Geologic Setting of Diverse Volcanic Materials in Northern Elysium Planitia, Mars

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INTRODUCTION

For more than a decade, analyses of the Viking Orbiter image data set have revealed the diversity of volcanic materials on Mars from scales ranging from <1 km to >1000s km. Global mapping at 1:25M (Scott and Carr, 1978) and 1:15M (Scott and Tanaka, 1986; Greeley and Guest, 1987), as well as numerous regional geological studies at 1:2M, have motivated detailed mapping at 1:500K under NASA's Mars Geologic Mappers Program in order to resolve local geologic relationships. One of several areas identified as important to the interpretation of the volcanic history of Mars is northern Elysium Planitia. Materials resulting from both lava-producing and explosive volcanic eruptions are believed to exist here (Mouginis-Mark et al., 1982, 1984; K. L. Tanaka, M. G. Chapman, and D. H. Scott, unpublished data, 1989), as well as the products of complex interactions between volcanic materials and subsurface volatiles (Mouginis-Mark, 1985). To the west and north of the volcano Hecates Tholus, numerous lava flows from Elysium Mons, collapse features, plains units, and possible melt water deposits have been identified by these mapping efforts. In addition, the morphology of Hecates Tholus indicates that explosive volcanism (rather than the eruption of lava flows) most likely dominated the eruptive history of the volcano (Mouginis-Mark et al., 1982); many valley networks and the absence of well-preserved lava flows make this volcano significantly different from those found within the Tharsis region (cf. Carr et al., 1977a).

By virtue of the variety of volcanic materials northern Elysium should be considered as a candidate landing site for a future Mars rover mission. Only by the in situ investigation of surface phenomena, and by the return of samples to Earth for dating and petrologic study, can details of the emplacement processes and chronology be resolved (Gooding et al., 1989). This study therefore presents the geologic objectives that such a rover mission to northern Elysium Planitia would address. The goals of this mission would be (1) to provide an age for plains materials that are sufficiently extensive that crater size/frequency curves derived from orbital data can be absolutely calibrated, (2) to permit petrologic studies of Elysium Mons lava flows, (3) the geologic interpretation of materials that may either be lava flows or lahar deposits, (4) to study the physical properties (the degree of cementation and particle size distribution of the surface, stratigraphic relationships, and microtopography) of the volcano Hecates Tholus in order to better define its eruptive history, and (5) to study stratigraphic sections of the boundary scarp that separates Elysium Mons lava flows from the northern plains.

ASSUMED ROVER CAPABILITIES

For the purpose of this investigation, it is assumed that the rover will land at the same locality as the sample return mission and that selected samples can be returned to Earth in addition to the rover performing in situ investigations. Alternative configurations have also been discussed (Blanchard et al., 1985; Mars Study Team, 1987; Gooding et al., 1989), but these configurations would not significantly affect the science objectives as they are described here, provided that the rover landed within ~10 km of the sample return vehicle. In this analysis the rover is assumed to have the following capabilities:

1. The spacecraft will have the ability to land a roving vehicle within a target ellipse approximately 10 x 6 km in size.

As with the site selection procedure for the Viking Landers (Masterson and Greybill, 1976a,b), possible hazards within the landing site ellipse are considered here to be either craters and their ejecta blankets, steep slopes, or areas of differential erosion (stripping, mantling, and texturing). From the analysis of 40 m/pixel Viking Orbiter images, it is assumed that areas that are free of resolvable impact craters and other hazardous features represent "safe" landing sites. However, as has been shown by the analysis of Viking Lander images (cf. Mutch et al., 1977; Garvin et al., 1981) and the interpretation of very high resolution orbital images (Zimbelman, 1987), the morphology of Mars appears to be very different at the 50 m/pixel, 10 m/pixel, and centimeter-scales. It is thus likely that...
Fig. 1. (a) Overview of the proposed rover traverse site in northern Elysium Planitia. Proposed landing site is marked by a star, and the six science stations are numbered 1 through 6. Portion of U.S. Geological Survey photomosaic MTM 35212. Width of image equivalent to 190 km, north is to the top. (b) Geologic map of the proposed rover traverse site in northern Elysium Planitia (area shown is the same as that in a). Unit abbreviations are as follows: "HT" — Hecates Tholus, "Fu" — undifferentiated flows, "F1" — lobate flows, "Np" — Northern Plains materials, "LIB" — upper fractured boundary materials, "LIB" — lower fractured boundary materials, and "Ce" — crater ejecta. Rim crests of meteorite craters are marked by barbed circles.
candidate landing sites will have to come under greater scrutiny for more detailed site selection during the Mars Observer (MO) Mission, when such sites could be imaged at a resolution of ~1.5 m with the MO high-resolution camera.

