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The science process for selecting the landing site for the 2011 Mars Science Laboratory

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ABSTRACT

The process of identifying the landing site for NASA's 2011 Mars Science Laboratory (MSL) began in 2005 by defining science objectives, related to evaluating the potential habitability of a location on Mars, and engineering parameters, such as elevation, latitude, winds, and rock abundance, to determine acceptable surface and atmospheric characteristics. Nearly 60 candidate sites were considered at a series of open workshops in the years leading up to the launch. During that period, iteration between evolving engineering constraints and the relative science potential of candidate sites led to consensus on four final sites. The final site will be selected in the Spring of 2011 by NASA's Associate Administrator for the Science Mission Directorate. This paper serves as a record of landing site selection activities related primarily to science, an inventory of the number and variety of sites proposed, and a summary of the science potential of the highest ranking sites.

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1. Introduction

The selection of the landing site for the National Aeronautics and Space Administration (NASA) 2011 Mars Science Laboratory (MSL) rover plays a crucial role in the success of the mission. Although this paper emphasizes science activities related to selection of the MSL landing site, a myriad of orbital datasets from multiple missions were utilized to characterize each potential landing site from a science and engineering standpoint. The objective of all landing site activities is to maximize the chance of landing safely with access to high-priority science targets.

Science and engineering characterization of the landing sites emphasizes data from the Mars Reconnaissance Orbiter (MRO) Compact Reconnaissance Imaging Spectrometer for Mars (CRISM, see Murchie et al., 2007), High Resolution Imaging Science Experiment (HiRISE, see McEwen et al., 2007), and Context Camera (CTX, see Malin et al., 2007) instruments, Mars Odyssey Thermal Emission Imaging System (THEMIS, see Christensen et al., 2004) instrument, Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC, see Malin et al., 1992), Mars Observer Laser Altimeter (MOLA, see Zuber et al., 1992), and the Mars Express Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA, Bibring et al., 2004) spectrometer and High Resolution Stereo Camera (HRSC, Jaumann et al., 2007).

The safe delivery of MSL to Mars' surface also depends upon the characterization of the atmosphere through which the spacecraft flies. The MSL spacecraft's entry, descent, and landing system involve a guided entry, parachute deployment, and a rocket-powered terminal descent to the surface. A team of atmospheric scientists has been advising the mission and providing model-based predictions of atmospheric density, winds, and the probabilities and effects of dust storms at the MSL arrival season. These atmospheric assessments will be described in a separate publication; here we focus on the terrain.

The inferred geologic setting of the site must lend confidence that the rocks and outcrops suitable for achieving core science objectives (Grotzinger, 2009; Table 1) are present and accessible. While both science and engineering aspects of landing site selection are critical to mission success, the engineering constraints trump science because there is no science return unless the mission lands safely on the surface of Mars. This paper provides a summary of the landing site selection process for the MSL rover with emphasis on the science activities related to selecting the optimal site.

Due to the diverse nature of the Martian surface and quantity of data available, the Mars science community was enlisted to assist in the site selection process via a series of workshops that were open to the science community and public. The process is modeled after the successful Mars Exploration Rover (MER) site selection process

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Table 1
Science Criteria used to guide the evaluate of the landing sites proposed for the Mars Science Laboratory Rover.

Criteria	Description
Diversity	To mitigate the risk of disappointment and ensure the greatest chance for science success, we want the greatest number of possible morphologic and mineralogic science objectives at a chosen landing site
Context	Rocks and soils investigated by the MSL rover must be put into a larger, more regional context. This regional context is important for constraining the past processes which may have led to habitable environments. How much of what will be observed by the rover can be placed into a geologic framework before landing?
Habitability	To identify a particular geologic environment (or set of environments) that would support microbial life and can be assessed and interrogated by the MSL rover
Fossils/biosignature preservation	How might have early preservation of organic matter and/or delicate textures proceeded on Mars and be evaluated?

Table 2
NASA Mars Science Laboratory Landing Site Steering Committee.

Co-Chairs	Affiliation
John Grant	Smithsonian Institution
Matthew Golombek	Jet Propulsion Laboratory
Members	**Affiliation**
Philip Christensen	Arizona State University
Dave Desmarais	NASA Ames Research Center
John Grotzinger	California Institute of Technology
Virginia Gulick	NASA Ames Research Center/SETI Institute
Bruce Jakosky	University of Colorado
Michael Malin	Malin Space Science Systems
Doug Ming	NASA Johnson Space Center
Richard Morris	NASA Johnson Space Center
John Mustard	Brown University
Timothy Parker	Jet Propulsion Laboratory
Roger Phillips	Washington University
Dawn Sumner	University of California Davis
Kenneth Tanaka	United States Geological Survey, Flagstaff
Rich Zurek	Jet Propulsion Laboratory

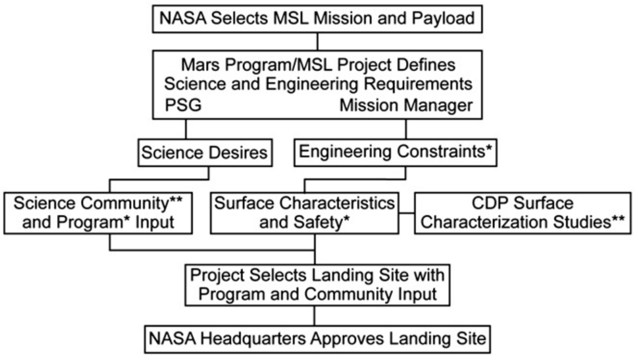


Fig. 1. Flow chart depicting major events related to science and engineering that enables selection of the MSL landing site. Input to the process by the science community is focused by the Landing Site Steering Committee and community co-chair (left side) to ensure comprehensive proposal and evaluation of all candidate sites by the MSL Project and NASA. The JPL Mars Exploration Program co-chair of the Landing Site Steering Committee works closely with the Project engineering teams and science community to facilitate evaluation of the sites including critical issues related to site certification. Ultimately, the MSL Project forms a recommendation on the candidate sites based on the science and engineering findings and that recommendation is presented to NASA's Associate Administrator for the Science Mission Directorate to be used in his or her selection of the landing site. (* denotes JPL Mars Exploration Program input to the process; ** denotes External Science Community input to the process.).

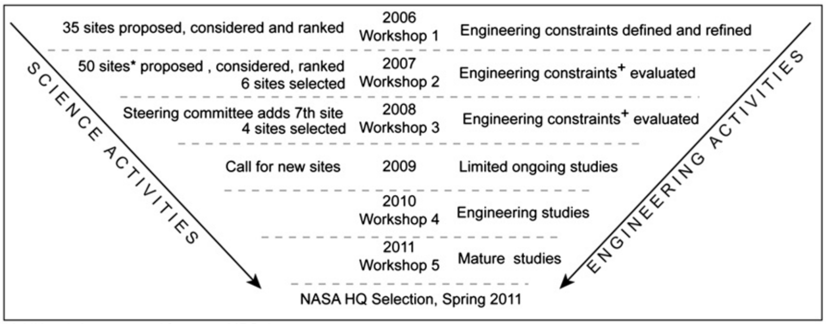
(Golombek et al., 2003; Grant et al., 2004). Cooperation between the MSL science and engineering teams (hereafter referred to as the "MSL Project" or "Project") and the science community is essential to the success of the process and is accomplished in part via oversight by a NASA-appointed Mars Landing Site Steering Committee (Fig. 1, Table 2). The Committee, co-chaired by a member of the Mars Exploration Program Office at the Jet Propulsion Laboratory (JPL) (Dr. Matthew Golombek) and a member of the science community (Dr. John Grant), includes members of the MSL Project, the MSL Sample Analysis at Mars (SAM) instrument suite, Mast Camera (Mastcam), Mars Hand Lens Imager (MAHLI), and Mars Descent Imager (MARDI), and Chemistry and Mineralogy X-Ray Diffraction Instrument (CheMin) science teams, and members of the science community with a range of scientific expertise (Table 2). The Steering Committee helps to ensure the process includes the broader science community, remains focused, on schedule, and emphasizes candidate sites with the highest science potential. Activities include advertising requests to propose candidate sites, convening open community workshops where the science merit of candidate sites is discussed, and helping to ensure that all relevant data are made available and used in the proposal, consideration, and selection of candidate sites. The science community, via the Steering Committee, advises the Project on the relative potential merits of candidate sites, which is ultimately selected by NASA's Associate Administrator for the Science Mission Directorate.

The science community and NASA are updated on the MSL site selection process via presentations at professional conferences (e.g., Golombek et al., 2006, 2007a, 2007b, 2008, 2010; Griffes et al., 2006, 2007, 2008a, 2008b; Smrekar et al., 2007), Mars Exploration Program Assessment Group (MEPAG) meetings, NASA Headquarters briefings, and presentations to the National Academies Committee on Planetary Exploration (COMPLEX) and Committee on the Origins and Evolution of Life (COEL). These presentations also serve to advertise upcoming community workshops. In addition, summaries of all activities, workshops, and workshop presentations are available online through NASA Ames Research Center (http://marsoweb.nas.nasa.gov/landingsites/) and the United States Geological Survey (USGS) (http://webgis.wr.usgs.gov/) websites.

2. Beginning the process of selecting the landing site for MSL

The landing site selection process focused on identifying and evaluating the best sites for the MSL rover to achieve science objectives related to the habitability of Mars (Grotzinger, 2009; Table 1). Activities began in earnest in 2006 (Fig. 2), well in advance of the original 2009 launch date and before MRO arrived in its mapping orbit, so that an initial list of potential sites would be ready for MRO. Initial discussions focused on the structure of the site selection process (e.g., number and format of community workshops) and identification and appointment of a MSL Landing Site Steering Committee (Table 2) to help guide input from the science community. Recognition of the need to involve additional people in the process, possessing experience in past and ongoing missions and site selection, led to solicitation of, and participation by, a variety of people in the science community and at NASA. In addition, the co-chairs of the Landing Site Steering Committee worked closely with NASA Headquarters, the MRO Project and the MSL Project to define the number and rate at which MRO images of candidate landing sites would be targeted and obtained.

A key element of the MRO imaging plan involved rapid release of data to scientists for further evaluation of their proposed site, thereby making data of scientifically interesting locations on Mars



*Additional sites proposed from new MRO data
+ Rock abundance, elevation, latitude, etc.

Fig. 2. Timeline of the converging, iterative steps taken to introduce and evaluate candidate landing sites via a series of open workshops attended by the MSL Project, Landing Site Steering Committee, and science community. The science merit of each of the ~60 candidate sites proposed through the first three workshops was considered. Several high priority sites were narrowed to four final candidate sites in 2010 (Table 5), which will be intensively studied prior to recommendation of the final site by the MSL Project and selection by NASA in 2011.

available to the science community before their regular release date. High resolution data from MRO of all sites proposed at the first community workshop were obtained before the second community workshop to enable further detailed analyses and discussion of the relative merits and risks of each site. The Steering Committee and MSL Project also depend on the work of investigators funded by the Mars Exploration Program through its Critical Data Analysis Program (CDP) to provide key higher-level data products that enable site characterization.

The first science community workshop, held in June, 2006, was attended by well over 100 people. The workshop was preceded by the initial definition of mission engineering parameters to constrain latitudinal range, elevation, surface temperature, roughness, rock abundance, and acceptable slopes (Table 3). These constraints were established by the MSL Project to maximize the likelihood of landing safely and ensuring rover trafficability while also opening up more of Mars to exploration than previous missions through larger latitude and elevation bounds and a significantly smaller landing error ellipse size (Table 3, Grant et al., 2004). Satisfying these constraints is paramount, as failure to land safely or to traverse after landing would result in reduced science from MSL. Engineering constraints were modified as the mission design matured (Table 3). Another unique aspect of the MSL mission is the possibility of “go to” sites, for which the rover would be expected to traverse outside of its landing ellipse to access the primary science target.

The science potential of the 33 landing sites proposed at the first science community workshop (Table 4, Fig. 3) that satisfied the initial engineering constraints were evaluated and ranked. All sites were characterized using geomorphic and/or spectroscopic evidence for settings that would satisfy the scientific objectives of MSL (Grotzinger, 2009). The resultant ranking of high, medium, or low based on science merit relative to MSL mission objectives and engineering constraints determined the priority for imaging by MRO and other orbiters (e.g., Mars Odyssey). The proposed sites were distributed across a wide range of elevations and latitudes, but the vast majority of the candidate sites were at elevations below 0 km (relative to the MOLA datum) and between 30° north and south of the equator.

