carr et al., 1987; Scott and Tanaka, 1986; Scott et al., 1992]. Although channel deposits are not obvious (both depositional and erosional fluvial units contain many of the same features), logic dictates that materials of fluvial origin must be located within the Chryse basin.

It is especially probable that Ridged plains materials, unit 2 (Hr2) is a fluvial deposit. The wrinkle ridges within this unit have a noticeable subdued appearance (e.g., compare wrinkle ridges in Viking orbiter frame 20A89 with those in 54A39) suggesting burial and subsequent tectonic deformation by a long-lived compressional stress regime in the region. The contact between Ridged plains materials, unit 2 and channel materials is gradational. As suggested by Masursky et al. [1980] and Scott et al. [1992, Figure 1], Ridged plains materials, unit 2 also appear to follow a topographic "trough" into Acidalia Planitia to the north (Plate 3), which would be the likely path of water released into the Chryse basin. Finally, several partially buried craters are present along the southern contact of this unit, which also suggests a sedimentary origin (Figure 6; Plate 2, dotted circles).

Analysis of the buried and modified craters in Ridged plains materials, unit 2 yields possible information about this unit's spatial distribution. Using Pike and Davis' [1984] equations for fresh martian craters, the rim heights for the buried craters (2.3-11.3 km in diameter) were calculated. These values were then compared to the actual rim heights measured from shadow lengths. Commonly referred to as the "DeHon technique," because he was the first to apply this method to determine the

Figure 6. Partially buried impact craters (arrows) south of the Viking 1 location. Crater rim height equations [Pike and Davis, 1984] and shadow measurements indicate that >50 m of material was deposited within the Ridged plains materials, unit 2 (Hr2) in this region (Viking orbiter photographs 20A70, 20A83-91, and 897A22).
we subtracted the rim heights of buried craters from their predicted, unmodified values to determine the possible thickness of these materials. From these data it appears that Ridged plains materials, unit 2 are ~50 m thick along its southern contact and possibly become thicker towards the basin interior. Basin-ward thickening is probable because the sharp bend-over in the size-frequency distribution curve at 5-km-diameter (Figure 4) suggests that most craters smaller than this diameter were eradicated during the emplacement of the unit. In order to remove these craters by burial, the Ridged plains materials, unit 2 would have to have a mean thickness of ~170 m.

We conclude that unit Hr2 consists of deposits from the formation of the circum-Chryse outflow channels. Wrinkle ridges alone do not provide the definitive morphologic criteria of a geologic unit's volcanic origin. The low elevation, the number of channels surrounding the Chryse basin, and the subdued texture of many of the geologic units and morphologic features suggest the probability that fluvial sedimentary deposits are present in Chryse Planitia. As originally suggested by Mutch et al. [1976a], and described below, some materials observed by the Viking 1 lander may also be fluvial in origin.

Geology of the Viking 1 Landing Site and the View From Orbit

Geology of the Landing Site

The Viking 1 lander is located within Ridged plains material, unit 2 (Hr2; Plate 2). Based on triangulation of topographic features visible in lander images with those seen in high resolution (~8 m/pixel) Viking orbiter images, the precise location of the lander was originally determined to be latitude 22.483°, longitude 47.968°, or line 293, sample 1099 in Viking orbiter frame 452B11 (NGF Rectilinear) (Fig. 7; [Morris and Jones, 1980]). The precise geographic coordinates changed in 1983 to 22.480°N, 47.962°W with an updated control network of Mars [Davies and Katayama, 1983]; however, the exact location of the lander within Viking orbiter frame 452B11 did not change. This location is estimated to be accurate to within 50 m [Morris and Jones, 1980] and is important for correlating the surface units seen in lander images to the regional geology described previously. This exercise also illustrates the importance of the high-resolution images within the Pathfinder landing ellipse. Once the spacecraft has successfully landed, these data will be useful in placing the lander into a local geologic context. These data will also likely become critical in planning Sojourner's traverses.

