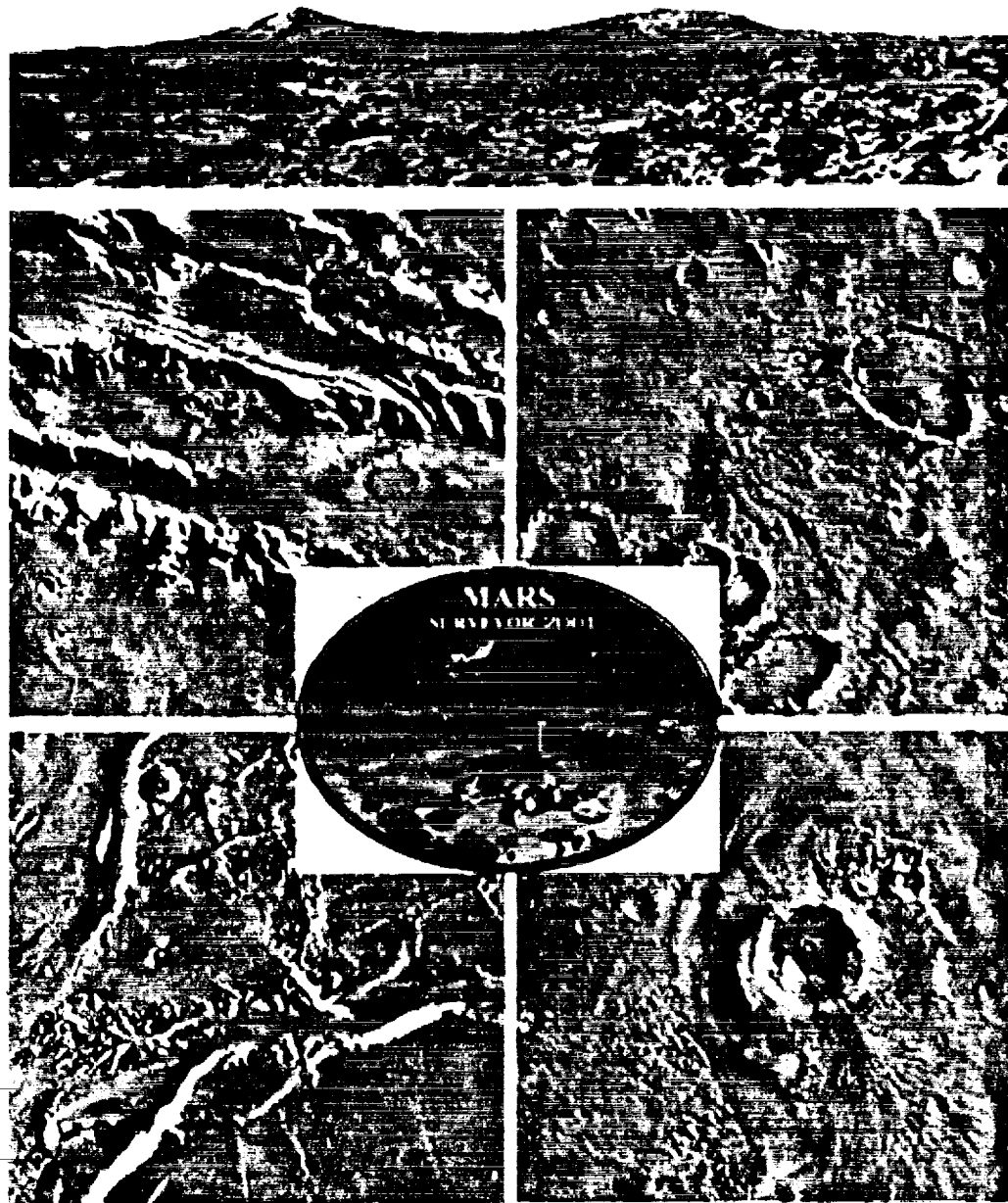


# MARS SURVEYOR 2001 LANDING SITE WORKSHOP



NASA-AMES RESEARCH CENTER  
MOFFETT FIELD, CALIFORNIA  
JANUARY 26-27, 1998



# MARS SURVEYOR 2001 LANDING SITE WORKSHOP

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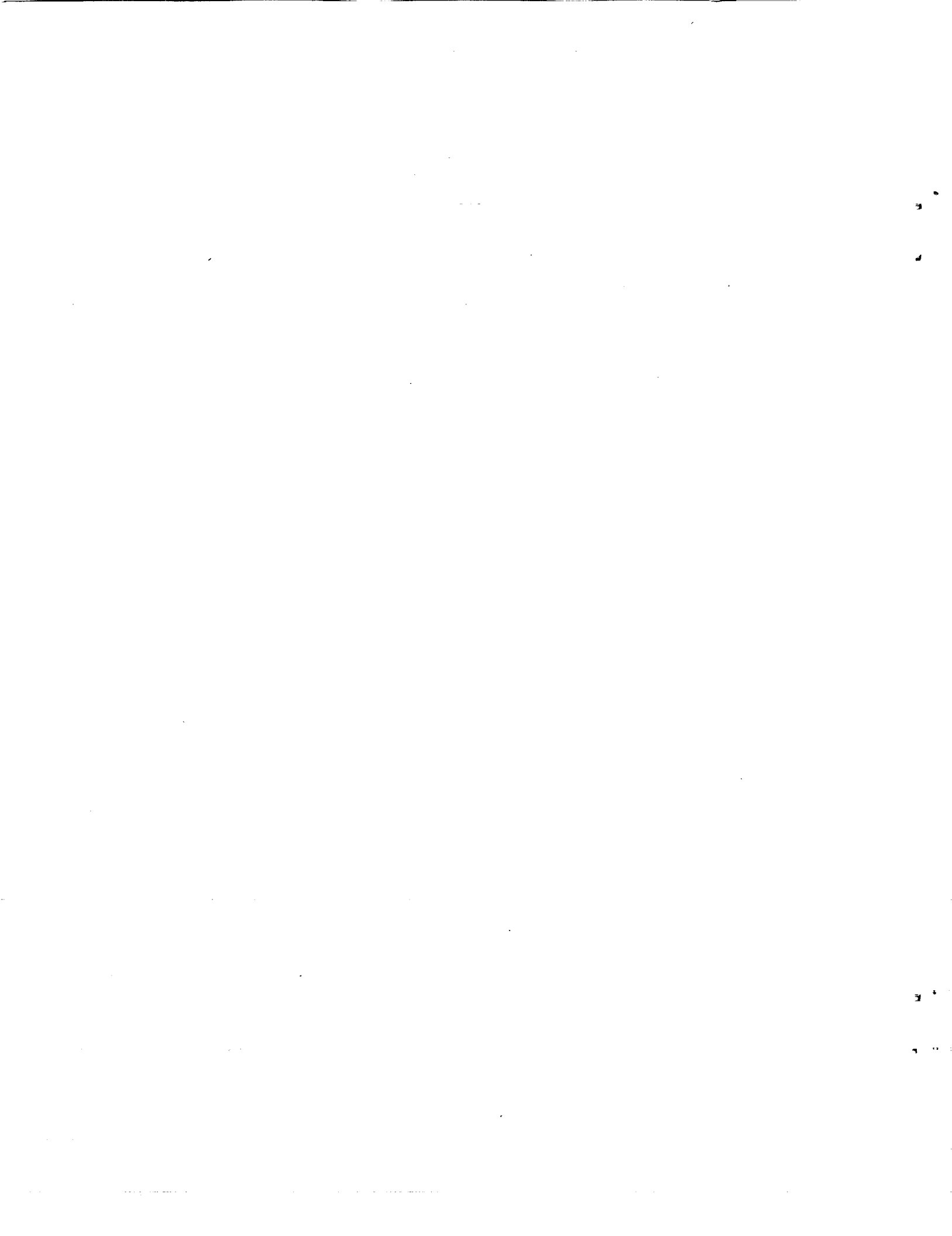
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Held at  
NASA Ames Research Center

January 26-27, 1998





# MARS SURVEYOR 2001 LANDING SITE WORKSHOP PROGRAM

## MONDAY 26TH: MORNING

Moderator: Geoff Briggs

- 8:30 INTRODUCTION AND WELCOME. *G. Briggs\**
- 8:45 MSP '01 STATUS/SURVEYOR SITE SELECTION PROCESS. *D. McCleese\**
- 9:15 THE ATHENA MARS ROVER SCIENCE PAYLOAD. *S.W. Squyres\*, J.F. Bell III, M. Carr, P. Christensen, D. Des Marais, T. Economou, S. Gorevan, G. Klingelhöfer, L. Haskin, K. Herkenhoff, A. Knoll, J.M. Knudsen, M. Malin, H. McSween, R. Morris, R. Rieder, M. Sims, L. Soderblom, H. Wänke, T. Wdowiak.*
- 9:45 A MISSION MODEL FOR THE 2001 MARS ROVER/ATHENA PAYLOAD. *R. E. Arvidson\*, C. S. Niebur, and J. Bowman.*
- 10:15 MGS RESULTS. *M. Carr\**
- 10:45 SELECTION AND ASSESSMENT OF PREDICTIONS OF THE MARS PATHFINDER LANDING SITE. *M. P. Golombek\*, H. J. Moore, A. F. C. Haldemann, R. A. Cook, T. J. Parker, and J. T. Schofield.*
- 11:15 USEFUL RADAR DATA FOR MARS 2001 LANDING SITE SELECTION. *A. F. C. Haldemann\*, M. A. Slade, R. F. Jurgens*
- 11:45 LANDING SITE MISSION IMPACTS. *D. Spencer\* and the Mars Surveyor 2001 Project, Mission Design & Navigation Team.*
- 12:15 LUNCH

## MONDAY 26TH: AFTERNOON

Moderator: Aaron Zent

- 1:30 HUMAN EXPEDITION CONSIDERATIONS. *M. Duke\**
- 1:45 EXOBIOLOGICAL CONSIDERATIONS FOR MARS 2001 LANDING SITES. *B. M. Jakosky\**
- 2:00 SITE SELECTION FOR MARS EXOPALEONTOLOGY IN 2001. *J. Farmer\**
- 2:15 POTENTIAL MARS SURVEYOR 2001 LANDING SITES: LOW-ELEVATION CRATERED "HIGHLANDS" IN CENTRAL AND EASTERN SINUS MERIDIANI AND NEAR AMENTHES FOSSAE. *K. S. Edgett\*, T. J. Parker, and S. N. Huntwork*

- 2:30 PROPOSED MARS SURVEYOR LANDING SITES IN NORTHERN MERIDIANI SINUS, SOUTHERN ELYSIUM PLANITIA, AND ARGYRE PLANITIA. *T. J. Parker\* and K. S. Edgett.*
- 2:45 THE SCHIAPARELLI BASIN AS A MARS SURVEYOR 2001 LANDING SITE. *N. G. Barlow\**
- 3:00 COFFEE BREAK
- 3:15 KAYNE CRATER: A POTENTIAL LANDING SITE ON MARS. *R. Greeley\* and R. Kuzmin*
- 3:30 WESTERN ARABIA TERRA: HIGHLAND MATERIALS AT LOW ELEVATION. *R.A. De Hon\**
- 3:45 HOT ROCKS, WET ROCKS, AND DEEP ROCKS: ERODED IMPACT CRATER AND CHANNEL DEPOSITS IN TIU VALLIS. *H. E. Newsom\**
- 4:00 POTENTIAL LANDING SITE FOR THE MARS 2001 MISSION: DOUBLE CRATER NEAR ARES VALLIS. *D.M. Nelson\*, R. Greeley, H.P. Klein.*
- 4:15 THE CONFLUENCE OF GANGIS, CAPRI AND EOS CHASMAS: A TOPOGRAPHIC TRAP FOR WATER AND DEBRIS AT THE EAST END OF VALLES MARINERIS. *S. M. Clifford\**
- 4:30 MARS SURVEYOR LANDING SITES IN VALLES MARINERIS: HIGHLAND SAMPLES FROM THE BASEMENT. *Richard A. Schultz\**
- 4:45 A PROPOSED MARS SURVEYOR 2001 LANDING SITE WEST OF CANDOR MENSA, VALLES MARINERIS. *B.K. Lucchitta\* and C.E. Rosanova.*
- 5:00 KASEI VALLES LANDING SITE. *F. Costard\*, J.P. Peulvast and Ph. Masson*
- 5:30 pm RECEPTION *Ames; Building 245; 2nd floor lobby*
- 7:00 pm DINNER *Chef Chu's, 1067 N. San Antonio Rd., Los Altos, 650-948-2696*

**TUESDAY 27TH: MORNING**

Moderator: Ginny Gulick

- 8:30 GEOLOGY OF THE TEMPE-MAREOTIS REGION, MARS. *H.J. Moore\*.*
- 8:45 RATIONALE FOR IN-SITU EXPLORATION OF THE OLYMPUS MONS AUREOLE DEPOSITS FROM A NEW STRUCTURAL MODEL. *P.J. McGovern\**
- 9:00 MULTIPLE MANGALA VALLES LANDING SITES. *M. G. Chapman\**

- 9:15 MANGALA VALLES AS A POTENTIAL LANDING SITE FOR THE MARS SURVEYOR 2001 LANDER. *R. Anderson\**
- 9:30 POTENTIAL MARS SURVEYOR 2001 LANDING SITES NEAR APOLLINARIS PATERA. *V. C. Gulick\**
- 9:45 SE ELYSIUM BASIN, MARS: A MARS 2001 CANDIDATE SITE OF LOCAL GEOLOGIC AND EXOBIOLOGIC INVESTIGATIONS. *J.M. Dohm\*, K.L. Tanaka, and J.H. Lias*
- 10:00 COFFEE BREAK
- 10:15 GUSEV CRATER PALEOLAKE: TWO-BILLION YEARS OF MARTIAN GEOLOGIC, (AND BIOLOGIC?) HISTORY. *N. A. Cabrol\*, E. A. Grin, R. Landheim, R. Greeley, R. Kuzmin, and C. P. McKay.*
- 10:30 SOUTHERN UTOPIA PLANITIA: GEOLOGY AND PROPOSED 2001 ROVER TRAVERSE NEAR THE LOWLAND/HIGHLAND BOUNDARY. *J.S. Kargel\**
- 10:45 SOUTHWESTERN ISIDIA PLANITIA, MARS: GEOLOGY AND ROVER TRAVERSES. *K. L. Tanaka\*, J. M. Dohm, and J. H. Lias.*
- 11:00 STRATEGIES AND RECOMMENDED TARGETS FOR MARS SURVEYOR PROGRAM LANDING SITES. *J. W. Rice, Jr.\* and D. H. Scott*
- 11:15 SW ISIDIS PLANITIA, MARS: VALLEY NETWORK SEDIMENTS, HIGHLAND ROCKS, AND INTERMEDIATE-AGE LAVAS. *L. S. Crumpler\**
- 11:30 .CONSIDERATIONS FOR SELECTING THE 2001 MARS LANDING SITE. *R. A. Craddock\*, T. A. Maxwell, A. D. Howard, and O. A. Krawciw.*
- 11:45 SCIENCE POTENTIAL OF NOACHIAN CLOSED DRAINAGE BASINS AS MARS LANDER/SAMPLE RETURN MISSION TARGETS *R D. Forsythe\* and C. R. Blackwelder*

**TUESDAY 27TH: AFTERNOON**

Moderator: Chris McKay

- 1:30 A REASON TO LAND IN THE DARK. *W. M. Calvin\**
- 1:45 STUDIES OF POTENTIAL MARS SURVEYOR 1998 LANDING SITES. *K. E. Herkenhoff\**
- 2:00 VOLCANIC INTRUSIONS ON MARS: HEAT SOURCES TO MAINTAIN VIABLE ECOSYSTEMS. *J. Head III\**
- 2:15 DISCUSSION

Site selection procedure  
Sites.  
Human Expedition Issues

3:30

**COFFEE BREAK**

**DISCUSSION CONTINUED**

**TITLE ONLY ABSTRACTS**

**DA VINCI CRATER: POTENTIAL LANDING SITE FOR THE MARS 2001 MISSION.** *D.M. Nelson, R. Greeley, H.P. Klein*

**GALILAEI CRATER AS A POSSIBLE LANDING SITE FOR THE MARS 2001 MISSION.** *D.M. Nelson, R. Greeley, H.P. Klein.*

**GALE CRATER: AN AMAZONIAN IMPACT CRATER LAKE AT THE PLATEAU/PLAIN BOUNDARY.** *N. A. Cabrol and E. A. Grin*

**MA'ADIM VALLIS ESTUARINE DELTA IN ELYSIUM BASIN AND ITS RELEVANCE AS A LANDING SITE FOR EXOBIOLGY EXPLORATION ON MARS.** *E. A. Grin and N. A. Cabrol*

**DEEP BASALT AQUIFERS IN ORCUS PATERA, ELYSIUM BASIN MARS: PERSPECTIVES FOR EXOBIOLGY EXPLORATION.** *E. A. Grin and N. A. Cabrol,*

**POSSIBLE LACUSTRINE DEPOSITS ON CRATER FLOORS AS TARGETS FOR MARS SURVEYOR SAMPLE RETURN MISSIONS.** *James R. Zimbelman*

**THE ATHENA MARS ROVER SCIENCE PAYLOAD.** S.W. Squyres (Cornell University, Ithaca, NY 14853 squyres@astrosun.tn.cornell.edu), R. Arvidson (Washington University, St. Louis), J.F. Bell III (Cornell University), M. Carr (USGS, Menlo Park), P. Christensen (Arizona State University), D. Des Marais (NASA Ames), T. Economou (University of Chicago), S. Gorevan (Honeybee Robotics), G. Klingelhöfer (T.H. Darmstadt), L. Haskin (Washington University, St. Louis), K. Herkenhoff (JPL), A. Knoll (Harvard University), J.M. Knudsen (Ørsted Institute, Copenhagen), M. Malin (Malin Space Science Systems), H. McSween (University of Tennessee), R. Morris (NASA JSC), R. Rieder (Max Planck Institut für Chemie, Mainz), M. Sims (NASA Ames), L. Soderblom (USGS Flagstaff), H. Wänke (Max Planck Institut für Chemie, Mainz), T. Wdowiak (University of Alabama, Birmingham).

**Introduction:** The Mars Surveyor missions that will be launched in April of 2001 will include a highly capable rover that is a successor to the Mars Pathfinder mission's Sojourner rover. The design goals for this rover are a total traverse distance of at least 10 km and a total lifetime of at least one Earth year. The rover's job will be to explore a site in Mars' ancient terrain, searching for materials likely to preserve a record of ancient martian water, climate, and possibly biology. The rover will collect rock and soil samples, and will store them for return to Earth by a subsequent Mars Surveyor mission in 2005.

The *Athena* Mars rover science payload is the suite of scientific instruments and sample collection tools that will be used to perform this job. The specific science objectives that NASA has identified for the '01 rover payload are to: (1) Provide color stereo imaging of martian surface environments, and remotely-sensed point discrimination of mineralogical composition. (2) Determine the elemental and mineralogical composition of martian surface materials. (3) Determine the fine-scale textural properties of these materials. (4) Collect and store samples. The *Athena* payload has been designed to meet these objectives. The focus of the design is on field operations: making sure the rover can locate, characterize, and collect scientifically important samples in a dusty, dirty, real-world environment.

**Imaging and Remote Mineralogy:** The topography, morphology, and mineralogy of the scene around the rover will be revealed by *Pancam/Mini-TES*, an integrated imager and IR spectrometer. *Pancam* views the surface around the rover in stereo and color. It uses two high-resolution cameras that are identical in most respects to the rover's navigation cameras. The detectors are low-power, low-mass active pixel sensors with on-chip 12-bit analog-to-digital conversion. Filters provide 8-12 color spectral bandpasses over the spectral region from 0.4 to 1.1  $\mu\text{m}$ . Narrow-angle optics provide an angular resolution of 0.28 mrad/pixel, nearly a factor of four higher than that of the Mars Pathfinder and Mars Surveyor '98 cameras. Image compression will be performed using a wavelet compression algorithm.

The Mini-Thermal Emission Spectrometer (Mini-TES) is a point spectrometer operating in the thermal IR. It produces high spectral resolution (5  $\text{cm}^{-1}$ ) image cubes with a wavelength range of 5-40  $\mu\text{m}$ , a nominal signal/noise ratio of 500:1, and a maximum angular resolution of 7 mrad (7 cm at a distance of 10 m). The wavelength region over which it operates samples the diagnostic fundamental absorption features of rock-forming minerals, and also provides some capability to see through dust coatings that could tend to obscure spectral features. The mineralogical information that Mini-TES provides will be used to select from a distance the rocks and soils that will be investigated in more

detail and ultimately sampled. Mini-TES is derived from the MO/MGS TES instrument, but is significantly smaller and simpler. The instrument uses an 8-cm Cassegrain telescope, a Michelson interferometer, and uncooled pyroelectric detectors. Along with its mineralogical capabilities, Mini-TES can provide information on the thermophysical properties of rocks and soils. Viewing upward, it can also provide temperature profiles through the martian atmospheric boundary layer.

**Elemental and Mineralogical Composition:**

Once promising samples have been identified from a distance using *Pancam/Mini-TES*, they will be studied in detail using up to three compositional sensors that can be placed directly against them by an Instrument Arm. The two compositional sensors presently on the payload are an *Alpha-Proton-X-Ray Spectrometer (APXS)*, and a *Mössbauer Spectrometer*. The APXS is derived closely from the instrument that flew on Mars Pathfinder. Radioactive alpha sources and three detection modes (alpha, proton, and x-ray) provide elemental abundances of rocks and soils to complement and constrain mineralogical data. The *Athena* APXS will have a revised mechanical design that will cut down significantly on backscattering of alpha particles from martian atmospheric carbon. It will also include a target of known elemental composition that will be used for calibration purposes. The *Athena* Mössbauer Spectrometer is a diagnostic instrument for the mineralogy and oxidation state of Fe-bearing phases, which are particularly important on Mars. The instrument measures the resonant absorption of gamma rays produced by a  $^{57}\text{Co}$  source to determine splitting of nuclear energy levels in Fe atoms that is related to the electronic environment surrounding them. It has been under development for space flight for many years at the Technical University of Darmstadt. The Mössbauer Spectrometer (and the other arm instruments) will be able to view a small permanent magnet array that will attract magnetic particles in the martian soil.

The payload may also include a *Raman Spectrometer*. If included, the Raman Spectrometer will provide precise identification of major and minor mineral phases. It requires no sample preparation, and is also sensitive to organics.

**Fine-Scale Texture:** The Instrument Arm also carries a *Microscopic Imager* that will obtain high-resolution monochromatic images of the same materials for which compositional data will be obtained. Its spatial resolution is 20  $\mu\text{m}/\text{pixel}$  over a 1-mm depth of field, and 40  $\mu\text{m}/\text{pixel}$  over a 1-cm depth of field. Like *Pancam*, it uses the same active pixel sensor detectors and electronics as the rover's navigation cameras.