Following the first community workshop, the co-chairs of the Landing Site Steering Committee together with the MRO science team targeted and imaged all sites remaining under consideration (a few were withdrawn by the proposers). These data were collected at the rate of ~3–5 targets per two week imaging cycle and required careful targeting (typically in coordination with the person proposing the site) of location and distribution within proposed ellipses to maximize the ability to assess science

Table 3
Summary of landing site engineering constraints and safety criteria for the Mars Science Laboratory (MSL) rover.

Engineering parameter	Requirement for landing sites	Notes/rationale
Latitude	30°N to 30°S[a]	Sites poleward of 30°N have degraded EDL communication
Elevation	< 0 km[b]	Relative to the Mars Orbiter Laser Altimeter (MOLA) datum
Radius and azimuth of landing Ellipse	≤ 12.5 km (down-track direction) ~10 km (cross-track direction)	Allows for wind-induced uncertainty during parachute descent
Terrain relief/ slopes	2–10 km length scale: $\leq 20°$	Radar spoofing in preparation for powered descent. Also applies to “warning track” region
	1–2 km length scale: ≤ 43 m relief at 1 km, linearly increasing to 720 m and 2 km	Radar spoofing in preparation for powered descent
	200–500 m length scale: ≤ 43 m relief	Control authority and fuel consumption during powered descent
	2–5 m length scale: $\leq 15°$	Rover landing stability and trafficability in loose granular material
Rock height	≤ 0.55 m	Probability that a rock > 0.55 m high occurs in random sampled area of 4 m^2 should be $< 0.50\%$ (suggests low to moderate rock abundance)
Radar reflectivity	Ka band reflective	Adequate Ka band radar backscatter cross-section (> -20 dB and < 15 dB)
Load bearing surface	Not dominated by dust	Thermal inertia $> 100\ \mathrm{J\ m^{-2}\ s^{-0.5}\ K^{-1}}$ and albedo < 0.25; radar reflectivity > 0.01 for load bearing bulk density
Surface winds for thermal environment[c]	During operation: < 15 m/s (steady) < 30 m/s (gusts) Non-Operation (sleeping): < 40 m/s (steady)	Constraints apply over all seasons and times of day, at 1 m above the surface. These constraints provide an environment in which the rover can perform science operations

[a] Updated after second workshop from original requirement of 45°N to 45°S.

[b] Updated in August 2009 from original requirement of $\leq +1$ km.

[c] Initial constraints now replaced by spacecraft performance tests using numerical models of Mars’ atmosphere.

Table 4
Summary of landing sites (sorted by East longitude) proposed for the Mars Science Laboratory Rover between June 2006 and December 2009. Number corresponds to location of candidate site in Fig. 3.

Location in Fig. 3	Site name[a]		Center of proposed ellipse			Target	Proposer(s)	Date proposed[b]
			Lat. (°N)	Lon. (°E)	Elev. (km)			
1	Melas Chasma		−9.8	283.6	−1.9	Paleolake, sulfates	C. Quantin, C. Weitz, R. Williams, G. Dromart, N. Mangold	W1
2	Western Candor Chasma		−5.5	284.5	2.0	Sulfates, layered deposits	N. Mangold, J.P. Bibring, A. Gendrin, C. Quantin, F. Poulet, J.F. Mustard, S. Pelkey	W1
			−5.5	284.5	2.0		S. Murchie, CRISM team	W2
3	Eastern Melas Chasma		−11.6	290.5	−5.8	Layered deposits	M. Chojnacki, B. Hynek	W1
4	Juventae Chasma		−4.5	297.5	−2.0	Layered sulfates	M. Golombek, J. Grotzinger	W1
			−4.8	296.8	−2.7	Sulfates	J.L. Bishop, M. Parente, D. Catling	W2
5	Ritchey crater		−28.3	308.9	−1.2	Clays, alluvial/fluvial deposits	R. Milliken	W2
6	Xanthe Terra		2.3	309.0	−2.0	Delta deposit	C. Popa, F. Esposito, L. Colangeli	Dec 2009
7	Northern Xanthe		8.0	312.7	−1.0	Hypanis Vallis highlands, valley walls	L. Crumpler	W1
			6.9	312.8	−1.0			
			11.4	314.7	−2.6			
8	ShalbatanaVallis		7.0	317.0	−1.3	Phyllosilicates	N. Demidov, A. Behar, I. Mitrofanov, DAN Science Team	W1
9	Eos Chasma Alluvial		−13.4	317.5	−3.5	Alluvial fan	R. Kuzmin, DAN Science Team	W1
10	Argyre		−49.7	316.0	unspecified	Ancient basin bedrock	B. Cohen	W1
11	Argyre		−56.3	318.0	−2.7	Glacial/lacustrine features	J. S. Kargel, J. M. Dohm	W1
			−55.2	322.4	−2.7			
12	Eos Chasma		−10.7	322.0	−3.8	Quartz or silica-rich materials, aqueous geomorphology	V. E. Hamilton, S. L. Cady, P. J. Boston	W1
13	Hale crater		−35.7	323.4	−2.4	Gullies	W. E. Dietrich, J. Schieber, B. Hallet, K. S. Edgett, M. C. Malin	W1
14	Valles Marineris		−3.8	324.6	−4.0	Floor/walls	J. George, S. Clifford	Dec 2009
15	Holden crater[c]		−26.7	325.0	−2.0	Layered fluvial and lacustrine materials, fans	M. C. Malin, K. S. Edgett	W1
			−26.4	325.1	−1.9		R. P. Irwin, J. A. Grant	
			−26.4	325.1	−1.9		J. Rice	
16	Eberswalde crater[d]		−24.0	325.6	−0.6 to −0.4	Layered deposits, fan delta, channels	J. Schieber, K. Edgett and M. Minitti	W1
			−23.8	327.0	−0.7 to −0.6			
			−23.9	326.7	−1.5		J. Rice	
			−23.0	327.0	−1.5		J.L. Dickson, C.I. Fassett, J.W. Head, M.A. Kreslavsky, J.B. Madeleine, and M.A. Ivanov	
17	Tiu Valles		22.9	327.8	−3.8	Fluvial and lacustrine deposits	F. Gómez, J. A. Rodriguez-Manfredi, J. Gomz-Elvira	W2
18	Ladon basin		−18.8	332.5	−2.1	Chloride and nearby phyllosilicates	P. Christensen, M. Osterloo, V. Hamilton, J. Bandfield, T. Glotch, A. Baldridge, F. S. Anderson, L. Tornabene	Dec 2009
19	Wirtz crater		−49.0	334.0	−0.6	Gullies	W. E. Dietrich, J. Schieber, B. Hallet, K. S. Edgett, M. C. Malin	W1
20	Margaritifer basin		−11.7	337.3	−2.2	Fluvial deposits	K. K. Williams, J. A. Grant, C. M. Fortezzo	W1
			−12.8	338.1	−2.1			
21	Samara Vallis		−23.6	339.8	−1.0	Valley networks, fluvio-lacustrine basin	R. Kuzmin, DAN Science Team	W1
22	Mawrth Vallis[e]	site 0	24.5	338.9	−3.0	Noachian layered phyllosilicates	J.-P. Bibring	W1
		site 1	24.7	340.1	−3.1		J. Michalski, E. Z. Noe Dobrea, J. Bishop, J. Wray, R. Fergason, J.-P. Bibring, W. Farrand, N. Mangold, F. Poulet	W1
		site 2	24.0	341.0	−2.3		J.-P. Bibring	W1
							N. Mangold, J.-P. Bibring, F. Poulet, D. Loizeau, J. Michalski	W3
		site 3	23.2	342.2	−3.4		J.-P. Bibring	W1
		site 4	24.9	339.4	−3.4		J.-P. Bibring	W3

Table 4. (*continued*)

23	Iani Chaos	−1.6	341.8	−2.5 to −2.8	Hematite- and sulfate-rich layered sediments	T. Glotch	W1
		−2.6	342.2	−2.7			
		−2.1	342.3	−2.8			
24	Margaritifer Terra Chloride Site 10	−13.1	345.3	−1.2	Chloride salts	P. Christensen, M. Osterloo, V. Hamilton, J. Bandfield, T. Glotch, A. Baldridge, F. S. Anderson, L. Tornabene	W2
25	Becquerel crater	21.5	351.4	−3.6 to −3.8	Layered deposits	J. C. Bridges, M. Balme	W1
		21.3	352.5	−3.6 to −3.8			
26	Chloride west of Miyamoto crater (site 17)	−3.2	351.6	−1.6	Chloride salts	P. Christensen, M. Osterloo, V. Hamilton, J. Bandfield, T. Glotch, A. Baldridge, F. S. Anderson, L. Tornabene	June 2008
27	Miyamoto crater[f], Southwestern Meridiani (formerly Runcorn)	−1.8	352.4	−2 to −1.7	Layered deposits, hematite	H. Newsom	W1
		−3.5	352.3	−1.9	Layered phyllosilicates and chloride deposits, inverted channels	H. Newsom, A. Ollila, N. Lana, V. Hamilton, S. Wiseman, R. Arvidson, T. Roush, CRISM Team	W2
		−3.4	352.6	−2.0	Phyllosilicates, sulfates, adjacent to hematite-bearing plains	S. M. Wiseman, R.E. Arvidson, F. Poulet, S. Cull, J.L. Griffes, S. Murchie, H. E. Newsom, CRISM Team	
28	East Margaritifer Terra	−5.6	353.8	−1.3	Chlorides, phyllosilicates	P. Christensen, M. Osterloo, V. Hamilton, J. Bandfield, T. Glotch, A. Baldridge, F. S. Anderson, L. Tornabene	Dec 2009
29	Meridiani Planum bench	8.3	354.0	∼−1 to−1.5	Hematite- and sulfate-rich layered sediments	A. D. Howard, J. M. Moore	W1
		7.9	354.0				
		8.4	354.5				
30	South Meridiani Planum	−3.3	354.4	−1.6	Sulfate plains and phyllosilicate uplands	R. Arvidson, S. Wiseman	June 2008
		−3.1	354.6			R. Arvidson, S. Wiseman	W3
						D. C. Fernandez-Remolar	W3
31	Vernal crater (Southwest Arabia Terra)	6.0	355.4	−1.7	Layered deposits (fluvio-lacustrine?), methane, spring deposits	C. Allen, D. Oehler, J. Wilkinson, M. Salvatore, K. Paris	W1
32	Northern Sinus Meridiani	1.6	357.5	−1.3	Layered deposits, ridges, hematite	K. S. Edgett, M. C. Malin	W2
33	Northern Sinus Meridiani crater lake	5.5	358.1	−1.5	Layered deposits	L. V. Posiolova, K. S. Edgett, M. C. Malin	W1
34	West Arabia Terra	8.9	358.8	−1.5	Layered deposits	E. Heydari, L. C. Kah, M. C. Malin, P. C. Thomas, K. S. Edgett	W1
35	Northern Sinus Meridiani	2.6	358.9	−1.6	Layered deposits	K. S. Edgett, M. C. Malin	W1
36	Northern Sinus Meridiani	1.9	0.4	−1.4	Layered deposits	K. S. Edgett, M. C. Malin	W1
		3.1	3.3	−1.4			
		2.4	3.5	−1.5			
37	East Meridiani	0.0	3.7	−1.3	Sulfate and hydrated materials, phyllosilicates in region	B. Hynek	W1
38	Chloride Site 15	−18.4	4.5	0.2	Chloride salts	P. Christensen, M. Osterloo, V. Hamilton, J. Bandfield, T. Glotch, A. Baldridge, F. S. Anderson, L. Tornabene	W2
39	Northern Sinus Meridiani	2.4	6.7	−1.1	Layered deposits	K. S. Edgett, M. C. Malin	W1
40	Southern mid-latitude (SML) craters	−49.0	14.0	0.5	Recent climate deposits (viscous flow features, gullies, patterned ground, dissected mantles)	M.A. Kreslavsky, J.L. Dickson, C.I. Fassett, J.W. Head, J.B. Madeleine,M. I. Ivanov	W1
41	Hellas	−44.0	46.0	−2.6	Ancient basin bedrock	B. Cohen	W1
42	Terby crater	−27.4	73.4	−4.7	Hydrated layered deposits (lacustrine?), fluvial and ice-related morphology	S. A. Wilson, A. D. Howard, J. M. Moore	W1
		−27.6	74.0	−4.7		E. Noe Dobrea	
		−28.0	74.1	−4.5	Ancient basin bedrock	B. Cohen	
43	Nili Fossae Trough[g]	21.0	74.5	−0.6			W1