Several impact craters hundreds of meters in diameter are near the Viking 1 Lander and are plainly visible in the lander images [Morris and Jones, 1980]. The most prominent feature besides impact craters is a wrinkle ridge of the Xanthe Dorsa system, located ~500 m to the east of the lander and extending to the north. A portion of this ridge is visible from the lander between azimuths 72° and 90° relative to north [Morris and Jones, 1980]. A less obvious feature visible from the lander is a depression seen between azimuths 182° and 244°. This depression can be seen from orbit in Viking orbiter frame 452B11 as an area between two ridges just south of the lander (Figure 7). Analysis of stereo images suggests that the southern depression is not unique. Due north and due south of the lander, a series of undulations a few tens of centimeters high can be seen (Figure 8). These undulations are not apparent in the east or west directions and suggest a series of low amplitude "ridges" that run east-west. Such fine-scale, low-amplitude features are not visible in the...
A

B

Figure 8. Two stereo views of the Viking 1 landing site showing undulating topography. The Rocky physiographic unit (see Figure 7) is predominantly featured in both views. (a) Figure centered at ~170° south (Viking lander images 11B037, left, and 12A212, right). (b) Figure centered at ~190° south (Viking lander images 12A211, left, and 11B036, right). Both figures indicate that the undulation crests trend in an east-west direction. These undulations may be the result of sand ripples, lava flow fronts, or sediment waves. Arrow on Figure 8b, left (Viking 1 Lander image 12A211) points to a putative bedrock outcrop. Based on geologic mapping we interpret this to be Ridged plains materials, unit 1 (Hr1) appearing as a window (i.e., fenster) in Ridged plains materials, unit 2 (Hr2). Local thinning of Hr2 materials was probably caused by a preexisting ridge of the Xanthe Dorsa system (Figure 7). Outcrops such as this are too small to be mapped at either the 1:500,000 scale or at the scale of the physiographic map presented in Figure 7; however, larger occurrences of such materials may occur throughout the Chryse basin. If such features do represent volcanic materials from the base of the Hesperian (i.e., Hr1 materials), they are potentially the most important samples to obtain and date from a future surface mission (see discussion by Craddock [1992]).

High-resolution (~8 m/pixel) Viking orbiter frames (Figure 7). This rolling topography may represent sand ripples from aeolian processes, volcanic flow fronts, or ripples or large sediment waves from fluvial processes. The resolution of available Viking orbiter images is at the threshold of allowing detailed mapping and correlation to be made with lander images. Presently, however, mapping of fine-scale features seen by the Viking lander will have to wait for data comparable to those of the Mars Global Surveyor camera.

There are several surface units seen by the Viking 1 Lander of sufficient scale to be mapped on Viking orbiter images. These physiographic units can be separated based on the amount of loose, wind-blown drift material contained between the rocks on
Plate 3. Regional topographic map of the Viking 1 and Mars Pathfinder landing sites. Note that the topography is slightly higher in the western portion of the map near Lunae Planum, suggesting that features formed by Maja Valles channeling episodes were elevated enough not to have been modified by later, more intense flooding events from other channels. Note also the topographic depression connecting the Chryse and Acidalia basins and the direction where flood waters may have eventually drained (white arrow). Black arrows point to a slight topographic "tongue" that might represent high-standing deposits probably emplaced from Kasei Valles flooding (data from U.S. Geological Survey [1992]).
crusty to cloddy material described by the Viking Lander team [e.g., Moore et al., 1987] are at a scale much too small to be mapped at Viking orbiter image resolution. These materials are incorporated in both the Moderately rocky and Rocky units.

Although it is apparent from Figure 7 that physiographic units visible by the Viking 1 lander are not clearly distinguishable in high-resolution images, placing the local geology into a regional context illustrates several important points. (1) It provides us with a physical description and an idea of the spatial variation of at least one geologic unit on Mars (Hr2). It should be possible to produce a true geologic map based on compositional and spectral data at the Mars Pathfinder landing site. (2) From a stationary spacecraft with a vantage point approximately equivalent to that of a person standing on the surface, it is possible to roughly characterize an area of about 4 to 9 km². It will be interesting to compare this result with those obtained by Mars Pathfinder and, perhaps more importantly, Sojourner. Although Sojourner will have the vantage point of only a few centimeters above the ground, its maneuverability has the potential of providing information for an even broader area than Viking. (3) Although observations made by the Viking lander agree in general with the remote sensing data [Christensen, 1982; Jakosky and Christensen, 1986a], the diverse physiographic units identified by the lander have actually provided the information necessary for interpreting the remote sensing data. For example, the presence of case-hardened crust (often erroneously referred to as duricrust [Sharp and Malin, 1984]) observed in some surface materials (i.e., the Rocky and Moderately Rocky units) is a possible mechanism for creating higher thermal inertia materials [Jakosky and Christensen, 1986b]. Had the Viking landers come down in a place that was dominated by low thermal inertia, high-albedo materials, we probably would not have the appreciation of the importance of case-hardened crust on Mars. The possible ubiquitous extent of case-hardened crust is illustrated by the physiographic map and the occurrence of the Rocky and Moderately Rocky units where the crust was found (Figure 7).