**Instrument Arm:** The Instrument Arm is a three degree-of-freedom arm that uses designs and

components from the Mars Pathfinder and Mars Surveyor '98 projects. Its primary function is instrument positioning. Along with the instruments noted above, it also carries a brush that can be used to remove dust and other loose coatings from rocks.

**Sample Collection and Storage:** Martian rock and soil samples will be collected using a low-power rotary coring drill called the *Mini-Corer*. An important characteristic of this device is that it can obtain intact samples of rock from up to 5 cm within strong boulders and bedrock. Nominal core dimensions are 8x17 mm. The Mini-Corer drills a core to the commanded depth in a rock, shears it off, retains it, and extracts it. It can also acquire samples of loose soil, using soil sample cups that are pressed downward into loose material.

The Mini-Corer can drill at angles from vertical to 45° off vertical. It has six interchangeable bits for long life. Mechanical damage to the sample during drilling is minimal, and heating is negligible. After acquisition, the sample may be viewed by the arm instruments, and/or placed in one of 104 compartments in the Sample Container. A subset of the acquired samples may be replaced with other samples obtained later if desired. The Sample Container has no moving parts, and is mounted

external to the rover for easy removal by the Mars Surveyor 2005 flight system.

**Operations:** Operation of the rover will make extensive use of automated onboard navigation and hazard avoidance capabilities. Otherwise, use of onboard autonomy is minimal. Data downlink capability is about 40 Mbit/sol, and the use of the Mars Surveyor '01 orbiter for data relay imposes a limit of at most two command cycles per sol. Because of the significant amount of time available between command cycles, all payload elements will be operated sequentially, rather than in parallel; this approach also significantly simplifies operations and minimizes peak power usage.

The landing site for the '01 rover has not been selected yet. Site selection will make as full use as possible of Mars Global Surveyor data, and will involve substantial input from the broad Mars science community.

**Summary:** The following table describes the mass, power, providers, and key scientific objectives of all the major elements of the Athena payload.

Additional Athena payload information may be found at:  
<http://astrosun.tn.cornell.edu/athena/index.html>.

Payload Element	Mass, kg	Peak Power, W	Provider	Key Objectives
<b>Remote Sensing Science</b>				
Pancam / Mini-TES	3.41	5.4	JPL / SBRS / ASU	Investigate site geologic setting and processes; determine mineralogy remotely, particularly aqueous materials that may preserve climate and biology evidence; aid in rover navigation
<b>In-Situ Science</b>				
Instrument Arm	1.31	15.9	JPL	Provide instrument positioning against rocks and soils for Microscopic Imager, APXS, Mössbauer, and Raman Spectrometers
Microscopic Imager	0.075	0.1	JPL	Image fine-scale morphology of samples at high resolution; assist in interpreting compositional data
Alpha Proton X-Ray Spectrometer	0.47	1.3	MPI Mainz (Germany) / U. Chicago	Determine abundances of rock-forming elements; provide fundamental knowledge about crust formation, weathering processes, and water activity
Mössbauer Spectrometer	0.47	1.6	TU Darmstadt (Germany)	Determine iron oxidation state; detect and identify Fe-carbonates, sulfates, nitrates, and minerals that could preserve early environmental and biological evidence
Raman Spectrometer	1.75	2.5	JPL	Precisely identify major and minor rock-forming minerals; identify aqueous minerals and organic compounds
<b>Sample Collection and Storage</b>				
Mini-Corer	3.97	17.0	Honeybee Robotics/ JPL	Drill and collect 1.7-cm long rock cores from up to 5 cm within boulders and bedrock; collect soil samples
Sample Container	0.5	5.0	JPL	Retain 91 rock cores (with option to replace 39 cores) and 13 soil samples in sample container to be returned by '05 mission

**A Mission Model for the 2001 Mars Rover/Athena Payload:** R. E. Arvidson, C. S. Niebur, and J. Bowman, Department of Earth and Planetary Sciences, Washington University, St. Louis, Mo. 63130

Over the span of approximately an Earth year, the Athena Payload on the Mars Surveyor Program 2001 Rover will conduct remote sensing (multispectral imaging and emission spectroscopy) and in-situ (microscope imaging; Alpha-proton-xray, Moessbauer, and perhaps Raman Spectroscopy) observations, and collect samples (rock drill cores and soils) for possible return to Earth. The rover will communicate with Earth twice per day for a daily data return of approximately 40 Mbits. A total traverse distance of up to approximately 10 km is possible. Careful planning and tradeoffs are needed to accomplish science objectives (search for evidence of paleoclimatic conditions, prebiotic compounds, and life) within power, data rate, and mobility restrictions placed upon the mission. The purpose of this abstract is to introduce a rover mission model that shows in a quantitative fashion what science and traversing can be accomplished within the envelope of environmental and engineering constraints placed on operations.

The mission model is a daily plan, using standard spreadsheet software, of rover activities that charts various aspects of rover operations for a given site. For each sol of the year-long mission a series of tasks are specified, including remote sensing, in-situ analyses, sampling, traversing, and engineering activities. The power required to perform the tasks, the total power available, the amount of data acquired during the tasks, the amount of data stored, and data transmitted to Earth are tabulated each sol.

Power availability is a strong constraint on mission operations and is highly dependent on the landing site latitude. Landing occurs during the northern winter season. We have opted in our initial model to land in the southern hemisphere at approximately 6.5 deg S, 358 deg W, on a valley network in Terra Meridiani. This site exhibits a meandering channel system with evidence for modification by sapping processes. The site thus provides access to Noachian terrain and a channel system that may have produced spring-derived aqueous sedimentary rocks. At this latitude, power is highest during the initial phase of the mission and decreases with time as the southern winter is approached (Figure 1).

With the landing site chosen, the total power availability curve for that latitude can be used to determine power available for mission operations. The total power predicted to be available at 6 degrees south latitude was reduced by 4% relative to project-supplied data in order to account for the presence of the Athena mast, which will cast shadows on the solar panel. The power available was further reduced by another 10% in order to provide a safety margin for operations.

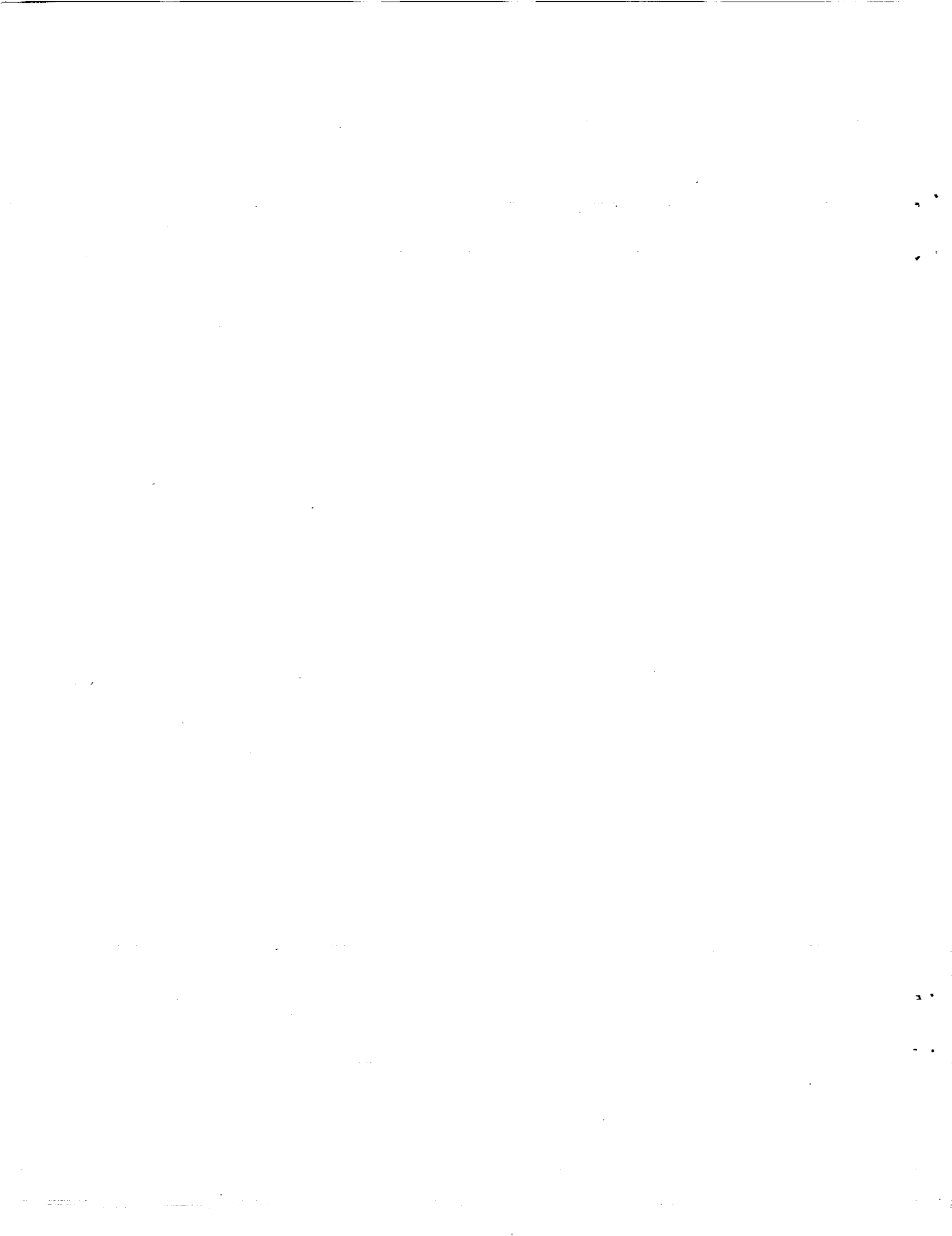
With the power available calculated, the power required for each scientific instrument in the Athena Payload and for rover traverses of different lengths was estimated. The time needed to complete scientific measurements, sampling, and rover traverses was also estimated.

Using the daily power available values and the required power and time estimates, a daily plan for rover activities was generated. Three mission phases were created, each approximately one and a half Earth months long, focusing on intensive science activities at three separate sites. The first is located at the landing site and the assumption is that measurements and sample collection would be done in the immediate vicinity of the lander before long traverses were attempted. The two other science-intensive sites were assumed to be far from the landing site and could represent, for example, good exposures of Noachian rocks at one site and aqueous sediments at the other site. At each of these three sites in-situ analyses are done (microscope imaging, APXS, Moessbauer and Raman Spectroscopy for each rock target, with each analysis requiring 1 sol) and samples are acquired and cached.

The other two mission phases consist of traverses totaling 10 km, requiring a period of 8 months to accomplish. The traverse phases focus on remote sensing science and mobility. At the end of each sol during a traverse phase, the Athena stereo cameras acquire a panorama for immediate transmission to Earth. These data are used for traverse planning for the next sol. The cameras only reveal the 30 to 50 m of terrain in detail, limiting the distance traveled on any given sol is limited to that these values. It requires approximately one hour to traverse these distances for reasonable terrain.

Results for the mission model are shown graphically in Figure 1 and in tabular form in Table 1. The model also contains a plan for daily data management. The daily data generated are estimated and added to the log of data stored onboard the rover. For each of the two daily communication sessions, the data transmitted to Earth are prioritized based on data needed to plan tasks for the next sol.

Under the assumption that 10 km distance is needed to get to relevant sites, traverses will consume the greatest amount of time, thus limiting the number of science-intensive sites that can be visited and studied. The duration of the traverse phases is controlled fundamentally by the distance the rover can travel in a given sol. For the three science-intensive sites, at total of only 17 rocks are analyzed by each instrument and 17 cores are obtained, along with a half dozen soil samples. A total of 13 Gbits of data are returned. Clearly, the mission model shows that a landing site must be chosen that minimizes traverse distances in order to maximize time spent at science-intensive sites. Further mission modeling will assume that not all in-situ instruments will be used for each rock or soil target. Even so, there will need to be continuing trade studies between traversing and science-intensive studies, particularly since results of solar panel degradation due to dust accumulation have not yet been factored into the mission model.





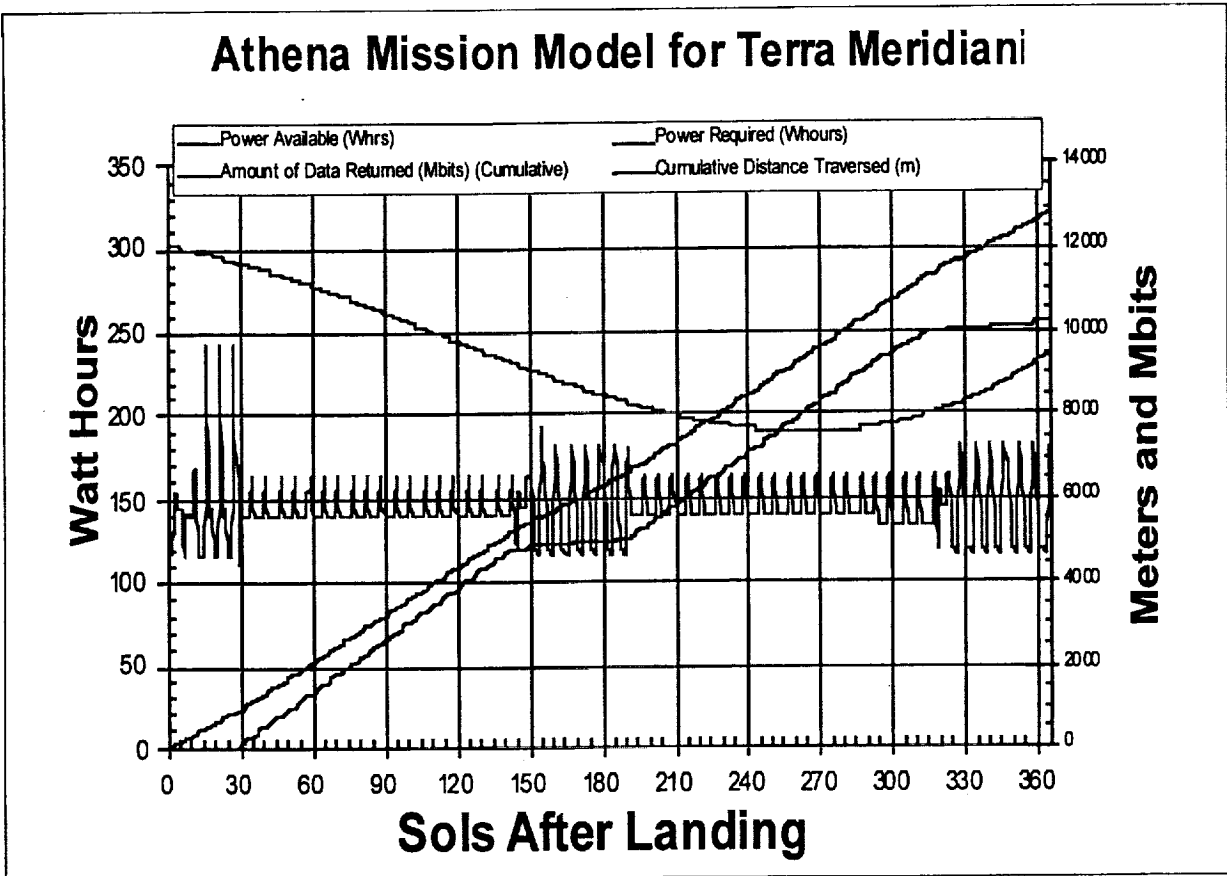
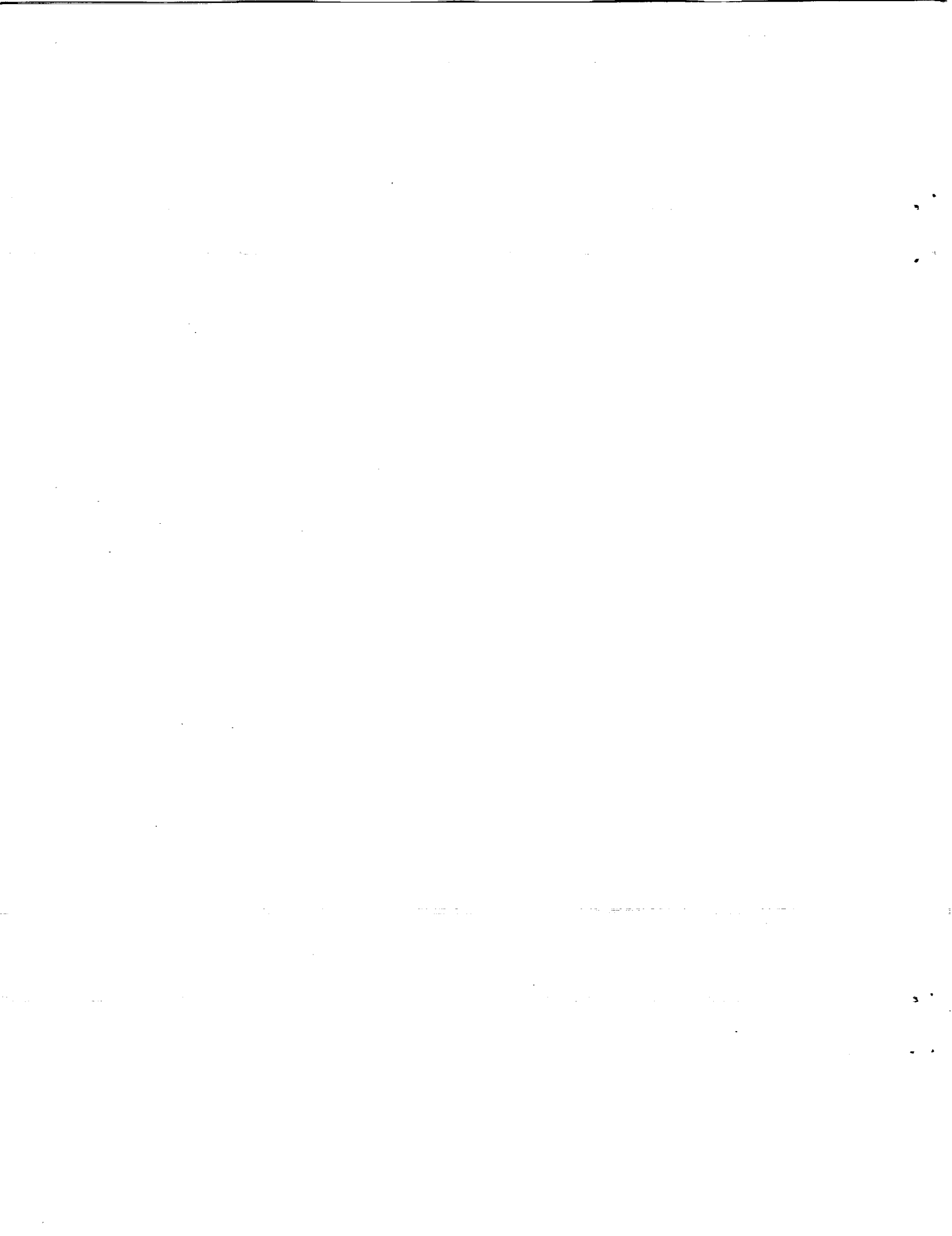


Figure 1. Athena Mission Model for Terra Meridiani. The figure plots the daily power required and total power available versus sols after landing. The total distance traversed (in meters) and the total amount of data transmitted to Earth (in megabits) are also plotted versus sol number.

In-Situ Measurements and Samples	17
PanCam images	271
Mini-TES images	69
Total Distance Traversed	10.2 km

Table 1. Summary of mission model. In addition to 17 rock samples, a half dozen soil samples were analyzed and collected.



**SELECTION AND ASSESSMENT OF PREDICTIONS OF THE MARS PATHFINDER LANDING SITE.** M. P. Golombek<sup>1</sup>, H. J. Moore<sup>2</sup>, A. F. C. Haldemann<sup>1</sup>, R. A. Cook<sup>1</sup>, T. J. Parker<sup>1</sup>, and J. T. Schofield<sup>1</sup>, <sup>1</sup>Jet Propulsion Laboratory, Caltech, Pasadena, CA 91109, <sup>2</sup>U. S. Geological Survey, Astrogeology Team, Menlo Park, CA 94025.

The successful landing of the Mars Pathfinder spacecraft on Mars allows the review of the process of selecting the landing site and assessing predictions made for the site based on Viking and Earth-based data. Selection of the landing site for Mars Pathfinder was a two-phase process. The first phase took place from October 1993 to June 1994 and involved: initial identification of engineering constraints, definition of environmental conditions at the site for spacecraft design, and evaluation of the scientific potential of different landing sites [1]. This phase culminated with the first "Mars Pathfinder Landing Site Workshop", held at the Lunar and Planetary Institute in Houston, Texas on April 18-19, 1994, in which suggested approaches and landing sites were solicited from the entire scientific community [2]. A preliminary site was selected by the project for design purposes in June 1994. The second phase took place from July 1994 to March 1996 and involved: developing criteria for evaluating site safety using images and remote sensing data, testing of the spacecraft and landing subsystems (with design improvements) to establish quantitative engineering constraints on landing site characteristics, evaluating all potential landing sites on Mars, and certification of the site by the project. This phase included a second open workshop, "Mars Pathfinder Landing Site Workshop II: Characteristics of the Ares Vallis Region and Field Trips in the Channeled Scabland, Washington" held in Spokane and Moses Lake September 24-30, 1995 [3] and formal acceptance of the site by NASA Headquarters.

Engineering constraints on Pathfinder landing sites [1] were developed from the initial design of the spacecraft and the entry, descent and landing scenario. The site must be within 5° of the subsolar latitude at the time of landing (15°N) for maximum solar power and flexible communications with Earth. It also must be below 0 km elevation to enable enough time for the parachute to bring the lander to the proper terminal velocity for landing. The entire landing ellipse, which is 70 km by 200 km due to navigational, ephemeris and atmospheric uncertainties, must be free of steep slopes, scarps and obvious hazards in Viking orbiter images, have acceptable radar reflectivity, moderate rock abundances and have little or no dust.

Scientific considerations of the Mars Pathfinder payload and mission indicate that analyses of "grab bag" samples at the mouths of outflow channels can offer a first order assessment of a variety of rock types on Mars [1, 2]. Highland sites offer the advantage of in situ analysis of ancient rocks on Mars that record crustal differentiation and the nature of the early environment. Dark gray sites offer the potential of analyzing unweathered and unoxidized materials. Following a general assessment of the safety of different sites, a preliminary selection of a

"grab bag" site was made. This site, Ares Vallis, is near the mouth of an outflow channel that may contain ancient Noachian terrain, Hesperian ridged plains, and reworked channel materials.