					Noachian phyllosilicates, bedrock, clay-rich ejecta, Hesperian volcanics	J.F. Mustard, B. Ehlmann, F. Poulet, N. Mangold, J-P. Bibring, R.E. Milliken, S. Pelkey, L. Kanner	
44	Northeast Syrtis Major	17.1	75.4	−1.1	Hesperian volcanic, Noachian layered deposits	R. P. Harvey	W1
		16.1	76.7	−2.2			
		16.4	77.4	−2.8			
		16.3	78.0	−3.2			
		16.2	76.6	−2.1	Diverse mafics, Noachian layered phyllosilicates	B. Ehlmann, J.F. Mustard, R. Harvey, M. Rampey	W2
		17.8	77.1	−2.6	Diverse aqueous alteration minerals on Noachian–Hesperian boundary	J.F. Mustard, B. Ehlmann	Dec 2009
45	Nilo Syrtis	23.0	76.0	< −2.0	Phyllosilicates	J.F. Mustard	W2
46	Nili Fossae crater (Jezero)	18.4	77.6	−2.6	Fan, layered deposits, inverted channels	J. Rice; R. P. Harvey	W1
47	East Nili Fossae	21.8	78.6	−1.2	Phyllosilicates, mafics	N. Mangold, F. Poulet, J.-P. Bibring, J.F. Mustard	W2
48	Nili Fossae carbonate	21.7	78.8	−1.5	Phyllosilicates, carbonates	J.F. Mustard, B. Ehlmann	Dec 2009
49	Nili Fossae carbonate plains	21.9	78.9	−4.5	Layered phyllosilicates under sulfates	J.F. Mustard, B. Ehlmann	June 2008
50	Western Isidis	14.2	79.5	−3.5	Escarpment, volatile sink	L. Crumpler	W1
		18.0	79.6	−3.5			W2
51	Dao Vallis	−38.9	81.2	−6.0	Valley terminus, layered deposits	L. Crumpler	W1
		−39.5	82.7	−6.0			
		−41.2	84.4	−6.0			
		−40.7	85.6	−5.4			
		−41.7	85.8	−5.4			
		−43.3	86.8	−5.4			
52	Vastitas Borealis	70.5	103.0	−4.0	Salt, ice/impact tectonics	P. Aftabi	Dec 2009
53	Aeolis Region	−5.1	132.9	−2.3	Lobate fan delta	R. Kuzmin, DAN Science Team	W1
54	Gale crater[h]	−4.6	137.4	−4.5	Layered deposits, exhumed channels	J. Bell, K. Edgett, S. Rowland, M. Malin N. Bridges	W1
		−5.7	137.6	−3.6			
55	Northwestern slope valleys	−4.9	146.5	−2.3	Flood, fluvial morphology	J. M. Dohm, R. C. Anderson, V. Baker, T. M. Hare, S. J. Wheelock	W1
56	South Terra Cimmeria	−36.0	156.0	0.4	Gullies	W. E. Dietrich, J. Schieber, B. Hallet, K. S. Edgett, M. C. Malin	W1
		−35.0	156.0				
57	Athabasca Vallis	10.0	157.0	−2.5	Dunes, streamlined forms, fissures	D.M. Burr, A.J. Brown, R.A. Beyer, A.S. McEwen, K.L. Tanaka, L.P. Keszthelyi, J.P. Emery, P.D. Lanagan	W1
58	Elysium (Avernus Colles)	1.4	168.7	−2.5	Iron-rich materials at valley terminus	L. Crumpler	W1
		−3.1	170.6				W2
		−3.1	170.7				W1
		0.2	172.5				W1
59	Ariadnes Colles	−35.0	174.2	−0.1	Phyllosilicates, possible sulfates	E. Noe Dobrea	W2

[a] Name given by presenter might not be an official USGS place name.

[b] W1 (Workshop 1, June 2006); W2 (Workshop 2, October 2007); W3 (Workshop 3, September 2008).

[c] Holden crater presentations at W3: John Grant, Ross Irwin, John Grotzinger, Ralph Milliken, Kelin Whipple, Livio Tornabene, Alfred McEwen, Cathy Weitz, Steve Squyres, Tim Glotch, Brad Thomson, James W. Rice, M.C. Malin, K.E. Edgett; R. Irwin; R. Milliken; K.X. Whipple, K. Wakefield.

[d] Eberswalde crater presentations at W3: J. Rice; J. Schieber and M. Malin; J. Moore, A.D. Howard, R.P. Irwin, G. Parker, W.E. Dietrich, C.J. Barnhart; K. Lewis, O. Aharonson.

[e] Mawrth Vallis presentations at W3: J. Bishop, N. McKeown and M. Parente; J. Wray; E. Noe Dobrea; J. Bandfield, J. Michalski and S. Ruff.

[f] Miyamoto crater presentations at W3: J. Bandfield, D. Rogers; H. Newsom, A. Ollila, N. Lanza, S. Wiseman, L. Tornabene, C. Okubo, T. Roush, G. Marzo, L. Crumpler, M. Osterloo; Sandra M. Wiseman, R.E. Arvidson, J.C. Andrews-Hanna, R.N. Clark, N. Lanza, D. Des Marais, G.A. Marzo, R.V. Morris, S. Murchie, H.E. Newsom, E.Z. Noe Dobrea, A.M. Ollila, F. Poulet9, T.L. Roush F.P. Seelos, G.A. Swayze, and the CRISM Science Team.

[g] Nili Fossae Trough presentations at W3: J. Bandfield, D.J. Des Marais, B.L. Ehlmann, J.F. Mustard, N. Mangold, J.F. Mustard, B. Ehlmann, F. Poulet, N. Mangold, J-P. Bibring, DesMarais, F. Seelos, O. Barnouin-Jha.

[h] Gale crater presentations at W3: K.S. Edgett, D.Y. Sumner, R.E. Milliken, L.C. Kah, R. Milliken, B. Thompson, N. Bridges.

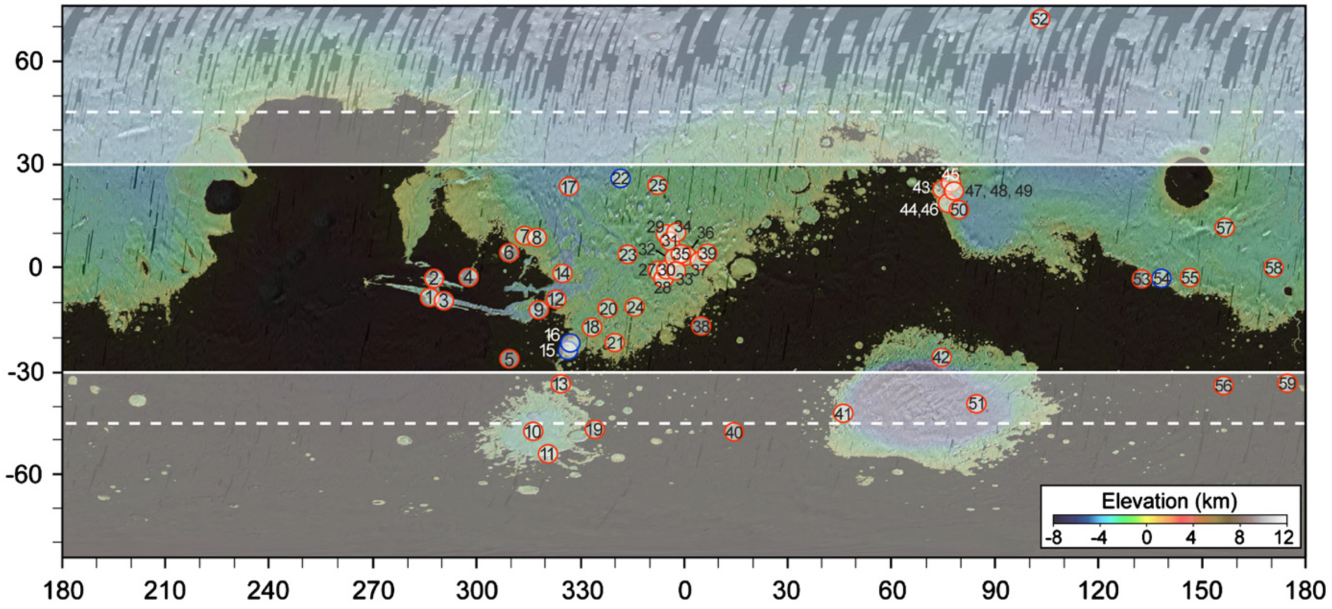


Fig. 3. Global map of Mars (East longitude and degrees North latitude from ~75 to −90) showing location all landing sites proposed for the Mars Science Laboratory (See Table 4). Holden crater (15), Eberswalde crater (16), Mawrth Vallis (22), and Gale crater (54) in blue represent the four landing sites under consideration as of June 2010. Black and white shaded areas represent elevations and latitudes, respectively, which are outside the safety and operation limits of the spacecraft. Initial latitude constraints of 45° (dashed white lines) were changed to 30° (solid white lines). Elevation constraints were changed from ≤ +1 km to < 0 km as spacecraft design matured (Table 3). Many of the sites proposed were in close proximity to one another and some included multiple ellipses. The actual size of the landing ellipse is smaller than the dots indicated on the map. Colorized MOLA data over global THEMIS daytime infrared data (black areas indicate gaps in coverage).

Table 5
Summary of top sites throughout the second, third and fourth community workshops (W2, W3, and W4, respectively).

End of W2 (2007)	Modification after W2 (2007)	Between W2 & W3 (June, 2008)	Start of W3 (2008)	End of W3 (2008)	Between W3 & W4	
					December, 2009	May, 2010
Top six sites	*Top six sites*	*Call for new sites*	*Top seven sites*	*Top four sites*	*Call for new sites*	*Final four*
Nili Fossae Trough	Nili Fossae Trough	S. Meridiani Planum	Eberswalde	Eberswalde	Nili Fossae carbonate	Eberswalde
Holden	Holden	Chloride West of Miyamoto	Holden	Gale	NE Syrtis Major[a]	Gale
Mawrth	Mawrth	Gale	Gale	Holden	Xanthe Terra	Holden
Miyamoto	Miyamoto	Nili Fossae Carbonate	Mawrth	Mawrth	East Margaritifer[a]	Mawrth
Terby	Eberswalde		Nili Fossae Trough		Ladon basin	
Jezero	N. Meridiani		S. Meridiani		Valles Borealis	
			Miyamoto		Vastitas Marineris	
Second tier sites						
Eberswalde						
NE Syrtis						
Chloride sites						
E. Meridiani						
Melas						

[a] Recommended for additional imaging and analysis by the Steering Committee.

characteristics. The opportunity to target and quickly receive MRO images became a powerful incentive to participate in the site selection process for those not involved on MRO science teams. Throughout 2007, imaging activities were supported and catalogued in accordance with mission engineering constraints that were continually refined by the MSL Project. The year culminated in the second community workshop and a subsequent meeting of the Steering Committee and MSL Project.

A total of ~50 sites were considered at the second workshop, including sites presented at the first workshop and new sites proposed based on discoveries from MRO data (Table 4). Because most sites proposed and discussed at the second workshop continued to fall between 30° north and south of the equator and at elevations below 0 km, the elevation and latitude constraints were modified after the workshop to 0 km and × 30°, respectively, reflecting the clustering of sites (Fig. 3) and allowing some relief to the MSL spacecraft design.

The second workshop was attended by more than 150 people and resulted in initial convergence on a list of eleven high priority sites that was culled to six at the end of the workshop (Table 5). Science criteria used to distinguish the sites (Grotzinger, 2009) included: (1) the expected ability to characterize the geology, (2) likelihood of accessing a present or past habitable environment, (3) preservation potential of the depositional setting, and (4) ability to assess biological potential of deposits at the site. Workshop attendees voted on each of the sites based on these criteria to identify the top eleven.

