MARS EXPLORATION ROVER LANDING SITE SELECTION. M. Golombek[1], J. Grant[2], T. Parker[1], D. Kass[1], J. Crisp[1], S. Squyres[3], M. Adler[1], A. Haldemann[1], M. Carr[4], R. Arvidson[5], C. Weitz[6] and R. Zurek[1], [1]Jet Propulsion Laboratory, Caltech, Pasadena, CA 91109, [2]Smithsonian Institution, Washington, D.C. 20560, [3]Cornell University, Ithaca, NY 14853, [4]U.S. Geological Survey, Menlo Park, CA 94025, [5]Washington University, St. Louis, MO 63130, [6]NASA Headquarters, Washington, DC 20546.

Introduction: Selection of the landing sites for the Mars Exploration Rovers has involved over 2 years of research and analysis effort that has included the participation of broad sections of the planetary sciences community through a series of open landing site workshops. The effort has included the definition of the engineering constraints based on the landing system, mapping those engineering constraints into acceptable regions and prospective sites, the acquisition of new information from Mars Global Surveyor and Mars Odyssey orbiters, the evaluation of science and safety criteria for the sites, and the downselection and final site selection based on the sites science potential and safety. The final landing sites (Meridiani Planum and Gusev crater) were selected by NASA Headquarters on April 11, 2003, prior to launch in June.

Engineering Requirements: Analysis of the entry, descent and landing system and atmospheric profiles for the season and time of arrival indicates that the MER spacecraft are capable of landing below –1.3 km, with respect to the MOLA defined geoid [1, 2, 3]. This requirement stems mostly from the need for an adequate atmospheric density column for the parachute to bring the spacecraft to the correct terminal velocity and provide enough time for the radar altimeter to measure the closing velocity, inflate the airbags and fire the solid rockets. Low-altitude winds and wind shear together are major concerns and are significant concerns and must contribute less than ~20 m/s to the horizontal velocity after correction.

Analyses of power generation/usage and thermal cycling of the rovers for the required 90 Sols restricts the landing sites to near the subsolar latitude at arrival. This translates to 5°N to 15°S for MER-A and 10°N to 10°S for MER-B, which arrives at Mars 21 Sols after MER-A. (The preliminary latitude constraint for MER-B was 15°N to 5°S, based on arriving 5 weeks after MER-A.) Operations considerations and optimal data relay through Mars orbiters require the two landing sites to be separated by a minimum central angle of 37° on the surface.

Because of the arrival geometry and prograde entry into the atmosphere, landing ellipse size and orientation change significantly with latitude and time of arrival. Preliminary analysis of the expected flight path angle at atmospheric entry and dispersions produced by the atmosphere for the opening of the launch period yield 3 sigma landing ellipses for MER-A that vary linearly in length and azimuth from 77 km by 30 km, oriented at 66° at 15°S to 219 km by 30 km, oriented at 88° at 5°N. For MER-B, preliminary 3 sigma landing ellipses vary linearly in length and azimuth from 130 km by 30 km, oriented at 79° at 10°S to 338 km by 30 km, oriented at 99° at 10°N. Changes to the size of the landing ellipses occurred several times through the selection process with final ellipses smaller than these.

Surface slopes are an obvious concern for the landing system. Steep slopes can spoof the radar altimeter and cause premature or late firing of the solid rockets and airbag inflation. Small slopes over large distances can lead to additional horizontal velocity and prolonged bouncing by the lander within the inflated airbags. Slopes over 10 m scale can also negatively affect the first few bounces, the stability of the lander, rover deployment and trafficability, and power generation. As a result, surface slopes should be <2° over 1 km; <5° over 100 m, and <15° over 5 m.

The MER airbags have been qualified to protect the lander from damage when landing on 0.5 m high rocks in any orientation. This requires a landing site with less than 1% of the surface covered by rocks greater than 0.5 m high. Model rock size-frequency distributions based on Viking, Mars Pathfinder and rocky locations on the Earth [4], generally suggest this requirement can be satisfied at locations with total rock coverage of <20% as derived from thermal infrared measurements [5].