All potential landing sites on Mars that met basic safety criteria were analyzed in detail [1]. Sites (100 by 200 km target ellipses) were considered safe if they were below 0 km elevation, were free of obvious hazards (high-relief surface features) in high-resolution (<50 m/pixel) Viking orbiter images and had acceptable reflectivity and roughness at radar wavelengths, high thermal inertia, moderate rock abundance, low red to violet ratio, and low albedo. Only 4 sites on Mars met all the above criteria, which included 1995 opposition 3.5 cm delay-Doppler radar data. Complete data were evaluated for 7 sites and the Viking landing sites for comparison for all the above criteria as well as crater abundance, hill and mesa abundance, slopes over meter to kilometer scales, low altitude winds (from global circulation models and slopes), the size-frequency distribution of large rocks, as well as rover trafficability and science potential [1].

Discussion of potential hazards at Ares Vallis using a variety of data sets (including radar) at a second open workshop [3], indicated this site cannot be shown to be any more hazardous than the Viking landing sites. Field trips to the Channeled Scabland and the Ephrata Fan, analogs for Ares Vallis and the landing site, respectively, provided valuable insight into possible geologic processes and potential surface characteristics [1].

Three sites met all the data requirements and safety criteria for landing Pathfinder. Ares Vallis was selected by the project because it appeared acceptably safe (although it appeared to have greater rock abundances than other sites, its elevation was likely the best known) and offered the prospect of analyzing a variety of rock types expected to be deposited by catastrophic floods, which would enable addressing first-order scientific questions such as differentiation of the crust, the development of weathering products, and the nature of the early martian environment and its subsequent evolution. The selection was reviewed by an external board at a number of meetings and accepted, and the site was approved by NASA Headquarters [1].

Data gathered by the Pathfinder lander and rover provides the opportunity to test the predictions made for the site in the selection process based on remote observations from Earth, orbit, and the surface. The discussion below is taken from Golombek et al. [4] to which the reader is referred for a more complete discussion and a complete list of references, which are omitted here for brevity. Many characteristics of the landing site are consistent with its being shaped and deposited by the Ares and Tiu catastrophic floods. The rocky surface is consistent a depositional plain comprising semi-rounded

pebbles, cobbles and tabular boulders (some of which appear imbricated and/or inclined in the direction of flow) that appear similar to depositional plains in terrestrial catastrophic floods (see later discussion). The Twin Peaks appear to be streamlined hills in lander images, which is consistent with interpretations of larger hills in Viking orbiter images of the region that suggest the lander is on the flank of a broad, gentle ridge trending northeast from Twin Peaks [4]. This ridge, which is the rise to the north of the lander, is aligned in the downstream direction from the Ares and Tiu Valles floods, and may be a debris tail deposited in the wake of the Twin Peaks. Channels visible throughout the scene may be a result of late stage drainage.

As predicted by delay-Doppler radar measurements and tracking results, the average elevation of the center of the site was about the same as Viking Lander 1 relative to the 6.1 mbar geoid. The Doppler tracking and two-way ranging estimate for the elevation of the spacecraft is only 45 m lower than the Viking 1 Lander and within 100 m of that expected, which is within the uncertainties of the measurements. After landing, surface pressures and winds (5-10 m/s) were found to be similar to expectations based on Viking data, although temperatures were about 10 K warmer. The temperature profile below 50 km was also roughly 20 K warmer. As a result, predicted densities were 5% higher near the surface and up to 40% lower at 50 km, but within the entry, descent and landing design margins. The populations of craters and small hills and the slopes of the hills measured in high-resolution (38 m/pixel) Viking orbiter images and the radar derived slopes of the landing site are all consistent with observations of these properties in the lander images [4].

A rocky surface was expected from Viking Infra-Red Thermal Mapper (IRTM) observations and comparisons with the Viking landing sites. The observed cumulative fraction of area covered by rocks with diameters greater than 3 cm and heights greater than 0.5 m (potentially hazardous to landing) at Ares is similar to that predicted by IRTM observations and models of Viking lander and Earth analog rock size-frequency distributions. The IRTM prediction postulated an effective thermal inertia of 30 ( $10^{-3}$  cgs units -  $\text{cal cm}^{-3} \text{s}^{-0.5} \text{K}^{-1}$ ) for the rock population, but we obtain a slightly different effective thermal inertia for the actual rock population.

The validity of interpretations of radar echoes prior to landing are supported by a simple radar echo model, an estimate of the reflectivity of the soil from its bulk density, and the fraction of area covered by rocks. In the calculations, the soil produces the quasi-specular echo and the rocks produce the diffuse echo. The derived quasi-specular cross section is comparable to the cross-sections and reflectivities reported for 3.5-cm wavelength observations. The model yields a diffuse echo that is modestly larger than the polarized diffuse echo reported for 3.5-cm wavelength observations. At 12.5-cm wavelength, similar rock populations at Ares and the Viking 1 site were expected because the diffuse echoes are

comparable, but the large normal reflectivities suggests that bulk densities of the soils at depth are greater than those at the surface. We also obtain a fine-component inertia near 8.4 which agrees with the fine-component inertia of 8.7 (in  $10^{-3}$  cgs units) estimated from thermal observations from orbit by the IRTM; for this estimate, we used a bulk thermal inertia of 10.4 for the landing site, an effective thermal inertia near 40 ( $10^{-3}$  cgs units) for the rock population, and a graphical representation of Kieffer's model.

Color and albedo data for Ares suggested surfaces of materials at Ares Vallis would be relatively dust free or unweathered prior to landing compared with the materials at the Viking landing sites. This suggestion is supported by the abundance of relatively dark-gray rocks at Ares and their relative rarity at the Viking landing sites, where rocks are commonly coated with bright red dust. Finally, the 40 km long Ephrata Fan of the Channeled Scabland in Washington state, which was deposited where channelized water flowing down the Grand Coulee filled the Quincy Basin, was suggested as an analog for the landing site because the overall geology and geomorphology of the landing site, as interpreted from orbital images prior to landing, are compatible with such a depositional plain. The geology and geomorphology of the landing site (discussed earlier) is similar to such a depositional plain and the abundance and size of pebbles, cobbles and boulders are consistent with the expected general decrease in clast size from the mouth of the channel.

The prediction of the important characteristics of the site for safe landing and roving indicates that remote sensing data at scales of kilometers to tens of kilometers can be used to infer surface properties at a scale of meters. The prediction that the site would be a plain deposited by a catastrophic flood [1] is consistent with that found at the surface and implies that some geologic processes observed in orbiter data can be used to infer surface characteristics where those processes dominate over other processes affecting the martian surface layer. Analyses of rock chemistry and close up rover images suggest that a variety of rock types are present, consistent with it being a "grab bag" of materials deposited by the flood [4].

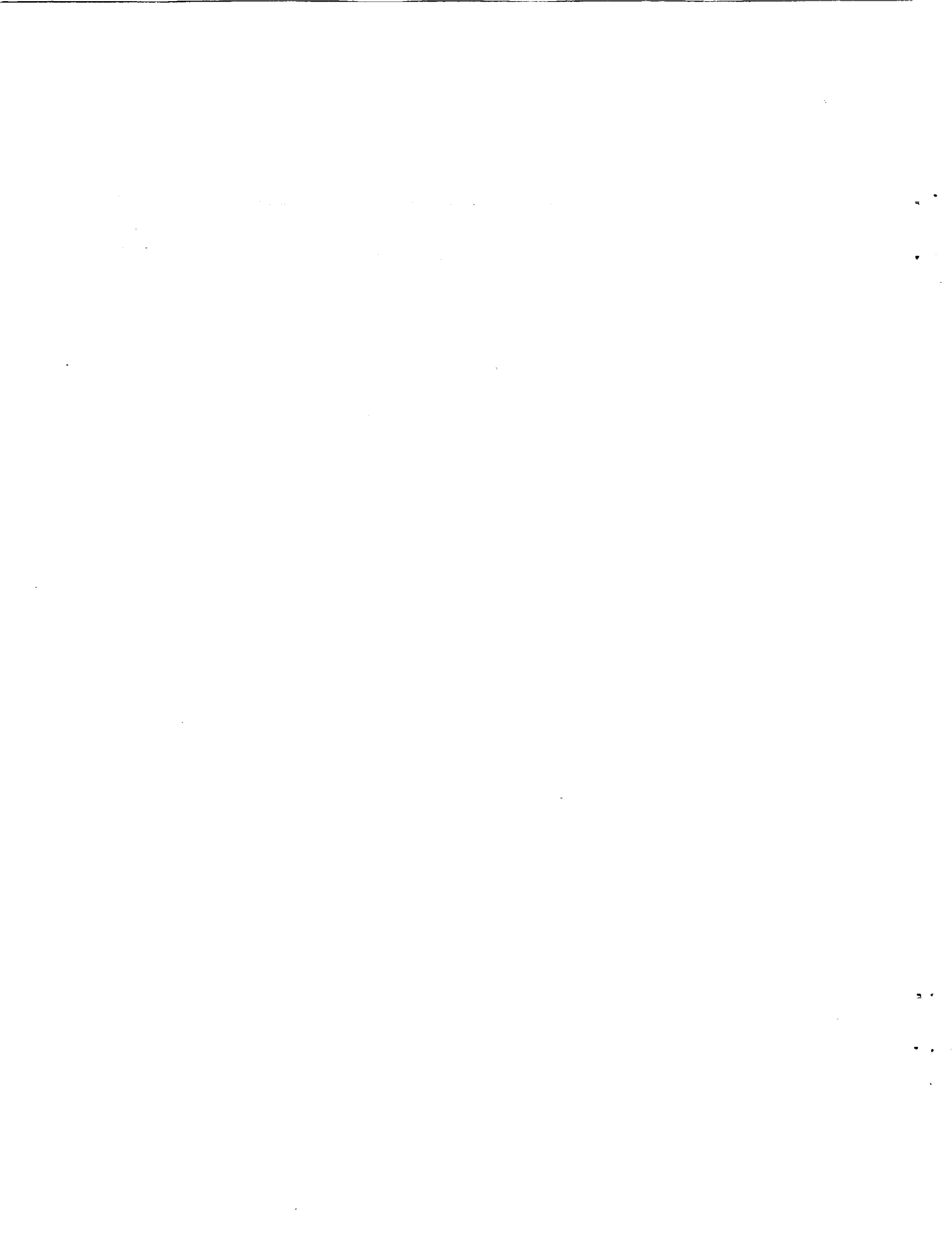
References: [1] Golombek, M. P., et al., 1997, Selection of the Mars Pathfinder landing site: *J. Geophys. Res., Planets* 102, 3967-3988. [2] Golombek, M. P., ed., Mars Pathfinder Landing Site Workshop, Lunar Planet. Inst. Tech. Rep. 94-04, 1994, 49pp. [3] Golombek, M. P., et al., eds., Mars Pathfinder Landing Site Workshop II: Characteristics of the Ares Vallis Region and Field Trips in the Channeled Scabland, Washington, Lunar Planet. Inst. Tech. Rep. 95-01, 1995, Part 1, 63 pp; Part 2, 47 pp. [4] Golombek, M. P. et al., 1997, Overview of the Mars Pathfinder mission and assessment of landing site predictions: *Science* 278, 1743-1748.

## Useful Radar Data for Mars 2001 Landing Site Selection

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Radar data, of both Doppler-only and delay-Doppler varieties, played a useful role in the landing site certification process for Mars Pathfinder. Radar provides information on the elevation of the planetary surface, on its radar reflectivity and on the surface roughness. The elevation is important for proper entry, descent and landing, as is the reflectivity if a radar altimeter is to be used on the lander. Both the reflectivity and the surface roughness can measure the rockiness of the surface, important for a safe landing, as well as for rover trafficability. The spatial resolution of this Earth-based remote sensing technique is around 10 km in longitude by some 150 km in latitude. In the case of Pathfinder the regionally averaged properties were confirmed by ground truth at the landing site in Ares Vallis.

The landing site assessment for Pathfinder relied principally on data from the 1995 Mars opposition when sub-Earth latitudes on Mars ranged from 16 to 22 degrees north. Data from earlier oppositions (1992-93, 1990, 1988-89) are available and cover latitudes from 25 south to 25 north at various longitudes. The available data will be presented at the symposium. The data are of varying quality, although ranging data is available for about 20 radar tracks per opposition, reflectivity and roughness analyses may not always be possible. Some older data are also available (1982, 1980) with range-only information.



# Landing Site Mission Impacts

Mars Surveyor 2001 Project, Mission Design & Navigation Team

15 December 1997

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*Summary. This table summarizes the top-level mission impacts of landing site location.*

*Rover:*                    30°N     Lander power is not sufficient to deploy Rover until 50 days after landing.  
                                  0° - 15°N    Rover lifetime up to 365 Earth days.  
                                  15°S     Rover lifetime 200 - 300 Earth days.

*Lander:*                    30°N     No Lander science for first 20 - 30 sols.  
                                  0° - 15°N    Lander lifetime greater than 300 Earth days.  
                                  15°S     Lander lifetime of about 200 Earth days.

*Note: Mission Requirement for Lander lifetime is 100 days.*

*Landing Accuracy:*    30°N     Landing footprint 30 km end-to-end (3-sigma).  
                                  15°N     Landing footprint 25 km end-to-end (3-sigma).  
                                  0°        Landing footprint 15 km end-to-end (3-sigma).  
                                  15°S     Landing footprint 10 km end-to-end (3-sigma).

*Landing Risk:*            Rock abundances similar to those found at the VL-1 site result in a probability of landing failure due to rock impact of less than 0.01.

*Rock abundances similar to those found at the VL-2 site result in a probability of landing failure due to rock impact of about 0.07.*

*Dust storms are more likely in Southern hemisphere.*

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## 1.0 Introduction

This document is intended to provide the Mars Surveyor 2001 Project Science Group (PSG) with an overview of all the significant impacts of landing site location on the flight system, mission design, and science return. In order to facilitate the design of the Rover and Lander systems, the Project has requested that the PSG select a 15° latitude band within the 15°S to 30°N region, at the site selection workshop to be held at NASA Ames Research Center on January 26-27, 1998.

## 2.0 Requirements

The requirements for the selected landing site for the Mars Surveyor 2001 mission<sup>(1)</sup> are as follows:

- (1) The landing site latitude shall be within the latitude region from 15°S to 30°N.
- (2) The maximum elevation of the landing site with respect to the Mars reference ellipsoid (defined as a 6.1 mbar datum) shall be less than or equal to 2.5 km. [Note: all terrain within the predicted 3-sigma landing footprint ellipse must meet this requirement.]

## 3.0 Rover Impacts

### 3.1 Rover Energy Requirements

The design lifetime of the Rover is 360 sols (= 1 Earth year). Normal surface operations will consist of 6 hours of Rover C&DH per sol (9:00 LTST to 15:00 LTST) and 18 hours of Rover sleep mode (15:00 LTST to 24:00 LTST and 0:00 LTST to 9:00 LTST) per sol. The Rover C&DH consists of housekeeping activities (e.g., health checks, command and telemetry handling, monitoring, etc.), heating of components (primarily the battery), and battery charging. The Rover sleep mode consists of the rover electronics powered off during all but perhaps two 10 min UHF communication passes which occur at roughly 16:00 LTST and 4:00 LTST. These communication passes, which consist of not greater than 4 min per pass of command and telemetry transmissions, are powered by battery energy. Rover C&DH requires 115 Whr of energy, which includes the battery charging required to replace the battery energy used during the communication passes. The rover 'dies' when the solar panel can no longer produce the energy required for C&DH.

Rover traverse mode consists of Rover C&DH along with driving, steering, hazard avoidance, navigation, monitoring of performance and imaging associated with documentation of the traverse. Rover traverse mode energy requirements vary according to distance traveled and terrain encountered. As an example, 25 Whr of energy is required for 1hr of operation in traverse mode. Without significant excursions for hazard avoidance, the rover will travel 50 m in 1hr.

Rover battery charging mode consist of Rover C&DH with any remaining energy developed by the solar panel devoted to recharging the battery. Charging efficiency is expected to be approximately 40%. The rover enters the battery charging mode whenever the battery reaches 30% state of charge. Rover energy profiles for various latitudes are shown in Figure 3.1.1.

### 3.2 Rover Deployment and Landing Latitude

The Rover batteries are expected to be depleted upon arrival at Mars. As a consequence, the Rover will enter battery charging mode upon landing. At 30°N latitude, the energy produced by the solar panel per sol begins at 120 Whr and increases to 150 Whr per sol after 3 months. As a consequence, upon deployment from the lander, the Rover will require approximately 1 month before beginning payload operations (see below). At



other latitudes in the range of the Mars Surveyor 2001 mission, the delay before beginning payload operations is less. At 15°N through 15°S there is no delay.

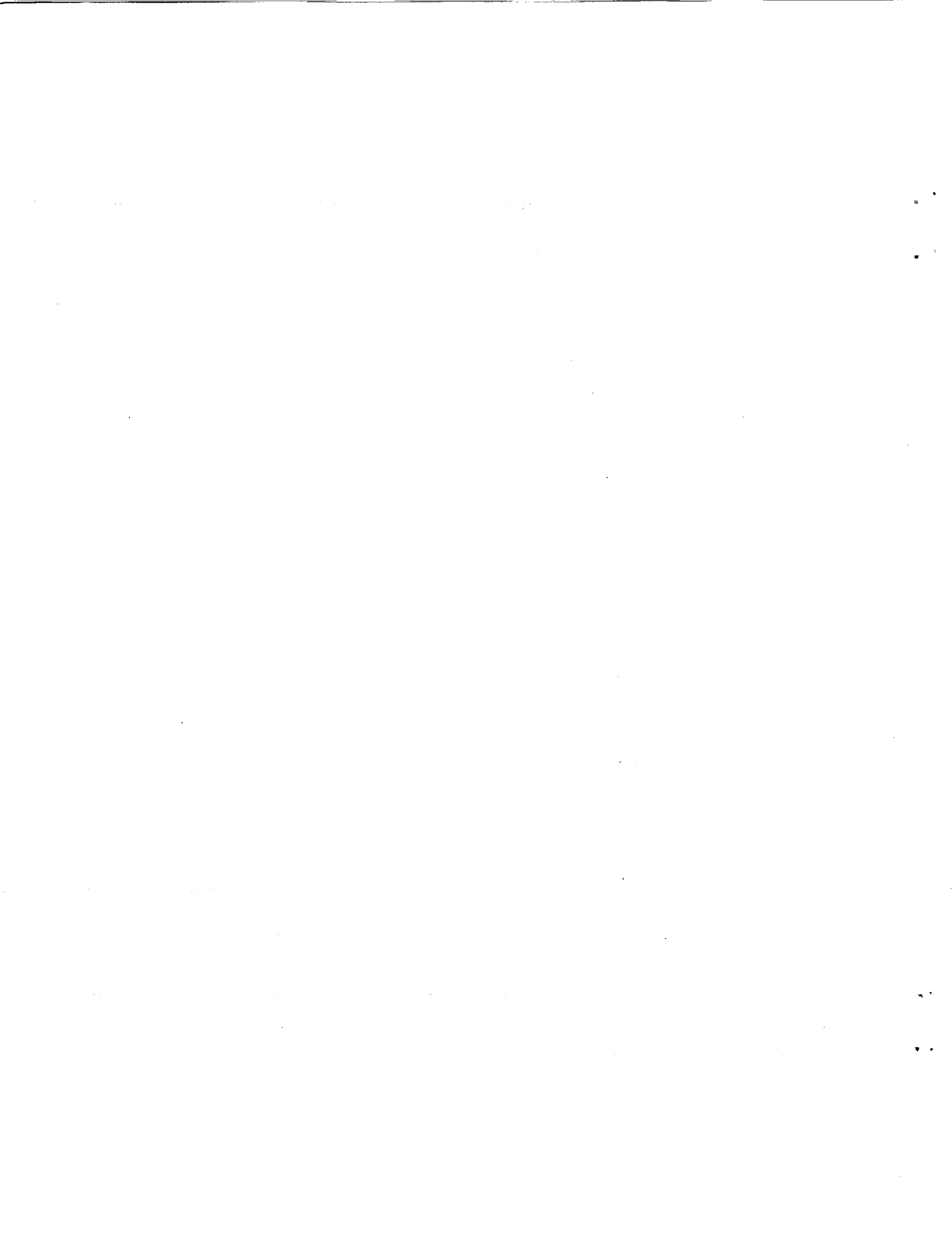
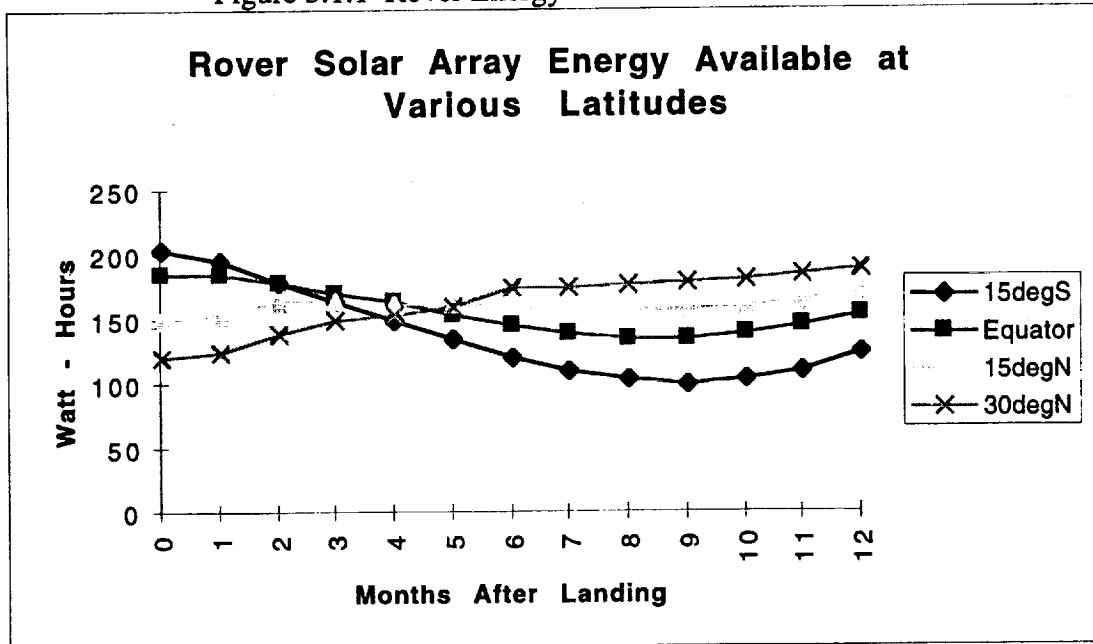


Figure 3.1.1 Rover Energy Profiles for Various Latitudes



### 3.3 Payload Operations and Landing Latitude

Payload operations primarily occur during the 6 hour period defined for Rover C&DH. If there is sufficient energy produced by the rover solar panel for the Rover to perform the traverse mode, there is sufficient solar energy to perform payload operations. The exception is coring, which may require up to 25 W of power applied for 2 hr to obtain a core sample. Coring will be scheduled as opportunities and available battery energy permit.