2. A key aspect of the mission would be the return to Earth of at least three selected samples that are obtained from documented in situ localities. The rover must therefore be capable of visiting suitable localities identified either from orbit or from terminal-descent imaging. It is assumed here that each of these sample localities may be up to 10 km from the return of the samplecraft. An extended surface traverse will begin once the collected samples are placed within the sample return vehicle.

3. The rover vehicle must have a range capability of ~200 km over surfaces expected to locally possess a few meters of vertical relief (i.e., comparable to the topography on terrestrial aa and pahoehoe flows; B. Campbell, S. H. Zisk, and P. Mouginis-Mark, unpublished data, 1989) and have boulders populations comparable to those seen at the Viking Lander sites (Garvin et al., 1981). The rover will also have the ability to climb (or descend) slopes of ~2°-3° for traverses perhaps 10-15 km in horizontal extent and to communicate directly with Earth (i.e., there will be no need for the rover to communicate with Earth via the landing craft). An alternative way to achieve this goal is for the rover to communicate with Earth via a Mars-orbiting relay station (Mars Study Team, 1987).

4. The instrument complement of the rover will depend upon the specific mission science requirements, but, as discussed by Singer (1988), it should carry suitable instruments that will enable it both to navigate across the martian surface and to perform sample identification. For the proposed northern Elysium traverse the minimum capabilities and payload of the rover would comprise: (1) an onboard computer that has sufficient artificial intelligence to permit terrain navigation without frequent delays due to the round-trip time involved with communications with Earth (Solar System Exploration Committee, 1986, pp. 226-227); (2) a video camera system (probably stereographic) for terrain navigation; (3) an imaging spectrometer that has moderate-to-high-spectral resolution for mineral characterization and sample selection with a spatial resolution sufficient to identify individual rock samples and, preferably, mineral grains at close proximity; (4) a drill capable of obtaining unweathered samples from rock outcrops; (5) a surface sample that will be able to conduct trenching experiments comparable to those by the Viking Landers (Moore et al., 1982) to enable the investigation of materials at depths of 10-20 cm beneath the surface; (6) a gravimeter for measuring local gravity anomalies; and (7) an active seismic experiment for the investigation of shallow crustal structure (within ~5 km of the surface) along the rover traverse.

The life expectancy of the rover is not defined as part of this analysis, but it is presumed that the vehicle will have the ability to operate for a sufficient duration on the martian surface to complete the traverse. The traverse described here is ~165 km in length, and science investigations at each station would involve drilling, sampling, and imaging, so that a one Earth year life expectancy should be planned for the rover. Assuming 10 hours of traverse time per martian day, and two days spent at each science station and the landing site (including three visits to return samples), the rover would have to travel at a mean speed of ~50 m/hour when traversing the martian surface.

