Available online at www.sciencedirect.com
SCIENCE DIRECT®
Planetary and Space Science 52 (2004) 11–21
Planetary and Space Science
www.elsevier.com/locate/pss

Selecting landing sites for the 2003 Mars Exploration Rovers

John A. Grant[a,*], Matthew P. Golombek[b], Timothy J. Parker[b], Joy A. Crisp[b], Steven W. Squyres[c], Catherine M. Weitz[d]

[a] *Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, 6th St. and Independence Avenue SW, Washington, DC 20560-0315, USA*
[b] *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*
[c] *Department of Astronomy, Space Sciences Bldg., Cornell University, Ithaca, NY 14853, USA*
[d] *NASA Headquarters, Code SE, 300 E St. SW, Washington, DC 20546, USA*

Received 15 January 2003; received in revised form 4 June 2003; accepted 29 August 2003

Abstract

A two-plus year process of identifying and evaluating landing sites for the NASA 2003 Mars Exploration Rovers began with definition of mission science objectives, preliminary engineering requirements, and identification of $\sim$ 155 potential sites in near-equator locations (these included multiple ellipses for locations accessible by both rovers). Four open workshops were used together with ongoing engineering evaluations to narrow the list of sites to four: Meridiani Planum and Gusev Crater were ranked highest for science, with southern Isidis Basin and a "wind safe" site in Elysium following in order. Based on exhaustive community assessment, these sites comprise the best-studied locales on Mars and should possess attributes enabling mission success.
Published by Elsevier Ltd.

Keywords: Mars; Landing sites; Rovers; 2003; Exploration; Selection

1. Introduction

The process of identifying and evaluating landing sites for the 2003 Mars Exploration Rovers (MER-A and MER-B) began in September of 2000 and has involved a broad cross-section of the planetary science community. Activities built upon the premise that all engineering requirements (e.g., acceptable surface rock abundances and slopes) must be met in order to maximize the probability of landing safely; given that these constraints are satisfied, then locations were evaluated where the scientific objectives of the mission could best be achieved. Outcomes included a shortlist of four sites with generally high science potential.

The MER mission consists of two identical rovers to be launched in June, 2003. The first MER will land on January 4, 2004 and the second will land on January 25, 2004. Each rover will conduct science operations for a minimum of 90 Martian days (sols) using the Athena Science Payload (Squyres et al., 1998). The MER mission will use the Mars Pathfinder airbag system for landing (Crisp, 2001), though scaled up considerably due to the higher mass of the MER lander. After landing and deployment, at least one rover must traverse up to 600 m to achieve mission success (Weitz, 2001).

2. Guiding principles and participants

Landing site selection activities built on unchanging guiding principles that include the recognition that: (A) identifying optimal sites within the limits enabled by data and resources (e.g., sufficient solar energy for operations) is critical to mission success, and (B) the assistance of the science community is crucial in identifying optimal science sites. Nevertheless, final site recommendation was the job of the Athena Science Team and MER Project at the Jet Propulsion Laboratory (JPL), whereas site selection was made by the Associate Administrator for Space Science at NASA Headquarters. Finally, there was no predetermined outcome to any aspect of the landing site selection process and participants were kept up-to-date on activities via posting of materials at two

---

* Corresponding author. Tel.: +1-202-633-2474; fax: +1-202-786-2566.
E-mail address: grantj@nasm.si.edu (J.A. Grant).

0032-0633/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.pss.2003.08.011

Table 1
NASA Mars landing site steering committee

	Affiliation
Co-Chairs	
John Grant	Smithsonian Institution
Matthew Golombek	Jet Propulsion Laboratory
Members	
Michael Carr	US Geological Survey, Menlo Park
Philip Christensen	Arizona State University
Jack Farmer	Arizona State University
Virginia Gulick	NASA Ames Research Center
Bruce Jakosky	University of Colorado
Michael Malin	Malin Space Science Systems
George McGill	University of Massachusetts
Richard Morris	NASA Johnson Space Center
Timothy Parker	Jet Propulsion Laboratory
Roger Phillips	Washington University
Michael Shepard	Bloomsburg University
Kenneth Tanaka	US Geological Survey, Flagstaff

Table 2
Summary of landing site engineering constraints[a]

MER mission engineering parameter	Requirement for MER mission landing sites
Altitude	$\leqslant -1.3$ km relative to MOLA defined Geoid[b]
Approximate ellipse dimensions	∼ 155 km × 16 km at 11°N, ∼ 96 km × 19 km at 15°S
Approximate ellipse orientation	∼ 94° at 11°N to 76° at 15°S (w/respect to north)
Site separation latitude (MER A and MER B)	Solid angle ∼ 37° 5°N–15°S and 10°N–10°S, respectively
1 km length-scale slopes	Must be less than 2°
100 m length-scale slopes	Must be less than 5°
10 m length-scale slopes	Must be less than 15°
Minimal local high relief	Hazard-free in Viking MDIM[c]
Rock abundance	Should be $< 20\%$ (from thermal inertia)
Minimal hazardous rocks	Should be $< 1\%$ larger than 0.5 m high
Trafficability	Minimal decimeter-scale roughness from radar
Horizontal winds (shear/turbulence)	Generally $\leqslant 0.9 \leqslant 2.1$ (being refined)
Horizontal winds (sustained mean)	Must impact surface at < 16–20 m/s
Acceptable vertical winds	Must impact surface at < 12–15 m/s
Minimum temperature at site	Warmer than −97°C
Thermal inertia	Greater than 200–250 SI units (see albedo)
Albedo	Less than 0.18 and 0.26 (see thermal inertia)
Local dust environment	Relatively dust free from MGS TES[d] and albedo
Surface must be load bearing	Defined on basis of radar and geology
Radar reflectivity	Must be > 0.05

[a] Engineering constraints remain under evaluation at the time the paper was accepted for publication and the actual values may differ.
[b] As described in Smith and Zuber (1998) and Smith et al. (1999).
[c] Second generation Viking Mars Digital Image Map.
[d] Thermal Emission Spectrometer.

open URL's: http://marsoweb.nas.nasa.gov/landingsites/ and http://webgis.wr.usgs.gov/.

To ensure a robust, comprehensive process, multiple groups were solicited for input in evaluating potential landing sites. Activities were led by a Steering Committee that was responsible for approving modifications to the process and adjudicating if community consensus was not achieved (never required). The Steering Committee was co-chaired by the first two authors of this paper, and both were selected via NASA peer- review. Other Steering Committee members were appointed by NASA Headquarters to ensure breadth of science expertise and mission involvement (Table 1). In addition, the broader science community and investigators in the NASA Mars Data Analysis Program were targeted, thereby enlisting individuals developing and applying new data analysis techniques relevant to evaluating site safety. Finally, additional members of the science and spacecraft engineering community and NASA ex-officios were invited to provide mission experience, provide feedback, and enable access to data collected by the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) and Mars Odyssey Thermal Emission Imaging System (THEMIS) imagers.

3. Basis for site selection

Requiring that any recommended site must satisfy all mission engineering/safety and science requirements placed strict constraints on the regions accessible to landing during the MER mission (Golombek et al., 2001, 2002, 2003). For example, latitude, altitude, and temperature constraints (Table 2) limited potential landing sites to a discontinuous equatorial band that covers approximately 5% of the planet. Application of all remaining mission engineering constraints (Table 2) further reduced potential landing areas.