The surface must be radar reflective for the descent radar altimeter to work properly, so radar reflectivity must be greater than ~0.03. The surface must be load bearing for the rover and lander and excessive dust would coat rocks, which are of prime scientific interest (but which can impede mobility), and could reduce surface lifetime by covering the solar panels. Extremely high albedo and low thermal inertia regions should therefore be avoided [6]. Areas with fine component thermal inertia of less than 125-165 J m^{-2} $s^{-0.5}$ K^{-1} or SI units should therefore be avoided [7, 8]. Extremely low temperatures likely at low thermal inertia, high albedo sites further requires bulk thermal inertia to be >250 and >200 SI units with albedos <0.26 and <0.18, respectively.

Potential Landing Sites: MOLA elevations were plotted within the 30° latitude band from 15°N to 15°S. Because the southern hemisphere of Mars is dominantly heavily cratered highlands, little area is actually below –1.3 km in elevation for the MER-A (5°N to 15°S). The largest region below this elevation is in southern Elysium and Amazonis Planitiae. Unfortunately, most of this area (150°W to 200°W) is dominated by extremely low thermal inertia, with fine component thermal inertias below 125 and so is excluded. For the initial latitude band of MER-B (15°N to 5°S), more area is below –1.3 km elevation. Nevertheless, most of the area between 135°W and 190°W is excluded on thermal inertia grounds. Areas available to seek landing sites are thus reduced to southern Isidis and Elysium Planitiae in the eastern hemisphere and western Arabia Terra, Terra Meridiani, Xanthe Terra, Chryse Planitia, and the bottom of Valles Marineris in the western hemisphere, which is just ~5% of the surface area of Mars.

Landing ellipses were placed in all locations that are below –1.3 km in elevation, have acceptable fine component thermal inertia values, and are free of obvious hazards in the MDIMs (Mars Digital Image Mosaics). Only site ellipses that appear smooth and flat in the MDIM without scarps, large hills, depressions or large fresh craters (>5 km) were acceptable.

Nearly 200 potential landing sites meet these criteria: 100 sites for MER-A and 85 for MER-B. Even though the area available to land north of the equator is at least twice as great as south of the equator, the smaller ellipse size towards the south compensates. Geologic units accessible are diverse and range from Noachian Plateau 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.

Downselection Process: Following the First Landing Site Workshop for MER held January 2001, at NASA Ames Research Center, Mountain View, CA, roughly 25 sites from a possible ~185 were selected on the basis of their science potential [1, 2] and targeted for MOC (Mars Orbiter Camera) imaging. These included sites in Valles Marineris (e.g., Melas and Eos), possible crater lakes (e.g., Gale, Gusev and Boedickker), and sites in Terra Meridiani, Isidis and Elysium Planitiae. The basic characteristics of these sites were then investigated in more detail and the engineering constraints on the landing sites were better defined.

The remaining 25 sites were discussed at the Second Landing Site Workshop, October 2001, in Pasadena, CA [2]. This workshop focused on evaluation of the science that can be accomplished at each site. Each site had a science spokesperson who discussed the science potential, the testable hypotheses, and specific measurements and investigations possible by the Athena science instruments at that site. In addition, safety considerations for the sites were discussed (ellipses did not fit within some prospective sites). Consensus was reached on 4 prime sites and 2 backups. Ellipse locations were moved slightly after the workshop to improve their science potential or safety.