3. Narrowing the list of candidate sites

Most of the top eleven sites emerging from the second community workshop (Fig. 3, Table 5) can be grouped generally by location. Such sites include the Nili Fossae Trough (21.0°N, 74.5°E), northeast Syrtis (16.2°N, 76.6°E), and Jezero crater (18.4°N, 77.6°E) northwest of Isidis Basin; Holden crater (26.4°S, 325.1°E) and Eberswalde Crater (23.9°S, 326.7°E) in southern Margaritifer Terra; Miyamoto crater (3.5°S, 352.3°E), a site exposing putative chlorides (13.1°S, 345.2°E), and east Meridiani (0.0°N, 3.7°E) in the vicinity of Meridiani Planum; and Melas Chasma (9.8°S, 283.6°E), Mawrth Vallis (24.0°N, 341.0°E), and Terby crater (27.4°S, 73.4°E). Collectively, these sites represent a range of inferred depositional settings deemed highly relevant to the science objectives of MSL and are very briefly summarized below.

Three of the highly rated sites are located northwest of Isidis basin and provide access to ancient Noachian altered crustal materials (Fig. 3). The Nili Fossae Trough ellipse is characterized by a diverse assemblage of alteration minerals and carbonates (Mustard et al., 2008, 2010; Poulet et al., 2005) and provides access to both altered and unaltered Noachian crustal materials to the west of the ellipse and impact ejecta and Hesperian volcanic materials within the ellipse. Accessible rocks and alteration products may have formed in a variety of environments including hydrothermal, alluvial/fluvial, and shallow crust/pedogenic settings that were potentially habitable (Ehlmann et al., 2010; Mangold et al., 2007; Michalski et al., 2010; Mustard et al., 2008, 2010).

The proposed landing ellipse at the northeast Syrtis Major site is located on the northern margin of the Syrtis Major volcanic complex. A northward traverse would cross the boundary between distinct, diverse units exposing Hesperian and Noachian-aged sequences with hydrated and phyllosilicate mineral signatures (Bibring et al., 2005, 2006; Ehlmann et al., 2010; Mustard et al., 2008, 2010; Poulet et al., 2007). Many of the mineral signatures may comprise evidence for past habitable environments (Farmer and Des Marais, 1999).

In Jezero crater, the candidate ellipse is located on likely volcanic materials that partially fill the crater floor east of phyllosilicate-bearing, late-Noachian fluvial fan deposits extending from the west and northwest walls (Ehlmann et al., 2008a; Fassett and Head, 2005). The watershed for the input valleys would have likely transported diverse altered materials from eroded Noachian-aged crust to the west of the crater (Ehlmann et al., 2008a).

Two of the highly rated sites, Holden and Eberswalde craters, are located in the Noachian terrain of southern Margaritifer Terra (Scott and Tanaka, 1986; Fig. 3). Both Holden and Eberswalde craters are probably no older than Late Noachian in age (Grant et al., 2008a; Moore et al., 2003; Pondrelli et al., 2005, 2008) and contain distinctive stratigraphic and morphologic expressions of deltaic/lacustrine sedimentation that were deposited no earlier than the Late Noachian (Grant et al., 2008; Moore et al., 2003). These deposits also coincide with phyllosilicate mineral enrichments (Grant et al., 2008; Milliken and Bish, 2010), which points to accumulation in a body of standing water. Such possible crater-lake environments constitute high priority targets for habitability, as well as retaining strong potential for retention of biosignatures including organic compounds (Farmer and Des Marais, 1999; Summons et al., 2010).

The ellipse for the Holden crater candidate site is located on a broad alluvial bajada flanking portions of the southwestern wall of the crater (Moore and Howard, 2005; Pondrelli et al., 2005). The prime target within Holden, however, lies southeast of the ellipse where a series of finally bedded, phyllosilicate-bearing (Milliken et al., 2008; Milliken and Bish, 2010) deposits (Grant and Parker, 2002; Grant et al., 2008; Malin and Edgett, 2000; Pondrelli et al., 2005) likely record deposition into a late-Noachian lake flooding much of the crater floor (Grant et al., 2008).

Eberswalde crater predates and lies just to the north of Holden crater (Fig. 3) and preserves a broad fluvial fan delta along its western wall (Lewis and Aharonson, 2006; Malin and Edgett, 2003; Moore et al., 2003) that was likely deposited over a period ranging from decades (Jerolmack et al., 2004) to more than a hundred thousand years to (Bhattacharya et al., 2005) time. The fan, incorporating phyllosilicates likely eroded from the source basin to the west of the crater, built into a lake covering a portion of the crater floor (Milliken and Bish, 2010; Pondrelli et al., 2008). The candidate ellipse lies east of the fan and would provide relatively direct access to lake deposits, pre- or post-lake fluvial materials, and perhaps outcrops of Holden crater ejecta.

In the vicinity of Meridiani Planum (Fig. 3), an ellipse placed in western Miyamoto crater targets a series of raised curvilinear ridges and other, sometimes phyllosilicate-bearing features and deposits inferred to represent late-Noachian fluvial deposits (Newsom et al., 2010). These deposits are distributed in a patchwork fashion amongst other, younger materials of less certain origin and are located west of layered sulfate and hematite-bearing deposits forming Meridiani Planum (Arvidson et al., 2004; Squyres et al., 2006). The layered Meridiani Planum materials may have originally extended further to the west and into the portion of Miyamoto crater that includes the proposed landing ellipse (Hynek and Phillips, 2008; Malin and Edgett, 2000; Wiseman et al., 2008a). The transition between the Noachian materials in the ellipse and the younger sulfates to the east was proposed as a possible long range target for exploration by MSL.

The ellipse associated with the putative chloride site south of Meridiani Planum provides access to a small basin near the terminus of a valley network where putative chloride deposits have been identified (Osterloo et al., 2008). The chloride deposits, inferred to have formed via in situ precipitation within a sedimentary sequence, would have required substantial water prior to their emplacement and could comprise a good setting for preservation of any organic materials (Osterloo et al., 2008).

The ellipse for the East Meridiani landing site is located approximately 600 km to the northeast of the Mars Exploration Rover Opportunity landing site in Meridiani Planum (Fig. 3). Considered one of the safer candidates from an engineering perspective, this site targets a sequence of diverse sulfate and hydrated mineral-bearing layers that likely record ancient aqueous depositional and/or alteration settings good for the preservation of organics and biosignatures (Hynek and Phillips, 2008; Hynek et al., 2002; Poulet et al., 2008).

The candidate landing site in Melas Chasma (Fig. 3) is within a small basin on the southern wall of the larger chasmata (Quantin et al., 2005). The proposed site targets layered sedimentary beds deposited in a postulated paleolake that was fed by tributaries of Hesperian age (Dromart et al., 2007; Metz et al., 2009; Quantin et al., 2005). Some of the beds may have been deposited in sublacustrine fans (Metz et al., 2009) and the depositional setting suggests significant water was present and stable for at least hundreds to thousands of years (Metz et al., 2009).

A proposed ellipse in the upland region to the west of Mawrth Vallis (Fig. 3) marks a candidate landing site that is characterized by a thick, widespread, and layered sequence. Exposed rocks incorporate phyllosilicates and likely reflect a complex aqueous history and alteration of basalt (Bibring et al., 2005; Bishop et al., 2008; Loizeau et al., 2007; Michalski and Noe Dobrea, 2007; Poulet et al., 2005; Wray et al., 2008). Within the Mawrth sequence, Al-phyllosilicates overlie Fe/Mg phyllosilicates without any observable inter-bedding. While at least some of the layered materials predate Mawrth Vallis (Loizeau et al., 2010), it is unclear when their alteration ended, as development of the uppermost Al-phyllosilicate bearing units may post-date formation of Mawrth Vallis (Wray et al., 2008). The phyllosilicates also outcrop well to the south of Mawrth Vallis (Noe Dobrea et al., 2010) and such a broad extent could imply they formed in situ. Although the

Mawrth layered materials may reflect pedogenic alteration (Loizeau et al., 2010) or aqueous alteration of volcanic ash deposits (Noe Dobrea et al., 2010), the depositional setting remains uncertain (Bibring et al., 2005; Bishop et al., 2008; Michalski and Noe Dobrea, 2007; Noe Dobrea et al., 2010; Wray et al., 2008).

Terby crater in northern Hellas Planitia (Fig. 3) is the final high priority candidate site identified at the second community workshop. The crater preserves a ~2 km thick sequence of well-exposed, Noachian-aged, phyllosilicate-bearing, light and intermediate-toned sedimentary layered deposits and the candidate ellipse is on the crater floor near the base of the deposits. The observed gravitational control on the morphology of the layered deposits and their hydrated mineral signature (Ansan et al., 2005) is consistent with deposition in a long-lived lacustrine environment, but a loess-like origin cannot be ruled out (Wilson et al., 2007). The crater also preserves younger glacial, alluvial, and other mass wasting deposits in addition to ancient bedrock materials in the crater walls and rim that may be representative of the greater Hellas region (Wilson et al., 2007).

In response to guidance from NASA, the list of eleven high priority sites was further culled to six sites at the end of the second community workshop in order to limit safety concerns of the southern higher-latitude sites (Fig. 3) and reduce the overall site assessment workload. After considerable discussion related to the interpretations and science and/or engineering merits of each site (as defined at that time), the community agreed that Nili Fossae Trough, Holden crater, Mawrth Vallis, Miyamoto crater, Terby crater, and Jezero crater possessed the highest potential relative to MSL objectives and should remain under consideration (Table 5).

Further scrutiny by the MSL Project and Steering Committee shortly after the second workshop further illuminated potential engineering concerns for some sites that led to the demotion of Jezero and Terby craters from the top six candidate sites. Jezero crater was eliminated due to concerns about the rock abundance in the proposed landing ellipse and Terby crater was dropped because of thermal concerns associated with the relatively high southern latitude of the site that could negatively impact mission operations. Sites in North Meridiani and Eberswalde crater were selected by the MSL Project to replace Jezero and Terby to bring the list of candidate sites back to six (Table 5), and to ensure that a diversity of sites was retained. The north Meridiani site was viewed as satisfying MSL Project engineering desires for a very safe landing site while continuing to provide potential good science targets for MSL (Golombek et al., 2008) in the form of widespread sulfate deposits. North Meridiani provided access to layered sulfates in the landing ellipse near the base of the unit traversed by the Opportunity rover. Exploration to the north and out of the ellipse would provide access to ridge-forming material with inverted channels and other evidence for past fluvial activity (Edgett, 2005). By contrast, an ellipse in Eberswalde crater was added back to the list for consideration because the earlier engineering concerns regarding relief within the candidate ellipse were viewed to be less serious than initially thought and because of the high science potential of the site (Table 5).

A call was then made for additional candidate sites that were considered in June 2008 (Fig. 2, Table 5) to ensure comprehensive consideration of compelling new targets identified using the ever increasing amount of available MRO and Odyssey data (e.g., Rogers and Bandfield, 2009). The four new candidate sites proposed included (Table 4, Fig. 3): South Meridiani Planum (3.3°S, 354.4°E), a putative chloride deposit (“site 17”) west of Miyamoto crater (3.1°S, 351.6°E), Gale crater (4.5°S, 137.4°E), and Nili Fossae Carbonate (21.9°N, 78.9°E).

The candidate ellipse for the South Meridiani Planum site is located on the hematite and sulfate plains south of the area traversed by the Opportunity rover (Arvidson et al., 2004; Squyres et al., 2006). These rocks (Arvidson et al., 2004; Edgett, 2005) would be analyzed using the MSL payload before traversing south into adjacent phyllosilicate-bearing, Noachian uplands (Wiseman et al., 2008b). The upland units are characterized by diverse, well-exposed phyllosilicate materials on highland valley slopes that are embayed by the hematite and sulfate plains to the north (Wiseman et al., 2008b).

An additional putative chloride site west of Miyamoto crater was proposed to examine the deposits in a small basin based on rationale similar to that given for the previous chloride site south of Meridiani Planum and proposed at the second workshop (Osterloo et al., 2008).