Mission science objectives are tightly coupled to the NASA Mars Program objectives and relate to defining the aqueous, climatic, and geologic history on Mars in locations where conditions were favorable for preserving clues to environmental conditions when liquid water was present (Crisp, 2001; Weitz, 2001). Proposed landing sites include locations possessing evidence for surface processes involving water and examples of how the Athena instruments can be used to achieve the objectives via hypothesis testing.

4. The first two landing site workshops

Definition of the landing sites for the 2003 Mars Exploration Rovers began in earnest following definition of preliminary engineering constraints in September, 2000.

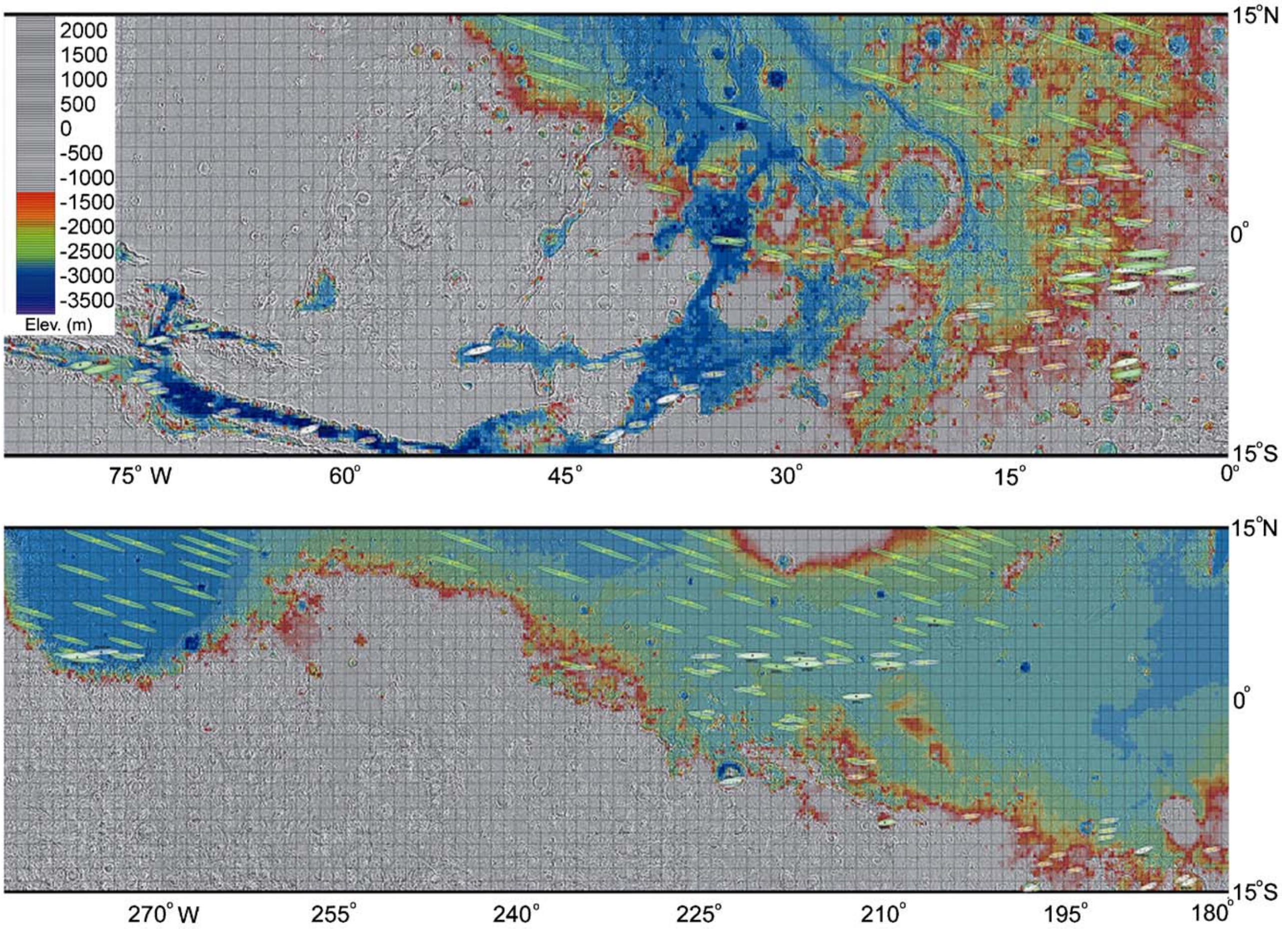


Fig. 1. Map of the equatorial region of Mars showing location of initial ∼ 155 landing ellipses (white and green) for the MER rovers. Areas in grey are outside of the elevation requirements. Colored regions represent potentially acceptable regions and display MOLA topography.

Using site requirements as a guide, ∼155 landing (99% probability) ellipses were identified (including multiple ellipses for some sites accessible by both rovers) to provide access to terrains ranging from Noachian highland dissected, hilly, cratered, and subdued cratered units; to Hesperian ridged plains, channel materials, and the Vastitas Borealis Formation; to Amazonian smooth plains, channel materials, volcanics, knobby materials, and the Medusae Fossae Formation (Fig. 1, see Table 3 for specific ellipses in each terrain type as defined in Scott and Tanaka, 1986; and Greeley and Guest, 1987). Ellipses range in length and width from approximately 90 km × 20 km and 160 km × 15 km from south to north, respectively. The scientific community was encouraged to review all suggested sites and to propose additional sites if appropriate. All locations were discussed at an open landing site workshop in January, 2001, at the NASA Ames Research Center (Golombek and Grant, 2001).

Community consensus at the first workshop served to define the highest priority sites and other sites that were of high, but somewhat lesser priority. Listed in Table 3 and described by Golombek and Grant (2001), the initial suite of proposed highest priority landing sites target recently identified coarse-grained hematite deposits in Meridiani Planum (Christensen et al., 2000, 2001), locations in Valles Marineris (e.g., in Melas and Eos Chasmata, see Weitz et al., 2003; Greeley et al., 2003a), putative paleo-crater-lake deposits (e.g., in Gale and Gusev Craters, see Cabrol and Grin, 1999), and locations with access to in situ (Meridiani Highlands) or transported (Isidis Basin) highlands materials. The Meridiani Planum site received the strongest support and includes multiple sites to permit some choice related to future safety concerns or targeting the most interesting geology. Nevertheless, each of the highest and high priority sites relates to the possibility of sampling materials deposited or shaped by water.