**THE LANDING SITE**

The landing site chosen for this study is located at 33.0°N, 212.4°W and is devoid of meteorite craters larger than ~300 m in diameter (Fig. 1). Although no good estimates of absolute elevation exist for this site, the elevation is believed to be about 5 km (U.S. Geological Survey Map F-1120, 1978). However, stereogrammetrically derived data for the area surrounding Elysium Mons (Blasius and Qualls, 1981) show that the elevation of the proposed landing site may be less than 3 km above the 6.1 mb mean Mars datum [Earth-based radar topography data of Downs et al. (1982) can be used to provide an absolute reference datum for the stereographically derived elevation]. In addition to representing a safe landing site, the primary criterion for selecting this landing site is the collection and return to Earth of a sample of the plains materials that underlie the lobate lava flows from northern Elysium Mons. The plains materials are interpreted to be undifferentiated lava flows of Lower Amazonian age that form part of the Elysium formation (Unit Ael1 of Greeley and Guest, 1987) and have a crater frequency of ~250 craters larger than 2-km diameter per 106 km2. Because these Unit Ael1 flows cover a large portion of Elysium Planitia, obtaining a sample would enable an absolute age-calibration point to be added to the crater-frequency curves that are currently used to interpret relative martian ages (Neukum and Hiller, 1981; Albee, 1988). Neukum (1988) has argued that it is particularly important to obtain an absolute age for Lower Amazonian to Lower Hesperian materials, because these materials evidently were erupted during a transition from a decaying crater flux to a steady-state crater flux. Determining the radiometric age for Lower Amazonian samples may thus aid in the determination of the absolute age of the inflection point in the martian cratering rate, thereby defining much of the absolute chronology for the planet.

**GEOLGIC OBJECTIVES**

In order to define the range of volcanic materials in northern Elysium, six science stations have been investigated via analysis of the 30-50 m/pixel Viking Orbiter images of this area. The geologic objectives at each station are as follows.

**Station 1**

Seven kilometers to the east of the landing site is a prominent lobate lava flow that appears to have been erupted from the northern flanks of Elysium Mons (Fig. 2). This flow can be traced for ~150 km toward the summit of Elysium Mons before Viking Orbiter image resolution is insufficient to resolve individual flow lobes. This lava flow is one of many
such flows associated with Elysium Mons (and other martian volcanoes) that are very long compared to terrestrial examples (e.g., Wood, 1984; Cattermole, 1987). The reason these flows are so long is poorly known. By analogy with lava flows on Earth, martian flows may attain such a size due to high effusion rate (Walker, 1973), mafic chemistry and its effects on flow viscosity (Cattermole, 1987), or other flow properties such as their propensity to form tube-fed flows (Greeley, 1987a). Additionally, super-elevated eruption temperatures similar to those inferred for terrestrial komatiites (Basaltic Volcanism Study Project, 1981) may lead to high effusion rates. A returned sample from this lava flow thus not only would provide an age date for the late-stage eruptions of Elysium Mons, but also would permit the geochemistry of such long-runout lava flows to be investigated. It is expected that the collected sample from Station 1 would be returned to the ascent vehicle prior to visiting Station 2, in order to minimize mission loss should the rover fail during the visit to Station 2.

**Station 2**

This station is located 8 km to the west of the landing site where there is an unusual low-relief flow that does not appear to be a lava flow based on its subdued morphology (Fig. 2). Such flows not only lack lobate edges and the rugged surface texture of lava flows on Mars (Theilig and Greeley, 1986) but are also evidently thinner than the lava flows in this area. Mouginis-Mark (1985) proposed that these unusual flows are similar to Icelandic jökulhlaups, produced by the release of sediment-laden melt water by the interaction of magma and layers of ground ice.