Remote sensing data suggest that both the Viking 1 and Pathfinder landing sites are similar, although the Pathfinder landing site may have slightly more rocks and a lower albedo [Edgett, 1995; Edgett and Christensen, this issue]. It was initially argued by Edgett et al. [1994] that Pathfinder should land in an area more representative of the remote sensing end members, primarily because it appears that both Viking landers landed in "anomalous regions" [Jakosky and Christensen, 1986a]. However, the variety of surface materials observed by the Viking 1 lander is analogous to a "grab bag" for remote sensing data, and it is very likely that the Pathfinder site will be as well. This is more useful than a simple end member site in that it will provide a more robust test of the accuracy of existing remote sensing models.

Possible Origins of the Rocks

Essentially, the Viking 1 lander is sitting on Ridged plains material, unit 2 (Hr2; Plate 2), and, from the orbiter-based geology, the physiographic units seen by the lander (Figure 7) are likely modified components of this unit. Based on surface texture and apparent vesicles, the rocks visible in lander images are thought to be predominantly basaltic [Mutch et al., 1976a; Binder et al., 1977; Garvin et al., 1981; Sharp and Malin, 1984] in composition. Jones et al. [1979] and Sharp and Malin [1984] also make the case that some of the rocks at the Viking 1 landing site may be breccias of impact or volcanic origin. Arguments were presented above as to why the Ridged plains material, unit 2 (Hr2) is likely sedimentary. However, the origin of the rocks seen by the Viking 1 lander is a contentious issue. Multiple modes of emplacement for the rocks, which are observed in both the Rocky and Moderately rocky units, have been suggested. The mechanisms most frequently cited in the literature are in situ weathering of lava flows [Mutch et al., 1976a; Binder et al., 1977; Garvin et al., 1981] and ejecta fragments emplaced by local impact craters [Garvin et al., 1981; Sharp and Malin, 1984; Arvidson et al., 1989]. Because impact breccias represent most of the returned Apollo samples [e.g., Taylor et al., 1991] and there are obviously impact craters near the Viking lander, it seems inarguable that at least some fraction of the rocks were generated by impact processes. However, compared to images of the lunar surface the entire population of rocks at either of the Viking landing sites appears to be too high and uniformly distributed across the surface to have been emplaced entirely by impact processes. Thus, it is probable that at least one other process was involved.

A useful characteristic for determining sediment emplacement processes is the size distribution of material. Although several different attempts have been made at quantifying this value [Garvin et al., 1981; Moore et al., 1987; Moore and Keller, 1990; Golombek and Rapp, 1995; Golombek et al., this issue] the results consistently point out the fact that the size distributions of rocks are different between the two landing sites. Garvin et al. [1981] suggest that the exposure ages may be different between the two sites and this may have affected the distribution of rock sizes. However, both the Viking 1 lander unit (Hr2) and the Viking 2 lander unit (Hesperian Vastitas Borealis Formation, Knobby member, HvK [Greeley and Guest, 1987]) are the same relative age based on geologic mapping. This implies that the size distributions may actually reflect different emplacement processes or, alternatively, multiple emplacement processes that were working to varying degrees between the two sites. Garvin et al. [1981] made an additional effort to characterize the Viking rock populations by their shape. The roundness and sphericity of a rock or smaller particle can be used in a general way to infer something about the duration of transport and reworking. Roundness is typically more useful for environmental interpretations [Tucker, 1981, p. 17], and sphericity can be used to estimate the relative distance a particle travels [Krumbein and Sloss, 1963, p. 110]. Based on the average sphericity (0.63) of the rocks at the Viking landing sites, Garvin et al. [1981] stated emphatically that they were not emplaced by fluvial processes. Typical sphericity values for basalt pebbles and cobbles (16 to 256 mm in diameter) deposited through fluvial processes (i.e., in a river) are > 0.65 (76% confidence [Dobkins and Folk, 1970]). Sphericity values for individual river localities, however, range from 0.64 to 0.72 [Dobkins and Folk, 1970], which is close to their measured value and really within their margin of error. Making accurate measurements of the rocks seen by the Viking landers is not easy to do, primarily because at best only two of the
three axes can be measured within any degree of certainty: the short axis, which the rock naturally rests on, and the axis that is most close to being perpendicular to the lander cameras.