Selected payload operations are also planned to occur outside the 6 hour period defined for Rover C&DH. These operations include measurements by the APXS, Mossbauer or Raman spectrometer accompanied by motion of the payload instrument deployment arm. These operations will be scheduled as opportunities and available battery energy permit.

### 3.4 Rover Life Limitations

There are three life limiting elements of the rover mission: battery charging cycles, solar array dust accumulation and brush motor wear. These are each briefly described in the following paragraphs.

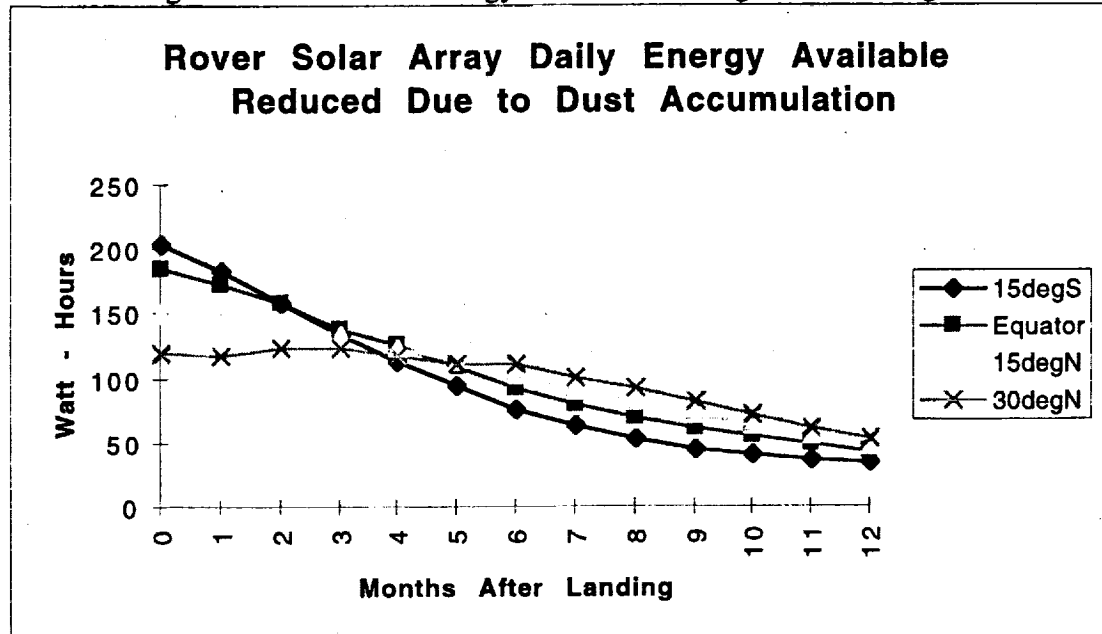
#### 3.4.1 Battery Charging Cycles

The specific chemistry of the rover battery has not yet been selected among those generally described as Li-ion chemistry batteries. Characterization of this battery technology indicate that after 200 charge/discharge cycles significant degradation in battery performance can occur. The rover battery has been sized at 10 A-hr. To compensate for charge life, the rover will carry a spare battery of 5 A-hr.

### 3.4.2 Solar Array Dust Accumulation

During the Mars Pathfinder mission, dust accumulation was observed on both the rover and lander solar panels. Within measurement variance, solar panel energy production degraded by a factor of 0.2% per sol due to such dust accumulation. Assuming this rate of degradation without compensation, the Rover would 'die' after 5 months at any latitude (see Figure 3.4.2.1 below). A more detailed assessment of dust accumulation effects is currently underway.

Figure 3.4.2.1 Rover Energy Levels Assuming 0.2%/Sol Degradation



### 3.4.3 Brush Motor Wear

Due to mass, volume and cost considerations, the Rover actuators are implemented using brush motors. These motors exhibit degradation leading to failure due to brush wear. Lifetime of the motor is quoted in terms of inches of brush wear per inch of surface travel. At the expected gearing ratio and torque characteristics, 2.6 billion inches of travel are required per inch of brush wear to ensure 10 km of travel (with a lifetime factor of 4). At the time of this writing, the motor baselined for this application has demonstrated 1.8 billion inches of travel per inch of brush wear, resulting in an expected Rover integrated travel distance capability of roughly 7 km.

## 4.0 Lander Impacts

This section is written with the assumption that the Lander will need to provide power for science payloads after landing. Due to funding uncertainties, it is not yet clear whether the science payloads will be self-sustaining, or dependent upon the Lander. If the Lander science payloads are all self-sustaining, then the power and thermal constraints detailed here do not apply.

#### 4.1 Site Latitude Range

Narrowing the range of landing site latitude to a 15° band permits a point design for the Lander, rather than a robust design needed to cover the entire latitude range from 15°S to 30°N. Due to Project cost constraints, narrowing the latitude range has been given a high priority. The identification of a 15° latitude band will allow a streamlined thermal design for heat rejection and insulation, and solar array sizing that may result in mass savings and packaging simplifications. The reduced latitude range will also decrease the required Entry, Descent and Landing trade studies and Mission Operations planning.

#### 4.2 Lander Energy Requirements

The design lifetime for the Lander is 100 sols. Normal surface operations will consist of 7 hours of Lander C&DH per sol (650-714 W-hrs) and 17 hours of Lander sleep mode per sol. There is nominally one 10 minute UHF pass during nighttime. No power is provided to payloads when the Sun is below the horizon, except "keep alive" power as specified in the PIP.

The Soil/Dust investigation requires sample delivery from the surface to the Lander. It is assumed that the Lander Robotic Arm is used for sample delivery. The Soil/Dust experiment is operated only on days in which a sample is delivered. Mars In-Situ Propellant (MIP) operations will be limited to solar energy measurements on sample delivery days. MIP and radiation investigations are not operated on the same days as Soil/Dust experiments.

The Lander Science mission is suspended when the payload energy goes to zero. The Lander "dies" when Lander energy plus heater energy exceeds the available energy. Figure 4.2.1 shows the available payload energy as a function of landing site latitude over the first 300 sols. It should be noted from Figure 4.2.1 that for a landing site latitude of 30°N, no science activities can be performed for the first 20 - 30 sols after landing. For a landing site latitude of 15°S, science activities will cease around sol 175. For latitudes from 0° to 15°N, sufficient power should be available to keep the Lander alive for up to a year.

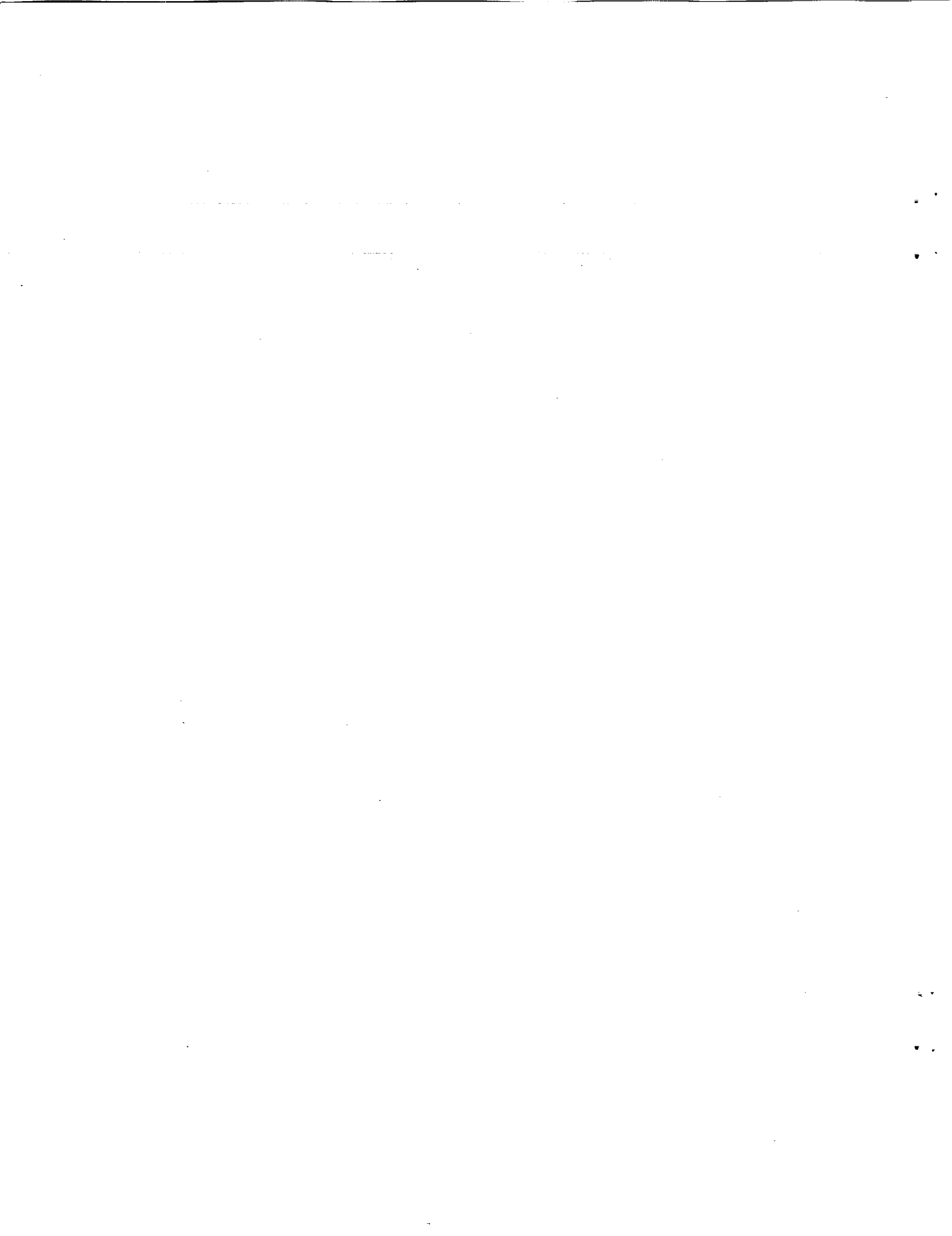
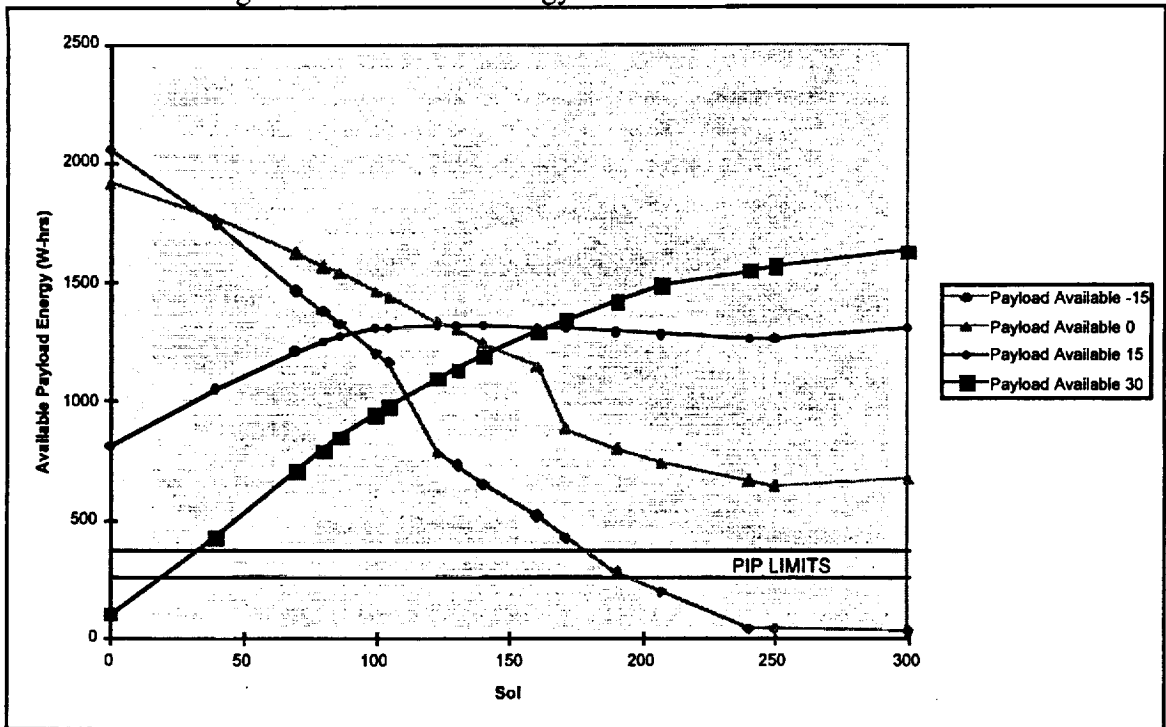


Figure 4.2.1 Lander Energy Profiles for Various Latitudes



## 5.0 Landing Accuracy

The landing footprint size on the surface of Mars is determined largely by the accuracy of the approach Navigation, and the ability of on-board guidance to correct for errors in the entry state and atmospheric dispersions during the atmospheric entry portion of flight. The Project requirement on landing accuracy is a miss-distance less than 50 km. NASA's Human Exploration Development of Space (HEDS) is funding a precision landing demonstration, with a goal of deploying the parachute within 10 km of the desired location.

Figure 5.0.1 shows the approach Navigation delivery ellipse mapped onto the Mars B-Plane, for landing site latitudes ranging from 30°N to 15°S. It is apparent from Figure 5.1 that the relative sizes of the delivery ellipses remain unchanged with latitude, however, the ellipses' orientation with respect to the entry corridor constraint lines (representing maximum and minimum allowable entry flight path angles) vary significantly with latitude.

The entry flight path angle uncertainty for entry trajectories targeted to 15°S is less (by about a factor of 2) than that for trajectories targeted to 30°N. Due to the evening arrival times associated with retrograde entry trajectories, only prograde trajectories are being considered.

The ability of on-board guidance to remove trajectory errors through control of the vehicle lift vector during atmospheric entry is currently being evaluated. Different classes of guidance schemes, of varying complexity, are being considered. Figure 5.0.2 shows representative landing accuracy performance to landing sites ranging from 30°N to 15°S, at 15° intervals. Landing accuracy is significantly better for sites in the Southern hemisphere than for those in the Northern hemisphere.

Map-tie errors (errors in the cartographic representation of surface features relative to inertial coordinates) are currently believed to be on the order of 10 - 20 km in magnitude. It is likely that the magnitude of map-tie errors will be reduced to less than 1 km prior to the Mars Surveyor 2001 mission.

Figure 5.0.1 B-Plane Delivery Ellipses for Various Target Latitudes

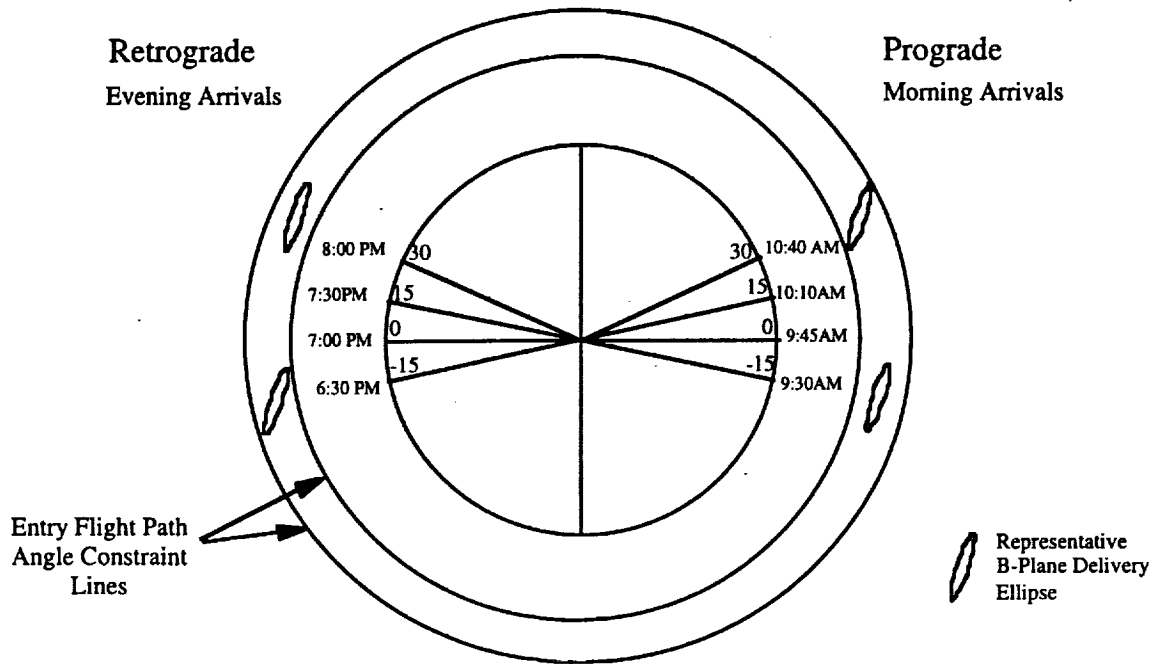
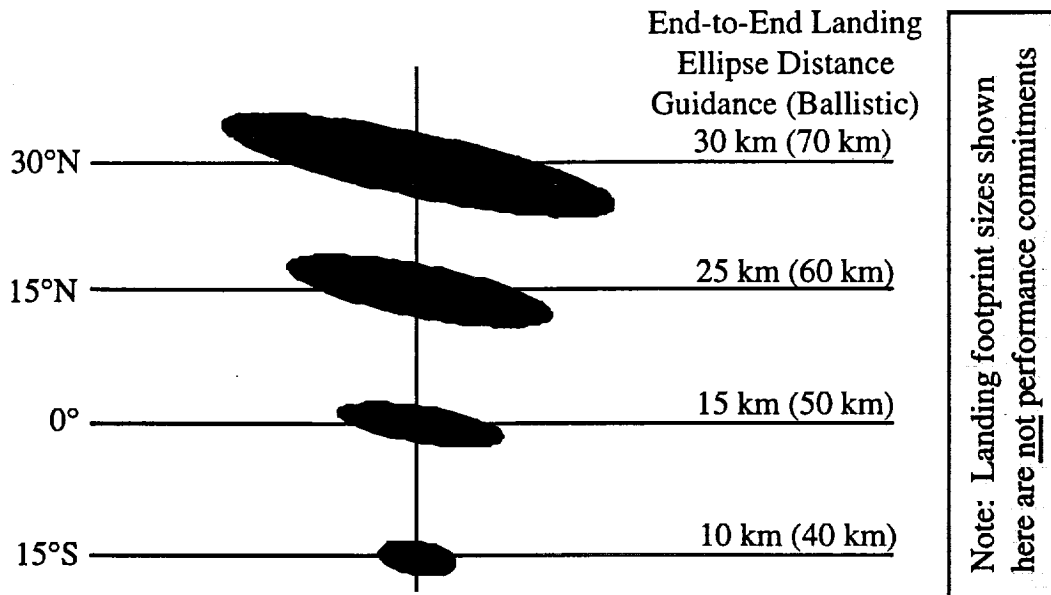


Figure 5.0.2 Landing Accuracy Dependency upon Target Latitude





- MSP'01 landing accuracy requirement: miss distance < 50 km ( $3\sigma$ )
- HEDS Precision Landing goal: miss distance at chute deploy  $\leq$  10 km ( $3\sigma$ )
- 15°S landing site may allow opportunity to traverse rover to any location within landing ellipse.

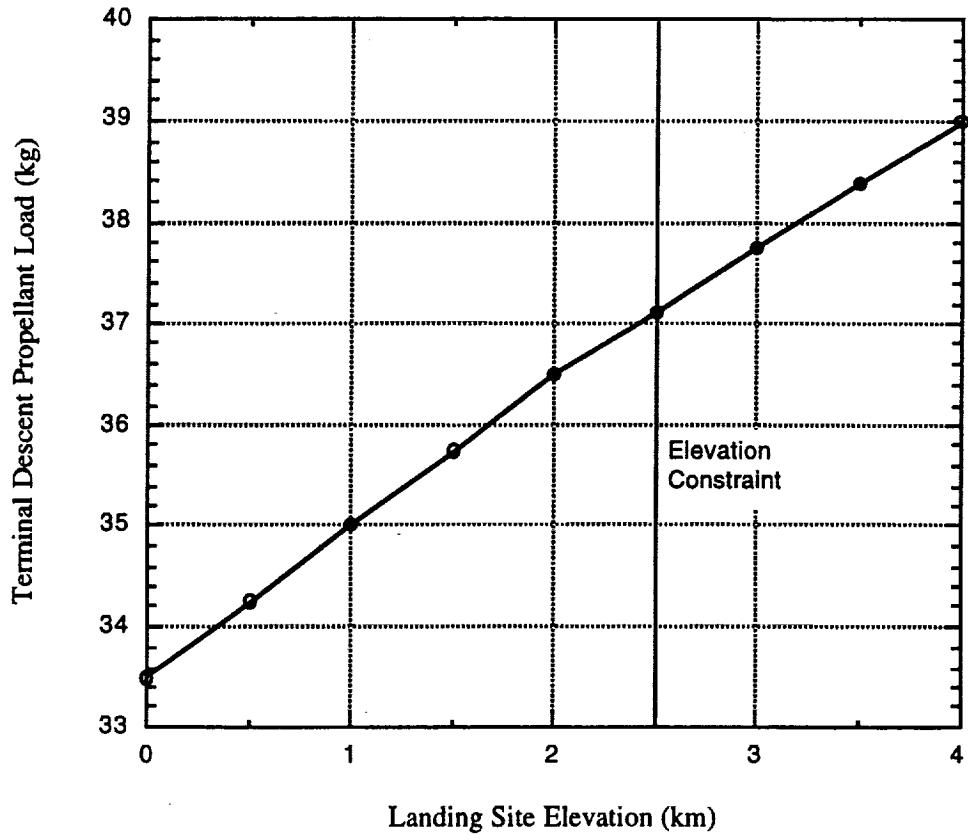
## 6.0 Site Elevation

The elevation of the landing site with respect to the Mars reference ellipsoid (defined as a 6.1 mbar datum) is required to be less than or equal to 2.5 km, including elevation uncertainties. All of the terrain within the predicted 3-sigma landing footprint ellipse must meet this requirement. This elevation requirement is shared by the Mars Pre-Projects' definition for the Mars Sample Return mission, scheduled for launch in 2005.

### 6.1 Terminal Descent Propellant Load

Following altimeter acquisition of the ground during terminal descent (after parachute deployment), the parachute will be cut away and the Lander flight system will initiate a propulsive gravity turn to decelerate and perform a soft landing. The amount of propellant used during terminal descent is a function of landing site elevation; to land at higher elevations more propellant must be expended, as seen in Figure 6.1.1. Selection of a lower elevation site will benefit the flight system in terms of mass margin and propellant margin.