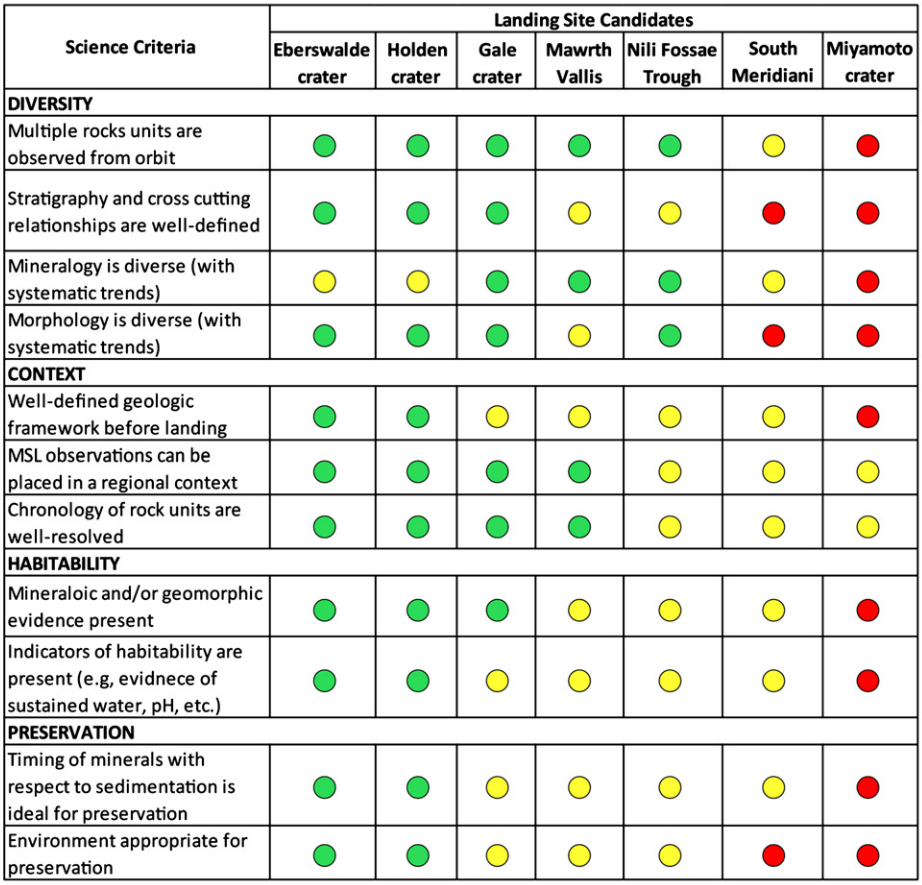
Gale crater was proposed at the first and second community workshops (Table 3), but new data from the CRISM and HiRISE instruments on MRO revealed the ~5 km-thick sequence of layered materials within the crater (Malin and Edgett, 2000) had an intriguing sequence of phyllosilicate-bearing layers beneath sulfate-bearing layers, implying at least some of the sequence was deposited in an aqueous setting (Milliken et al., 2010). Moreover, the setting provides an opportunity to evaluate the transition hypothesized elsewhere from Noachian-aged, phyllosilicate-bearing rocks to Hesperian-aged, sulfate-rich rocks, which may preserve a record of changing environmental conditions (Milliken et al., 2010). The proposed ellipse, located north of the layered mound on a small alluvial fan, provides access to the layered mound as a “go to” site.

Finally, a new site located east of Nili Fossae Trough and northwest of Isidis was dubbed “Nili Fossae Carbonate” based on the detection of carbonate-bearing rocks (Ehlmann et al., 2008b). The carbonate site also provided access to various phyllosilicate-bearing lithologies, thereby enabling the relationship between these altered minerals and the regional Nili Fossae olivine unit to be analyzed (Ehlmann et al., 2008b).

These four “new” candidate sites were considered by the Steering Committee and MSL Project in July 2008, under direction from NASA that no more than one could be added to the list under formal consideration. The consensus of both groups was that Gale crater should be added to the list. Concerns about limited diversity at the Chloride Site (“site 17”) west of Miyamoto and uncertainties in the interpretation of the setting at the carbonate site (largely due to limited existing high resolution image coverage at the time of review) led to their demise. Finally, the new South Meridiani site replaced the North Meridiani site because it was viewed to be as safe by the MSL Project and more attractive scientifically by the Steering Committee and Project because it granted MSL access to sulfate and older phyllosilicate terrains.

4. The third community workshop and beyond

Seven candidate landing sites remained under consideration at the third community workshop that was held in September, 2008: Nili Fossae Trough, Mawrth Vallis, South Meridiani, Miyamoto crater, Eberswalde crater, Holden crater, and Gale crater (Tables 4 and 5, Fig. 3). Extensive discussion was devoted to each site during the workshop and the excellent presentations demonstrated that all seven possessed very high science value and appeared compelling when compared to the MSL mission objectives. In order to distinguish the sites, however, a series of specific questions were derived from the MSL science objectives (Grotzinger, 2009; Table 1) to emphasize the positive aspects of each site and formed the basis for developing a point-by-point ranking that was used to reduce the list to five by the end of the third workshop (Table 5, Fig. 4). The five sites remaining at the



Science Criteria	Landing Site Candidates						
	Eberswalde crater	Holden crater	Gale crater	Mawrth Vallis	Nili Fossae Trough	South Meridiani	Miyamoto crater
DIVERSITY							
Multiple rocks units are observed from orbit	🟢	🟢	🟢	🟢	🟢	🟡	🔴
Stratigraphy and cross cutting relationships are well-defined	🟢	🟢	🟢	🟡	🟡	🔴	🔴
Mineralogy is diverse (with systematic trends)	🟡	🟡	🟢	🟢	🟢	🟡	🔴
Morphology is diverse (with systematic trends)	🟢	🟢	🟢	🟡	🟢	🔴	🔴
CONTEXT							
Well-defined geologic framework before landing	🟢	🟢	🟡	🟡	🟡	🟡	🔴
MSL observations can be placed in a regional context	🟢	🟢	🟢	🟢	🟡	🟡	🟡
Chronology of rock units are well-resolved	🟢	🟢	🟢	🟢	🟡	🟡	🟡
HABITABILITY							
Mineraloic and/or geomorphic evidence present	🟢	🟢	🟢	🟡	🟡	🟡	🔴
Indicators of habitability are present (e.g, evidnece of sustained water, pH, etc.)	🟢	🟢	🟡	🟡	🟡	🟡	🔴
PRESERVATION							
Timing of minerals with respect to sedimentation is ideal for preservation	🟢	🟢	🟡	🟡	🟡	🟡	🔴
Environment appropriate for preservation	🟢	🟢	🟡	🟡	🟡	🔴	🔴

Fig. 4. Summary of the criteria used to evaluate the candidate landing sites at the third community landing site (Grotzinger, 2009). The criteria, divided into four groups, were posed as questions relating to the major science objectives of the MSL mission (Table 2). Everyone in attendance at the third community workshop voted on each of the criteria for each of the seven sites discussed (high relative value = green, medium relative value = yellow, low relative value = red). Although each site was viewed as having high overall merit, voting on the specific criteria revealed concerns that distinguished the top five sites (Eberswalde crater, Gale crater, Holden crater, Mawrth Vallis, and Nili Fossae Trough). A subsequent meeting of the Steering Committee and the Project reviewed the results of the third workshop and confirmed that all five possessed high merit, but based on a Project desire to reduce the number of sites to four, Nili Fossae Trough was dropped from consideration (see text for discussion).

end of the third workshop included Eberswalde crater, Holden crater, Gale crater, Mawrth Vallis, and Nili Fossae Trough. A subsequent meeting of the MSL Project and Landing Site Steering Committee further integrated known engineering concerns into consideration of the sites and reduced the list of sites to four (Fig. 5) by dropping the Nili Fossae Trough site. While Miyamoto crater, South Meridiani, and Nili Fossae Trough sites were all viewed to be highly compelling scientifically, the reasons they were dropped from consideration are summarized below.

The priority of Miyamoto crater was relatively diminished due to uncertainties about the depositional setting preserved on the floor of the crater and concerns about relatively widespread surficial materials that might hamper access to older, higher priority deposits possibly emplaced in an aqueous setting. The ranking of South Meridiani was high, but suffered relative to other sites because of uncertainties regarding the interpreted settings preserved in the Noachian highlands and their association with the phyllosilicate-bearing units. Additionally, the occurrence of sulfates was viewed as a weak indicator of habitability, based on the salinity arguments developed in Tosca et al. (2008) and the Project was beginning to view each of the seven sites discussed at the third workshop as "safe," thereby negating the need for an "ultra safe" landing site. The Nili Fossae Trough was also viewed as very interesting and ranked close to Mawrth Vallis (Fig. 4), but finished below Mawrth due to lingering uncertainties regarding aspects of the geologic setting and engineering concerns about the relatively high elevation of the site (that may result in increased risk during atmospheric entry, descent, and landing of the rover on Mars). Shortly after convergence on the four final sites, the launch of MSL slipped from 2009 to 2011 and activities other than continued imaging by MRO were placed on hold for several months.

In August 2009, another call was made to the science community for new candidate landing sites. The objective of the call was to ensure review and consideration of candidate sites emerging from analyses of MRO and Mars Odyssey data collected during the hiatus in site selection activities. The Steering Committee was directed to evaluate any new sites submitted in response to the call relative to the four existing sites (Eberswalde, Gale, Holden, and Mawrth) to assess whether any were potentially more compelling scientifically and as safe. In order for any new candidate site to be deemed as safe as the existing four sites, they were required to be within the elevation and latitude range of the existing sites (below -1 km elevation and between 25°N and 27°S latitude) as well as meeting all other safety criteria (Table 3). With these guidelines in mind, seven new candidate sites were submitted by the science community and discussed by the Steering Committee in December 2009 (Tables 4 and 5, Fig. 3): 1) Nili Fossae carbonate plains (Ehlmann et al., 2008b) including ultramafic, phyllosilicate-bearing, and carbonate-bearing outcrops (21.7 N, 78.8E), 2) a diverse assemblage of minerals straddling the Noachian–Hesperian boundary in northeast Syrtis Major (16.7°N, 76.9°E) with an ellipse to the north of the previous Syrtis sites (e.g., Bibring et al., 2005, 2006; Ehlmann et al., 2010; Mustard et al., 2008, 2010; Poulet et al., 2007), 3) a delta deposit