Given the present level of uncertainty, it does not seem reasonable to rule out the possibility that some of the rocks seen by Viking 1 were emplaced by fluvial processes. Again, the results of our mapping effort indicate that the Viking 1 spacecraft is resting on sedimentary material. Because of their close proximity to the landing site and young age, Kasei and/or Maja Valles are likely sources for the rocks. If this is true, then the rocks would have been derived from the Lunae Planum plateau, which is thought to be composed of flood basalts based on a variety of observations [Plescia and Golombek, 1986; Craddock and Maxwell, 1991; Watters, 1991; Tanaka and Chapman, 1992], leading to the basaltic composition inferred from the appearance of the rocks [Mutch et al., 1976a; Binder et al., 1977; Jones et al., 1979; Garvin et al., 1981; Sharp and Malin, 1984]. The Viking lander is situated near the axis of a wrinkle ridge so that materials interpreted to be bedrock outcrops (Figure 8b) [Mutch et al., 1976a,b; Binder et al., 1977; Jones et al., 1979; Sharp and Malin, 1984; Moore et al., 1987; Arvidson et al., 1989] may represent Ridged plains material, unit 1 (Hr1) which were not buried by channel deposits (i.e., Hr2 materials) or which have been subsequently exhumed by aeolian erosion. Some of the rocks visible may be the result of in situ weathering of Ridged plains material, unit 1. The inference in either case is that Hr2 materials vary considerably in thickness (from negligible to tens of meters) across Chryse Planitia, similar to the interpretation of Greeley et al. [1977].

Although the rock shape measurements of Garvin et al. [1981] are not conclusive, more accurate and perhaps more definitive measurements can be made at the Mars Pathfinder landing. The perspective offered by Sojourner will be useful for determining the precise shapes of rocks in a large area around the Mars Pathfinder spacecraft. However, prior to the mission, it is important to develop diagnostic characteristics for separating the emplacement mechanism for a rock by its shape. The Dobkins and Folk [1970] template used by Garvin et al. [1981] only describes rocks in a river or beach environment, and this may not be applicable to the rocks and boulders observed by Mars Pathfinder. Templates describing the diagnostic shapes of rocks emplaced by in situ weathering as well as a wider variety of fluvial and sedimentary processes need to be devised. An additional benefit that will also be provided by Mars Pathfinder is the compositional and spectral information that may be helpful in distinguishing rocks derived from different sources. Using the Viking 1 analogy it may actually be possible to separate rocks deposited as Hr2 material versus those that were emplaced by in situ weathering of Hr1 material during the Mars Pathfinder mission.

**Surficial Materials**

Fine-grained materials occur between rocks in the Rocky unit, blanket rocks in the Moderately rocky unit, and occur as contiguous deposits in the Drift materials. Because remote sensing data indicate that the Viking 1 landing site has an anomalously high albedo in relation to its thermal inertia when compared to the planetary average, a microns-thick layer of bright dust may be blanketing the entire area [Jakosky and Christensen, 1986b], a suggestion supported by Viking trenching operations [Moore et al., 1987]. Subsequently, however, lander color images suggest that this deposit was removed by local aeolian processes following the two global dust storms observed by Viking [Guinness et al., 1979]. The origin of the Drift materials is less speculative than the rocks as their shapes, possible exposed cross-bedding, ripples, lee-side tails, and basal scours are evidence for wind-blown material [Mutch et al., 1976a,b; Binder et al., 1977; Sharp and Malin, 1984; Moore et al., 1987; Arvidson et al., 1989]. However, the scoured appearance of the drifts, the presence of exposed layering, the cap of fine-grained material on top of Big Joe, and the lack of noticeable growth of the drifts during the Viking mission have led investigators to suggest that at present the drifts are undergoing deflation [Mutch et al., 1976a, b; Binder et al., 1977; Arvidson et al., 1979; 1989]. Thus, the drifts appear to represent an older period of aeolian deposition.