Top 6 Landing Sites: Presentations at the second workshop [2] indicate all of the sites show evidence for surface processes involving water and appear capable of addressing the science objectives of the MER missions, which are to determine the aqueous, climatic, and geologic history of sites on Mars where conditions may have been favorable to the preservation of evidence of possible pre-biotic or biotic processes. TES spectra indicate coarse-grained hematite distributed across a basaltic surface at the Hematite site, suggesting precipitation from liquid water or a hydrothermal deposit [9]. MOC images of the center of the Melas ellipse show what appear to be layered sediments likely deposited in standing water [10]. Gusev has been interpreted as a crater lake with interior sediments deposited in standing water [11]. The ellipse in southernmost Isidis Planitia is located to sample ancient Noachian rocks shed off the highlands [12] that might record an early warm and wet environment as suggested by abundant valley networks. Athabasca Vallis is an extremely young outflow channel with young volcanics that might contain hydrothermal deposits [13]. Eos Chasma is located to sample a variety of materials draining a lake in Vallis Marineris [14].

Comparison of the thermophysical properties of the sites [5, 6, 7, 8] with the Viking (VL) and Pathfinder (MPF) landing sites allows an interpretation of their surface characteristics. The Hematite site has moderate thermal inertia and fine component thermal inertia and very low albedo. This site will likely look very different from the three previous landing sites in having a darker surface, few rocks and little dust. Melas Chasma has moderate thermal inertia and fine component thermal inertia and low albedo. This site will likely be moderately rocky but with less dust than the MPF and VL landing sites. Gusev crater has comparable thermal inertia, fine component thermal inertia and albedo to the VL sites and so will likely be similar to these locations, but with fewer rocks. The Athabasca Vallis site has high albedo and moderate thermal inertia, suggesting a moderately rocky and dusty site. The Isidis and Eos sites have high to very high thermal inertias suggesting a crusty surface. The Isidis site has moderate albedo and a high red/blue ratio, suggesting a rocky weathered crusty surface without too much dust. Eos has low albedo, suggesting a rocky and crusty surface with some dust.

3rd Workshop Results: Evaluation of the 6 high priority landing sites indicated serious engineering/safety concerns at three of them (Melas, Eos, and Athabasca) [3]. Engineering sensitivity studies identified 3 dominant concerns for the MER landing system: (1) horizontal winds and wind shear at a few kilometers altitude, while the spacecraft is on the parachute, which could impart horizontal velocity to the lander, (2) surface slopes at the scale of the airbags, which is equivalent to adding a horizontal velocity to the lander, and (3) rocks at the surface that could rip the outer airbag layers or stress the interior bladders and must be cushioned from the lander during impact. Models of horizontal winds and wind shear at the two sites within Valles Marineris (Melas and Eos) appear to be near or beyond the limit of the capabilities of the landing system and were removed from further consideration. Slopes at these sites were also dangerous. Preliminary engineering analyses suggest that the landing system may be able to accommodate slightly non-optimal conditions for 1 or 2, but not all 3 of these dominant engineering concerns. High radar backscatter at the Athabasca site suggested a rough untrafficable surface. As a result, Athabasca was demoted to a backup site and later removed from further consideration. Isidis was promoted from a backup to a prime site, and a search was made for an additional safe low-wind site.

Search for Low Wind Site: The search for a safe, low-wind site involved identifying atmospherically quiet regions in 2 global circulation models (GCM) for the season and time of arrival [15, 16]. Because low winds were the prime consideration, latitudinal and elevation constraints were relaxed from those originally considered [1] to include areas up to 15°N and areas up to 0 km elevation. Four potential areas were investigated: east of the existing Meridiani site, southeast of Isidis, Elysium and the area south and east of Viking Lander 1. The area south and east of Viking Lander 1 was found to be a region of strong storm tracks and so was omitted from further consideration. Regional mesoscale wind models were evaluated for each remaining region [17]. A handful of prospective sites were identified in each area and evaluated in terms of science potential and safety. The sites east of Meridiani are likely too cold (i.e., low thermal inertia) and too close to the existing site (thereby reducing data return) and the areas southeast of Isidis had low science appeal. The sites with the highest science interest were in the highland/lowland boundary in Elysium Planitia. They are located on a Hesperian-age surface transitional between the highlands and lowlands and may preserve reworked Noachian highlands (EP78B2 ellipse is 155 km by 16 km oriented at an azimuth of 94° at 11.91°N, 236.10°W and EP80B2 ellipse is 165 km by 15 km oriented at an azimuth of 95° at 14.50°N, 244.63°W in MDIM2 coordinates).