Figure 6.1.1 Terminal Descent Propellant Load as Function of Landing Site Elevation

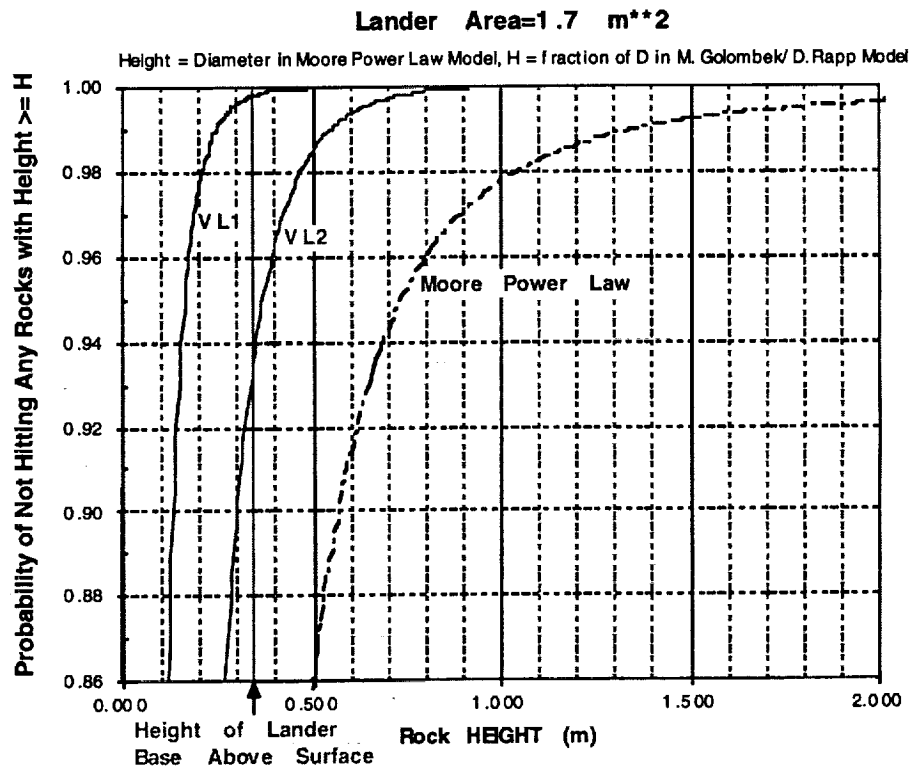


## 7.0 Rock Distribution

The rock distribution on the surface of Mars poses a potential hazard to the Lander. Catastrophic failure could occur if the vehicle lands on a rock, or rocks, of sufficient size<sup>[2]</sup>. Lander safety is characterized in Figure 7.0.1 as the probability of not landing on any rocks with height greater than or equal to some value such as the lander clearance of 35 cm. Curves in Figure 7.0.1 are shown for the very rocky VL2 landing site (rock abundance 17.6%, similar to the Pathfinder site) and the more likely, but less rocky, VL1 site rock abundance (6.9%). For a less rocky site such as VL1, there is a 99% probability of not landing on any rocks greater than 35 cm in height. For the more rocky sites such as VL2, there is about a 93% chance of not landing on any rocks greater than 35 cm in height. Therefore, such rocky sites as VL2 and Pathfinder result in a 7% chance of lander failure, which is cause for concern. The Project goal for Entry, Descent and Landing probability of success is 99%. This implies that the selected landing site should have a rock abundance that results in a probability of failure due to rock impact of less than 0.01 (1%).

Figure 7.0.1

Figure 1 Probability of Not Hitting Any Rocks As Function of Rock Abundance



## 8.0 Dust Storms

Dust storms could potentially pose a hazard to the Lander and Rover missions, due to high winds, increased dust erosion on the Lander heatshield, and reduced power availability to the solar arrays. Lander arrival will occur at an areocentric longitude of the Sun (Ls) between 311° and 322°, depending on the launch date. This is near the end of the observed dust storm "season" which is commonly thought to stretch from Ls = 160° to Ls = 330°.

### 8.1 Dust Storm Probability

The probability that a major dust storm will occur in a given dust storm season is estimated to be between 1 in 3 and 1 in 2<sup>[3]</sup>. The probability that a major dust storm will be active on the Lander arrival date (or that increased dust levels from the aftermath of a dust storm will be present) is currently being evaluated. Observations indicate that major dust storms are more likely to originate in the Southern hemisphere than the Northern hemisphere, with the most likely region being 20°S to 50°S<sup>[4]</sup>.

### 8.2 Ability to Retarget During Mars Approach

The capability exists to avoid a regional dust storm observed late in cruise. A change in landing site latitude of up to 45° can be attained through a 5 m/s maneuver performed at 10 days before Mars arrival. A late maneuver of this size is undesirable, however, because approach Navigation accuracy will be corrupted. Changes in landing site longitude are more costly; a 3 m/s burn at 10 days prior to Mars arrival can change the landing site longitude by 2°.

A potential scenario for landing site refinement following early Orbiter observations is being considered. If the Orbiter focuses its initial observations on the target landing site, it may be possible to shift the center of the target landing ellipse by a small amount (most likely, within the original landing ellipse) to increase the likelihood of landing near a particularly interesting geologic site.

## 9.0 References

- [1] "Mars Surveyor Program Announcement of Opportunity, 2001 Lander Mission, Proposal Information Package," 30 June, 1997.
- [2] J.C. Smith, "Influence of Landing Site on Probability of Safe Landing for '01 Mission," IOM 312/97D-021, 11 December 1997.
- [3] C.G. Justus, "Mars Dust Storm Probability for MSP'01 Mission," Memo in response to action item from August 7, 1997 Aerocapture Review, 20 August 1997.
- [4] "Mars," University of Arizona Press, 1992.

## **EXOBIOLOGICAL CONSIDERATIONS FOR MARS 2001 LANDING SITES.**

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With the overarching scientific goal of the Mars Surveyor mission being the search for evidence of past or present life, it makes sense to consider the relevance to exobiology in choosing landing sites. The major considerations are well known and involve looking for locations that at one time would have had the necessary environmental conditions to allow the sustenance of biological activity or prebiological chemistry. The relevant conditions are thought to include (i) the presence of liquid water, (ii) access to the biogenic elements, and (iii) a source of energy that can drive chemical disequilibrium so that the "slide" back toward equilibrium can provide energy for life:

**Liquid water.** Liquid water is thought to have been more stable at the martian surface during its earliest history than it is today, based on the geological considerations. Although there is no real agreement as to what this means, it does not necessarily mean that there were standing bodies of water or an Earth-like environment. Also based on the geological evidence, it is clear that there has been liquid water present in the martian subsurface throughout geologic time. It is not obvious that there have been episodic events that provided longstanding periods in which liquid water was present at the surface subsequent to the apparent change in the climate some 3.5 b.y.a. Thus, at the minimum it is clear that liquid water was present at the surface to some degree between about 4.0 and 3.5 b.y.a., and beneath the surface both during this period and throughout subsequent eras. Although not demonstrated, it is likely that there is abundant subsurface liquid water at the present.

**Biogenic elements.** Access to elements such as C, H, O, N, S, P, Ca, Fe, and so on, is required in order to have the building blocks for prebiotic chemistry or for biological activity. All of these are present in seemingly appropriate amounts, based on the direct measurements from Viking, Pathfinder, and the martian meteorites. In particular, carbon is present in substantial abundance as CO<sub>2</sub>, and is likely to be present within the crust as carbonate minerals. This is the case whether or not all of the carbon from a putative thick, early, greenhouse atmosphere still is present on or within Mars, rather than having been lost to space. Given the abundant geological activity on Mars, it is likely that the required elements are available throughout the crust. Certainly, the weathered materials present at the surface are probably widely distributed.

**Energy.** Available and accessible energy represents the biggest uncertainty in supporting possible life. The most plausible source of energy would be geochemical energy, involving either chemical weathering of minerals within the crust or conversion of geothermal energy to chemical energy within hydrothermal systems driven by volcanic activity. (Alternatives which probably, but not certainly, are less relevant include oxidation of organic molecules brought in from space and a primitive form of photosynthesis involving uv-stimulated emission of electrons from elements in minerals.) We (Jakosky and Shock, 1998) have done an inventory of the geochemical energy available on the martian surface and within the crust, over the entire 4 billion years of observable martian history; this allows us to obtain an upper limit as to how much life could have existed on Mars. The answer is--not much. The available energy will support

the construction of only ~20 g biota/cm<sup>2</sup> over 4 billion years. This is 4 million times less life than is present on Earth (with the large difference primarily being due to terrestrial photosynthesis), and is the amount of life that could have been created on the early Earth by the same geochemical processes in only ~100 million years.

**Discussion.** It is clear that the limiting factors on the presence of life are likely to be the geographical and temporal distributions of access to liquid water and to usable energy. In particular, the energy may be extremely limiting:

- It is likely that there was insufficient access to energy to allow much life to be created, even though all of the necessary environmental conditions were met widely over the planet.

- It is unlikely that evidence for life will be found in samples of the martian surface collected from random locations. Rather, it is essential that they be collected from places that are the most likely "reservoirs" for life, present or past.

- These best places include volcanic sites where there may have been liquid water in hydrothermal systems driven by the heat from the volcanism, the ancient terrain where liquid water would have been more available during the early history of the planet, places where the deep crust can be sampled and where liquid water might have been present for long periods of time, and probably many (if not most) of the sites to be discussed at the meeting.

- The worst sites would include everything else, including safe landing sites not selected specifically for their exobiological potential.

# SITE SELECTION FOR MARS EXOPALEARONTOLOGY IN 2001.

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## Introduction

The microbial fossil record encompasses a wide range of information, including cellular remains, stromatolites, biofabrics, trace fossils, biominerals and chemofossils. The preservation of fossils is strongly influenced by the physical, chemical and biological factors of the environment which, acting together, ultimately determine the types of information that will be captured and retained in the rock record.

The critical factor in assessing the suitability of a site for a microbial fossil record is the paleoenvironment. The reconstruction of ancient sedimentary environments usually requires the integration of a wide variety of geological information, including the shape, geometry and internal structure of sedimentary deposits, their mineralogy, and geochemistry. For Mars, much of our knowledge about past environments is based on orbital imaging of geomorphic features. This evidence provides an important context and starting point for site selection. However, our knowledge of the martian surface is quite limited, and a major goal of the upcoming exploration effort is to reconstruct the history of Martian volatiles, climate, and hydrology as a context for the exploration for past or present life. Mineralogical mapping from orbit will be an important key in this effort.

In exploring for evidence of past life, terrestrial experience suggests that the long-term preservation of biological information as fossils occurs under a fairly narrow range of geological conditions that are well known to paleontologists (1). In detrital sedimentary systems, microbial fossilization is favored by rapid burial in fine-grained, clay-rich sediments. In chemical sedimentary systems, preservation is enhanced by rapid entombment in fine-grained chemical precipitates. For long term preservation, host rocks must be composed of stable minerals that resist chemical weathering, and which form an impermeable matrix and closed chemical system that can protect biosignatures from alteration during subsequent diagenetic change or metamorphism. In this context, host rocks composed of highly ordered, chemically-stable mineral phases, like silica (forming cherts) or phosphate (forming phosphorites), are especially favored. Such lithologies tend to have very long crustal residence times and (along with carbonates and shales), are the most common host rocks for the Precambrian microfossil record on Earth.

**Subsurface Environments.** If we assume that a subsurface hydrosphere has been present throughout martian history, then life could have originated there at any time, perhaps emerging at the surface periodically when climate changes, induced by external forcing or endogenous processes (e.g. volcanism), allowed liquid water to exist at the surface. The recent discovery of subsurface chemolithoautotrophic organisms which are capable of synthesizing organic substrates from CO<sub>2</sub> and H<sub>2</sub> liberated from the aqueous weathering of basalt, is especially relevant as a model for martian life (2). While a subsurface habitable zone may yet exist on Mars, access to such environments will likely require drilling to depths of several kilometers (3). Given the technological challenge of deep drilling, this is unlikely to occur prior to human missions. So, even if there is extant life on Mars today in subsurface habitats, it may be much easier to find its fossil counterparts in ancient deposits exposed at the surface.

In exploring for a fossil record in subsurface environments on Mars there are several geological situations that may provide access to the appropriate materials. These include 1) ejecta from impact craters, 2) talus slopes, debris flows or alluvial fans developed below the walls of deep canyons, and 3) the deposits of outflow channels. Examples of aqueous mineral deposits of formed in subsurface environments that could harbor a microbial fossil record include such things as cements in detrital sedimentary rocks, low temperature diagenetic minerals deposited in veins, or filling vesicles in volcanic rocks, and hydrothermal deposits formed below the upper temperature limit for life (~160 degrees C). There are many sites within the present latitudinal constraints for the 2001 mission (15degS to 30degN) that meet these requirements. But the practical problem with these kinds of deposits is that they tend to be disseminated, making up only a small percentage of a host rock. Even with mineralogical information provided by the Thermal Emission Spectrometer (TES) presently in orbit around Mars (4), predicting their occurrence ahead of time may be quite difficult.

**Surface Hydrothermal Deposits.** The deposits of surficial aqueous sedimentary systems are likely to provide the largest targets for site selection in 2001. Of these, the deposits of hydrothermal systems (subaerial and subaqueous thermal springs) have been discussed previously (5). It is likely that hydrothermal systems were widespread on Mars early in its history and a number of common geo-tectonic settings on Mars are likely to have hosted hydrothermal activity (6). Most of these are represented within the latitudinal constraints presently identified for 2001. However, the deposits of surface spring systems are likely to be difficult to find as well. On Earth, exposure areas for hydrothermal spring mounds are typically a few square kms, less than a single TES

pixel. But such deposits may be quite abundant within some volcanic terrains. It is estimated, for example, that between 15-20% of the floor of Yellowstone caldera is covered by thermal spring deposits. In such abundances, subaerial sinters could well be detected by TES. Where exposed, the shallow subsurface portions of these systems may be quite a lot larger (perhaps tens of square kms), although (as noted above) mineralization may be finely disseminated in the basement rock, making remote detection more difficult.

**Paleolake Basins.** There are a large number of potential paleolake basins on Mars (inclusive of impact craters and volcanic calderas) that have been previously identified using Viking images (7). Most of these lie in the southern highlands beyond the 15degS constraint for 2001. However, deposits of paleolakes may offer the largest and most easily identified exopaleontological targets from orbit. Based on a variety of arguments, some workers have suggested that there was once an ancient ocean on the northern plains (8), and some sites of interest (potential shoreline terraces) fall within the 30degN constraint. From a paleontological standpoint the most interesting places of this type are terminal paleolake basins which are likely to have been both saline and alkaline. Models by Schaefer (9) suggest such environments could be widespread on Mars. The conditions in terminal lake basin settings favor widespread chemical sedimentation, an important condition for microbial fossilization. Important lithological targets for a microbial fossil record in terminal lake basins include spring-deposited carbonates, shoreline cements, a wide variety of evaporite minerals and fine-grained detrital sediments including shales, marls, and water-lain volcanic ash deposits.

**Facies Models as Tools for Exploration.** In developing a strategy to explore for ancient hydrothermal deposits on Mars, we can learn from the methods that have been developed by explorationists to explore for economic mineral deposits on Earth (10). Due to their simple mineralogy, hydrothermal deposits can often be detected using remote sensing methods (11). Common thermal spring mineral assemblages include silica, carbonate, and various metallic oxides and sulfides. But there are also a number of diagnostic silicate minerals, including clays, formed by the hydrothermal alteration of country rocks (12). These hydrothermal minerals have characteristic spectral signatures that could be detected from Mars orbit using high resolution infrared remote sensing methods (13). In playa lake settings, evaporite deposits often form a predictable "bull's eye" pattern with carbonates being deposited in marginal basin areas, and sulfates and halides occurring progressively more basinward (14). The floors of some impact craters on Mars, such as "White Rock" (16) and Bequeral Crater (see Oxia Palus NE, Site 148, ref. 17), have floor deposits that could be evaporites, inclusive of carbonates. Evaporite minerals possess characteristic spectral signatures in the infrared (15) and could similarly be identified from Mars orbit using high resolution remote sensing methods. Clearly, utilization of TES data will be important for optimizing site selection for Exopaleontology, and every effort should be made to benefit from that data before a final decision is made.

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**POTENTIAL MARS SURVEYOR 2001 LANDING SITES: LOW-ELEVATION CRATERED "HIGHLANDS" IN CENTRAL AND EASTERN SINUS MERIDIANI AND NEAR AMENTHES FOSSAE.** K. S. Edgett<sup>1,2</sup>, T. J. Parker<sup>3</sup>, and S. N. Huntwork<sup>4</sup>, <sup>1</sup>Department of Geology, Box 871404, Arizona State University, Tempe, AZ 85287-1404 USA; <sup>2</sup>Effective February 1998: Malin Space Science Systems, P.O. Box 910148, San Diego, CA 92191-0148 USA; <sup>3</sup>Jet Propulsion Laboratory, M/S 183-501, 4800 Oak Grove Dr., Pasadena, CA 91109 USA; <sup>4</sup>Student, North High School International Baccalaureate Program, 1101 E. Thomas Road, Phoenix, AZ 85014 USA.

### **Introduction, Philosophy and Approach**

The main scientific goal for the *Mars Surveyor Program 2001 (MSP 01)* landed mission is to collect and characterize 91 rock and 13 soil core samples using an integrated instrument suite onboard the *Athena* Rover. If possible, these samples will be retrieved and returned to Earth via a *MSP 05* or *MSP 07* mission.

Preliminary engineering constraints for the *MSP 01* landing site call for a location that lies between 15°S and 30°N, and below ~2 km elevation (based on *Viking*-era topography). Desirable landing sites for *MSP 01* are to be located "in the ancient highlands where the environmental conditions may have been favorable to the preservation of evidence of possible prebiotic or biotic processes including the emergence (and, potentially, the persistence) of life" [1]. We interpret this to mean that the desirable sites include those that have evidence of aqueous sediments that might have been deposited during the Noachian and/or Hesperian Epochs of Mars' history.

In addition to the search for subaqueous sedimentary deposits, we took into consideration the fact that the rover, *Athena*, will need to be able to access these materials. Thus, a site where aeolian deflation has occurred might be desirable because it might expose, *in situ*, layered sedimentary deposits. Deflated areas, of course, might include potential landing hazards in the form of meter-scale buttes and mesas (*e.g.*, Christmas Lake Valley, OR [2, 3]), thus careful study of such sites with high resolution images will be required before a decision is made to land.

We have been examining three regions that have potential to be considered for *MSP 01* landing sites. This work is based on *Viking* (VIS, IRTM) and *Phobos 2* (Termoskan) observations and should be regarded as preliminary because we believe that the final site selection should also be based upon analysis of *Mars Global Surveyor* observations that help constrain mineralogy (TES) and local geomorphology (MOC, MOLA).

#### **(1) Eastern Sinus Meridiani Region (proposed by K. S. Edgett)**

Sinus Meridiani is a persistent low-albedo (< 0.16) region on the martian equator that has been recognized for ~400 years. All of Sinus Meridiani is below the 2 km elevation constraint for *MSP 01*. The region includes cratered highlands, valley networks, aeolian dunes, and possible aqueous sedimentary deposits [4, 5].

The landing site study region is located in the eastern portion of Sinus Meridiani. It is bounded by latitudes 10°S to 2°N, longitudes 355°W to 345°W, and the elevations are mostly 1–2 km. The center of this area contains a medium-albedo (0.19–0.21), relatively smooth-surfaced deposit that was suggested by Rice [6] to be a lacustrine deposit. Several potential landing areas can be suggested within this region. Based on *Viking* and *Phobos 2* data, the favored sites so far are centered at 7.6°S, 346.9°W and 0.8°S, 349°W. Thermal inertias [7] are  $3.2\text{--}7.0 \times 10^3 \text{ cal cm}^{-2} \text{ s}^{-0.5} \text{ K}^{-1}$ ; and rock abundances [8] are around 2–6%.

The site at 7.6°S, 346.9°W is at the southern end of the smooth, medium-albedo unit that might have a lacustrine origin [6]. At this location, numerous channels appear to have drained toward the smooth unit. *Viking* images from orbit 747A show this area at about 15 m/pixel ground resolution. The images reveal that aeolian deflation has occurred along the deposit's margins. Bright (*i.e.*, albedo  $\geq 0.21$ ) aeolian dunes are present on the channel floors and in some of the depressions on the smooth unit [9]. The bright, apparently active dunes might consist of material (perhaps lake-deposited sands) that has been eroded from the smooth unit [9].

The site at approximately 0.8°S, 349°W is selected because it offers an opportunity to solve a long-standing puzzle about Mars remote sensing. There are three main "color" units on Mars: "dark red, dark gray, and bright red" [10]. This landing site would allow the *Athena* rover an opportunity to investigate all three materials within close proximity (the best place on Mars to do so). There are no high resolution (better than 100 m/pixel) *Viking* or *Mariner* images of this site.

#### **(2) Central Sinus Meridiani Region (proposed by K. S. Edgett and T. J. Parker)**

Central Sinus Meridiani is characterized by two types of surfaces [4]. One is like typical martian cratered highlands elsewhere—there are old valley networks and old impact craters. The other is relatively smooth and flat. These two units are in contact around 3.1°S between 5°W and 4°E longitudes. Valley networks—including one at 6°S, 358°W that rivals the Grand Canyon of Arizona—once drained toward the smooth unit. Edgett and Parker [4] proposed that the smooth unit might consist of sediments laid down in a large Noachian-aged sea/ocean that would have covered much of the northern hemisphere. Schultz and Lutz [11] suggested that it is a paleopolar layered deposit. Regardless, the smooth unit where it contacts the cratered terrain would make an excellent site for *Athena* rover to investigate. The site is best seen in *Viking* high resolution images from orbits 408B (~30 m/pixel) and 746A (~12 m/pixel). These images suggest that aeolian deflation has occurred along the margin of the smooth unit, and this deflation has exposed horizontal layers of material. The elevation is about 0.5 km; thermal inertias [7] are  $6.5\text{--}8.0 \times 10^{-3} \text{ cal cm}^{-2} \text{ s}^{-0.5} \text{ K}^{-1}$ ; rock abundances [8] are 2–4%; and the surface is probably sandy with dark drifts and ripples but almost no actual dunes [5]. We suggest a landing around 3.2°S, 3.0°W would test the aqueous sediment hypothesis and provide a potentially smooth surface on which to land.

### (3) Amenthes Fossae Region (*proposed by S. N. Huntwork and K. S. Edgett*)

The Amenthes Fossae are a series of graben/fissures that are circumferential to the southeast side of Isidis Planitia. These fissures cross a variety of ancient, heavily cratered Noachian terrain and younger, Hesperian and Amazonian terrain [12]. We focused our search on a region 0°–15°N, 250°–270°W. Elevations are -0.5 to 2 km. Depending upon whether Isidis Planitia was ever a water-rich environment [*e.g.*, 13, 14], this region might have been influenced by aqueous sedimentation. Valley networks are common, and they drained toward the north and northwest.