The strong cohesiveness of the drifts (1-2 kPa derived from sample trenches [Moore et al., 1987]), their scoured appearance, the failure of steep slopes, and exposed cross-bedding indicate that the drifts are loosely bonded, perhaps similarly to the case-hardened crust observed in the surrounding soil [Jones et al., 1979]. In this issue, Rice and Edgett [this issue] suggest the possibility that the drifts at the Viking 1 landing site are composed of remnant fines deposited during the waning stages of outflow floods. This hypothesis, however, is untenable when local superposition relations are considered. The drifts are deposited on top of everything, including materials ejected from surrounding impact craters. Because many of these craters are relatively small (tens of meters), they must have formed well after catastrophic flooding occurred and sedimentary material was emplaced. If the drifts are primary sedimentary features, then they should be at least partially blanketed by crater ejecta.

Recognizing the probability that the martian drifts are inactive aeolian features, Arvidson et al. [1979] suggested that they may be on the order of 15,000 years old corresponding to the time interval during which the sub-solar point at perihelion precessed from the latitude of the landing site to its current location. Since the orbital plane of Mars precesses with a period of ~7,000 years [Ward, 1992], it follows that Chryse Planitia (i.e., Ridged plains materials, unit 2 and perhaps unit 1 as well) are periodically blanketed by aeolian materials, which then migrate across the basin floor. Subsequently, these aeolian materials become inactive and, perhaps, loosely bonded when conditions change to those observed presently. As suggested by Moore et al. [1987], current seasonal and diurnal changes in martian atmospheric conditions may occasionally remove the agent that binds the drift material, in part, causing slopes to fail in places.

Possibly, aeolian weathering of the Drift material could be due to a change in the prevailing wind direction with time. The orientation of the Drift material (Figure 7) appears to be predominantly in a northwesterly direction, suggesting that the prevailing winds were also in this direction when the drifts were deposited. In contrast, the current direction of the strongest prevailing winds (7 m s⁻¹) measured by Viking 1 are currently north to northeast [Hess et al., 1977]. This observation is also supported by the NNE orientation of wind streaks in the map area.
crater located at 23.12 \degree N, 48.68 \degree W, or approximately 50.5 km northwest of the Viking landing site. Based on the observed position of the Viking 1 lander [Morris and Jones, 1980], this crater is at an azimuth of 318 \degree from Mars' north and should occupy 9.0 \degree of angular width along the horizon. Lexington is a 5.0-km-diameter blocky ejecta crater located at 22.05 \degree N, 48.65 \degree W approximately 41.7 km southwest of the landing site at an azimuth of 233.5 \degree from Mars' north and having an angular width of 6.9 \degree along the horizon. The immediate problem with viewing objects at these distances from the lander is the curvature of Mars. If Mars is considered to be a perfect sphere with a radius of 3389.32 km [Davies and Katayama, 1983] and negligible atmospheric refraction, at the nominal height of the Viking lander cameras (1.3 m [Liebes and Schwartz, 1977]) the distance at which an object on Mars can be seen by the Viking landers is 2.97 km. However, this does not take the height of the object or the local topography into account. Including these considerations, the distance at which an object can be seen before disappearing below the horizon (d) is

\[
d = (R + r) \sin q_1 + 2.97 \text{ km}
\]

where \(R\) is the radius of the planet, \(r\) is the height of the object, and \(q_1\) is the angle between the apparent horizon for the observer and the object measured from the center of the planet. This significantly increases the distance over which objects can be viewed.

Rim height estimates for Yorktown and Lexington were made using equations from Pike and Davis [1984]. Elevation differences between the base of the crater rims and the landing site were determined from U.S. Geological Survey [1976, 1977] topographic data. The rim of Yorktown is -480 m above the elevation of the Viking 1 lander and should be visible up to 60.17 km away. Likewise, the rim of Lexington is -380 m above the elevation of the Viking 1 lander and should be visible up to 53.82 km away. Examination of Viking 1 lander photographs show that distinct features are visible at the predicted locations of both craters (Figure 9).