There is increasing morphologic evidence that interactions between magma and subsurface volatiles took place over an extended period of martian geologic history (Allen, 1979; Mouginis-Mark, 1985; Squyres et al., 1987). Mouginis-Mark (1985) hypothesized that within northern Elysium Planitia this release of melt water may have been related to late-stage...
Fig. 3. Station 3 (located at 33.37°N, 211.12°W) is at the boundary between Hecates Tholus (lower right) and the undifferentiated lava flows from Elysium Mons. This station is key to identifying the relative age of the channel systems that are found on Hecates Tholus; channel deposits on the plains would indicate a relatively recent period of erosion long after the formation of the volcano and would considerably extend the time over which the volcano may have been active. Station 3 (located at 33.30°N, 210.93°W) is located on the flanks of Hecates Tholus, at a location where the lack of major channels would permit the rover to ascend and descend the flanks. Either drill core or trenching experiments could be performed at this location in order to investigate the possible explosively derived origin of these volcanic materials. Viking Orbiter frame 86A38, resolution 38 m/pixel. Image width is equivalent to 40 km and north is to the top.
intrusive events rather than the emplacement of lava flows at
the surface (i.e., comparable to events hypothesized to occur
in other areas of Mars by Squyres et al., 1987), and so the
age of the jokulhalou deposits may be considerably younger
than the adjacent lava flows. The goals for collecting and
returning to Earth a sample from Site 2 are therefore: (1) to
identify the process by which the flow was emplaced,
specifically distinguishing (via visual observations made from
the rover's video camera) between a volcanic origin and a
chaotic debris flow produced by volcano/ground-ice interac-
tions; and (2) to obtain a relative age determination for
this material (via an analysis of the degree of development
of weathering rinds on materials within the jokulhalou deposit
and the adjacent lava flows) to see how recently the
hypothesized subsurface volatiles may have been released to
the surface. Should the material at Station 2 indeed prove to
be related to melt-water release, obtaining an age estimate for
the clays and/or other fine particles expected to be within the
jokulhalou deposit would help constrain the polerward
migration of subsurface volatiles and the probable depth of ice
as a function of geologic time (as modeled by Fanale et al.,
1986). The sample from Station 2 would also be returned to
the ascent vehicle prior to the rover starting the traverse to
Station 3. It is assumed that after the collection of samples from
the landing site, Station 1, and Station 2 the return stage of the
lander would begin its return to Earth while the rover initiates
a more far-ranging exploration of the region.

Station 3
Two scientific sites are located on the northwest flank of
the volcano Hecates Tholus (Fig. 3), which lies ~80 km
northeast of the landing site. Of particularly scientific interest
at Station 3 would be the analysis of materials that are expected
to lie at the distal ends of numerous digitate channels that are
very numerous on all flanks of the volcano. Although the lower
slopes of the Hecates Tholus edifice are embayed by Elysium
Mons lava flows, these channels are of uncertain age and origin
and thus could have formed after emplacement of the lavas.
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ignimbrites and lahar deposits (Guest et al., 1988); cross-bedded surge deposits were found to be
associated with variable thicknesses of ignimbrites (analogs to
the volcanic debris avalanches described by Reimers and Komar (1979), while lahars (water-laden flows) tended to fill
preexisting depressions and have relatively uniform thickness in
longitudinal section. In addition, terrestrial lahars (and probably
marchian examples, too) may be distinguished from
other volcaniclastic and fluvial deposits by a greater abundance
of clay-sized particles and the presence of extremely large
boulders (Fisher and Schmincke, 1984, pp. 307-311). Water-
carved channels are expected to have fine-grained lacustrine
deposits at the margins of the flows. In the case of the Elysium
examples, morphologic evidence for late (post-Elysium Mons
flows) channel formation on the flanks of the volcano
would be particularly important to search for with the rover.
If such evidence were found, this would imply that volatile
release took place from Hecates Tholus in the relatively recent
history of Mars (i.e., postdating the age of the lava flows
sampled at the landing site).