Because of the possibility of placing multiple landing ellipses within some highest and high priority sites, a total of 29 locales emerged from the first workshop (Table 3). No decision was reached regarding whether sites reachable by either MER-A or MER-B would be assigned to a particular rover, and none of the sites was formally selected for landing at that time. Concern was expressed that features in some ellipses were distributed at scales placing them beyond roving range, but sites characterized by closely spaced or mul-

Table 3
Highest and high priority landing sites being considered after the first site selection workshop

Location	Location of ellipse center (Lat: °N/S, Lon: °W)	MER-A	MER-B	Geological unit[c]	Elevation (km)	Identifier
Highest priority sites[a]						
Eos Chasma	13.34S, 41.39W	X		Hch	−4.0	VM41A
Elysium Outflow	7.40N, 205.60W		X	Ael$_1$	−3.0	EP49B
Gale	5.81S, 222.23W	X		S	−4.5	EP82A
Gusev	14.85S, 184.16W	X		Hch	−1.9	EP55A (S)
	2.50S, 3.30W		X	Npl$_2$	−1.3	TM21B
	1.99S, 6.01W		X	Npl$_2$	−1.3	TM20B
Meridiani	1.20S, 5.30W		X	Npl$_2$	−1.3	TM19B
	2.20S, 6.60W	X		Npl$_2$	−1.7	TM10A
	1.20S, 5.60W	X		Npl$_2$	−1.3	TM9A
Isidis	4.64N, 275.88W		X	Aps	−4.0	IP98B
	4.7N, 274.68W	X		Aps	−4.5	IP85A
Melas Chasma	8.8S, 77.8W	X		Avf	−3.5	VM53A
	8.8S, 77.8W		X	Avf	−3.5	B site
High priority sites[b]						
Apollinaris	~9.50S, 190.20W	TBD	TBD	AHa	TBD	TBD
Boedickker Crater	15.30S, 197.44W	X		Npl$_1$	−2.1	EP64A
Central Valles Marineris	13.10S, 62.50W	X		Avf	−4.5	VM44A
Durius Valles	14.6S, 188.1W			Npl$_1$		EP56A
Meridiani	3.40S, 7.20W		X	Npl$_2$	−1.7	TM22B
	3.10S, 3.10W		X	Npl$_2$	−1.4	TM23B
	3.60S, 2.90W	X		Npl$_2$	−1.3	TM12A
	3.40S, 6.90W	X		Npl$_2$	−1.6	TM11A
Isidis	4.50N, 271.90W	X		Aps	−4.5	IP84A
	4.48N, 271.60W		X	Aps	−4.5	IP96B
Meridiani Crater	8.60S, 7.1W	X		S	−1.9	TM15A
	9.36S, 6.76W	X		S	−1.9	TM16A
Meridiani Highlands	3.00S, 10.00W	X		Hr	−1.8	TM13A
	2.80S, 10.10W		X	Hr	−1.8	TM24B
NE Valles Marineris Outflow	11.10S, 38.05W	X		Hch	−4.0	VM37A
Un-named Crater	9.20S, 209.60W	X		Npl$_1$	−1.7	EP69A

[a] Targeted by MGS MOC when accessible by rotating off orbit track (ROTO) and during nadir passes.

[b] Targeted by MGS MOC during nadir passes only.

[c] Geological units were assigned using the maps by Scott and Tanaka (1986) and Greeley and Guest (1987). First letter indicates units of Noachian (N, generally older than ~ 3.5 b.y.), Hesperian (H, generally younger than ~ 3.5 b.y. to perhaps as young as ~ 1.8 b.y.), and Amazonian (A, present to perhaps as old as ~ 2.0 to ~ 3.0 b.y.) age: Npl$_1$: cratered plateau material; Npl$_2$: subdued crater plateau material; Hr: ridged plains material; Hch: channel and chaotic material; Aps: smooth plains material; Ael$_1$: Elysium formation (unit 1); Avf: Valles Marineris floor material; AHa: Apollinaris Patera Formation; S: smooth crater floor material.

tiple targets, such as Meridiani Planum and Melas Chasma, or "grab bag sites" such as Eos Chasma and Isidis Basin are least susceptible to this problem. The location of the sites can be reviewed at: http://marsoweb.nas.nasa.gov/landingsites/ and http://webgis.wr.usgs.gov/.

The first workshop was followed by collection of the additional data needed to assess site science potential and refine engineering and safety constraints. Data included images from MGS MOC, other derived data sets (e.g., Mars Orbiter Laser Altimeter (MOLA) pulse width data used to characterize local slopes and roughness), and a more complete definition of rover capabilities.

Follow-on analyzes indicated that the rover lifetime would be reduced if nighttime temperatures consistently fell below −97°C. Corresponding revision of the thermal inertia and albedo requirements (Table 2) caused deletion of the Elysium Outflow highest priority site and the Apollinaris and Durius Valles high priority sites. Concerns related to landing safety also caused deletion of sites in Ganges and Candor Chasma. Finally, the MER Project at JPL approved a fifth spacecraft navigation trajectory correction maneuver (TCM-5) shortly before arrival at Mars, together with Doppler tracking of the spacecraft using multiple receiving stations (referred to as DeltaDOR). Implementation of TCM-5 and DeltaDOR leads to better knowledge of spacecraft position and trajectory and a slight reduction in the sizes of landing error ellipses. In light of this, a reexamination of acceptable landing regions (including sites proposed for the cancelled Mars 2001 Lander, see Gulick, 1998, 1999; Marshall and Weitz, 1999) led to identification of a new highest priority ellipse in Elysium (Athabasca Vallis) and eight new high priority sites. Although a reexamination of ellipse sizes shortly thereafter yielded some growth, the new Athabasca Vallis site and five new high priority sites remained viable (in Elysium, an Ares Vallis tributary, the Sinus Meridiani highlands, and multiple ellipses in Isidis, see Golombek et al., 2002).

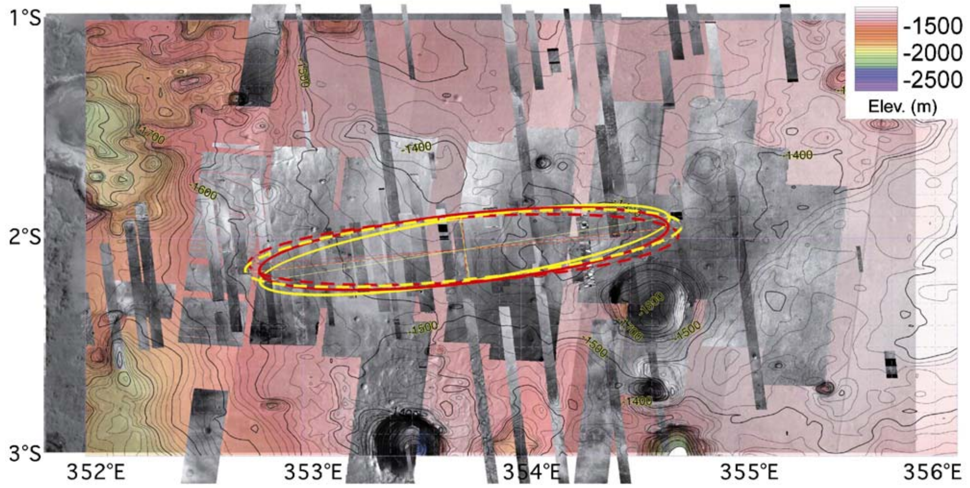
A second open workshop was convened in October 2001 to further prioritize the sites and set the stage for detailed evaluation of safety issues. The workshop focused on the relative merits of the sites emerging from the first workshop in the context of mission science objectives and engineering requirements. Community voting named Meridiani Planum, Gusev Crater, Melas Chasma, and Athabasca Vallis sites as primary, highest priority sites, and locations in Isidis Basin and Eos Chasma as alternates. All other sites were eliminated from further consideration because they were deemed of lesser scientific value or because of a failure to satisfy engineering requirements. Deletion of the Gale Crater site is an example of the latter; an ellipse could not fit inside the crater.