Symmetrical mounds centered in the direction anticipated for Yorktown crater subtend 8.9 \degree of azimuth (to the nearest 0.1 \degree), the left part of which may be obscured by a small crater closer to the lander (Figure 9a). These measurements retain the precision of the Viking lander cameras [Patterson et al., 1977] and compare well to the predicted arc of 9.0 \degree for the visible crater rim. Of particular importance is the height of these mounds. The visible (or apparent) height of the crater rim above the horizon can be calculated from the equations

\[
q_2 = \tan^{-1}(d_m - 2.97/R)
\]

\[
r_e = (R/\cos q_2) - R = R((1/\cos q_2) - 1)
\]
Figure 9. The craters (a) Yorktown (Viking lander image 12A165) and (b) Lexington (Viking lander image 12A237) as imaged by the Viking 1 lander. Arrows point to the crater rims.
where $q_2$ is the angle between the observer's horizon and the object, $d_m$ is the measured cartographic distance from the observer to the object, and $r_b$ is the amount of object obscured by the curvature of the planet. From these equations, 200 m, or approximately 75% of the total rim height of Yorktown, should be visible from the Viking 1 lander. This translates into an angular height of 0.42°; however, only a maximum value of 0.15° can be measured for the mounds from lander photographs. Partial obstruction of the crater rim by another topographic feature in the field of view seems likely.

Equations (2) and (3) indicate that all the crater rim of Lexington (-190 m) and perhaps some of the surrounding terrain should be visible at the location of the Viking 1 lander. A subtle feature is visible in the predicted location of Lexington (Figure 9b). Binder et al. [1977] suggested that this object was a ridge; however, it occupies most of the predicted angular width for Lexington crater before being obscured by local topography (5.0° versus 6.9°), and it is centered at the predicted location of Lexington. This feature possesses a distinct albedo difference with the foreground and is truncated sharply to the left, suggesting that it is not related to a ridge of the Xanthe Dorsa complex. It has a measured angular height of 0.21° versus a predicted 0.28°, suggesting that, like Yorktown, a portion of the crater rim is being obscured by intervening topographic obstacles. In either case, such topographic obstacles would only need to be ~100 m high somewhere between these craters and the lander to account for the observed discrepancies. Ridges of the Xanthe Dorsa system are at the right amplitude, occur between each crater, and thus make logical candidates for features to produce partial crater obstruction. Locating Yorktown and Lexington in Viking lander images extends the distance over which features can be seen from the surface by an order of magnitude and improves confidence in the Lander 1 position determined by Morris and Jones [1980]. Given that the proposed Mars Pathfinder landing site is in the vicinity of the mouths of Ares and Tiu Valles, many tall (hundreds of meters) streamlined hills, and several large impact structures, it is probable that the view across the plains of Chryse Planitia from this location will be more exciting than anything seen thus far on Mars.

Geologic History of Central Chryse Planitia

The geologic history of central Chryse Planitia and the Viking 1 Landing Site

The geologic history of central Chryse Planitia and the Viking 1 landing site (Plate 4) can be summarized as follows.

The formation of the Chryse Planitia depression occurred during the Noachian, probably as the result of a giant impact [Schultz et al., 1982]. The northern rim of this basin was excavated when the Acidalia Planitia basin was formed, probably also as a result of a giant impact [Schultz and Frey, 1990]. The intersection of these two basins, or the resulting overlap in topography, produced a large trough connecting Chryse Planitia to the plains to the north.

Emplacement of the Ridged plains materials, unit 1 (Hrl) occurred during the early Hesperian. These materials are seen primarily in southern Chryse Planitia, as windows (i.e., fensters) in the central portion of the basin, and possibly as bedrock outcrops in lander images (Figure 8b). Because they predate most of the other material in the region, their exact extent is uncertain. Morphologically, they are very similar to ridged plains materials seen elsewhere on Mars. Crater size-frequency distribution curves indicate that they are also identical in age to the ridged plains materials in Lunae Planum bordering Chryse Planitia, immediately to the west of the basin. The Ridged plains, unit 1 probably represent flood lavas extruded through deep-seated faults associated with the formation of the Chryse Planitia impact basin, or alternatively, they may represent fluvial sediments from early channel forming events. The sharply defined wrinkle ridges (and superposed ridges in channel materials) suggest that regardless of lithology, these materials have been subjected to a compressional stress regime that was stable for a long period of time (early Hesperian through at least the middle Amazonian).