Station 4
Hecates Tholus has a basal diameter of ~190 km, and is
believed to rise ~6 km above the surrounding plain (Hord et
al., 1974). The science objective at Station 4 is primarily to
investigate the origin of the materials on the flanks of the
highland paterae. In order to access Station 4, the rover must
be able to ascend and descend slopes of 3-4 degrees for a
distance of ~5 km (Fig. 3). Although the physical strength of
the flanks is unknown, it is likely that the volcano's surface
materials are less consolidated than the adjacent Elysium Mons
lava flows, as the flanks appear to be relatively easy to erode
and have permitted the formation of numerous digitate
channels. Thus, although vehicle traction and surface gullying
on these slopes may reduce the ability of the rover to reach
Station 4, it is likely that the flanks of Hecates Tholus are
probably sufficiently consolidated to support a rover as no
evidence of wind erosion of friable materials (e.g., yardangs)
can be found on the flanks.

Hecates Tholus is comparable to Hadrira, Tyrrhena, and
Apollinaris Paterae in that each of these volcanoes have
channelized flanks but lack any lobate lava flows (Reimers
and Komar, 1979). It has been proposed by Mouginis-Mark et al.
(1982) that Hecates Tholus experienced numerous explosive
(plinian) eruptions that produced flanks comprised of ash
deposits rather than lava flows. Similar models for the early
histories of the volcanoes Tyrrhena Patera (Greeley and Spudis,
1981) and Alba Patera (Mouginis-Mark et al., 1988) have also
been proposed. Rover investigations of the physical properties
of the flank deposits of Hecates Tholus, particularly studies
that involve the use of a trenches tool to dig a few tens of
centimeters beneath the surface of a (possible) duricrust layer,
would help resolve a crucial issue pertaining to the diversity
between these types of deposits will depend upon analyses of
the grain size distribution, thickness, and detailed stratigraphy
within the deposits. Comparable facies studies have been
conducted on Monti Vulturii Volcano, Italy, to discriminate
between the ignimbrites and lahar deposits (Guest et al.,
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release took place from Hecates Tholus in the relatively recent
history of Mars (i.e., postdating the age of the lava flows
sampled at the landing site).
Fig. 4. Station 5 (33.84°N, 210.88°W) is selected to provide sampling opportunities for the analysis of the isolated masses that characterize the northern plains in Utopia Planitia. Currently unresolved is the issue of whether these masses are remnants of a once more regionally extensive cap-rock of Elysium Mons lava flows or, alternatively, basement materials that have now been almost completely buried by sediments within the northern plains. Viking Orbiter image 86A39, resolution 38 m/pixel. Image width is equivalent to 40 km and north is to the top.
of styles of volcanic eruptions on Mars. If the flanks of Hecates Tholus were indeed produced by plinian eruptions as proposed by Mouginis-Mark et al. (1982), then layers of ash deposits should be found, thereby indicating that the early volcanic history of Mars was significantly different from the activity that characterized the late-stage (Amazonian) lava-producing eruptions on the Tharsis shield volcanoes (Carr et al., 1977a; Scott and Tanaka, 1986). Alternative interpretations for the Hecates Tholus flank deposits include pyroclastic flows [as hypothesized for Alba Patera (Mouginis-Mark et al., 1988), which would also imply explosive volcanic eruptions] or, possibly, hydrothermally altered lava flows.

A separate issue relating to the possible ash deposits on the flanks of Hecates Tholus is the determination of the magma chemistry. Francis and Wood (1982) have argued against silicic explosive volcanism on Mars, but it is theoretically possible for Mars to have experienced basaltic plinian eruptions (Wilson et al., 1982). Identifying silicic materials on Mars would thus have significant implications for crustal differentiation and would also be relevant to the current debate about the mode of formation of the enigmatic deposits within the Amazonis region of Mars, which Scott and Tanaka (1982) hypothesize are ignimbrite deposits. Although silicic deposits may be interpretable from orbit, by using the imaging spectrometer onboard the rover it would be possible to investigate the geochemical diversity and thickness of individual strata within the drainage valleys upon the flanks of Hecates Tholus without returning samples of these materials to Earth. Particularly if this spectrometer were to operate in the 5-12-μm wavelength region (where a number of characteristic silicate emission features exist), it should be possible to determine whether the inferred explosive eruptions were due to variations in magma chemistry or the inclusion of nonjuvenile volatiles within the magma (Mouginis-Mark et al., 1982), and the approximate magnitude of the eruptions (Wilson et al., 1982).