We focused our work on a set of *Viking* orbiter high-resolution images, 719A 1–48. These have resolutions 16–24 m/pixel. We examined images 20–23, centered at 2°N, 258°W. This site, on the plains just southwest of a 42 km-diameter crater, includes a valley network channel, a relatively young crater ejecta deposit, a few buttes composed of presumably ancient, Noachian bedrock, and a “plains” unit. The plains might make an ideal landing surface, except for the presence of some fine-scale ridges (oriented approximately N–S). The ridges are probably yardangs, thus this site offers a place where aeolian deflation has probably exposed some of the layered rock units that comprise the “plains”. Thermal inertias [7] are  $7.9\text{--}8.3 \times 10^{-3} \text{ cal cm}^{-2} \text{ s}^{-0.5} \text{ K}^{-1}$ ; and rock abundances [8] are 10–15%. A rover traverse might include the opportunity to go down to the floor (and sample along the walls) of the valley network channel at 2°N, 258.1°W.

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**PROPOSED MARS SURVEYOR LANDING SITES IN NORTHERN MERIDIANI SINUS, SOUTHERN ELYSIUM PLANITIA, AND ARGYRE PLANITIA.** T. J. Parker<sup>1</sup> and K. S. Edgett<sup>2</sup>, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, tparker@jpl.nasa.gov, <sup>2</sup>Affiliation for second author (full mailing address and e-mail address).

### Introduction

Our objective is to propose two landing sites that the Mars Surveyor 2001 Lander and Athena Rover could go to on Mars that should meet the safety requirements of the spacecraft landing system and optimize surface operations (chiefly driven by power and communications requirements). An additional site within Argyre Planitia, initially proposed by Parker to the Mars Surveyor Landing Site program, is also proposed for potential consideration for post-2001 missions to Mars, as it is well outside the current latitude limits for the Athena Rover. All three sites are designed to be situated as close to a diversity of geologic units within a few kilometers of the landing site so that diversity can be placed in a geologic context. This objective is very different from the Mars Pathfinder requirement to land at a site with a maximum chance for containing a diversity of rocks within a few tens of meters of the lander. That requirement was driven by the Sojourner mobility limit of a few tens of meters. It can be argued that the Athena project, with its much larger mobility capability, might actually want to avoid such a site, because placing collected samples in geologic context would be difficult. While it has been argued, both before and after the Mars Pathfinder landing, that the provenance for local blocks may be determined by orbiter spectra, primarily from the MGS TES instrument, our ability to do so has yet to be demonstrated. Indeed, several months after conclusion of the Pathfinder mission, we have yet to reach a consensus on the composition of local materials.

Our primary data set for selecting a landing site within the latitude and elevation constraints of the 2001 mission is the Viking Orbiter image archive. The site must be selected to place the landing ellipse so as to avoid obvious hazards, such as steep slopes, large or numerous craters, or abundant large knobs. For this purpose, we chose a resolution limit of better than 50 m/pixel. This necessarily excludes from the present study images from current and future orbiter spacecraft, until such data does become readily available. Within each proposed region, it may be possible to identify additional sites once these data become available.

Second, the fine-component thermal inertia data, [1] compiled by P. Christensen and made available to the Mars Pathfinder project, should be greater than about 5 or 6 cgs units ( $\cdot 10^{-3} \text{ cal} \cdot \text{cm}^{-2} \cdot \text{s}^{-0.5} \cdot \text{K}^{-1}$ ). Low thermal inertias imply dusty environments, which could pose a mobility hazard. Similarly, the albedo ([2] digital file made available to the Mars Pathfinder project by P. Christensen) of the site should not be particularly high, which would also suggest dusty surfaces. Low albedos are preferred, as they often coincide with low Viking red:violet ratios and indicate less dusty surfaces. Next, the Modeled Block Abundance [1] should also not be too high or too low. Based on the Viking

Lander and Mars Pathfinder experiences, percentages of blocks should be on the order of 5-25%. Too many blocks could pose a hazard to the landing and mobility. Too few blocks could also indicate a dusty surface.

### Primary Landing Site: Northern Meridiani Sinus (Proposed by T. J. Parker and K. S. Edgett)

Vital Statistics:

\*Latitude, Longitude: 0-3°N, 350-2°W.

\*Elevation (Viking): ~0.5-1.5 km.

\*Viking Orbiter Image coverage: Excellent coverage by 15-25 m/pixel images (orbits 709A and 410B). Possible stereo coverage in region where two orbits overlap (probably small parallax angle, as these orbits are not listed in NASA Contractor Report 3501)\*

\*Albedo: ~.18-.26

\*Block Abundance: 5-26%

\*Fine-Component Thermal Inertia: 5-9 cgs units

This region consists of bright deposits similar to those described by Edgett et al. [3], that also lie within a prominent dark albedo region. These deposits are flat-lying, to such a degree that they ramp against topography rather than draping over it. This led Edgett and Parker [4] to suggest that they may be subaqueous sediments, possibly lacustrine or marine evaporites, laid down sometime from the late Noachian to middle Hesperian (age determination pending crater counts). A contact between this material and elevated, dissected highlands to the south was identified [4], and is described by Edgett et al. [3].

Our desire in proposing this landing site is to sample the edge of this deposit where it has been exposed through etching, presumably eolian deflation (the deposit, though in the highlands, is itself only lightly to moderately cratered). This should enable access to *in situ* stratigraphy. The actual landing site will be selected where slopes are not expected to be steep, such that the rover itself should be able to traverse them and sample layered materials on the way, either up or down the slope. Perhaps due to uncertainties at this time as to the friability or meter-scale roughness of the deposit, it might make sense to place the landing ellipse on the exhumed highland surface adjacent to the deflated margin of the deposit and plan on driving to the deposit rather than landing on it and driving downslope. This should also enable imaging the margin for evidence of layering should it prove too difficult to climb. A target ellipse on the highland surface should also allow Athena access to ancient Noachian highland materials, particularly if placed near crater ejecta or an inlier of knobby material.

### Secondary Landing Site: Southern Elysium Planitia (Proposed by T. J. Parker)

Vital Statistics:

\*Latitude, Longitude: 1.5-3.5°S, 195-198°W.

- \*Elevation (Viking): -1.0 km.
- \*Viking Orbiter Image coverage: Excellent coverage by 15-25 m/pixel images (orbit 725). Possible stereo coverage between images from beginning and end of orbit that overlap (probably small parallax angle, as these orbits are not listed in [5])\*
- \*Albedo: ~.27-.28
- \*Block Abundance: 4-7%
- \*Fine-Component Thermal Inertia: ~3 cgs units

This region consists of eroded knobby material, probably of Noachian age, though much of the crater population has been destroyed, that is overlapped at a sharp contact by an extensive plains unit in southern Elysium Planitia that is Amazonian in age. The plains materials have been attributed to unusually low-viscosity flood lavas [6] from fissures south of the Elysium volcanic rise, or to lacustrine materials associated with a large, Amazonian lake at the source of Marte Vallis [7]. Parker and Schenk [8] presented evidence in support of the latter interpretation, though they attributed the putative shore morphology to an embayment of a northern plains ocean into the southern Elysium region. Detailed examination of the margin of the deposit, showing erosion, not simply burial, of small crater rims and fluidized ejecta blankets, also points to lacustrine or marine sedimentation rather than volcanic plains burial.

The plains surface exhibits a "crusty" appearance that many researchers have attributed to pressure ridges in lava flows. In a lacustrine context, they also resemble pressure ridges in desiccated evaporite deposits and salt-rimmed pools (now dry) similar in scale and morphology to spectacular, hundred meter-scale pool rims in alkaline Lake Natron, East African Rift.

The eroded highland margin surface adjacent to these plains appears to be fairly smooth, even at 15 m/pixel. Isolated knob inliers are scattered from a few kilometers to several tens of kilometers apart. Heights of the knobs have not been measured yet but, based on experience with similar features in the Pathfinder landing ellipse, are probably typically on the order of several tens of meters high and smaller, though some of the largest knobs in the region are probably up to a few hundred meters high. Two craters larger than a kilometer in diameter, with fluidized ejecta deposits, lie nearby the proposed landing site.

Very high-resolution images from MOC should help to determine whether a landing site navigable by the Athena rover could be placed in this region. The space between knobs and craters is large enough to enable placement of a target landing ellipse between them but still provide access to one or more of them and to the margin of the Elysium plains material.

**Post-2001 Mars Surveyor Landing Site: Argyre Planitia (Proposed by T. J. Parker)**

- Vital Statistics:
- \*Latitude, Longitude: 55-56°S, 41-43°W.
- \*Elevation (Viking): 1.0 km.
- \*Viking Orbiter Image coverage: Excellent coverage by 40 m/pixel images (orbits 567B, 568B, and 569B). Excel-

lent stereo coverage with large parallax angles over the entire landing site region, and much of central and southern Argyre.

- \*Albedo: ~.23-.24
- \*Block Abundance: No data
- \*Fine-Component Thermal Inertia: No data

The floors of both the Argyre and Hellas basins contain etched layered materials that are probably thick accumulations of channel or lacustrine sediments [9,10]. The deposits in Hellas are much more eroded than those in Argyre, and Hellas lacks a channel outlet. Argyre is unique in that Uzboi Vallis flowed out of the basin, requiring overflow of a standing body of water within Argyre [11]. This makes it the largest impact basin on Mars with channels both draining into it and flowing out from it. Hellas' channels may be catastrophic flood channels, whereas Argyre was fed by modest-scale valley networks, though the outlet at Uzboi Vallis was a catastrophic flood.

Highland craters and basins of this kind should be high-priority landing targets for missions intended to focus on the search for either prebiotic organic materials or even simple fossil microorganisms. Basins with internally-draining valley networks should be preferred over flood channels, as they could have provided the long-term influx of water favorable to the origin of life. (Catastrophic floods are not conducive to fossil preservation, due to their very short durations and high transportation energies). They also afford an opportunity to study the evolution of the planet's climate and volatiles during the period of time between the late Noachian and early Hesperian, when a drastic change from a proposed early warm, wet climate to one more closely resembling the modern environment is thought to have occurred. Large basins of this type are better targets than smaller ones, because the local environment would be less susceptible to freezing or drying caused by large swings in climate.

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Three spacecraft have now successfully landed on the surface of Mars (Viking 1, Viking 2, and Mars Pathfinder), all within the geologically young northern plains. The next lander, the Mars Surveyor 1998, will land in polar layered deposits near the south pole, another geologically young terrain. The time has come for a spacecraft to sample an area representative of the ancient terrain of Mars, which covers about 60% of the martian surface. The Mars Surveyor 2001 Lander is designed to investigate such an area. However, the constraint that the landing site must be at an elevation less than 2.5 km eliminates much of the ancient highlands. The floor of an old impact basin in the ancient highlands can overcome the elevation problem and still permit analysis of old material. The Schiaparelli impact basin is one such location which provides an excellent site for the Mars 2001 lander to investigate questions relating to the evolution of the martian ancient terrain.

#### **Geologic Setting**

Schiaparelli is an approximately 470-km-diameter impact basin centered at 2.5°S 343.3°W [1]. USGS topographic maps place the 2-km contour along the rim and the southern exposed portion of a 230-km-diameter central ring [2]. The rim of the crater is highly eroded and dissected by small channels, indicating a relatively old age for the crater. The crater is superposed on Noachian-aged terrain, including Noachian aged ridged plateau (Nplr) to the north and Noachian-aged dissected plateau (Npld) to the south, east, and northwest [3, 4]. To the west is the Hesperian-aged smooth unit of the plateau sequence (Hpl<sub>3</sub>) and within the basin are Hesperian-aged ridged plains (Hr). The rim is listed as Noachian-aged hilly material (Nplh). Based on the stratigraphic information, Schiaparelli probably formed during the late Noachian, which crater density estimates suggest occurred between 3.5 Gyr to perhaps as early as 4.3 Gyr [5].

The Noachian-aged dissected plateau (Npld) unit to the east, south, and northwest is highly eroded by small valley networks, including Evros Vallis about 400 km south of the southern rim of Schiaparelli. Although no fully-formed valley networks transect the rim of Schiaparelli, small gullies are predominant around the entire circumference of the rim. High resolution imagery from the Mars Global Surveyor mission of one of these gullies on the south side of the basin (MOC 2-15B and MOC 2-15C) reveal small depressions with faint dark lines crossing lighter floors. These regions have been likened to dry lake beds, with the light material being salts or other minerals deposited when an earlier lake evaporated. The dark lines are interpreted as mud cracks or freeze-thaw-produced cracks. These

initial results suggest that evidence of water (either surface or subsurface) is retained in the Schiaparelli area. Since one of the scientific objectives of the Mars Surveyor 2001 mission is to obtain "rocks and soil likely to preserve evidence of ancient martian environmental conditions and possible life", such material from the nearby highlands likely will have been deposited along the inner rim of the Schiaparelli basin. We thus propose a landing site near the rim of Schiaparelli to allow sampling of such material.

In the southeastern portion of the basin is a streak of dark material about 150 km long and up to 20 km across. This dark deposit is superposed on the Hesperian-aged ridged plains that fill most of the basin floor and envelopes many of the small craters in this region, indicating the deposit is young (i.e., probably of Amazonian age). The northern end of this deposit appears to emanate from one of the gullies along the rim, although no obvious source of this material can be discerned in the Viking imagery. A Mars Global Surveyor image (MOC 2-18C) lies just to the north of this region and sheds no light on the source of the dark material. Similar dark deposits (although smaller in areal extent) are found within the floors of many other old craters throughout the region suggesting that the source may be a widespread buried layer which can only be tapped through a combination of impact excavation and eolian and/or fluvial dispersion.

#### **Proposed Landing Site and Scientific Rationale**

The southeastern portion of the floor of the Schiaparelli impact basin provides an area of smooth Hesperian-aged plains and, based on Mars Global Surveyor data, surface dust deposits. The smoothness of the region compared to other locations in the heavily cratered martian terrain increases the odds of a successful landing. Since a major objective of the Mars Surveyor 2001 landing site is to sample material from the ancient martian highlands, we propose a landing site within the Schiaparelli basin just below its rim. The location of the dark material deposit near the southeast rim provides an opportunity for the Mars 2001 rover to sample not only material from the rim but also material from the dark deposit. A landing site that would allow access to both types of materials within the rover's proposed 10 to 20 km traverse range occurs at 3.9°S 340.0°W. This site is located along the eastern edge of the dark deposit and near the mouth of one of the rim gullies. The Viking data covering this region is not sufficient to determine slopes, but it may be possible for the rover to traverse at least part-way up the gully for further soil and rock analysis and collection. A small impact crater (approximately 4-km-diameter) with a fresh fluidized ejecta blanket is

located about 10 km north of the landing site and could be an alternate target of exploration by the rover.

The Mars Surveyor 2001 lander site proposed above will be able to address several of the science objectives of the lander mission. It provides access to rocks and soil deposited from the ancient highlands into the bottom of the basin while still providing a smooth landing site within the latitude and topographic constraints of the mission. The dark deposit can be sampled and its mineralogy constrained--since this dark material is apparently widespread throughout the region, this analysis will help provide a possible origin for this material and clues to the geologic evolution of the region. Water has likely affected the surrounding highlands material, as indicated by the abundance of valley networks and the possible "evaporite deposits" identified in Mars Global Surveyor imagery of an area to the south of the proposed landing site. The abundant evidence of water in the region makes the area a good location to look for evidence of ancient martian life. In fact, one of the proposed source craters for the martian meteorite ALH84001, which has been interpreted as possibly containing biogenic material, is located approximately 500 km southwest of the proposed landing site [6]. Mars Global Surveyor imagery suggests the floor of Schiaparelli is blanketed by dust, which could be aeolian or perhaps lacustrine in origin. The origin of these dust deposits is another question which the Mars Surveyor 2001 lander can help address. Thus, a landing within the Schiaparelli impact basin near 3.9°S 340.0°W will provide an opportunity to address many questions regarding the early environment of Mars.

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## **KAYNE CRATER: A POTENTIAL LANDING SITE ON MARS**

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Kayne Crater is a 33-kilometer impact structure located in the ancient highlands west of Gusev Crater and centered at 15.6 degrees south, 186.4 degrees west at an elevation of about 1 km above Mars mean datum. The general region was mapped geologically by Kuzmin et al. (1) and shown to have a geologically complex and interesting history (2,3). Key features of the region include the Noachian-age basement complex (including some of the oldest recognizable units on Mars and high-standing massifs, some of which could be volcanic constructs), complex valley networks, Hesperian to Amazonian age outflow channels which appear to have experienced repeated episodes of channel formation, and ejecta-flow craters ranging in diameter from 6 to 14 km, suggesting the presence of a subsurface water zone at the time of their formation. Kayne Crater represents a young (Amazonian) impact and its ejecta has the potential to contain all of the materials outlined here.

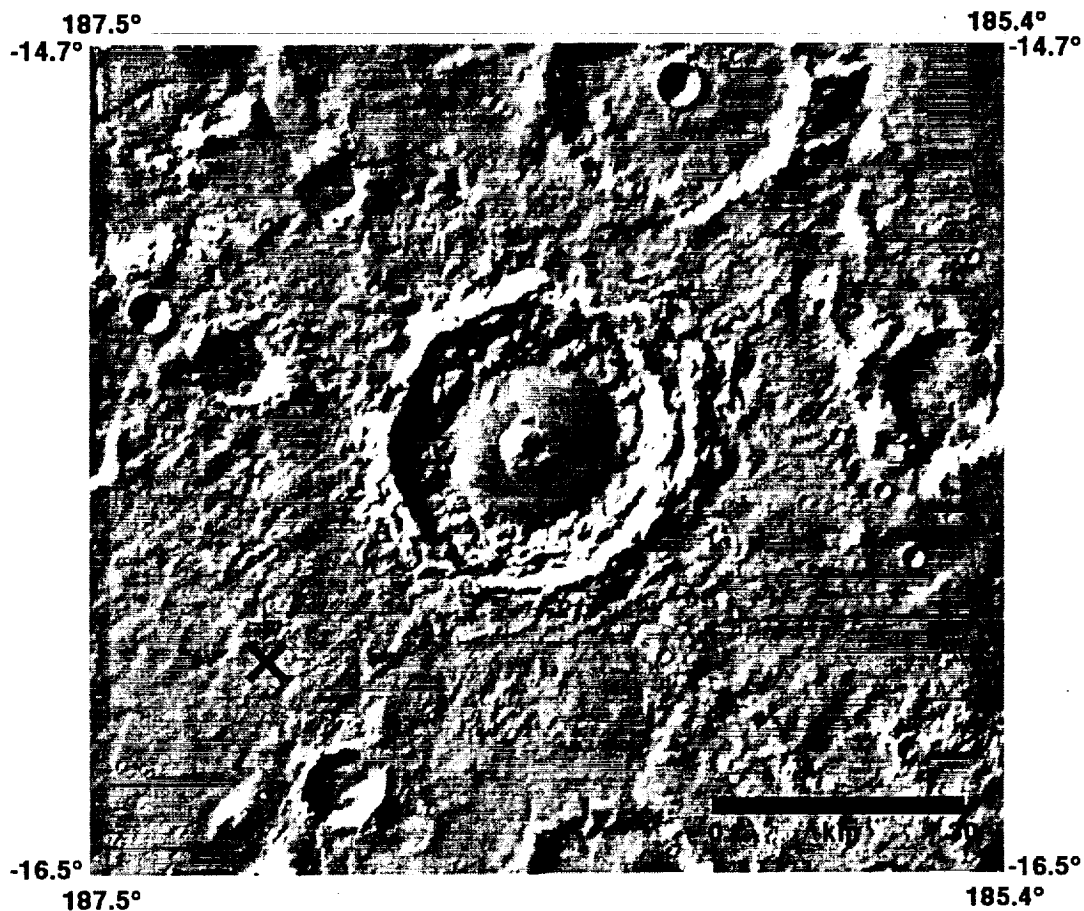
Crater counts of the major units in the vicinity of Kayne Crater suggest that nearly the entire geological column of Mars is represented. Thus, there is the possibility to sample the full range of uses within the ejecta deposits of Kayne. The scientific potential of these materials includes determining the age and composition of the ancient highland crust, assessment of Noachian, Hesperian, and Amazonian paleoenvironments in which liquid water appears to have been present, study of aqueous alteration products for comparisons with the Alan Hills meteorite ALH84001, and the opportunity to date a large, recent crater to aid in calibrating the impact cratering flux for Mars.

The specific landing site is proposed on the boundary of the continuous and discontinuous ejecta deposits from Kayne Crater at 187 degrees west, 16 degrees south, although other localities can also be identified in the area. Some specific issues of concern include the complexities that would be posed by working with ejecta deposits which might have been severely shocked and the uncertainties in placing samples into their original geologic context. However, the ability to rove to multiple sites and to select samples for their diversity, coupled with their subsequent analysis, could provide a rich harvest of information. Anticipated remote sensing information, as from the Mars Observer Thermal Emission Spectrometer, will enable a better assessment of the potential diversity of the Kayne site. Other concerns, such as elevation, surface roughness, and trafficability of the site will also be addressed by data from the laser altimeter and imaging system on Mars Observer.

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**KAYNE CRATER.** *R. Greeley; R.O. Kuzmin.*



Viking Orbiter mosaic of the 33-km-diameter Kayne Crater, Mars, centered at 186.4°W, 15.6°S, at +1 km. The ejecta blanket southwest affords the opportunity to sample a wide variety of material penetrated by the impact.



**WESTERN ARABIA TERRA: HIGHLAND MATERIALS AT LOW ELEVATION:** R.A. De Hon, Department of Geosciences, Northeast Louisiana University, Monroe, LA 71209.

**SUMMARY.** A landing site near 5° N lat. and 5° W long. is proposed as a low-elevation site with potential for sampling and characterizing in situ Noachian highland material--the most widespread materials on the surface of Mars. An alternate site near 1° S lat. and 8.5° W long. would allow sampling of Noachian highland material and Hesperian ridged plains material.