Elysium Site Selection: Both Elysium ellipses were targeted for the acquisition of new MOC and Thermal Emission Imaging System (THEMIS) images and safety and science potential were evaluated. Comparison of the thermophysical properties [5, 6, 7, 8] of Elysium with the Viking and Pathfinder landing sites indicates that the Elysium ellipses have comparable thermal inertia, fine component thermal inertia and albedo to the Viking sites and so will likely be as dusty as these sites, but with fewer rocks. Rock abundance estimates from thermal differencing techniques show an average of 5% at EP78B2 and 9% at EP80B2. EP78B2 also appears smoother than EP80B2 in: Mars Orbiter Laser Altimeter (MOLA) estimates of 1.2 km scale adirectional and bi-directional slopes, 100 m scale MOLA pulse spread [18], extrapolations of the 100 m relief from Hurst exponent fits to the Allen variation at longer baselines [19], and 6 MOC images and 4 THEMIS images per ellipse that had been acquired. High-resolution mesoscale wind models [17] for the 2 sites show slightly lower horizontal winds are expected at EP78B2 (similar to Meridiani) than EP80B2 (similar to Gusev), with similar estimates of wind shear and turbulence (both sites are comparable to Meridiani, but slightly more turbulent). EP78B2 is also slightly farther south so solar power should be greater. Science evaluation showed no strong preference of one site over the other. Both sites appear to be on reworked highlands material. EP80B2 has greater relief, but less thermophysical variation in THEMIS thermal images with more dust and sand dunes in the lows. On the basis of these evaluations, EP78B2 was selected as one of the final 4 ellipses and EP80B2 was eliminated at a meeting of the Mars Landing Site Steering Committee and the THEMIS team at Arizona State University in August 26-27, 2002.

Science and Safety: Further discussion and evaluation of these four landing sites took place at the 4th MER Landing Site Workshop (January 2003 in Pasadena, CA). The 4th Workshop focused on the identification of testable hypotheses at the 4 sites, the definition of the observations that can be made by MER to test the hypotheses and the measurements that can be made by the Athena payload to carry out these investigations. Results show that measurements by the Athena payload should be able to distinguish most of the competing hypotheses for the origin of the sites by observing rock textures and fabrics as well as rock mineralogy and chemistry.

The results of the 3rd and 4th workshops indicate that the Meridiani and Gusev sites most directly address MER scientific objective because they have strong mineralogical and geomorphological indicators of liquid water in their past, respectively. Isidis and Elysium may also address these scientific objectives if Noachian rocks are preserved at the sites and either formed in a warmer and wetter past or were deposited by liquid water.

A major science objective at the Meridiani Planum site is to determine what process formed the hematite, which is inferred from analyses of Thermal Emission Spectrometer data to cover approximately 15 to 20 percent of the surface [9]. Preferred mechanisms for the hematite formation include direct precipitation from oxygenated, iron-rich water in a lake [20], or precipitation from iron-rich hydrothermal fluids involving water percolating through the ground at high temperatures, or low-temperature dissolution and precipitation (*i.e.*, leaching) [21]. Geologic hypotheses for the origin of the hematite deposits include deposition in an ancient lake, as a volcaniclastic unit within a stack of ancient Noachian units emplaced either directly as discrete grains or within glassy coatings, or via alteration after burial of the deposits, or as magnetite rich lavas that have undergone high-temperature alteration. The Athena payload is particularly well suited to measure iron rich minerals and thus should be able to differentiate among these hypotheses.