Station 5

Upon leaving the lower flanks of Hecates Tholus, the rover will traverse the boundary between the lava flows of Elysium Mons and the plains units that compose part of Utopia Planitia in the northern plains of Mars (Fig. 1). The boundary between these two surface units cannot be located to better than ~10 km on the available Viking Orbiter images due to insufficient image resolution, but it is clear that during a traverse of ~40 km the morphology of the surface changes from subdued lava flows in the southwest to smoother plains materials in the northeast. These materials in the northeast appear to overlie a unit that is now exposed only as a series of isolated masses (Fig. 4), as well as to possess numerous enigmatic sinuous ridges. These ridges have been hypothesized by Lucchitta et al. (1986) to be compressional features formed in sediments, while Parker et al. (1987) have documented morphologically similar features elsewhere on Mars that they compare to tombolos on Earth (bars created by wave action on open bodies of water that deposit sediments at the shoreline).

The primary science objective at Station 5 is to investigate the morphology of the surficial deposits at this site and, via the imaging spectrometer, attempt a spectroscopic determination of the composition of the isolated masses that project through the surficial cover of the plains materials. On stratigraphic grounds these masses may be some of the oldest materials exposed in this region of Mars, or, alternatively, they may be remnants of the Elysium Mons lava flows that have been down-dropped in the rest of this area and almost completely buried by the younger, presumably sedimentary, deposits.

Station 6

Exploration of an area of chaotic terrain commences at Station 6, where the rover can gain easy entrance to a series of interconnected canyons (Fig. 5). These canyons measure about 10-15 km in length, have widths of ~500 m-1 km, and are estimated from shadow length measurements to be about 400-600 m deep. This area was described by Carr and Schaber (1977) as a likely area for the collapse of surface materials following the release of subsurface volatiles, and further mapping of the boundary scarp by Mouginis-Mark (1985) supports the idea of melt-water release from the scarp following the emplacement of lava flows from Elysium Mons. At Station 6, depending upon the degree of talus covering the slope face, the stratigraphy of the scarp may be interpretable using the rover’s imaging spectrometer insofar as a section that cuts through the surface layers of Elysium Mons lava flows and the underlying megaregolith may be visible. In addition to this compositional mapping, which may identify volatile-rich sediments that are important for the analysis of paleoclimates (Markun, 1988), it is also possible that geomorphic evidence (e.g., stream channels, mounds, or freeze/thaw phenomena) might be found that would help resolve the mode of formation of the canyon system.

After completion of the geological objectives at Station 6, it is possible that the rover might be able to explore further the canyon system along the base of the boundary scarp and investigate the local stratigraphy of the wall rock. Such a task may be more hazardous than the earlier parts of the traverse, so that this exploration is reserved until the end of the proposed mission in case the rover is lost. Within the canyon system it is possible that in addition to Elysium Mons lava flows and the topmost layers of the megaregolith, distal layers of ash from Hecates Tholus also may be found as the summit of the volcano is only ~120 km from the scarp. If this is the case, such ash deposits may be spectroscopically identified, permitting further assessments of the eruptive history of the volcano to be made (specifically, placing constraints on the dispersal of ash from the volcano, which pertains to the height of the eruption column in plinian eruptions; Wilson et al. (1982), Mouginis-Mark et al. (1988)).