*Mission:* Mars Surveyor 2001 Lander

*Proposed Site:*

Within the region 0° to 10° N lat. and 0° to 10° W long. in western Arabia Terra

*Primary Goal:*

Establish geochemical and mineralogical character of the early (primitive) crust of Mars

*Secondary Goals:*

Search for evidence of ancient martian life  
Sample multiple units  
Characterize weathering processes

*Site characteristics:*

*Elevation:* -1 km to +1 km elevation [1]  
*Roughness:* Moderately rugged at Viking Orbiter resolutions  
*Materials:* Noachian plateau sequence materials [2], possible lacustrine or marine material [3], and crater ejecta

*Advantages:*

*Engineering:* Low elevation facilitates aerobraking and landing  
Near equatorial landing zone maximizes the lifetime of the lander

*Science:* Reasonable assurance of sampling primitive materials

*Problems and Pitfalls:*

*Engineering:* Rugged terrain may hamper mobility and shorten line of sight  
*Science:* May be deeply weathered  
May have already sampled this material at the Ares Valles site and as martian meteorites  
Existing elevation data is suspect

*Useful Data From Precursor Missions:*

High resolution imaging  
Improved elevation data  
TES or other geochemical data to determine whether material is unaltered or highly weathered

**DISCUSSION.** Several siting philosophies are valid for the Mars Surveyor 2001 lander. Possible strategies include attempts to sample recent volcanism, lacustrine or marine sediments, especially enigmatic materials, or ancient crustal material. Recent volcanic materials would convey some idea of the extent of the evolution of magmas with time. Lacustrine or marine environments are sought as those most likely to allow life to proliferate. Noachian material represents the oldest and most widespread material on the planet. A candidate landing site in western Arabia Terra is offered to sample materials of the ancient Noachian crust. A Noachian site would provide information on the chemical and mineralogical character of ancient crustal materials of Mars.

Current landing constraints require that the 2001 mission target a strip extending from 30° N. to 15° S. latitude and that the landing site lies below 2.5 km elevation. This strip provides access to Amazonis Planitia, Chryse Planitia, a part of Xanthe Terra, Margaritifer Sinus, western Arabia Terra-Terra Meridiani, Syrtis Major, Isidis Planitia, southern Elysium Planitia, highlands southeast of Isidis Planitia, and south of Elysium Planitia. If the landing site is to be in highland terrain, then two possible regions remain: one region consists of terrain along the northern edge of the highland southeast of Isidis Planitia and south of Elysium Planitia, and the other region is in western Arabia Terra. The terrain south of Elysium Planitia is chiefly dissected Noachian plateau material (unit Npld) which is highly eroded and probably highly altered material [4]. Western Arabia Terra (vicinity of 5° N lat. and 5° W long.) is suggested as the region, within the 2001 engineering constraints, most likely to meet engineering and science criteria for a successful rover mission to Noachian highland terrain. Noachian plateau sequence materials--including plateau cratered material (unit Npl1), subdued cratered material (unit Npl2), etched material (unit Nple)-- are found in the area [2]. Cratered plateau material is considered the material most likely to retain its original character. Post-Noachian eolian, fluvial, and perhaps lacustrine materials are also present. An alternate site (vicinity of 1° S lat. and 8.5° W long.) in Terra Meridiani maintains the advantages of low elevation, Noachian material, and also provides an opportunity to reach Hesperian ridged plains material (unit Hr).

Arabia Terra-Terra Meridiani landing sites place emphasis on geochemical and mineralogical character of the ancient and most common material of the martian surface. It is most likely to consist of ancient crustal material from multiple sources mixed by repeated impact gardening. In the worst case scenario, this material may be similar to that already sampled by Pathfinder rover at Ares Valles, or it may be highly altered by weathering. In either possibility, the science community will at least have mineralogical data that is not now available. It is not a particularly favorable site for searching for evidence of past martian life; however, if sampling should find evidence of past life in these materials, that would support the view that at some time in the past life was widespread on the surface of Mars.

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**HOT ROCKS, WET ROCKS, AND DEEP ROCKS: ERODED IMPACT CRATER AND CHANNEL DEPOSITS IN TIU VALLIS.** H. E. Newsom, University of New Mexico, Institute of Meteoritics and Department of Earth and Planetary Sciences, Albuquerque, NM 87131, newsom@unm.edu.

Many scientific problems will contribute to deciding on a landing site for the 2001 Mars rover mission. Foremost of these questions are the characterization of environments favorable for the evolution or flourishing of pre-biotic organic chemistry or primitive life, and the characterization and sampling of mantle and crustal samples that will constrain the origin and geochemical evolution of Mars. In this work, I will focus on the exploration of large dissected impact craters to address the scientific problems, and use the Tiu Vallis area as an example.

Understanding hydrothermal processes on Mars, including chemical transport of mobile elements, is fundamental to the following problems:

- Identifying and characterizing environments for the origin and evolution of life [1].
- Determining the chemical and isotopic evolution of the atmosphere.
- Understanding the origin of the Martian soil, and inverse modeling to obtain the average global composition of the crustal source [2].
- Characterizing potential hazards for human exploration.

Hydrothermal systems are associated with two geological processes, volcanism [3] and impact crater formation [4]. For numerous reasons given below, large dissected impact craters provide the best chance of finding samples to address the problems listed above.

Advantages of large impact craters as sampling targets include the following points:

- Hydrothermal processes are ubiquitous in impact melt deposits on the crater floor, in central uplifts and rim deposits. The heat sources include impact melt deposits (Fig. 1) and geothermal heat from uplifted crust and mantle.
- Uplifts and ejecta may provide samples of deep crust or mantle. Volcanoes can also bring up samples from great depths as xenoliths, but these are rare on the Earth.
- The formation of lakes supplied from groundwater or large outflow channels are likely due to the depth of large craters (Fig. 2), and lake deposits may be exposed on the crater floors [5,6].
- Lake waters are derived from broad regional aquifers, potentially collecting biological material from a wide region and providing many different environments for such life forms to flourish.
- Lakes in large impact craters heated by impact melt, geothermal heat, and the latent heat of fusion of ice can last for tens to hundreds of thousands of years (Fig. 3).
- Impact generated breccias are susceptible to hydrothermal alteration, even under low water/rock ratios, in contrast to typical volcanic rock, where alteration may be

concentrated in widely separated cracks, which are hard to sample.

- The scale of a large impact crater provides unlimited opportunity for extended exploration.

Because of the limitations of sampling with a rover without deep drilling, the selection of a crater that has been dissected by a large outflow channel has many advantages including:

- Exposed cross sections of hydrothermal systems or landslide deposits of altered materials in the floors, walls (e.g. Sudbury), or basement uplifts (e.g. Manson).
- Exposed layers of lake sediments due to aquifer penetration during crater formation.
- Exposure of layered ejecta and impact melt, including samples from great depths.
- Exposure of fluvial or periglacial deposits created between the time of crater formation and the outflow episode.
- Exposure of buried soil layers or volcanic ash deposited between the time of crater formation and the outflow episode.
- Possible lake deposits or evaporites from the outflow episode.
- Sampling of material carried in by the floods from upstream.

The candidate Tiu Vallis landing site (Fig. 4) at approximately 12 degrees North, 32 degrees west, is upstream from the Pathfinder landing site, and is situated in a 100 km diameter dissected crater. The site contains eroded crater walls, as well as eroded deposits on the crater floor. Remnants of a peak ring may also be present.

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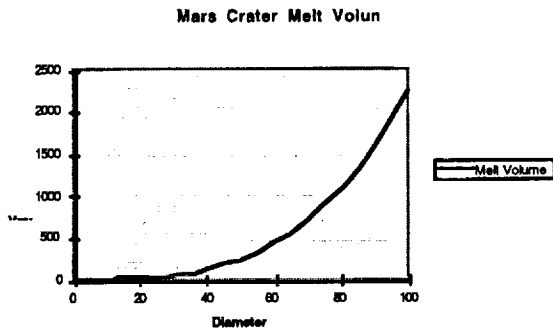


Fig. 1 Impact crater depths in the Martian Highlands.

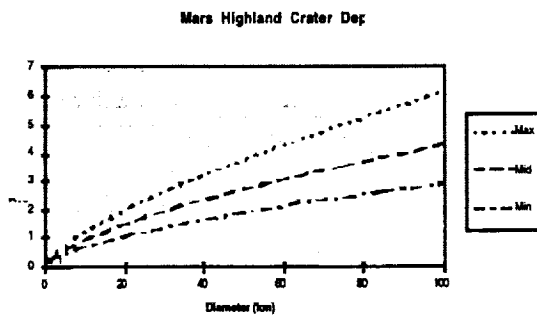


Fig. 2 Impact melt volumes in Martian impact craters, after Clifford (1993).

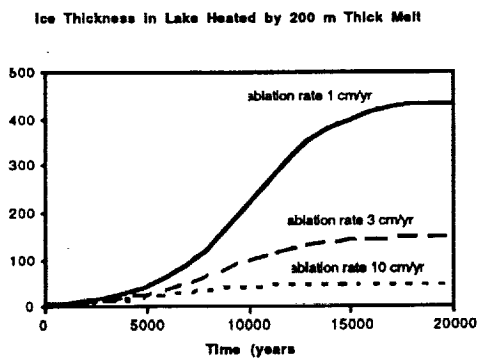


Fig. 3 Ice thickness on an impact crater lake heated by a 200 m thick melt sheet as a function of time. The ablation rate, which is balanced by the freezing rate below the ice, controls the final equilibrium ice thickness after heat from the impact melt sheet is gone [4].



Fig. 4 Tiu Vallis landing site in dissected large impact crater. Note dissected rim and crater floor deposits.

**POTENTIAL LANDING SITE FOR THE MARS 2001 MISSION: DOUBLE CRATER NEAR ARES VALLIS.** *D.M. Nelson<sup>1</sup>, R. Greeley<sup>1</sup>, H.P. Klein<sup>2</sup>*. 1. Dept. of Geology, Arizona State University, Box 871404, Tempe, AZ 85282-1404. E-mail: nelson@dione.la.asu.edu.  
2. SETI Institute, 2035 Landings Dr., Mountain View, CA, 94043.

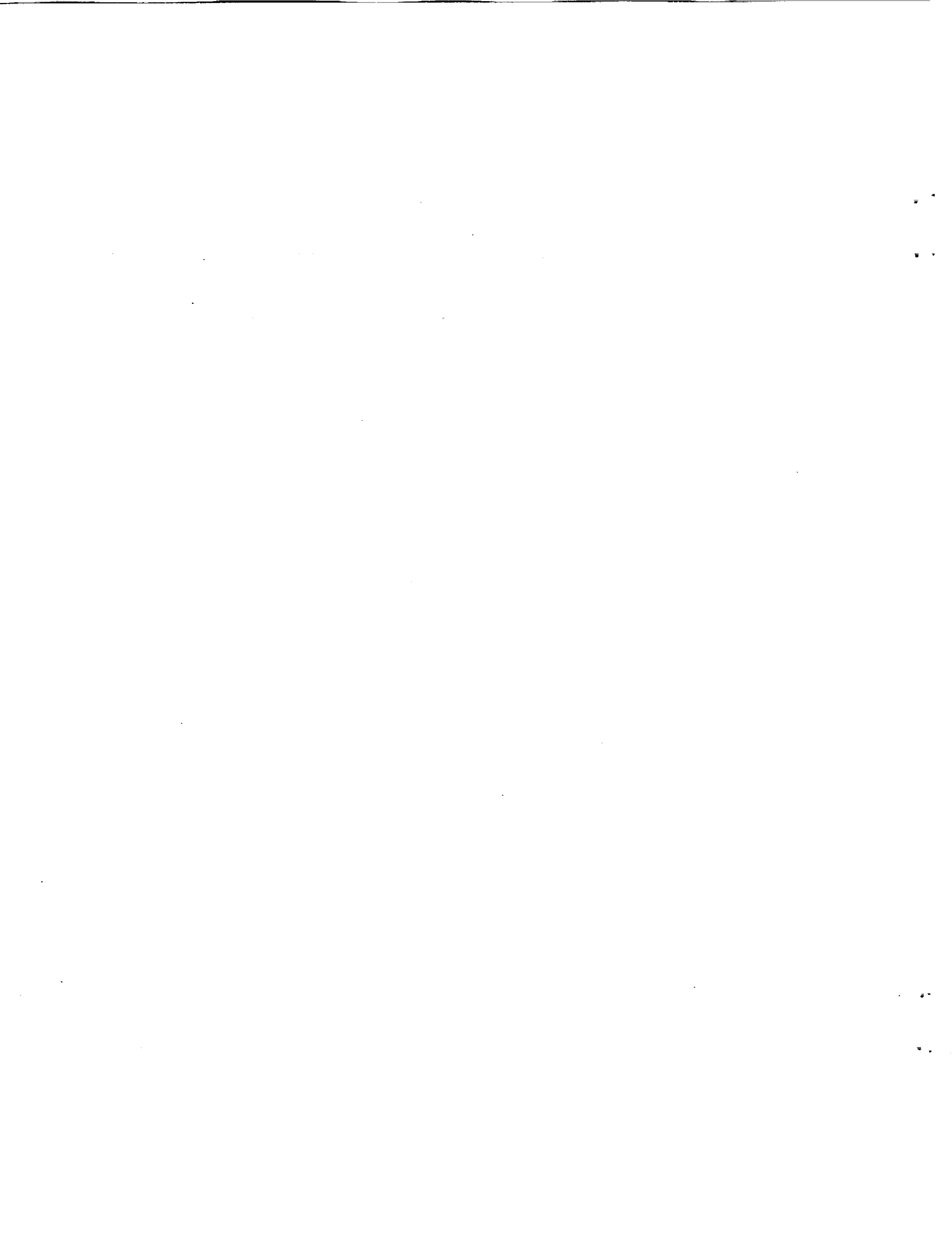
A potential landing site, considered for both geology and exobiology, is proposed for the Mars 2001 mission. A pair of unnamed craters, ~50 km (east-west) by ~80 km (north-south) diameter, are located on the northeast margin of Ares Vallis, at 12°N, 26°W; the floor is -1 km planetary datum (Figure 1). The smooth crater floor, fluvial scour and drainage features to the south and west of the crater, and proximity to Ares Vallis suggest that this crater was subject to one or more floods. As a site presumed to have contained liquid water, possibly recharged repeatedly from Ares Vallis floods, it is also considered a potential exobiology site.

This crater pair is located along the edge of Ares Vallis on the southern margin of Arabia Terra. The craters formed on Noachian highland plateau in subdued cratered material (Npl2), interpreted to be brecciated lava flows [1]. The floor of the crater is a smooth deposit. The southern crater rim has been eroded in places to the level of the surrounding terrain, and a small zone of chaotic terrain formed between the craters and the channel. Because the crater is situated near the widening of Ares Vallis, where the flow energy might have decreased [2], it could have been far enough away from

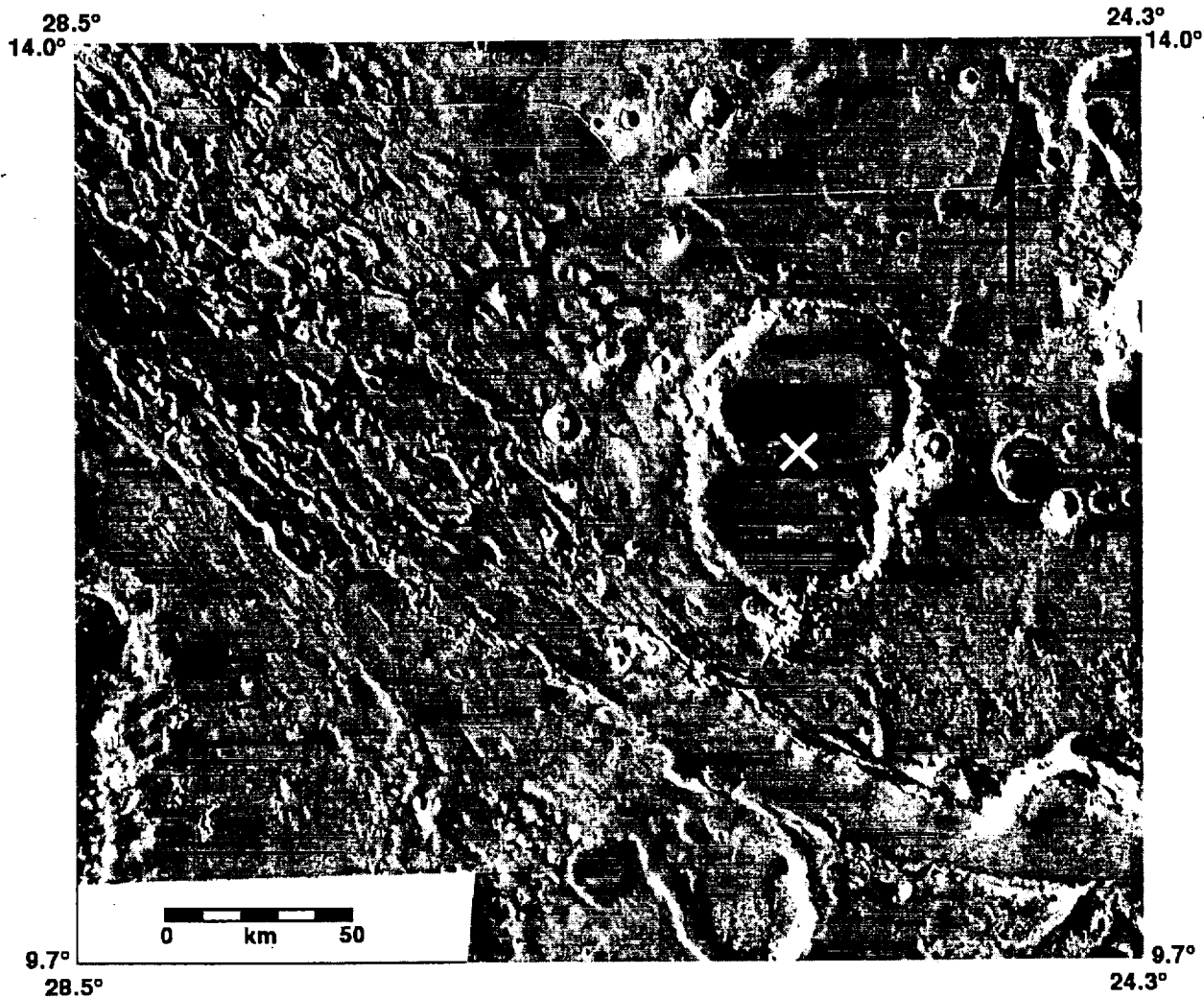
the channel that water overflowing the banks of Ares would have filled the craters with water and fluvial materials. The source of water to the craters include Iani and Aram Chaos from the southeast and Hydaspis from the south, thus sediment within the crater was derived from two sources.

The site was also assessed for potential exobiology by criteria outlined by *Farmer et al.* [3]. If standing water endured, being replenished from possible multiple floods, potential biotic communities, or at least the environment and/or materials required to sustain life, could have developed. However, because the water source is distant (Aram, Iani, and Hydaspis Chaos are all >500 km away), there is potentially no local heat source.

Materials from these craters could provide useful information regarding standing water bodies and potential exobiology sites on Mars. Rocks could include materials reworked and potentially hydrated by Ares Vallis flooding, the water sources of which are Aram, Iani, and Hydaspis Chaos. In addition, indicators for exobiology, fossil-bearing sediments and/or organic materials could also be present for examination.



**DOUBLE CRATER NEAR ARES VALLIS.** *D.M. Nelson, R. Greeley, H.P. Klein.*

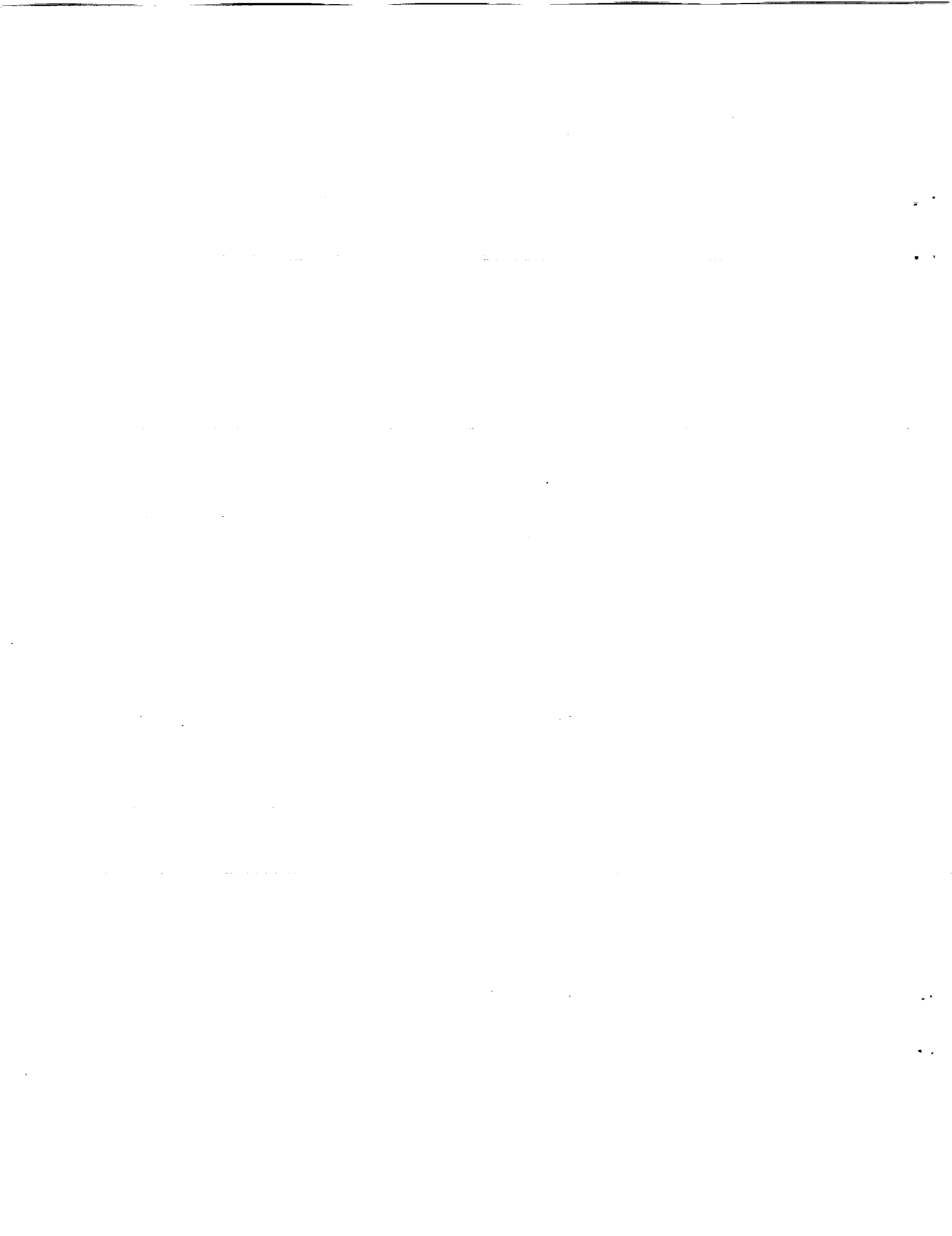


**Figure 1.** Double crater near Ares Vallis (12°N, 26°W, at -1 km).

Ares Vallis trends from southeast (smooth floor) to northwest through etched materials. Arabia Terra, a Noachian plain consisting of brecciated volcanic flows, lies to the northeast. The landing site is indicated by cross-hairs.