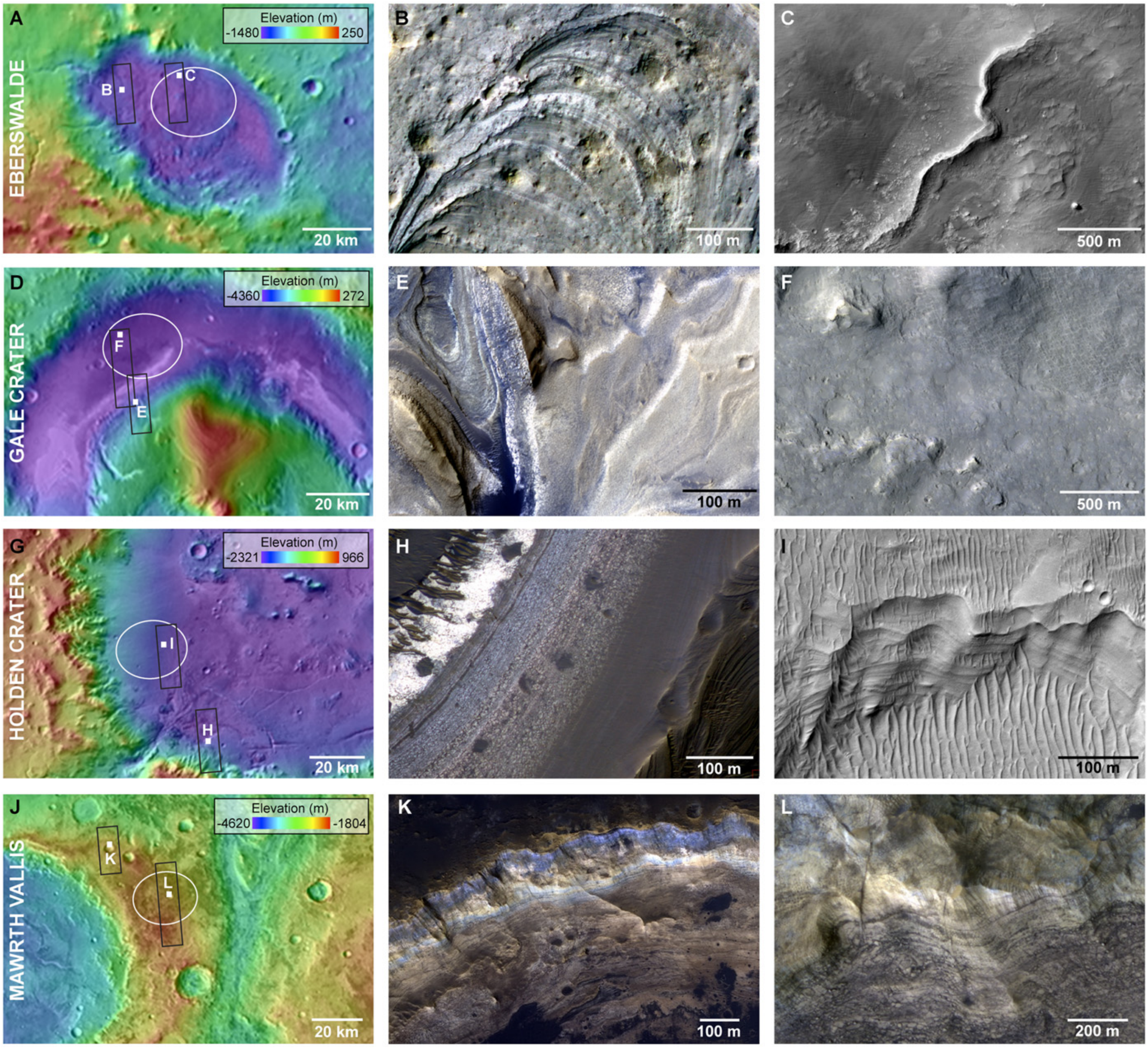


Fig. 5. Final four MSL candidate landing sites and corresponding example science targets: Eberswalde crater (A–C), Gale crater (D–F), Holden crater (G–I) and Mawrth Vallis (J–L). Left column (A, D, G, and J) shows MOLA topography over THEMIS daytime images of candidate sites with approximate locations of the proposed landing ellipse (white outline) and example HiRISE images (black boxes) and science targets (white filled boxes) detailed outside the ellipses (middle column) and within the ellipses (right-hand column). (A) The proposed landing ellipse in Eberswalde crater is located east of an exposed, phyllosilicate-bearing delta complex. (B) A point bar deposit within the delta complex is the primary science target in Eberswalde (subset of false color HiRISE PSP_001336_1560, 1 m pixel-scale). (C) Within the proposed landing ellipse, several sinuous, light-toned, inverted channels are examples of local science targets (subset of PSP_0010474_1560_RED, 25 cm pixel-scale). (D) The proposed ellipse in Gale is located to the north of the large, layered mound in the center of the crater. (E) A portion of a ~5 km sedimentary sequence of phyllosilicate-bearing strata under sulfate-bearing strata in Gale crater is located south of the landing ellipse and could help constrain the changing environmental conditions related to habitability on early Mars (subset of false color HiRISE PSP_009149_1750, 50 cm pixel-scale). (F) The proposed landing ellipse in Gale is on the surface of a fan that is sourced from a channel incising the adjacent crater wall and represents and an example of a local science target (subset of false color HiRISE image PSP_009650_1755, 50 cm pixel-scale). (G) The proposed landing ellipse in Holden is on the southwestern crater floor. (H) At Holden crater, the highest priority target is a ~150 m thick sequence of finely layered, phyllosilicate-bearing (and likely) lacustrine beds east of the landing ellipse (subset of false color HiRISE PSP_003077_1530, 1 m pixel-scale). (I) Local science targets in the Holden landing ellipse include layers exposed on the alluvial fan surface (subset of HiRISE ESP_016276_1535_RED, 25 cm pixel-scale). (J) At Mawrth Vallis, the proposed landing ellipse is west of the valley floor. (K) A sequence of Al-phyllosilicates over Fe/Mg phyllosilicates in Mawrth Vallis is well-exposed northwest of the proposed landing ellipse shows no inter-bedding and may record a complex aqueous alteration history (subset of false color HiRISE PSP_004052_2045, 50 cm pixel-scale). (L) Similar stratigraphy as seen outside the Mawrth ellipse (K) is exposed in a small crater within the landing ellipse (subset of false color HiRISE ESP_011884_2045, 50 cm pixel-scale).

with possible toe-of-slope silica deposits (Popa et al., 2010) within a crater in Xanthe Terra (2.3°N, 309°E), 4) a putative chloride deposit (Osterloo et al., 2008) and possible overlying phyllosilicate deposits in east Margaritifer Terra (5.6°S, 353.5°E), 5) a putative chloride deposit (Osterloo et al., 2008) and nearby phyllosilicates deposits in Ladon basin (18.8°S, 332.5°E), 6) ice within a crater (Aftabi, 2008) in Vastitas Borealis (70.5°N, 103°E), and 7) on the floor and near the wall of Valles Marineris (3.8°S, 324.6°E). Four of these sites were essentially reincarnations of previous sites (Table 5) whose stock had risen as a result of new data/interpretations on the safety and/or science of the proposed ellipse and surroundings.

After considerable discussion about the merits of each site, the new northeast Syrtis site and the putative chloride and phyllosilicate site in east Margaritifer Terra were deemed of the highest merit and recommended for additional imaging to better assess the setting and potential hazards related to landing and rover trafficability. The assemblage of diverse alteration minerals near and perhaps at the new northeast Syrtis site (pending confirmation in new images) coupled with the possibility of traversing rocks that record the transition from the Noachian through Hesperian made it very compelling. The possibility that chlorides and phyllosilicates may occur in a stratigraphic sequence within a small basin at the mouth of a valley system made the chloride site in east Margaritifer Terra intriguing (Osterloo et al., 2008).

The other sites that were proposed were dismissed for a variety of reasons. Vastitas Borealis (Aftabi, 2008) and the floor of Valles Marineris were declared outside the bounds of existing safety requirements for MSL. Vastitas Borealis exceeds the latitude limits and violates planetary protection issues related to near-surface water ice. Valles Marineris was dropped because of concerns about possible slope winds from nearby canyon walls, a paucity of nearby mineralogical indicators, and the great length of the proposed traverse. The ellipse for the new Nili Carbonate outcrop site was located in nearly the same location as the ellipse for the Nili Carbonate site (Ehlmann et al., 2008b) that was proposed prior to the third workshop (Tables 4 and 5), but was reconsidered as the interpretation was deemed much more mature. However, more complete information about the distribution of potential science targets and hazards in the ellipse revealed extensive eolian bedforms that raised new concerns. The delta deposit in Xanthe Terra (Popa et al., 2010) was intriguing, but was dropped because the relationship between the depositional setting and remote detection of nearby amorphous silica was uncertain, nearby phyllosilicates might not be accessible, and slopes within the proposed landing ellipse were relatively high. Although the putative chloride deposits (Osterloo et al., 2008) in Ladon basin are near phyllosilicate deposits, the stratigraphic relationship between them was unclear from available images during the initial discussions and resulted in diminished appeal.

Following a period of extensive imaging that resulted in nearly complete high spatial and spectral resolution coverage of both the northeast Syrtis and east Margaritifer Terra candidate sites, the Steering Committee convened in May 2010, to reevaluate both sites. The Committee concluded the northeast Syrtis site was scientifically compelling because it displayed an exposed rock sequence spanning the Noachian–Hesperian boundary, abundant and varied aqueous mineralogy, and likely represented diverse geologic settings and was probably formed in situ. Significant concerns were raised, however, about slopes, scarps, and other landing hazards that were unlikely to be eased by small reductions in landing ellipse size or re-centering of the ellipse. The Committee felt that the "land on science" nature of the east Margaritifer Terra Site was attractive, but questions were raised regarding the depositional setting and stratigraphic context of the putative chloride and phyllosilicate deposits. Moreover, eolian ripples and other potential hazards to landing safely and rover trafficability became apparent in the new image data. As a result, the Committee made the recommendation that neither the northeast Syrtis nor east Margaritifer Terra should be added to the existing four final MSL candidate landing sites.

5. Converging on the final MSL landing site

At the time this paper was published, imaging of the four candidate landing site finalists by MRO and other orbital spacecraft is largely complete. These data are being used to further characterize the science potential of the sites that includes constraining geologic setting, indentifying potential science targets, and determining the distribution of landing and roving hazards.

A fourth community landing site workshop is planned for September 2010, and will focus on the outstanding science questions, surface characteristics, and relative merits of the final four MSL landing sites remaining under consideration. The workshop will draw from the results of an MSL Project activity (with some participation by members of the science community) geared towards interpretation and study of science targets in, and adjacent to, the proposed ellipses. This MSL Project activity will involve deliberations on complex tradeoffs between in situ measurements, remote sensing, and mobility/driving for each site in order to optimize the MSL surface mission. In addition, high quality HiRISE data makes it possible to evaluate specific strategies for science at each site both within and outside the landing ellipse.

At the fourth workshop, input from the science community, detailed discussion of surface characteristics, together with data from the MSL Project activity, will collectively be used to develop hypotheses related to mission science goals (Grotzinger, 2009) that could be tested during interrogation of specific targets at each site using the MSL science instruments. It is anticipated that a subsequent meeting of the Landing Site Steering Committee and the MSL Project will convolve engineering data and concerns in order to confirm each of the remaining sites remains viable.

A fifth, final landing site assessment activity involving the science community is tentatively planned for March or April 2011, and will likely emphasize the specific science plans for each site. That workshop may include the results of a detailed study by the MSL Project on how the final engineering constraints impact the ability to land and access identified science targets at each of the sites. Outcomes of this final activity should include a more robust list of MSL-relevant hypotheses for each site that can be tested using the MSL payload including, but not restricted to, whether each may have been habitable in the past and whether evidence of organics and the past environmental conditions is likely to be preserved and accessible to the rover. This activity will allow for the final community input into the site selection process and they will be provided to the MSL Project as input to their development of a recommendation on the relative merits of the sites. That recommendation will be made to the Associate Administrator for the Science Mission Directorate at NASA Headquarters, who will then select the landing site during the Spring of 2011 (Fig. 2).

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References

Aftabi, P., 2008. Laboratory testing of the ice-salt intrusions and extrusions in craters for determining Mars landing site. Lunar Planet. Sci. XXXIX, Abstract 1179, LPI, Houston, TX.

Ansan, V., Mangold, N., Lucas, A., Gendrin, A., Le Mouelic, S., Poulet, F., Bibring, J.-P., Omega co-Investigator Team, 2005. Analysis of Layered deposits in Terby Crater (Hellas region, Mars) using multiple datasets MOC, THEMIS and OMEGA/MEX. Lunar Planet. Sci. XXXVII, Abstract 1378, LPI, Houston, TX.

Arvidson, R.E., Anderson, R.C., Bartlett, P., Bell III, J.F., Christensen, P.R., Chu, P., Davis, K., Ehlmann, B.L., Golombek, M.P., Gorevan, S., Guinness, E.A., Haldemann, A.F.C., Herkenhoff, K., Landis, G., Li, R., Lindemann, R., Ming, D.W., Myrick, T., Parker, T., Richter, L., Seelos IV, F.P., Soderblom, L.A., Squyres, S.W., Sullivan, R.J., Wilson, J., 2004. Localization and physical properties experiments conducted by Opportunity at Meridiani Planum. Science 306, 1730–1733. doi:10.1126/science.

Bhattacharya, J.P., Payenberg, T.H.D., Lang, S.D., Bourke, M.C., 2005. Dynamic river channels suggest a long-lived Noachian crater lake. Geophys. Res. Lett. 32, L10201. doi:10.1029/2005GL022747.

Bibring, J.-P., Soufflot, A., Berthé, M., Langevin, Y., Gondet, B., Drossart, P., Bouyé, M., Combes, M., Puget, P., Semery, A., Bellucci, G., Formisano, V., Moroz, V., Kottsov, V., Bonello, G., Erard, S., Forni, O., Gendrin, A., Manaud, N., Poulet, F., Poulleau, G., Encrenaz, T., Fouchet, T., Melchiori, R., Altieri, F., Ignatiev, N., Titov, D., Zasova, L., Coradini, A., Capacionni, F., Cerroni, P., Fonti, S., Mangold, N., Pinet, P., Schmitt, B., Sotin, C., Hauber, E., Hoffmann, H., Jaumann, R., Keller, U., Arvidson, R., Mustard, J., Forget, F., 2004. OMEGA: Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité. In: Wilson, A. (Ed.), Mars Express: The Scientific Payload. ESA SP-1240. ESA Publications Division, Noordwijk, Netherlands, ISBN: 92-9092-556-6, pp. 37–49.