During the late Hesperian, Maja Valles formed. These channels cut volcanic material from Lunae Planum and carried the sediments into Chryse Planitia, debouching them into the lowest portions of the basin. Perhaps as much as 62,500 km$^3$ of water was released during the formation of these channels [DeHon and Pani, 1993]. This water may have formed a standing body several hundred meters deep in the Chryse basin. Formation of the circum-Chryse outflow channels to the south probably occurred soon after the Maja Valles event(s). The volume of water within Chryse probably exceeded the ~1 km topographic contour line and flowed northward into Acidalia Planitia.

Kasei Valles was the last outflow channel to have debouched into Chryse Planitia in the vicinity of the Viking 1 lander based on limited crater counts. The outflow events occurred during the late Hesperian through the early Amazonian. At times, sediments released during the flooding episodes may have debouched into a preexisting standing body of water, which could have caused the sediments to spread out due to density differences between the flood and the standing water (i.e., hypopycnal flow). Large particles were deposited onto the Chryse floor, which might be visible as the rocks and boulders in the Viking 1 lander images. Most of the fine-grained material remained suspended and may have been transported to far distances, probably into the northern plains. Whether the water released through channel formation was contained as a lake in the Chryse basin [Scott et al., 1992], or whether it fed into an ocean in the northern lowlands [Parker et al., 1989, 1993; Baker et al., 1991] cannot be resolved by features in the map area. It does not appear likely, however, that circum-Chryse channels could have fed the proposed "Oceanus Borealis" during the Amazonian, but they could have supported smaller bodies of water as suggested by Baker et al. [1991]. Crater size-frequency distribution curves (Figure 4, Table 1) indicate that much of the channeling had probably waned by the late Hesperian.

Crater size-frequency distribution curves presented in Figure 4 indicate that Maja Valles are older than Kasei Valles, suggesting that back-filling and deposition of materials eroded by Kasei were placed onto Maja Valles deposits. This could explain why channel scour does not extend to the Viking 1 landing site. Alternatively, Maja Valles may have debouched into a small standing body of water from an older channeling event; possibly water from the Vedra, Maume, and Bahram Valles channel-forming events, which pre-date Maja Valles [Theilig and Greeley, 1979]. Again, back-filling would prevent erosional features from being preserved and deltaic deposits from developing.
Plate 4. Cross sections showing the geologic history of the central Chryse Planitia region and the Viking 1 landing site. Topography based on a south to north profile taken at ~40° longitude [U.S. Geological Survey, 1992]. Cross sections are oldest to youngest, top to bottom; shown vertically exaggerated.
Throughout the Amazonian to the present, aeolian activity has been the dominant geologic process operating in Chryse Planitia. However, the indurated nature of many of the large aeolian drifts and their oblique orientation to the prevailing wind direction suggest that aeolian processes in Chryse Planitia has changed over recent geologic history. Due to precession of the martian orbital plane, aeolian deposition and mass transport of materials across the Ridged plains units may have intensified when the subsolar point last coincided with Mars perihelion at the latitude of the Viking 1 Lander (~15,000 years ago [Arvidson et al., 1979]). As conditions changed to those observed at present, drifts may have become loosely cemented. Currently these features are now being slowly modified.

Implications for Mars Pathfinder

Because of its proximity to the Ares Vallis landing site, the geology of the Viking 1 landing site has several important implications for the Mars Pathfinder mission. First, and perhaps most important, remote sensing data provides us with the confidence in knowing what the geologic environment will be on the surface ahead of time. Earth-based radar and thermal infrared data of the Pathfinder landing site suggest that this area will have slightly more rocks than the Viking I landing site and a lower overall albedo [Edgett, 1995]. In general, however, the surficial geology of both landing sites should be similar, primarily because both are located in the same region of Mars. If this is found to be the case, then the observed surficial geology could be effectively applied to a broad area of Mars. Identification of physiographic units such as Drift material at the Pathfinder landing site would imply that these materials are widespread and located across the Chryse basin. On the other hand, if the Pathfinder landing site appears to be extremely different, then it would imply that a variety of processes operated at different intensities within a small area on Mars. This later scenario could also have profound influences on future missions to the surface.