SURFACE PROPERTIES

En route Topography

While little is known about the meter-scale topography to be expected at this locality on Mars, it is likely that a combination of information from the two Viking Landers
Fig. 5. The distal end of the canyon system associated with the breakup of the cap-rock along the boundary of Elysium Planitia and Utopia Planitia marks the location of Station 6 (located at 33.97°N, 211.19°W). It is expected that at this location the stratigraphy of the escarpment could be observable to the rover's imaging device, and morphological evidence may be found to help in the interpretation of volcano/ground-ice interactions such as the release of basal melt water following the emplacement of the lava flows from Elysium Mons. Viking Orbiter image 86A37, image resolution 38 m/pixel. Image width is equivalent to 40 km and north is to the top.
(Mutch et al., 1977; Garvin et al., 1981), Viking Orbiter thermal inertia measurements (Christensen, 1986, 1988), and common experience with terrestrial volcanic plains (Aubele and Crumpler, 1988; Garvin and Zuber, 1988) can be used to predict the topography of a rover would have to traverse during the collection of samples for return to Earth (i.e., at the landing site and Stations 1 and 2) and during the traverse from the landing site to Station 3 and beyond.

From Viking images that have a resolution of 50 m/pixel, the morphology of the Elysium Mons lava flows in this area appears to be similar to that of flows found in the Tharsis region, where small-scale (~50 m horizontal spacing) pressure ridges and flow channels have been found (Thellig and Greeley, 1986). Analysis of the Earth-based radar data for some of the lava flows in Tharsis (Schaber, 1980) shows that these Tharsis flows have very high surface roughness values (rms slopes in excess of 3°-4°), so it is possible that the Elysium lava flows may be quite rough. However, because the Elysium flows are apparently older than the Tharsis lava flows (Scott and Tanaka, 1986; Greeley and Guest, 1987), it is also possible that the surfaces of the flows along the proposed rover traverse may not have such a high surface roughness provided that the weathering rates in Tharsis and Elysium are comparable.

The travel distances between each science station are presented in Table 1. From inspection of Fig. 1, it is evident that in order to find a "safe" landing site and sample the possible jokulhalup deposit at Station 2, a total rover range of the order of at least 164 km is required. In addition, this range estimate ignores possible diversions that may be needed to navigate across the (possibly) rugged surface of the lava flows in this area. From the perspective of providing an absolute age date of Lower Amazonian materials, determining the petrology of the lava flows and gaining an understanding the cause(s) of the long run-out lava flows in Mars, returned samples from the landing site and the lava flow at Station 1 would be the highest priorities. The need for sampling the jokulhalup deposit is less pressing. If confirmed as a mudflow, this deposit would provide evidence of relatively recent near-surface volatiles. Moving the landing site 18 km to the east of the proposed location and deleting Station 2 would reduce the total length of the traverse to Station 6 to 135 km without significantly affecting the hazard level of the landing site.

**En route Science**

Key geological observations can also be made during the drive between several of the primary science stations. Aubele and Crumpler (1988) have proposed a model for the *in situ* weathering of martian lava flows, based on observations of terrestrial flows. If this model is correct, it should be possible to obtain, in a relatively short period of time, imaging spectrometer data of chip fragments of the flows that could provide information on the heterogeneity of the lava flows during the traverse from Station 2 to Station 3. Depending upon the science instrumentation onboard the rover, important observations could also be made at the boundaries between the Elysium Mons lava flows, Hecates Tholus, and the northern plains. For example, from 20 km west of Station 3, continuing up the flank of Hecates Tholus to Station 4, and then on to Stations 5 and 6, both gravity measurements and active seismic experiments could help resolve the subsurface structure of the area and provide information on the original structure of Hecates Tholus volcano.

Based on numerical modeling of martian pyroclastic flows (Wilson et al., 1982; Mouginis-Mark et al., 1988), it is expected that such volcanic flows may have traveled about 350-400 km from the vent. Although it seems likely that Hecates Tholus has experienced explosive eruptions (Mouginis-Mark et al., 1982), geomorphic evidence only exists to support the hypothesis that plinian eruptions (producing ash falls rather than pyroclastic flows) took place on this volcano. Such ash fall materials are likely to be widely distributed at distances in excess of ~100 km from the vent, and their distribution should place an upper limit on the basal diameter of the volcano. Thus, if a buried lower flank of Hecates Tholus were revealed by seismic measurements from the rover, it would indicate that another form of volcanism, either subplinian pyroclastic flows or effusive activity, took place.