Bibring, J.-P., Langevin, Y., Gendrin, A., Gondet, B., Poulet, F., Berthé, M., Soufflot, A., Arvidson, R., Mangold, N., Mustard, J., Drossart, P., 2005. OMEGA team, 2005. Mars surface diversity as revealed by the OMEGA/Mars Express observations. Science 307, 1576–1581.

Bibring, J.-P., Langevin, Y., Mustard, J.F., Poulet, F., Arvidson, R., Gendrin, A., Gondet, B., Mangold, N., Pinet, P., Forget, F., 2006. OMEGA team, 2006. Global mineralogical and aqueous Mars history derived from OMEGA/Mars Express data. Science 312, 400–404. doi:10.1126/science.1122659.

Bishop, J.L., Noe Dobrea, E.Z., McKeown, N.K., Parente, M., Ehlmann, B.L., Michalski, J.R., Milliken, R.E., Poulet, F., Swayze, G.A., Mustard, J.F., Murchie, S.L., Bibring, J.-P., 2008. Phyllosilicate diversity and past aqueous activity revealed at Mawrth Vallis, Mars. Science 321, 830–833. doi:10.1126/science.1159699.

Christensen, P.R., Jakosky, B.M., Kieffer, H.H., Malin, M.C., McSween Jr., H.Y., Nealson, K., Mehall, G.L., Silverman, S.H., Ferry, S., Caplinger, M., Ravine, M., 2004. The Thermal Emission Imaging System (THEMIS) for the Mars 2001 Odyssey Mission. Space Science Reviews 110, 85–130.

Dromart, G., Quantin, C., Broucke, O., 2007. Stratigraphic architectures spotted in southern Melas Chasma, Vallis Marineris, Mars. Geology 35 (4), 363–366.

Edgett, K.S., 2005. The sedimentary rocks of Sinus Meridiani: five key observations from data acquired by the Mars Global Surveyor and Mars Odyssey orbiters. Mars 1, 5–58. doi:10.1555/mars.2005.0002.

Ehlmann, B.L., Mustard, J.F., Fassett, C.I., Schon, S.C., Head III, J.W., Des Marais, D.J., Grant, J.A., Murchie, S.L., 2008. CRISM team, 2008. Clay mineralogy and organic preservation potential of lacustrine sediments from a Martian delta environment, Jezero crater, Nili Fossae, Mars. Nature Geoscience, 1. doi:10.1038/ngeo207.

Ehlmann, B.L., Mustard, J.F., Murchie, S.L., Poulet, F., Bishop, J.L., Brown, A.J., Calvin, W.M., Clark, R.N., Des Marias, D.J., Milliken, R.E., Roach, L.H., Roush, T.L., Swayze, G.A., Wray, J.J., 2008b. Orbital identification of carbonate-bearing rocks on Mars. Science 322, 1828–1832. doi:10.1126/science.1164759.

Ehlmann, B.L., Mustard, J.F., Swayze, G.A., Clark, R.N., Bishop, J.L., Poulet, F., Des Marais, D.J., Roach, L.H., Milliken, R.E., Wray, J.J., Barnouin-Jha, Murchie, S.L., 2010. Identification of hydrated silicate minerals on Mars using MRO-CRISM: geologic context near Nili Fossae and implications for aqueous alteration. J. Geophys. Res. 114 (E00D08. doi:10.1029/2009JE003339.

Farmer, J., Des Marais, D., 1999. Exploring for a record of ancient Martian life. J. Geophys. Res. 104 (E11), 26977–26995. doi:10.1029/1998JE000540.

Fassett, C.I., Head, J.W., 2005. Fluvial sedimentary deposits on Mars: ancient deltas in a crater lake in the Nili Fossae region. Geophys. Res. Lett. 32, L14201. doi:10.1029/2005GL023456.

Golombek, M.P., Grant, J.A., Parker, T.P., Kass, D.M., Crisp, J.A., Squyres, S.W., Haldemann, A.F.C., Adler, M., Lee, W., Bridges, N.T., Arvidson, R.E., Carr, M.H., Kirk, R.L., Knocke, P.C., Roncoli, R.B., Weitz, C.M., Schofield, J.T., Zurek, R.W., Rice, J.W., 2003. Selection of the Mars Exploration Rover landing sites. J. Geophys. Res. 108, 8072. doi:10.1029/2003JE002074.

Golombek, M., Grant, J., Lorenzoni, L., Steltzner, A., Vasavada, A., Voorhees, C., Watkins, M., 2006. Preliminary constraints and plans for Mars Science Laboratory landing site selection. Lunar Planet. Sci. XXXVII, Abstract 2172, LPI, Houston, TX.

Golombek, M., Grant, J., Vasavada, A.R., Watkins, M., Lorenzoni, L., Griffes, J., 2007a. Preliminary constraints, plans, and proposed landing sites for the Mars Science Laboratory mission. In: Proceedings of the Seventh International Conference on Mars, Abstract 3037, California Institute of Technology, Pasadena, CA.

Golombek, M., Grant, J., Vasavada, A.R., Watkins, M., 2007b. Landing sites proposed for the Mars Science Laboratory mission. Lunar Planet. Sci. XXXVIII, Abstract 1392, LPI, Houston, TX.

Golombek, M.P., Grant, J.A., Vasavada, A.R., Watkins, M., Noe Dobrea, E., Griffes, J., Parker, T.J., 2008. Downselection of landing sites for the Mars Science Laboratory. Lunar Planet. Sci. XXXIX, Abstract 2181, LPI, Houston, TX.

Golombek, M.P., Grant, J.A., Vasavada, A.R., Grotzinger, J., Watkins, M., Kipp, D., Noe Dobrea, E., Griffes, J., Parker, T., Kirk, R., Beyer, R., Huertas, A., Milliken, R., Sun, Y., 2010. Landing sites under consideration for Mars Science Laboratory. Lunar Planet. Sci. XLI, Abstract 2407, LPI, Houston, TX.

Grant, J.A., Parker, T.J., 2002. Drainage evolution of the Margaritifer Sinus Region, Mars. J. Geophys. Res. 107, 5066. doi:10.1029/2001JE001678.

Grant, J.A., Golombek, M.P., Parker, T.J., Crisp, J.A., Squyres, S.W., Weitz, C.M., 2004. Selecting landing sites for the 2003 Mars Exploration Rovers. J. Planet. Space Sci. 52, 11–21.

Grant, J.A., Irwin III, R.P., Grotzinger, J.P., Milliken, R.E., Tornabene, L.L., McEwen, A.S., Weitz, C.M., Squyres, S.W., Glotch, T.D., Thomson, B.J., 2008. HiRISE imaging of impact megabreccia and sub-meter aqueous strata in Holden Crater Mars. Geology 36, 195–198. doi:10.1130/G24340A.

Griffes, J.L., Grant, J., McEwen, A., Golombek M., HiRISE Team, 2006. HiRISE over the MSL landing sites. Eos Trans. AGU 87(52), Fall Meet. Suppl., Abstract P23B-0057.

Griffes, J.L., Grant, J.A., McEwen, A.S., Golombek, M.P., HiRISE Team, 2007. HiRISE analysis of the potential MSL landing sites. Eos Trans. AGU, Fall Meeting, 88 Suppl. 52, Abstract P31B-0433.

Griffes, J.L., Grant, J.A., Golombek, M.P., Vasavada, A.R., McEwen, A.S., HiRISE Team, 2008a. HiRISE observations of potential Mars Science Laboratory landing sites. Lunar Planet. Sci. XXXIX, Abstract 1886, LPI, Houston, TX.

Griffes, J.L., Grant, J.A., Grotzinger, J., Golombek, M.P., McEwen, A., 2008b. Analysis of potential Mars Science Laboratory landing sites using HiRISE. European Planet. Sci. Cong. 3 EPSC2008-A-00567.

Grotzinger, J., 2009. Beyond water on Mars. Nat. Geosci. 2, 232–233 doi:10.1038.ngeo480.

Hynek, B.M., Arvidson, R.E., Phillips, R.J., 2002. Geologic setting and origin of Terra Meridiani hematite deposit on Mars. J. Geophys. Res. 107, 5088. doi:10.1029/2002JE001891.

Hynek, B.M., Phillips, R.J., 2008. The stratigraphy of Meridiani Planum, Mars, and implications for the layered deposits' origin. Earth Planet. Sci. Lett. 274, 214–220.

Jaumann, R., Neukum, G., Behnke, T., Duxbury, T.C., Floohrer, J., Gasselt, S.V., Giese, B., Gwinner, K., Hauber, E., Hoffmann, H., Hoffmeinster, A., Köhler, U., Matz, K.D., McCord, T.B., Mertens, V., Oberst, J., Pischel, R., Rei, D., Ress, B., Roasch, T., Saiger, P., Scholten, F., Schwarz, O., Stephan, K., Wählisch, M., 2007. HRSC Co-Investigator Team, 2007. The high resolution stereo camera (HRSC) experiment on Mars Express: instrument aspects and experiment conduct from interplanetary cruise through the nominal mission. Planet. Space Sci. 55, 928–952. doi:10.1016/j.pss.2006.12.003.

Jerolmack, D.J., Mohrig, D., Zuber, M.T., Byrne, S., 2004. A minimum time for the formation of Holden Northeast fan, Mars. Geophys. Res. Lett. 31, L21701. doi:10.1029/2004GL021326.

Lewis, K.W., Aharonson, O., 2006. Stratigraphic analysis of the distributary fan in Eberswalde crater using stereo imagery. J. Geophys. Res. 111, E06001. doi:10.1029/2005JE002555.

Loizeau, D., Mangold, N., Poulet, F., Bibring, J.-P., Gendrin, A., Ansan, V., Gomez, C., Gondet, B., Langevin, Y., Masson, P., Neukum, G., 2007. Phyllosilicates in the Mawrth Vallis region of Mars. J. Geophys. Res. 112, E08S08. doi:10.1029/2006JE002877.

Loizeau, D., Mangold, N., Poulet, F., Ansan, V., Hauber, E., Bibring, J.-P., Gondet, B., Langevin, Y., Masson, P., Neukum, G., 2010. Stratigraphy in the Mawrth Vallis region through OMEGA, HRSC color imagery and DTM. Icarus, 205, 396, 10.1016/j.icarus.2009.04.018.

Malin, M.C., Edgett, K.S., 2000. Evidence for recent groundwater seepage and surface runoff on Mars. Science 288 (5475), 2230–2335. doi:10.1126/science.288.5475.2330.

Malin, M.C., Edgett, K.S., 2003. Evidence for persistent flow and aqueous sedimentation on Mars. Science 302, 1931–1934. doi:10.1126/science.10905444.

Malin, M.C., Danielson, G.E., Ingersoll, A.P., Masursky, H., Veverka, J., Ravine, M.A., Soulanille, T.A., 1992. Mars Observer Camera. J. Geophys. Res. 97, 7699–7718. doi:10.1029/92JE00340.

Malin, M.C., Bell III, J.F., Cantor, B.A., Caplinger, M.A., Calvin, W.M., Clancy, R.T., Edgett, K.S., Edwards, L., Haberle, R.M., James, P.B., Lee, S.W., Ravine, M.A., Thomas, P.C., Wolff, M.J., 2007. Context Camera investigation on board the Mars Reconnaissance Orbiter. J. Geophys. Res. 112, E05S04. doi:10.1029/2006JE002808.

Mangold, N., Poulet, F., Mustard, J.F., Bibring, J.-P., Bondet, B., Langevin, Y., Ansan, V., Masson, Ph., Fasset, C., Head, J.W., Hoffmann, H., Neukum, G., 2007. Mineralogy of the Nili Fossae region with OMEGA/Mars Express data: 2. Aqueous alteration of the crust. J. Geophys. Res. 112, E08S04. doi:10.1029/2006JE002835.