Gusev is a Noachian-age, flat-floored crater that is 160 kilometers in diameter and close to the highland-lowland boundary south of Elysium [11]. Its southern rim is breached by Ma'adim Vallis, which, at 800 kilometers long, up to 25 kilometers wide, and 2 kilometers deep, is one of the largest branching valley networks on the planet and may drain a large area of the highlands [22]. Ma'adim Vallis appears to have been cut by running water, so that the crater would have filled with sediment carried in a standing body of water before it exited through a gap in the northern rim of the crater. A landing in Gusev therefore would provide an opportunity to study fluvial sediments derived from the southern highlands and deposited in a lacustrine environment. Such sediments may preserve important clues about environmental conditions on early Mars, which are, of course, of particular interest for determining the planet's potential habitability.

Evaluation of the dominant three safety criteria (slopes, rocks and winds) indicates that Meridiani is probably the most benign site, followed closely by Elysium, and then Gusev and Isidis [23]. Specifically, horizontal winds and wind shear are lowest at Meridiani and Elysium and higher at Gusev and Isidis. Rock abundance is lowest at Meridiani and Elysium, slightly higher at Gusev and higher still at Isidis. Slopes at the scale of the airbags are in order of increasing slopes: Meridiani, Elysium, Isidis and Gusev.

Selection: Winds, slopes and rocks were incorporated in a sophisticated simulation of entry, descent and landing by the project to determine the relative safety of the 4 sites. The landing simulations show that most of the simulated landing events are within the design specifications of the landing system at all four sites. The landing simulations also show, however, slightly more out of specification landing events at ellipses in Gusev crater and Isidis Planitia (consistent with the potentially higher winds, slopes and rocks at these sites) than at Meridiani Planum and Elysium Planitia. To balance science return and safety, NASA Headquarters selected Meridiani Planum and Gusev crater for the MER landing sites. To maximize surface lifetime and science return, the first landing will be targeted to Gusev crater on January 4, 2004 and the second landing will be targeted to Meridiani Planum on January 25, 2004.

References: [1] Golombek M. et al. (2001) *LPS XXXII,* Abs. #1234. [2] Golombek M. et al. (2002) *LPS XXXIII,* Abs. #1245. [3] Golombek M. et al. (2003) *LPS XXXIIII,* Abs. #1754. [4] Golombek, M., & Rapp, D. (1997) *JGR* 4117-4129. [5] Christensen P. R. (1986) *Icarus, 68*, 217-238. [6] Christensen P. R. & Moore H. J. (1992) in MARS, U. Ariz. Press, 686-727. [7] Christensen P. R. (1982) *JGR 87*, 9985-9998; (1986) *JGR 91*, 3533-3545. [8] Mellon M. T. et al. (2000) *Icarus 148,* 437-455. [9] Christensen P. et al. (2000) *JGR 105*, 9623-9642. [10] Weitz C. et al. (in press) JGR. [11] Grin E. & Cabrol N. (1997) *Icarus 130,* 461-474. [12] Crumpler L. et al. (2001) *LPS XXXII,* Abs. #1977; (in press) JGR. [13] Burr D. et al. (2002) *GRL 29*, 10.1029/2001GL013345. [14] Greeley R. et al. (in press) JGR. [15] Pollack J. et al., (1990) *JGR 95*, 1447-1473, 1990. Joshi M. et al., (2000) *JGR 105*, 17,601-17,615. [16] Richardson M. & Wilson R. (2002) *JGR 107* 10.1029/2001JE1536. [17] Rafkin S. et al., (2001) *Icarus 151*, 228-256. [18] Smith D. E. et al. (2001) *JGR 106*, 23,689-23,722. [19] Haldemann, A. & Anderson S. (2002) *Eos Trans. AGU*, *83*, Abs. P22A-0390. [20] Christensen P. et al. (2001) *JGR 106*, 23873-23886. [21] Arvidson R. et al. (in press) *JGR*. [22] Irwin R. et al. (2002) *Science 296*, 2209-2212. [23] Golombek M. et al. (in press) JGR.