Observational data and theoretical models indicate that the shallow martian crust is likely to contain several discontinuities (Davis and Golombek, 1989). From the analysis of the available Viking Orbiter images, it is possible to construct an idealized cross-section from the lower exposed flanks of Hecates Tholus to the isolated mesas north of the boundary scarp (Fig 6). The seismic and gravity data from the rover should provide measurements of the basal diameter of Hecates Tholus and the thickness of the Elysium Mons lavas in this area. In addition, spectroscopic measurements made from the rover on leaving Station 6 may also help resolve whether outliers of Elysium Mons lavas are preserved as cap-rock on the mesas north of the boundary scarp, improving our knowledge of the maximum radial extent of effusive volcanism from Elysium Mons.

A further science target during the drive from Station 4 to Station 5 is the ejecta blanket of the 5-km-diameter impact crater located at 33.6°N, 211.1°W. Like most fresh martian meteorite craters of this size, this crater has fluidized, lobate ejecta deposits (cf. Carr et al., 1977b). Several secondary craters can also be found around this crater in addition to the ejecta lobes, which is somewhat unusual for martian craters of this diameter (Schultz and Singer, 1980), and suggests that the primary crater ejected both coherent blocks and more

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<th>Location</th>
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<tr>
<td>Landing Site to Station 1 (round trip)</td>
<td>15 km</td>
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<tr>
<td>Landing Site to Station 2 (round trip)</td>
<td>13 km</td>
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<tr>
<td>Landing Site to Station 3</td>
<td>81 km</td>
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<tr>
<td>Station 3 to Station 4 (upslope)</td>
<td>11 km</td>
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<tr>
<td>Station 4 to Station 5 (downslope)</td>
<td>26 km</td>
</tr>
<tr>
<td>Station 5 to Station 6</td>
<td>18 km</td>
</tr>
<tr>
<td>Beyond Station 6 (canyon exploration)</td>
<td>?</td>
</tr>
<tr>
<td>Total Distance</td>
<td>104 km</td>
</tr>
</tbody>
</table>
Fig. 6. (a) Hypothetical cross-section extending from Station 4 to the boundary scarp beyond Station 6 (see b for location). Of particular interest is the determination (via active seismic or gravimeter experiments) of the maximum horizontal extent of the flanks of Hecates Tholus volcano, and the thickness of the lava flows from Elysium Mons. In this sketch the depth of excavation of the 5-km-diameter crater is schematic, but the determination of the depth of the breccia lens could be of value in the analysis of martian impact craters with fluidized ejecta deposits (cf. Mouginis-Mark, 1987). (b) Location of the cross-section (shown by dashed line) illustrated in (a). The positions of Stations 3-6 are also shown. Mosaic of Viking Orbiter images 86A35-40, resolution 38 m/pixel. Image width is equivalent to 68 km and north is to the top.
Some information on physical properties of the martian surface was obtained by the Viking Landers (e.g., Shortill et al., 1976; Moore et al., 1982), but remote-sensing data indicate that the Viking Lander sites are distinctive from most of the rest of Mars (Jakosky and Christensen, 1986). It is inferred here that it is likely that the undifferentiated lava flows that make up the northern Elysium Planitia landing site will be able to support the lander and permit the rover to reach the other two return sample sites (Stations 1 and 2). What is not so obvious is the bearing strength of the flanks of Hecates Tholus (Station 4), which on morphologic grounds could comprise relatively unconsolidated ash deposits or nonwelded pyroclastic flows (Mouginis-Mark et al., 1982, 1988). In order to answer these and other pertinent engineering and geologic issues for a variety of candidate landing sites on Mars, it therefore appears appropriate that new efforts be made to provide such information (via photogeologic and remote-sensing means) at this early stage of planning for a rover mission.

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REFERENCES