Although large-scale geologic mapping suggests that the Viking 1 site is located on a fluvial deposit, it is still reasonably uncertain as to what the emplacement mechanism was for the rocks observed by the lander. This is in spite of the fact that the Viking 1 landing site was chosen because of its proximity to several large outflow channels! Determining the emplacement mechanisms for rocks observed at the Mars Pathfinder landing site may also be problematic. Prior to the mission, it will be important to develop a series of templates relying on a rock's angularity and sphericity that will aid investigators in determining the likelihood of a rock being emplaced by either in situ weathering, impact cratering, or fluvial processes. The necessity for doing this increases when the probability that most rocks will be dust covered is considered: spectrally, all rocks may look the same to the IMP camera. The only mechanism for separating locally derived rocks from those brought in from great distances through fluvial transport may be based on the general shape of the rocks.

**Figure 10.** Models for the relative ages of the martian epochs: Amazonian (A), Hesperian (H), and Noachian (N). Model 1 represents the absolute ages for the epochs determined by Neukum and Wise [1976] and model 2 is based on Hartmann et al. [1981]. A sample returned from either an Amazonian or Noachian age unit during a future mission would not allow the accuracy of either model to be determined because of the overlap in the ages of these epochs. A sample of Hesperian bedrock, which was observed at Viking 1 and may be observed again with Mars Pathfinder, would allow the accuracy of the models to be checked because age of this epoch does not overlap. Data in figure are based on Tanaka [1986] and modified from Craddock [1992].
We have demonstrated the possibility that large objects such as impact craters may be visible up to 50 km away from the Viking 1 lander. Because the Pathfinder landing site is situated at an elevation that is hundreds of meters lower than Viking 1 [Haldemann et al., 1995; Harmon and Campbell, 1995] the capability of seeing objects in the distance is enhanced. Although this seems counterintuitive, it is analogous to having a better view of the bleachers by being on the field at a football stadium (Equations (1), (2), and (3)). It may be possible to obtain spectral information from crater rims or outflow channel terraces using the IMP camera, which would increase our understanding of the geology of southern Chryse Planitia to a regional scale.

Finally, one of the most important geologic materials Mars Pathfinder may observe is potential bedrock outcrops (Figure 8b), which were thought to have been observed at Viking 1 [Mutch et al., 1976a,b; Bender et al., 1977; Moore et al., 1987; Arvidson et al, 1989]. From the mapping effort presented here we have interpreted these materials as representing underlying Hesperian ridged plains, unit 1 that are essentially the same age as materials used as the referent for the Hesperian period [Tanaka, 1986]. Finding potential bedrock outcrops at the Mars Pathfinder landing site would not only allow us to determine if these materials are indeed bedrock, but it would also suggest that such materials are commonly found throughout the Chryse basin. Obtaining a radiometric age for these materials, which will probably only be possible through a sample return mission now planned for the next century, would provide us with the framework for determining relative ages for all the other geologic units on Mars. The reasoning for this statement becomes clear from Figure 10. The absolute ages of the martian epochs have been determined from two different estimates of the cratering flux. Essentially, the model of Neukum and Wise [1976] suggests that the period of heavy bombardment was short-lived, which implies that the Noachian and Hesperian were relatively short intervals in martian history. Conversely, the Hartmann et al. [1981] model suggests that the period of heavy bombardment was a long event, implying that the Noachian and Hesperian were longer intervals of time as well. In either model the Amazonian and Noachian epochs overlap, so a sample returned from these units would provide inconclusive age dates for determining which model is accurate. The Hesperian epoch, however, does not overlap between models, and a sample of Hesperian materials would establish the accuracy of either model. If potential bedrock outcrops are also found at the Mars Pathfinder landing site, then perhaps Chryse Planitia should be considered yet again for another mission to the martian surface.

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