5. Overview of the top sites

Comprehensive discussion of the science potential and safety characteristics of each of the primary and alternate sites is presented by Golombek et al. (2003). Therefore, only a brief summary is presented here.

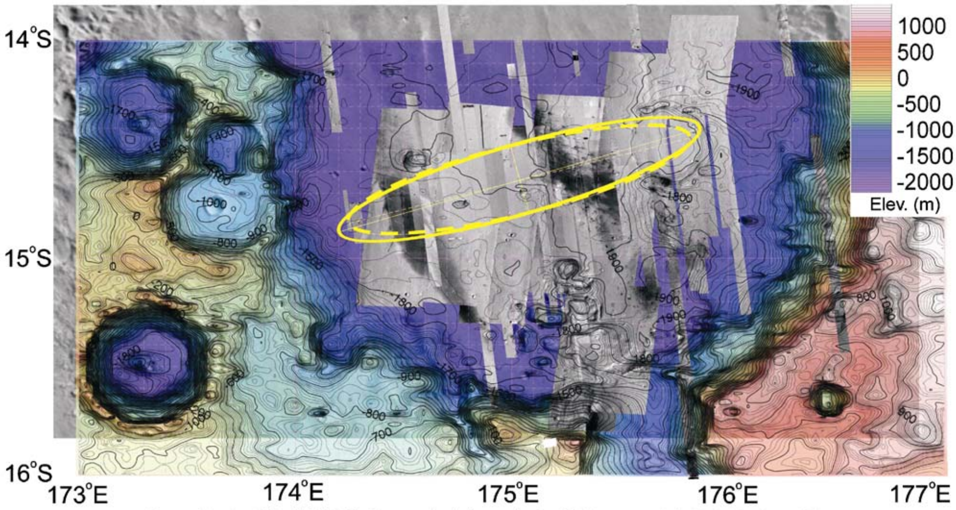
The landing site in the Meridiani Planum hematite deposits (Christensen et al., 2000, 2001) was regarded as possessing unique mineralogic properties and a high overall science potential. Within the primary ellipse (Fig. 2), coarse-grained crystalline hematite (Christensen et al., 2000, 2001) is distributed within a pervasive dark plains unit that overlies a brighter unit, and the dark plain has been locally eroded to form dunes (Arvidson et al., 2003). Although at the upper elevation range acceptable for landing, the site is otherwise benign, being characterized by low slopes at all scales, low winds, and acceptable rock abundance and dust properties (Golombek et al., 2002). While favored hypotheses for the origin of the hematite involve precipitation in oxygenated iron-rich water (Christensen et al., 2000, 2001), alternate explanations have been proposed that require minimal or no water. For example, the hematite and associated units have been interpreted as lava and tephra deposits erupted during past regional extension (Arvidson et al., 2003), or the hematite may have formed by high-temperature alteration of magnetite-rich lavas. It is also possible that the deposits are due to pedogenic alteration such as precipitation from iron-rich hydrothermal fluids, lateritic leaching by ground water and subsequent precipitation, or weathering and formation of coatings.

The ellipse within Gusev Crater (Fig. 3) is also highly regarded because it may provide access to paleo-lacustrine sediments deposited in water draining from Ma'adim Vallis to the south (Cabrol and Grin, 1999; Cabrol et al., 1996, 2001; Irwin et al., 2002). Gusev Crater is the southernmost of the proposed sites, and northward migration of the sub-solar point during the mission leads to limited rover power and lower ambient temperatures over time. Additional concerns relate to possible high slopes at 10-m length scales around craters and in etched areas. While the presence of water in the crater seems likely, whether it was long-lived remains uncertain as does the accessibility of associated deposits due to possible burial by eolian and/or volcanic materials (Milam et al., 2003; Greeley et al., 2003b). Nevertheless, small craters may expose water-lain sediments.



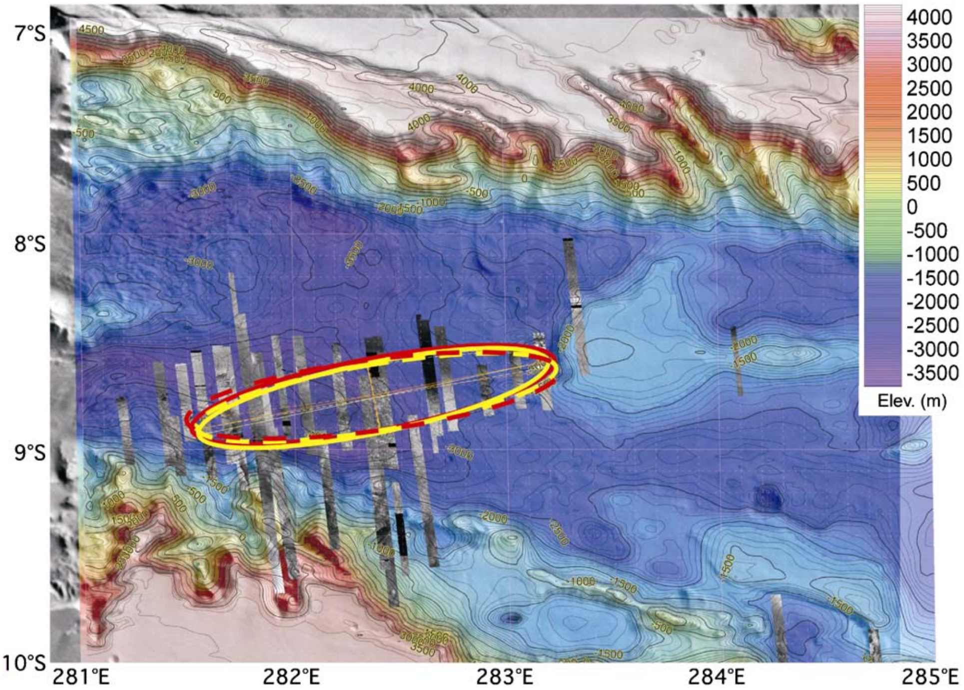
Meridiani "Hematite" Site: (MER-A=Yellow; MER-B=Red; Open of window=dashed, Close=solid) T. J. Parker, JPL

Fig. 2. The Meridiani Planum landing ellipse for MER-A (yellow) and MER-B (red). All maps of the landing ellipses (Figs. 2–8) represent the expected 3-sigma landing error and are derived using MOLA data overlain on the second generation Viking Mars digital image map (MDIM 2) and were compiled by Tim Parker. The location of supporting MGS MOC (narrow strips) and Mars Odyssey THEMIS (wider strips) image data for all of the ellipses is indicated and individual image identifiers can be viewed at http://marsoweb.nas.nasa.gov/landingsites/ and http://webgis.wr.usgs.gov/.



Gusev Crater Site (MER-A; Open of window=dashed, Close =solid) T. J. Parker, JPL

Fig. 3. The Gusev Crater landing ellipse for MER-A.



Valles Marineris Melas Site (MER-A=Yellow; MER-B=Red; Open of window=dashed, Close=solid) T. J. Parker, JPL

Fig. 4. The Melas Chasma landing ellipse for MER-A (yellow) and MER-B (red).