McEwen, A.S., Eliason, E.M., Bergstrom, J.W., Bridges, N.T., Hansen, C.J., Delamere, W.A., Grant, J.A., Gulick, V.C., Herkenhoff, K.E., Keszthelyi, L., Kirk, R.L., Mellon, M.T., Squyres, S.W., Thomas, N., Weitz, C.M., 2007. Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE). J. Geophys. Res. 112, E05S02. doi:10.1029/2005JE002605.

Metz, J.M., Grotzinger, J.P., Mohrig, D., Milliken, R., Prather, B., Pirmez, C., McEwen, A.S., Weitz, C.M., 2009. Sublacustrine depositional fans in southwest Melas Chasma. J. Geophys. Res. 114, E10002. doi:10.1029/2009JE003365.

Michalski, J.R., Noe Dobrea, E.Z., 2007. Evidence for a sedimentary origin of clay minerals in the Mawrth Vallis region, Mars. Geology 35, 830–833. doi:10.1130/G23854A.1.

Michalski, J., Poulet, F., Bibring, J.-P., Mangold, N., 2010. Analysis of phyllosilicate deposits in the Nili Fossae region of Mars: comparison of TES and OMEGA data. Icarus 206, 269–289. doi:10.1016/j.icarus.2009.09.006.

Milliken, R.P., Bish, D.L., 2010. Sources and sinks of clay minerals on Mars. Phil. Mag. 90 (17–18), 2293–2308.

Milliken, R.E., Grotzinger, J., Grant, J.A., Arvidson, R., Murchie, S., 2008. Understanding sedimentary sources and sinks on Mars from orbit. Geol. Soc. Am. Prog. Abs, Abstract 134-1.

Milliken, R.E., Grotzinger, J.P., Thomson, B.J., 2010. Paleoclimate of Mars as captured by the stratigraphic record in Gale Crater. Geophys. Res. Lett. 37, L04201. doi:10.1029/2009GL041870.

Moore, J.F., Howard, A.D., Dietrich, W.D., Schenk, P.M., 2003. Martian layered fluvial deposits: implications for Noachian climate scenarios. Geophys. Res. Lett. 30, E06001. doi:10.1029/2003GL019002.

Moore, J.M., Howard, A.D., 2005. Large alluvial fans on Mars. J. Geophys. Res. 110, E04005. doi:10.1029/2005JE002352.

Murchie, S., Arvidson, R., Bedini, P., Beisser, K., Bibring, J.-P., Bishop, J., Boldt, J., Cavender, P., Choo, T., Clancy, R.T., Darlington, E.H., Des Marais, D., Espiritu, R., Fort, D., Green, R., Guinness, E., Hayes, J., Hash, C., Heffernan, K., Hemmler, J., Heyler, G., Humm, D., Hutcheson, J., Izenberg, N., Lee, R., Lees, J., Lohr, D., Malaret, E., Martin, T., McGovern, J.A., McGuire, P., Morris, R., Mustard, J., Pelkey, S., Rhodes, E., Robinson, M., Roush, T., Schaefer, E., Seagrave, G., Seelos, F., Silverglate, P., Slavney, S., Smith, M., Shyong, W.-J., Strohbehn, K., Taylor, H., Thompson, P., Tossman, B., Wirzburger, M., Wolff, M., 2007. Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on Mars Reconnaissance Orbiter (MRO). J. Geophys. Res. 112, E05S03. doi:10.1029/2006JE002682.

Mustard, J.F., Murchie, S.L., Pelkey, S.M., Ehlmann, B.L., Milliken, R.E., Grant, J.A., Bibring, J.-P., Poulet, F., Bishop, J., Noe Dobrea, E., Roach, L., Seelos, F., Arvidson, R.E., Wiseman, S., Green, R., Hash, C., Humm, D., Malaret, E., McGovern, J.A., Seelos, K., Clancy, T., Clark, R., Marais, D.D., Izenberg, N., Knudson, A., Langevin, Y., Martin, T., McGuire, P., Morris, R., Robinson, M., Roush, T., Smith, M., Swayze, G., Taylor, H., Titus, T., Wolff, M., 2008. Hydrated silicate minerals on Mars observed by the Mars Reconnaissance Orbiter CRISM instrument. Nature 454, 305–309. doi:10.1038/nature07097.

Mustard, J.F., Ehlmann, B.L., Murchie, S.L., Poulet, F., Mangold, N., Head, J.W., Bibring, J.-P., Roach, L.H., 2010. Composition, morphology, and stratigraphy of Noachain/Phyllosian crust around the Isidis Basin. J. Geophys. Res. 114, E00D12. doi:10.1029/2009JE003349.

Newsom, H.E., Lanza, N.L., Ollila, A.M., Wiseman, S.M., Roush, T.L., Marzo, G.A., Tornabene, L.L., Okubo, C.H., Osterloo, M.M., Hamilton, V.E., Crumpler, L.S., 2010. Inverted channel deposits on the floor of Miyamoto crater, Mars. Icarus 205, 64–72. doi:10.1016/j.icarus.2009.03.030.

Noe Dobrea, E.Z., Bishop, J.L., McKeown, N.K., Fu, R., Rossi, C.M., Michalski, J.R., Heinlein, C., Hanus, V., Poulet, F., Mustard, R.J.F., Murchie, S., McEwen, A.S., Swayze, G., Bibring, J.-P., Malaret, E., Hash, C., 2010. Mineralogy and stratigraphy of phyllosilicate-bearing and dark mantling units in the greater Mawrth Vallis/west Arabia Terra area: constraints on geological origin. J. Geophys. Res., in press, doi:10.1029/2009JE003351.

Osterloo, M.M., Hamilton, V.E., Bandfield, J.L., Glotch, T.D., Baldridge, A.M., Christensen, P.R., Tornabene, L.L., Anderson, F.S., 2008. Chloride-bearing materials in the southern highlands of Mars. Science 319 (5870), 1651–1654. doi:10.1126/science.1150690.

Pondrelli, M., Baliva, A., Di Lorenzo, S., Marinangeli, L., Rossi, A.P., 2005. Complex evolution of paleolacustrine systems on Mars: an example from the Holden crater. J. Geophys. Res. 110, E04016. doi:10.1029/2004JE002335.

Pondrelli, M.A., Rossi, A.P., Marinangeli, L., Hauber, E., Gwinner, K., Baliva, A., Di Lorenzo, S., 2008. Evolution and depositional environments of the Eberswalde fan delta, Mars. Icarus 197, 429–451. doi:10.1016/j.icarus.2008.05.018.

Popa, C., Esposito, F., Colangeli, L., 2010. New landing site proposal for Mars Science Laboratory (MSL) in Xanthe Terra. Lunar Planet. Sci. XLI, Abstract 1807, LPI, Houston, TX.

Poulet, F., Bibring, J.-P., Mustard, J.F., Gendrin, A., Mangold, N., Langevin, Y., Arvidson, R.E., Gondet, B., Gomez, C., 2005. OMEGA Team, 2005. Phyllosilicates on Mars and implications for the early Mars history. Nature 438, 623–628.

Poulet, F., Gomez, C., Bibring, J.-P., Langevin, Y., Gondet, B., Pinet, P., Belluci, G., Mustard, J., 2007. Martian surface mineralogy from Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité on board the Mars Express spacecraft (OMEGA/MEx): global mineral maps. J. Geophys. Res. 112, E08S02. doi:10.1029/2006JE002840.

Poulet, F., Arvidson, R.E., Gomez, C., Morris, R.V., Bibring, J.-P., Langevin, Y., Gondet, B., Griffes, J., 2008. Mineralogy of Terra Meridiani and western Arabia Terra from OMEGA/MEx and implications for their formation. Icarus 195 (1), 106–160. doi:10.1016/j.icarus.2007.11.031.

Quantin, C., Allemand, P., Mangold, N., Dromart, G., Delacourt, C., 2005. Fluvial and lacustrine activity on layered deposits in Melas Chasma, Valles Marineris, Mars. J. Geophys. Res. 110, E12S19. doi:10.1029/2005JE002440.

Rogers, A.D., Bandfield, J.L., 2009. Mineralogical characterization of Mars Science Laboratory candidate landing sites from THEMIS and TES data. Icarus 203, 437–453. doi:10.1016/j.icarus.2009.04.020.

Scott, D.H., Tanaka, K.L., 1986. Geologic map of the western equatorial region of Mars. U.S. Geological Survey Miscellaneous Investigations Series I-1802-A, scale 1:15,000,000.

Smrekar, S.E., Golombek, M., Grant, J., 2007. Mars Science Laboratory landing site selection. In: Proceedings of the Second International Workshop on Exploring Mars and its Earth Analogues, June 19–23, Trento, Italy.

Squyres, S.W., Arvidson, R.E., Bollen, D., Bell III, J.F., Brückner, J., Cabrol, N.A., Calvin, W.A., Carr, M.H., Christensen, P.R., Clark, B.C., Crumpler, L., Des Marais, D.J., d'Uston, C., Economou, T., Farmer, J., Farrand, W.H., Folkner, W., Gellert, R., Glotch, T.D., Golombek, M., Gorevan, S., Grant, J.A., Greeley, R., Grotzinger, J., Herkenhoff, K.E., Hviid, S., Johnson, J.R., Klingelhöfer, G., Knoll, A.H., Landis, G., Lemmon, M., Li, R., Madsen, M.B., Malin, M.C., McLennan, S.M., McSween, H.Y., Ming, D.W., Moersch, J., Morris, R.V., Parker, T., Rice Jr., J.W., Richter, L., Rieder, R., Schröder, C., Sims, M., Smith, M., Smith, P., Soderblom, L.A., Sullivan, R., Tosca, N.J., Wänke, H., Wdowiak, T., Wolff, M., Yen, A., 2006. Overview of the Opportunity Mars Exploration Rover Mission to Meridiani Planum: Eagle Crater to Purgatory Ripple. J. Geophys. Res. 111, E12S12. doi:10.1029/2006JE002771.

Summons, R.E., Amend, J.P., Bish, D., Buick, R., Cody, G.D., Des Marais, D.J., Dromart, G., Eigenbrode, J.L., Knoll, A.H., Sumner, D.Y., 2010. Preservation of Martian organic and environmental records. Posted April 2010, by the Mars Exploration Program Analysis Group (MEPAG) at 〈http://mepag.jpl.nasa.gov/reports/〉.

Tosca, N.J., Knoll, A.H., McLennan, S.M., 2008. Water activity and the challenge for life on early Mars. Science 320, 1204–1207. doi:10.1126/science.1155432.

Wilson, S.A., Howard, A.D., Moore, J.M., Grant, J.A., 2007. Geomorphic and stratigraphic analysis of Crater Terby and layered deposits north of Hellas basin, Mars. J. Geophys. Res. 112, E08009. doi:10.1029/2006JE002830.

Wiseman, S.M., Arvidson, R.E., Andrews-Hanna, J.C., Clark, R.N., Lanza, N.L., Des Marais, D., Marzo, G.A., Morris, R.V., Murchie, S.L., Newsom, H.E., Noe Dobrea, E.Z., Ollila, A.M., Poulet, F., Roush, T.L., Seelos, F.P., Swayze, G.A., 2008a. The transition from phyllosilicate-bearing to sulfate-rich deposits within Miyamoto crater in southern Sinus Meridiani, Mars. Geophys. Res. Lett. 35, L19204. doi:10.1029/2008GL035363.

Wiseman, S.M., Arvidson, R.E., Poulet, F., Morris, R.V., Murchie, S., Seelos, F.P., Andrews-Hanna, J.C., CRISM Science Team, 2008b. Stratigraphic context of phyllosilicate deposits in Sinus Meridiani, Mars, Lunar Planet. Sci. XXXIX, Abstract 7035, LPI, Houston, TX.

Wray, J.J., Ehlmann, B.L., Squyres, S.W., Mustard, J.F., Kirk, R.L., 2008. Compositional stratigraphy of clay-bearing layered deposits at Mawrth Vallis, Mars. Geophys. Res. Lett. 35, L12202.

Zuber, M., Smith, D., Solomon, S., Muhleman, D., Head, J., Garvin, J., Abshire, J., Bufton, J., 1992. The Mars Observer Laser Altimeter Investigation. J. Geophys. Res. 97 (E5), 7781–7797.