An ellipse within western Melas Chasma in Valles Marineris (Fig. 4) encompasses a blocky unit composed of layered deposits (Weitz et al., 2003). Site safety concerns relate mostly to locally high relief and slopes at all length scales, moderate rock abundance, and trafficability issues. Moreover, a large fraction of the ellipse is occupied by sand dunes. Nevertheless, landing inside Valles Marineris would provide spectacular views of adjacent canyon walls and likely access to enigmatic layered deposits (McCauley, 1978). These layered deposits have been interpreted as mass wasting, carbonate, eolian, and volcanic deposits (e.g., McCauley, 1978; Nedell et al., 1987; Lucchitta, 1989; Malin and Edgett, 2000; Chapman and Tanaka, 2001). Understanding their origin may shed new light on the evolution of the Valles Marineris system.

The Athabasca Vallis site is located just downstream of the channel breakout from Cerberus Fossae (Fig. 5). The site is relatively far north (raising concerns about power availability) and possesses an anomalous radar signature implying significant decimeter-scale roughness that could impact

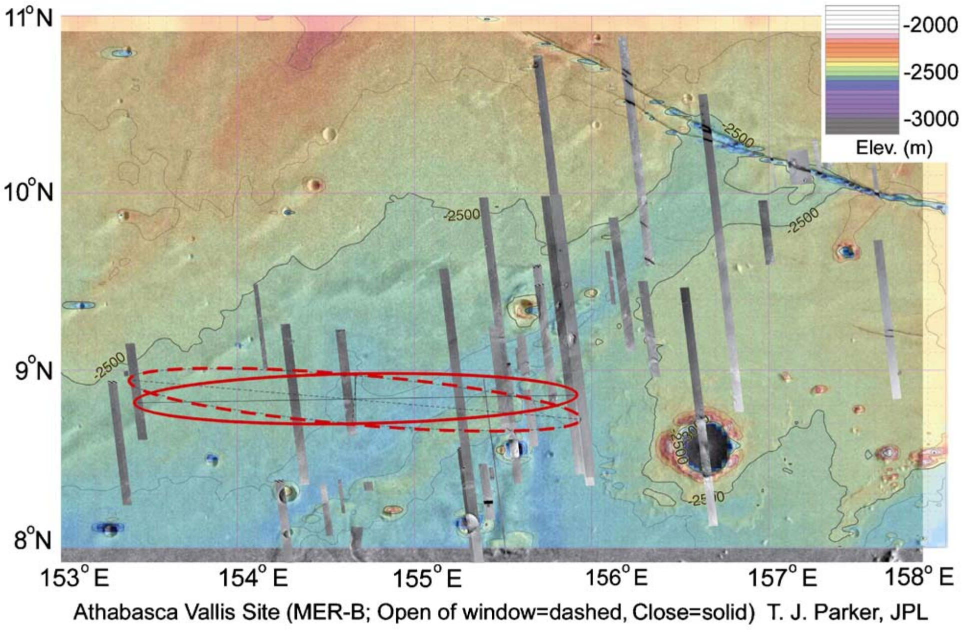


Fig. 5. The Athabasca Vallis landing ellipse for MER-B.

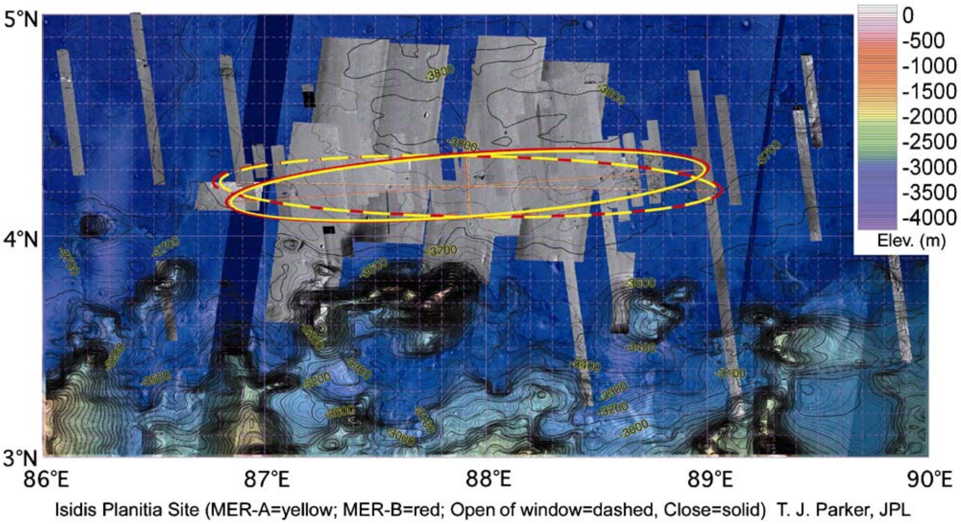
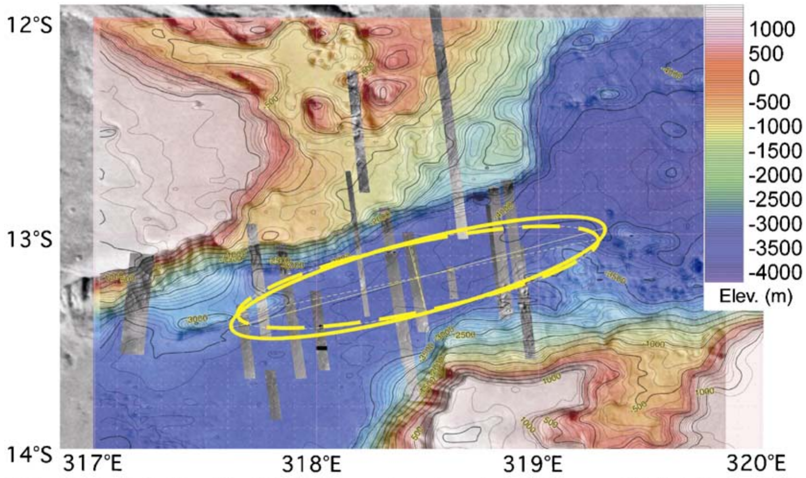


Fig. 6. The Isidis Basin landing ellipse for MER-A (yellow) and MER-B (red).

landing safely and rover trafficability. Moreover, the expectation of low temperatures and significant dust obscuration are concerns. In contrast to other sites, Athabasca Vallis provides potential access to some of the youngest lavas and channel deposits on the planet (Plescia, 1990; Edgett and Rice, 1995; Burr et al., 2002). Unfortunately, the site appears dominated by scour, and depositional units are locally derived. Nevertheless, possible shallow ground ice and hydrothermal deposits make it potentially attractive from an astrobiological perspective (Burr et al., 2002).

Ellipses near the southern margin of Isidis Basin (Fig. 6) and in Eos Chasma (Fig. 7) comprised the alternate sites. At Isidis, safety concerns relate to high rock abundance and their impact on landing and rover mobility. In addition, the site appears dusty and may possess relatively high slopes at 10-m length scales. Scientifically, Isidis may permit sampling of alluvium from the Noachian highlands to the south. Enthusiasm is tempered, however, by uncertainties regarding whether accessible materials might be those emplaced during later basin infilling by alternate processes (e.g., Grizzaffi and Schultz, 1989; Parker et al., 1989, 1993). In addition, transported materials may be primarily igneous, possess a paucity of fine alluvium and aqueous mineralogies, and may be limited to several small channels (either fluvial or volcanic) traversing the ellipse.



Valles Marineris Outflow Site (MER-A; Open of window=dashed, Close=solid) T. J. Parker, JPL

Fig. 7. The Eos Chasma landing ellipse for MER-A.

The Eos Chasma site (Fig. 7) is characterized by high rock abundance and possesses high slopes at all length scales (Table 2) that could adversely impact landing and rover mobility. The site preserves evidence of large-scale water discharge that caused predominantly scour, but also deposition in local lacustrine basins (Greeley et al., 2003a). Eroded materials were diverse and include chaotic terrains located further up the canyon (Greeley et al., 2003a). Although the Eos Chasma site would afford excellent views of the canyon walls, the layered deposits noted at the Melas Chasma site are not present.

6. The third and fourth landing site workshops

The final two workshops were held in March of 2002 and January of 2003 and dealt exclusively with the sites emerging from the second workshop. A primary outcome of the third workshop was compilation of a consensus view of the relative merits of the remaining sites (Table 4). Although inter-site evaluations were based on science, safety, and public engagement parameters, the first three science parameters were most heavily weighted and related to finding evidence for water at a site, likelihood that the geologic and climate history was addressable, and the possibility that either biotic or pre-biotic materials might be preserved. On this basis, the Meridiani Planum and Gusev sites emerged as favorites, with the Athabasca Vallis site being the lowest ranked. Note that each site possesses minor attributes that could impact mission science return (see Table 4). Each site is also characterized by a variety of potential safety and public engagement issues. Safety issues are elaborated upon below, whereas the public engagement factors were informational.

Perhaps the most significant outcome of the safety-based site comparisons related to results of wind modeling for the time and season of landing and the potential for winds to negatively impact entry, descent, and landing (EDL) (Table 4). For example, slope winds of tens of meters/second and associated shear within Valles Marineris are expected to blast both the Melas and Eos Chasma sites (Kass et al., 2003). Likewise, the Isidis site could experience relatively high slope winds, and concerns emerged regarding the potential for wind shear associated with a low latitude jet stream crossing the rim of Gusev Crater. Winds at the Meridiani site were deemed primarily convective in nature and within the capabilities of the EDL system. Presentation of the wind model results made it clear that some sites likely experience unacceptably high winds, thereby prompting reevaluation.

The Valles Marineris sites were the first casualties of this new concern. Collectively, expected high winds, high slopes, and/or dust and rock abundance resulted in both the Melas and Eos Chasma sites being dropped from consideration. In addition, the Isidis and Gusev sites were viewed with caution. Finally, the Athabasca Vallis site was dropped because of concerns related to the radar-implied surface roughness (Table 3). In light of these events, Isidis was promoted to a primary site and it became obvious that an additional site was required where winds and other safety concerns were minimized.

Efforts to locate a “wind safe” site required merging wind modeling results and prior engineering/safety analyzes and quickly converged on a region southwest of Elysium near the cratered highland–lowland boundary (Fig. 8). The Elysium “wind safe” region possesses a lower science potential than the other top sites (e.g., due to a lack of clear evidence of for past water activity), but is located where expected slopes, rock abundance, temperatures, and (most importantly) winds (Table 2) fall within acceptable values. Two ellipses were initially evaluated within the “wind safe” region, and one was selected based upon slightly higher science potential and lower safety concerns. Science potential

Table 4
Summary of MER landing site criteria after third landing site workshop[a]

Major questions/criteria	Landing sites					
	Meridiani	Gusev	Isidis	Melas	Eos	Athabasca
Science criteria[b]						
Evidence for water activity	🟢	🟢	🟢	🟢	🟢	🟢
Climate/geo. history addressable	🟢	🟢	🟢	🟢	🟢	🟡
May preserve (pre)biotic materials	🟢	🟢	🟡	🟡	🟡	🟡
Enables hypothesis testing	🟢	🟢	🟢	🟡	🟡	🟢
Accessible diversity within the site	🟢	🟡	🟢	🟡	🟡	🟢
Differs from other MER sites	🟢	🟢	🟢	🟢	🟢	🟢
Differs from VL and MPF sites	🟢	🟢	🟢	🟢	🟢	🟢
Has materials for Athena analyzes	🟢	🟢	🟢	🟢	🟢	🟢
Acceptable rock abundance	🟡	🟡	🟢	🟡	🟢	🟢
Good site trafficability	🟢	🟢	🟡	🟡	🟡	🔴
Degree of dust obscuration	🟢	🟡	🟡	🟢	🟢	🟡
Expected mission lifetime	🟡	🟡	🟢	🟢	🟢	🟡
Relief at scale of rover traverse	🟡	🟡	🟡	🟢	🟡	🟢
Site has potential earth analogs	🟢	🟢	🟢	🟢	🟢	🟢
Safety criteria						
1 km slope < 2°	🟢	🟢	🟢	🔴	🔴	🟢
100 m slope < 5°	🟢	🟢	🟢	🔴	🟡	🟢
10 m slope < 15°	🟢	🟡	🟡	🔴	🟡	🟢
Any local high relief (craters)?	🟢	🟡	🟡	🔴	🟡	🟡
Rock abundance/trafficability?	🟢	🟢	🟡	🟡	🔴	🔴
No potentially hazardous rocks	🟢	🟢	🟡	🟡	🔴	🟡
Horizontal winds (shear/turbulence)	🟢	🟡	🟡	🟡	🟡	🟡
Horizontal winds (sustained mean)	🟢	🟡	🟡	🔴	🔴	🟡
Acceptable vertical winds	🟡	🟢	🟡	🟡	🟡	🟡
Expected temperature at site	🟡	🟡	🟢	🟡	🟢	🟡
Local dust environment	🟢	🟡	🟡	🟢	🟢	🟡
Surface is load bearing	🟢	🟢	🟢	🟢	🟢	🟢
Elevation < – 1.3 km (MOLA def.)	🟢	🟢	🟢	🟢	🟢	🟢
Radar reflectivity > 0.05	🟢	🟢	🟢	🟢	🟢	🟢
Public engagement						
Site aesthetics	🟡	🟡	🟢	🟢	🟢	🟢
Site differs from VL or MPF sites	🟢	🟢	🟡	🟢	🟢	🟢
Potential habitability for life	🟢	🟢	🟡	🟡	🟡	🟡
Explainable to public	🟢	🟢	🟢	🟢	🟢	🟢

[a] Does not include criteria such as latitude, site separation, etc., previously described as site distinguishing factors.

[b] Top three science criteria are the highest priority 🟢 → no obvious concerns, 🟡 → potential concerns, 🔴 → recognized concerns.

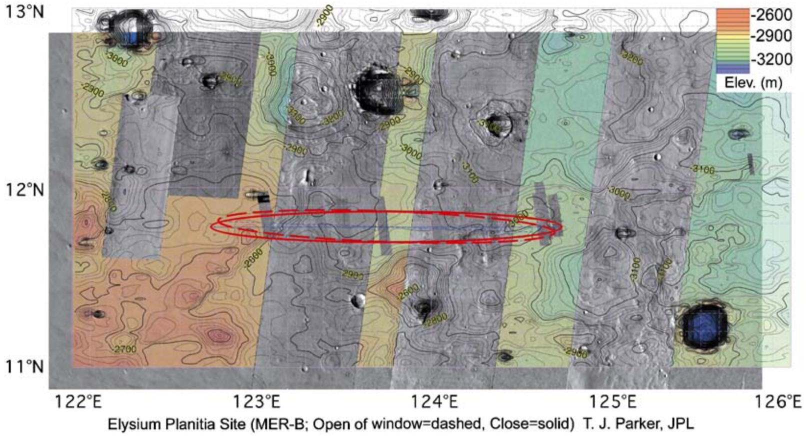


Fig. 8. The Elysium "wind safe" ellipse for MER-B.

Table 5
Summary characteristics of the final four candidate sites

Meridiani (accessible by MER-A or B)
Mineral evidence (coarse-grained hematite) for past water?
TM10A2 (MER-A) and TM20B2 (MER-B) both centered at:
  2.07°S, 6.08°W MDIM2
  2.06°S, 353.77°E MOLA
  2.060°S, 354.008°E IAU/IAG 2001
Ellipse center at −1.44 km MOLA elevation.
TM10A2 ellipse: 119 km × 17 km, oriented at 84° (clockwise from north), TM20B2 ellipse: 117 km × 18 km, 86°.
Viking IRTM Rock abundance: 1–7%

Isidis (accessible by MER-A or B)
Ancient rocks from a possibly wetter Mars past, transported by water and deposited in fluvial fans?
IP84A2 and IP96B2 both centered at:
  4.31°N, 271.97°W MDIM2
  4.22°N, 87.91°E MOLA
  4.220°N, 88.148°E IAU/IAG 2001
Ellipse center at −3.74 km MOLA elevation.
IP84A2 ellipse: 132 km × 16 km, oriented at 88°, IP96B2 ellipse: 135 km × 16 km, oriented at 91°
Viking IRTM Rock abundance: 13–15%

Gusev crater (MER-A)
Sediments deposited in a crater lake?
EP55A2 centered at:
  14.82°S, 184.85°W MDIM2
  14.64°S, 175.06°E MOLA
  14.640°S, 175.298°E IAU/IAG 2001
Ellipse center at −1.92 km MOLA elevation.
EP55A2 ellipse: 96 km × 19 km, oriented at 76°
Viking IRTM Rock abundance: 7–8%

Elysium “wind safe” (MER-B)
Unknown geology, possibly ancient highlands?
EP78B2 centered at:
  11.91°N, 236.10°W MDIM2
  11.73°N, 123.72°E MOLA
  11.73°N, 123.958°E IAU/IAG 2001
Ellipse center at −2.90 km MOLA elevation.
EP78B2 ellipse: 155 km × 16 km, oriented at 94°
IRTM Rock abundance 1–8%

---

at the “wind safe” site relates to the possibility of sampling reworked highland materials surrounding local inliers of possibly in situ Noachian highlands. The site displays few characteristics suggesting it is otherwise suited to achieving mission science objectives, but it joined Meridiani, Gusev, and Isidis as the four sites discussed at the final workshop (Table 5).

Activities at the fourth workshop concentrated on documenting scientific hypotheses related to the evolution of each site that could be tested using the Athena science payload. The purpose was to ensure that all ideas related to the setting of the sites had been vetted and to evaluate how the science instruments could distinguish between competing hypotheses. The workshop resulted in lists of scientific “pros” and “cons” for each site together with hypotheses and associated observations and measurements required to test them. The observations and measurements should form the basis for initial operations on Mars and confirmed Meridiani Planum and Gusev Crater as the top two science sites.

The Athena Science Team met shortly after the fourth Landing Site Workshop and made recommendations on favored sites (from the science perspective only) that closely match those made by the broader science community. The Science Team input was made on the basis of landing site science characteristics, objectives of the Athena investigation, the capabilities of the Athena payload and the MER rovers, and other factors that impact science return (e.g., mission lifetime).

Site safety evaluations were dealt with separately by the MER Project at JPL and resulted in a ranking of the sites, from highest to lowest, of Meridiani, Elysium, Gusev, and Isidis. All science and safety inputs were considered in generation of a final Project recommendation that was subjected to a thorough peer review prior to presentation to NASA Headquarters. On the basis of the MER Project recommendation and supporting presentations, the Associate Administrator for Space Science selected the Meridiani and Gusev Crater landing sites for the Mars Exploration Rovers on April 10, 2003.

7. Summary

The two-plus year process of identifying and evaluating landing sites for the 2003 Mars Exploration Rovers ended with selection of the Meridiani and Gusev sites by NASA’s Associate Administrator for Space Science in April, 2003. Beginning with definition of mission engineering requirements and accessible locations, the process employed open workshops to narrow ∼ 155 initial sites (included multiple ellipses for sites accessible by both rovers) to four: Meridiani and Gusev Crater were ranked highest for science, with the Isidis Basin and Elysium sites following in order (Table 5). Except for the Elysium site, all possess science and engineering characteristics deemed best suited to landing safely and achieving science objectives related to understanding the aqueous, climatic, and geologic history of Mars (Crisp, 2001; Weitz, 2001). The result has been extensive community participation in the evaluation of mineralogically and morphologically interesting sites (Figs. 2 and 3, Tables 4 and 5).

Acknowledgements

Reviews by George McGill and Dave Senske helped to improve the manuscript and are appreciated. Thanks to Ross Irwin for assistance in final preparation of the paper. Work was supported by NASA MDAP Grant NAG5-11198 to J. Grant and some of this work was carried out at and for the Jet

Propulsion Laboratory, California Institute of Technology, sponsored by NASA.

References

Arvidson, R.E., Seelos, F.P., IV, Deal, K.S., Koeppen, W.C., Snider, N.O., Kieniewicz, J.M., Hynek, B.M., Mellon, M.T., Garvin, J.B., 2003. Mantled and exhumed terrains in Terra Meridiani, Mars. J. Geophys. Res., in press.

Burr, D.M., McEwen, A.S., Sakimoto, S.E.H., 2002. Geophys. Res. Lett. 29, 10.1029/2001GL013345.

Cabrol, N.A., Grin, E.A., 1999. Distribution, classification, and ages of Martian impact crater lakes. Icarus 142, 160–172.

Cabrol, N.A., Grin, E.A., Dawidowicz, G., 1996. Ma'adim Vallis revisited through new topographic data: evidence for an ancient intravalley lake. Icarus 123, 269–283.

Cabrol, N.A., Wynn-Williams, D.D., Crawford, D.A., Grin, E.A., 2001. Recent aqueous environments in Martian impact craters: an astrobiological perspective. Icarus 154, 98–112.

Chapman, M.G., Tanaka, K.L., 2001. The interior deposits on Mars: sub-ice volcanoes?. J. Geophys. Res. 106, 10,087–10,100.

Christensen, P.R., Bandfield, J.L., Clark, R.N., Edgett, K.S., Hamilton, V.E., Hoefen, T., Kieffer, H.H., Kuzmin, R.O., Lane, M.D., Malin, M.C., Morris, R.V., Pearl, J.C., Pearson, R., Roush, T.L., Ruff, S.W., Smith, M.D., 2000. Detection of crystalline hematite mineralization on Mars by the thermal emission spectrometer: evidence for near-surface water. J. Geophys. Res. 105, 9623–9642.

Christensen, P.R., Morris, R.V., Lane, M.D., Bandfield, J.L., Malin, M.C., 2001. Global mapping of Martian hematite mineral deposits: remnants of water-driven processes on early Mars. J. Geophys. Res. 106, 23,873–23,885.

Crisp, J., 2001. Proposal information package for the Mars Exploration rover mission participating science program. NASA Announcement of Opportunity, NASA Headquarters Office of Space Science, Washington, DC.

Edgett, K.S., Rice Jr., J.R., 1995. Very young volcanic, lacustrine, and fluvial features of the Cerberus and Elysium Basin region, Mars. Lunar Planetary Science Conference XXVI. Lunar and Planetary Institute, Houston, TX, pp. 357–358.

Golombek, M., Grant, J.A., 2001. First Landing Site Workshop for the 2003 Mars Exploration Rovers. LPI Contributions, Vol. 1079. Lunar and Planetary Institute, Houston, TX.

Golombek, M., Parker, T., Scholfield, T., Kass, D., Crisp, J., Haldemann, A., Knocke, P., Roncoli, R., Lee, W., Adler, M., Bridges, N., Anderson, S., Grant, J., Squyres, S., 2001. Preliminary engineering constraints and potential landing sites for the Mars Exploration Rovers. Lunar Planetary Science Conference XXXII. Lunar and Planetary Institute, Houston, TX, abstract 1234.

Golombek, M., Grant, J.A., Parker, T.J., Schofield, T., Kass, D., Knocke, P., Roncoli, R., Bridges, N., Anderson, F.S., Crisp, J., Haldemann, A., Adler, M., Lee, W., Squyres, S.W., Arvidson, R., Carr, M.H., Weitz, C.M., 2002. Downselection of landing sites for the Mars Exploration rovers. Lunar Planetary Science Conference XXXIII. Lunar and Planetary Institute, Houston, TX, abstract 1245.

Golombek, M., Grant, J., Parker, T., Bridges, N., Anderson, S., Kass, D., Schofield, T., Zurek, R., Crisp, J., Haldemann, A., Adler, M., Lee, L., Knocke, P., Roncoli, R., Squyres, S., Arvidson, A., Carr, M., Kirk, R., Weitz, C., 2003. Selection of the Mars Exploration Rover landing sites. J. Geophys. Res., in press.

Greeley, R., Guest, J.E., 1987. Geologic map of the eastern equatorial region of Mars. US Geological Survey Miscellaneous Investigation Series, Map I-1802-B.

Greeley, R., Kuzmin, R.O., Nelson, D.M., Farmer, J.D., 2003a. Eos Chasma, Mars: a potential landing site for astrobiology. J. Geophys. Res., in press.

Greeley, R., Kuzmin, R.O., Rafkin, S.C.R., Michaels, T.I., Haberle, R., 2003b. Wind-related features in Gusev Crater, Mars. J. Geophys. Res., in press.

Grizzaffi, P., Schultz, P.H., 1989. Isidis basin: site of ancient volatile-rich debris layer. Icarus 77, 358–381.

Gulick, V.C., 1998. Mars Surveyor 2001 Landing Site Workshop. NASA Ames Research Center, Moffett Field, CA.

Gulick, V.C., 1999. Second Mars Surveyor Landing Site Workshop, SUNY at Buffalo. NASA Ames Research Center, Moffett Field, CA.

Irwin, R.P., Maxwell, T.A., Howard, A.D., Craddock, R.A., Leverington, D.W., 2002. A large paleolake basin at the head of Ma'adim Vallis, Mars. Science 296, 2209–2212.

Kass, D.M., Schofield, J.T., Rafkin, S.C.R., Toigo, A.D., Richardson, M.I., 2003. Analysis of atmospheric mesoscale models for entry, descent and landing. J. Geophys. Res., in press.

Lucchitta, B.K., 1989. Young volcanic deposits in the Valles Marineris, Mars. Icarus 86, 476–509.

Malin, M.C., Edgett, K.S., 2000. Sedimentary rocks of early Mars. Science 290, 1927–1937.

Marshall, J., Weitz, C., 1999. Workshop on Mars 2001: Integrated Science Preparation for Sample Return and Human Exploration. LPI Contributions, Vol. 9911. Lunar and Planetary Institute, Houston, TX.

McCauley, J.F., 1978. Geologic map of the coprates quadrangle of Mars. US Geological Survey Miscellaneous Investigation Series, Map I-897.

Milam, K.A., Stockstill, K.R., Moersch, J.E., McSween, H.Y., Tornabene, L.L., Ghosh, A., Wyatt, M.B., Christensen, P.R., 2003. THEMIS characterization of the MER Gusev Crater landing site. J. Geophys. Res., in press.

Nedell, S.S., Squyres, S.W., Anderson, D.W., 1987. Origin and evolution of the layered deposits in Valles Marineris, Mars. Icarus 70, 409–441.

Parker, T.J., Saunders, R.S., Schneeberger, D.M., 1989. Transitional morphology in west Deuteronilus Mensae, Mars: implications for modification of the lowland/upland boundary. Icarus 82, 111–145.

Parker, T.J., Gorsline, D.S., Saunders, R.S., Pieri, D.C., Schneeberger, D.M., 1993. Coastal geomorphology of the martian northern plains. J. Geophys. Res. 98, 11,061–11,078.

Plescia, J.B., 1990. Recent flood lavas in the Elysium region of Mars. Icarus 88, 465–490.

Scott, D.H., Tanaka, K.L., 1986. Geologic map of the western equatorial region of Mars. US Geological Survey Miscellaneous Investigation Series, Map I-1802-A.

Smith, D.E., Zuber, M.T., 1998. The relationship between MOLA northern hemisphere topography and the 6.1-mbar atmospheric pressure surface of Mars. Geophys. Res. Lett. 25, 4397–4400.

Smith, D.E., Zuber, M.T., Solomon, S.C., Phillips, R.J., Head, J.W., Garvin, J.B., Banerdt, W.B., Muhleman, D.O., Pettengill, G.H., Neumann, G.A., Lemoine, F.G., Abshire, J.B., Aharonson, O., Brown, C.D., Hauck, S.A., Ivanov, A.B., McGovern, P.J., Zwally, H.J., Duxbury, T.C., 1999. The global topography of Mars and implications for surface evolution. Science 284, 1495–1503.

Squyres, S.W., Arvidson, R., Bell, J.F., III, Carr, M., Christensen, P., Des Marais, D., Economou, T., Gorevan, S., Klingelhofer, G., Haskin, L., Herkenhoff, K., Knoll, A., Knudsen, J.M., Malin, M., McSween, H., Morris, R., Rieder, R., Sims, M., Soderblom, L., Wanke, H., Wdowiak, T., 1998. The Athena Mars rover science payload. Lunar Planetary Science Conference XXIX. Lunar and Planetary Institute, Houston, TX.

Weitz, C.M., 2001. Announcement of opportunity for the "Mars Exploration Rover Mission Participating Scientist Program." AO 01-OSS-04, NASA Headquarters Office of Space Science, Washington, DC.

Weitz, C., Parker, T., Bulmer, M., Anderson, F.S., Grant, J., 2003. Geology of the Melas Chasma candidate landing site for MER. J. Geophys. Res., 108,8082, doi:10.1029/2002JE002022.