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**THE CONFLUENCE OF GANGIS, CAPRI AND EOS CHASMAS: A TOPOGRAPHIC TRAP FOR WATER AND DEBRIS AT THE EAST END OF VALLES MARINERIS.** S. M. Clifford, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058, clifford@lpi.jsc.nasa.gov.

Given its complex geologic evolution, and the 4-10 km-deep exposures of Martian stratigraphy visible in its canyon walls, Valles Marineris has been the focus of intense scientific interest. At its west end, it is dominated by the tectonic complex of Noctis Labyrinthus; while ~3,500 km to the east, it grades into an extensive region of chaos, with evidence of enormous catastrophic fluvial discharge into the northern plains [1,2]. In the central portion of the system, debris derived from the interior layered deposits of Candor and Ophir Chasmas (which may have originated from the accumulation of lacustrine sediments [3,4]) spills out into the central trough. Massive landslides, possible volcanics on the canyon floor, ejecta from interior craters, and aeolian sediments, also contribute to the canyon's considerable geologic and environmental diversity.

But beyond its geologic significance, Valles Marineris is also a target of interest in the search for evidence of past life. As previously noted, the interior layered deposits of Candor, Ophir, and Hebes Chasmas, may represent sediments that were laid down in a long-standing aqueous environments, like an ice-covered lake [1,3,4]. The potential survival and growth of native organisms in such an environment, or in the aquifers whose disruption led to the formation of the chaotic terrains, raises the possibility that fossil indicators of life may be present in the local sediment and rock.

Because of the enormous distances over which these conditions occur, identifying a single landing site that maximizes the opportunity to retrieve samples of these diverse environments is not a simple task. However, the strategic location of a major topographic depression, at the eastern end of Valles Marineris, may provide an opportunity that is unequalled anywhere else within the system.

This depression, which lies at the confluence of the Aureum Chaos and Gangis, Capri and Eos Chasmas (5-12°S, 31-41°W; Figure 1), has the lowest elevation of any location accessible to the 2001 lander, with a maximum depth that lies below the -3 km contour of the Mars Digital Terrain Model [5] (no MGS MOLA observations of this region are yet available). The depth of this feature, and its location between Valles Marineris and the outflow channel that served as the canyon's sole outlet to the northern plains, should have made it an efficient topographic trap for the debris carried by any flood waters that originated from deeper within the canyon.

As a result, samples of ancient rock, originating from any depth within the stratigraphic sequence revealed in the canyon walls, may have been brought to the canyon floor by local landslides. Subsequent flooding, perhaps associated with the collapse of the thin partition between Melas and Candor Chasmas, may have then carried samples of this material (mixed with sediments derived from Candor's interior deposits) to the end of the canyon and into the northern plains. In the process, the flood waters may also have entrained samples of more recent volcanics and ejecta from the canyon floor. Given the numerous areas of chaos, and the extensive evidence of fluvial erosion, this scenario may have been repeated many times -- leading to the deposition of material representing a wide range of physical environments, ages, geographic locations, and depths within the stratigraphic column.

The location of this depression at the canyon's sole exit to the northern plains, also implies that it has likely been one of the most frequently, and persistently, wet regions on the planet. That is, with every discharge of water to the northern plains, the confluence of the Gangis, Capri and Eos Chasmas would have been flooded to a depth of ~1 km, creating a large (~2x10<sup>4</sup> km<sup>2</sup>) ice-covered lake that may have survived for a considerable length of time. If the aquifers from which this water was derived were already sustaining an active subsurface ecosystem, then it is likely that a geologic record of this life is preserved in the sediments and rocks that were deposited on the lake floor. The repeated occurrence of such discharges, and their inevitable formation of a standing body of water at the terminus of the canyon, may have left a rich stratigraphy of biological and geochemical markers that could provide invaluable insights as to how the planetary subsurface ecosystem evolved with time.

From a purely scientific perspective, the arguments in favor of this potential landing site are persuasive -- but it is a site that also entails some significant risk. The measured thermal inertia and inferred rock abundance for this region are among the highest on the planet [6]. Examination of moderate resolution Viking images (~200 m/pixel) reveals intermingled expanses of smooth floor, chasma channel, and chasma chaotic material [2], demonstrating significant heterogeneity in the nature

of the local terrain. Observations by the MGS MOC, MOLA, and TES instruments would greatly assist in evaluating whether the considerable scientific potential of this landing site is outweighed by the technical risk to the spacecraft.

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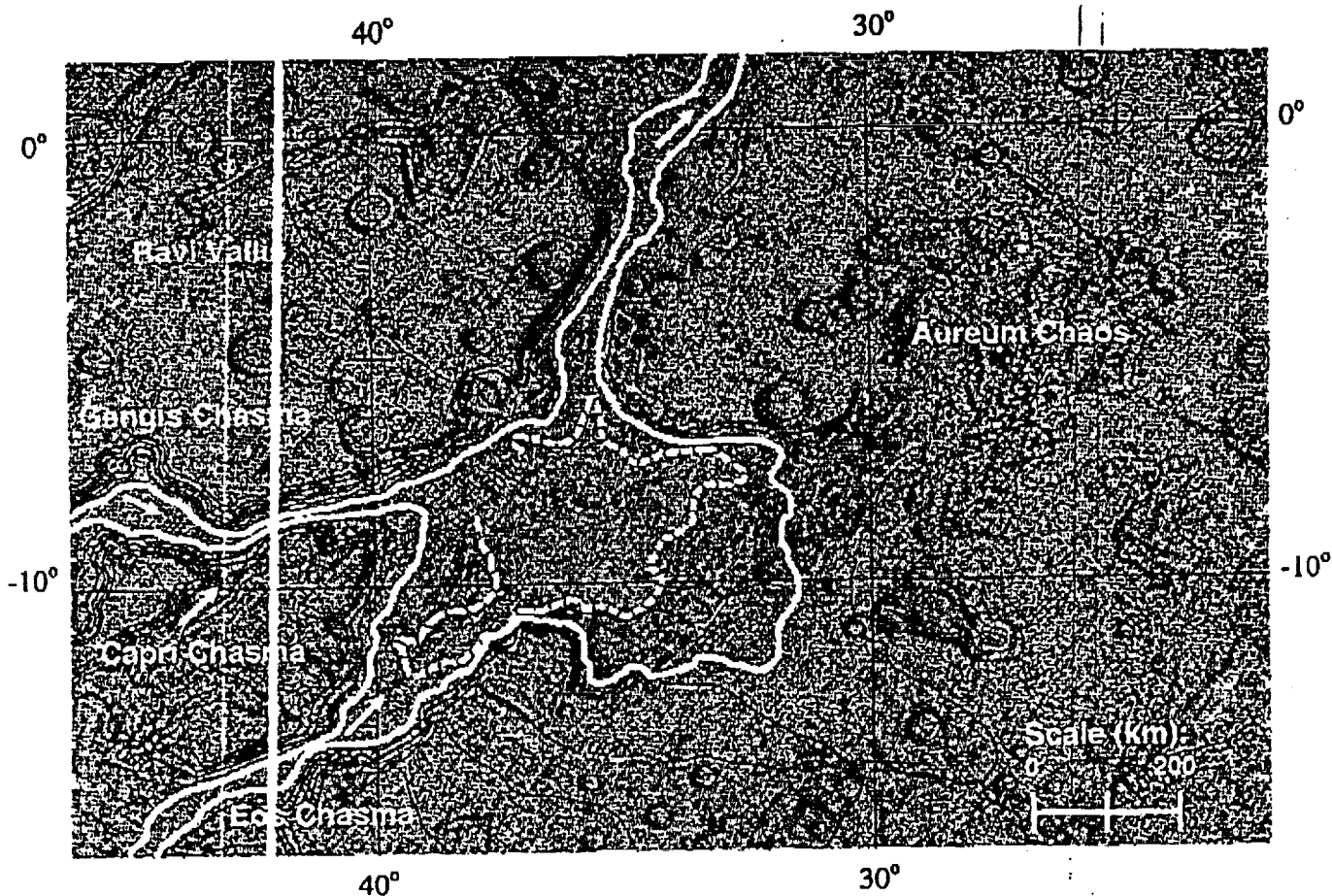


Figure 1. Confluence of Aureum Chaos and Gangis, Capri, and Eos Chasmas, at the eastern end of Valles Marineris.

**MARS SURVEYOR LANDING SITES IN VALLES MARINERIS: HIGHLAND SAMPLES FROM THE BASEMENT.** Richard A. Schultz, Geomechanics–Rock Fracture Group, Department of Geological Sciences/172, Mackay School of Mines, University of Nevada, Reno, NV 89557-0138 (<http://unr.edu/homepage/schultz>; [schultz@mines.unr.edu](mailto:schultz@mines.unr.edu)).

### Summary.

Two landing sites in Melas Chasma, central Valles Marineris, can address key questions in Martian geology. **Site A** (Melas Labes) would permit sampling of Hesperian ridged plains material (caprock) and two exposures of different Noachian basement rocks. **Site B** (Melas Chasma) allows collection of material from ridged plains caprock, Noachian basement, and layered basin beds. Analysis of these samples could pin the relative Martian chronology, improve understanding of early Martian processes, and decide the origin (fluvial or volcanic) of sedimentary sequences in the troughs.

### Scientific Framework.

The landing sites selected should maximize the scientific return of visited and sampled rock exposures. Specific objectives include characterization of near-surface mineralogy and processes, sampling of ancient crustal materials indicative of paleoclimates or biological processes, and collection of unaltered samples for later retrieval and return to Earth [1]. Aspects of these objectives can be achieved by taking advantage of the unique attributes of the Valles Marineris landing sites.

### Engineering Constraints.

The current latitudinal constraints on the 2001 landing sites are 30°N to 15°S, to be narrowed further during the scoping process. Site elevation must be lower than the 2.5 km USGS datum [2]. The Athena rover has a design traverse radius of 10 km, far greater than the Mars Pathfinder Sojourner rover [3], permitting visitation and sampling of diverse lithologies around a landing site. Sites should be reasonably smooth, although the increased rover size may allow target areas rockier than the Pathfinder site [4] to be successfully traversed.

### Candidate Landing Sites.

Many possible sites fit the engineering constraints and scientific objectives. Two potential sites are discussed here that present unusual opportunities for maximizing the scientific return of the mission.

**Site A—Melas Labes.** Located at 9°S, 72° at an elevation of ~ 0 km, this site is on a plateau of Lower Hesperian ridged plains caprock, of probable basaltic composition, located in the heart of Valles Marineris. The caprock [5] appears to be on the hanging wall (down-thrown side) of one of the large normal faults that bound Ophir Planum to the northeast, where the correlative caprock stands at ~9 km elevation. Some east-west trending normal faults and narrow grabens, similar to those on Ophir Planum and the Tharsis plateau [6], are developed on the exposure.

Of particular interest is the landslide apron that covers much of the plateau. The apron provides an opportunity to sample materials from the Noachian wallrock extracted from likely depths of 3–4 km below the caprock surface. Massifs of Noachian basement rocks on the western margin of the plateau provide an additional opportunity to sample what may be a more resistant and competent Noachian lithology.

A traverse radius of 10 km would enable the rover to visit and sample three distinct rocktypes: basaltic rocks of the caprock sequence, Noachian slide materials, and Noachian massifs. Sample return of caprock would permit radiometric age determination for the Early Hesperian time horizon, a key period in Martian history that may separate early Martian conditions from drier, more contemporary ones. Studies of the mineralogy, alteration, physical properties, and perhaps absolute age of the Noachian materials may address landslide emplacement processes (e.g., degree of water involvement) and the hydrologic characteristics of the material.

**Site B—Melas Chasma.** The second site is located at 10°S, 74° at 0 to –1 km elevation. The target region includes a trio of geologic units. The Melas Chasma trough floor is covered by a mantle of likely eolian origin that mantles the underlying cratered floor [e.g., 4]. Cliffs of layered basin beds that are eroded remnants of the formerly more extensive sequence of older interior layered deposits [e.g., 7] are nearby and accessible. A mesa some 5 km across resembles those downfaulted remnants of caprock identified in northern troughs such as Ophir and Candor Chasmata [8]; its weathering profile (spur and gully topography), planimetric shape, and

flat-topped morphology distinguish it from the adjacent, more friable, layered deposits. Given the low-resolution images currently available for this site ( $\sim 100$  m pixel<sup>-1</sup>) this mesa may represent an outcrop of caprock in fault contact with the stratigraphically higher (Upper Hesperian) basin beds.

Rover science at Site B would center on examining and collecting samples from three distinct units as well as field checking a structural interpretation for central Valles Marineris. The caprock remnant may permit sampling and radiometric dating of this key stratigraphic horizon, while the origin of the layered deposits—volcanic or fluvial—would be ascertained. A volcanic origin would suggest that the troughs, if structural in origin in the central region [e.g., 9–12], are “wet rifts” characterized by extensive volcanism in association with the normal faulting. A fluvial origin would demonstrate significant volumes of water at or near the planetary surface to relatively recent (Amazonian) times. Either result has important ramifications for the internal dynamics and evolution of Mars.

### Conclusions.

Either site can satisfy the main scientific objectives of the 2001 Lander/Athena payload mission. Site A would sample 2–3 relevant lithologies having an unambiguous geologic context. Site B would most directly address exobiological and paleo-hydrologic issues. Either site would require detailed investigations of the region around the landing site that would, as a benefit, advance the understanding of the local geology, the regional geology, structure, and geophysics of Valles Marineris, and global geologic problems.

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**A PROPOSED MARS SURVEYOR 2001 LANDING SITE WEST OF CANDOR MENSA, VALLES MARINERIS.** B.K. Lucchitta and C.E. Rosanova, U.S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86001. E-mail blucchitta@flagmail.wr.usgs.gov

The purpose of the Mars Surveyor 2001 lander and rover mission is to investigate a diversity of rocks in an area that may have harbored life in the past. The Athena instrument package on the rover is designed to identify minerals, elemental compositions, water, and iron-bearing phases and oxidation states. The central Valles Marineris provide a unique opportunity to visit a variety of rock types from different ages, including rocks from possible ancient lakebeds. The proposed site is at lat 5.4E S to 5.8E S, long 74.4E to 74.9E, elevation +1 km, in quadrangle MTM 105072 [1]. It is located on the valley floor west of Candor Mensa. The site falls within the range of constraints of the mission (lat 30E N to 15E S and elevation #2.5 km). Safe landing could be achieved within a 30-km (east-west) landing ellipse. From the optimum landing spot (lat 5.5° S, long 74.6°) a rover traverse of 15-20 km could reach wall rock, older interior layered deposits, a landslide containing wall rock, younger interior deposits, and a dark knob.

The Candor Mensa site is ideal in that it is in close proximity to rocks having a range of ages and compositions. The lack of extensive surfaces that can be dated by crater statistics, however, is a detriment. Thus collected samples, returned to earth during a later mission, cannot be tied to datable surfaces that may fix the martian time scale. On the other hand, the variety of rock types expected to be found at the site may outweigh this disadvantage.

From the landing site, the rover may traverse to the lower trough wall to the north, where ancient rocks of Noachian age are exposed. The most commonly accepted hypothesis is that these rocks are lunar highland-type breccia [2]. However, recent images of Ius Chasma, returned by the Mars Global Surveyor, show layered units exposed in trough walls several thousand meters below the plateau surface. The nature of the rocks in the layers is currently unknown, but several considerations apply. The rocks may be faulted down; evidence for possible faulting is seen in the walls in that area. Thus they may be part of the layered sequence commonly recognized below the plateau surface. On the other hand, the rocks resemble layered mafic intrusives, and may reflect magmatic activity, including perhaps the intrusion of very thick sills. Wilhelms and Baldwin [3] postulated the presence of sills; local outcrops of very dark layers within or at the base of trough walls support this contention. Inspecting the trough walls near the proposed landing site may shed light on these possibilities, and collecting samples at the base of the trough wall will give insights into the composition of the martian crust.

West of the landing site is a large landslide deposit originating from the wall. A variety of wall rocks should also be contained in the slide and would yield informative samples. The landslide may also incorporate plateau rocks of early Hesperian age. If basalts from near the surface [4] were sampled, future dating of these rocks may even give ages for the nearby plateau.

Older interior layered deposits (Hesperian-Amazonian age) occur east of the landing site in Candor Mensa. Their origin is uncertain. Sampling these rocks may shed light not only on the composition of these materials but also on the processes of emplacement. It is widely assumed that interior layered deposits were emplaced in lakes [5,6], even though a volcanic origin cannot be ruled out for some of them [7,8]. If they are lakebeds, perhaps even incorporating carbonates, their investigation and possible later return to earth offers us the best chance yet to discover fossil life. Recent studies [9] have revealed that some interior beds are tilted. This deformation may be due to collapse in response to loss of incorporated volatiles rather than due to tectonism. If correct, this observation would support deposition of interior layered materials as lakebed sediments.

Some light-colored rocks also crop out on the trough floor in the vicinity of the landing site. They are surrounded by darker, smooth mantling material. Examining the outcrops will answer questions pertaining to the origin of the subfloor in the landing area. The outcrops could

represent down-faulted older interior deposits, younger interior deposits, or late eolian fill. A dark rugged hill is within reach of the proposed site to the east. It could be a volcanic neck, a vent, a breccia pipe, or a knob of otherwise resistant material. Exploration may possibly give insights into the characteristics of volcanic rocks in the troughs and their emplacement mechanisms.

Rocks of late Hesperian to Amazonian age form the younger interior deposits. A thin layer of this enigmatic unit can be reached to the west of the landing site. It thinly covers part of the landslide. The origin of this post-landslide material is also unknown. The unit has light-colored flow lobes in west Candor Chasma on top of high mesas, and it fills low areas in this chasma possibly with several thousand feet of material. The unit could be volcanic [7], perhaps of felsic or palagonitic composition. However, other relations in the area suggest that the unit may be mass-wasted material, reworked from older interior deposits. In this case, the incorporation of volatiles may have facilitated flow. Sampling this material would not only solve the origin of a mysterious units on Mars, but may also potentially yield rocks that were exposed to water and may have harbored life.

Observations and sampling at the proposed landing site would also give insights into martian processes. By studying the landslide deposit and its matrix, one might answer the question whether the slides were wet debris flows [10] or dry rock avalanches [11]. If wet, the discovery would confirm the suspicion that the equatorial area contained water in the subsurface.

Wind deposits are abundant on the trough floors. Sampling them would shed further light on the nature of the martian wind regime and global dust. The landing site is very smooth and reddish dark, suggesting a thick layer of drift. The material may well be equivalent to the very smooth material recently seen on the floor of Gangis Chasma by Mars Surveyor. If so, the landing and rover traverses would be easy.

Overall, the proposed landing site offers a wealth of information pertaining to Mars' magmatic, volcanic, and climatic history. It also provides a good chance at obtaining evidence for former life. A bonus is that the images would be spectacular.

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**KASEI VALLES LANDING SITE.** F. COSTARD, J.P. PEULVAST and Ph. MASSON, Laboratoire de Géologie Dynamique de la Terre et des Planètes, EP 1748, Université Paris-Sud, 91405 Orsay Cédex, France. fcostard@geol.u-psud.fr

### **Geologic Setting**

An exploration site located to the East of Tharsis in Kasei Valles (landing site: 21°N / 77,5°W) has been selected for the definition of a small range rover mission. During its traverse, the rover will cross several geological and geomorphological units and perform geochemical and mineralogical analysis of soil samples at various selected points along the traverse.

### **Objectives.**

Here are the main scientific objectives of this mission:

#### **1) Kasei Valles, Hchp.**

From the beginning, sampling is proposed on the landing site itself. The in-situ analysis of samples and views should provide informations on the local lithology, on the origin of martian valleys (fluvial or glacial) and the geology of the cratered upland by materials carried by the outflow. Absolute age dating of the materials would allow to calibrate the craterization curve for the upper Hesperian period.

#### **2) Mineralogical analysis of the At4 unit.**

Crossing the geological unit At4 of the lower Amazonian age would specify certain characteristics of volcanism in the Tharsis region. The surface probably includes volcanic flows coming from Uranus Patera. These volcanic flows, which are probably basaltic, are relatively older than those coming from Olympus Mons, for example.

#### **3) Study of wrinkle ridges.**

Crossing wrinkle ridges (figure 1) will provide data about the superficial structure, as well as information about the type of compressive tectonics linked to the Tharsis bulge.

#### **4) Study of a rampart crater.**

Sampling in the immediate vicinity of fluidized ejecta should provide informations about how the fluidized ejecta get here, as well as a close views of the superficial fabric of fluidized ejecta. Furthermore, studying the blocks expelled during impact will provide informations about the nature of the substratum (up to 1 km deep), as well as the nature possible volatile materials.

#### **5) Study of the contact between geological units Ht2 and Hr.**

The contact by superposition between Ht2 and Hr is expressed by the passage of the lava flows to a plateau crossed by faults and ridges. Studying the contact between these two units by on-site analysis will specify volcanism's characteristics in the Tharsis region during the Hesperian period. Studying the mineralogical composition of the lava unit Ht2 by taking samples should provide

some answers about the old volcanic phases in the Tharsis region. As for the Hr unit, its origin is probably linked to fissural volcanism.

### **Potential Problems.**

A site selection is a combination of science criteria and engineering criteria. For obvious safety reasons, the rover's landing site must be an almost smooth surface, both on a metric and kilometric scale. In order to document this study, the estimated trafficability and the relative roughness characteristics of all geological units crossed during the rover traverse will be proposed. In this kind of approach, some photoclinometric data from impact craters, wrinkle ridges and grabens are proposed.

About this rover mission, IRTM data as well as Viking images seem to indicate a low rugged surface probably covered by a thin aeolian mantling that seems to be similar with the VL1 landing site. But a few high resolution Viking images certify locally the presence of young lava flows particularly rough. Low thermal inertia (between 104.6 to 150.6 SI) would certify the presence of a fine particle cating (<100 µm), a thickness of 1 m (locally of 2 m), overlapping the bedrock.

The discriminating element for the navigability of the rover is not necessarily the topography (elevation, slope) of craters, grabens or dunes, but seems to be rather the roughness at a metric and decimetric scale (blocs ...).

The landing site is located in Kasei Valles whose geological unit Hchp is characterized by a low rate of cratering and a slightly rough topography. Only 5% of the surface would be blocky. Such a mission implies that the rover can travel on a surface covered with decimetric blocks. Local dunes and aeolian mantling are probably also present during the traverse. Dunes can reach lengths of about a hundred meters, a height of ten meters and have a slope of 10 to 30%. Furthermore, metric blocks can cover most wrinkle ridges. The rover will have to go around them and be able to climb the slopes of these ridges, which are supposed to be between 10 to 30%.

Site Name: Kasei Valles

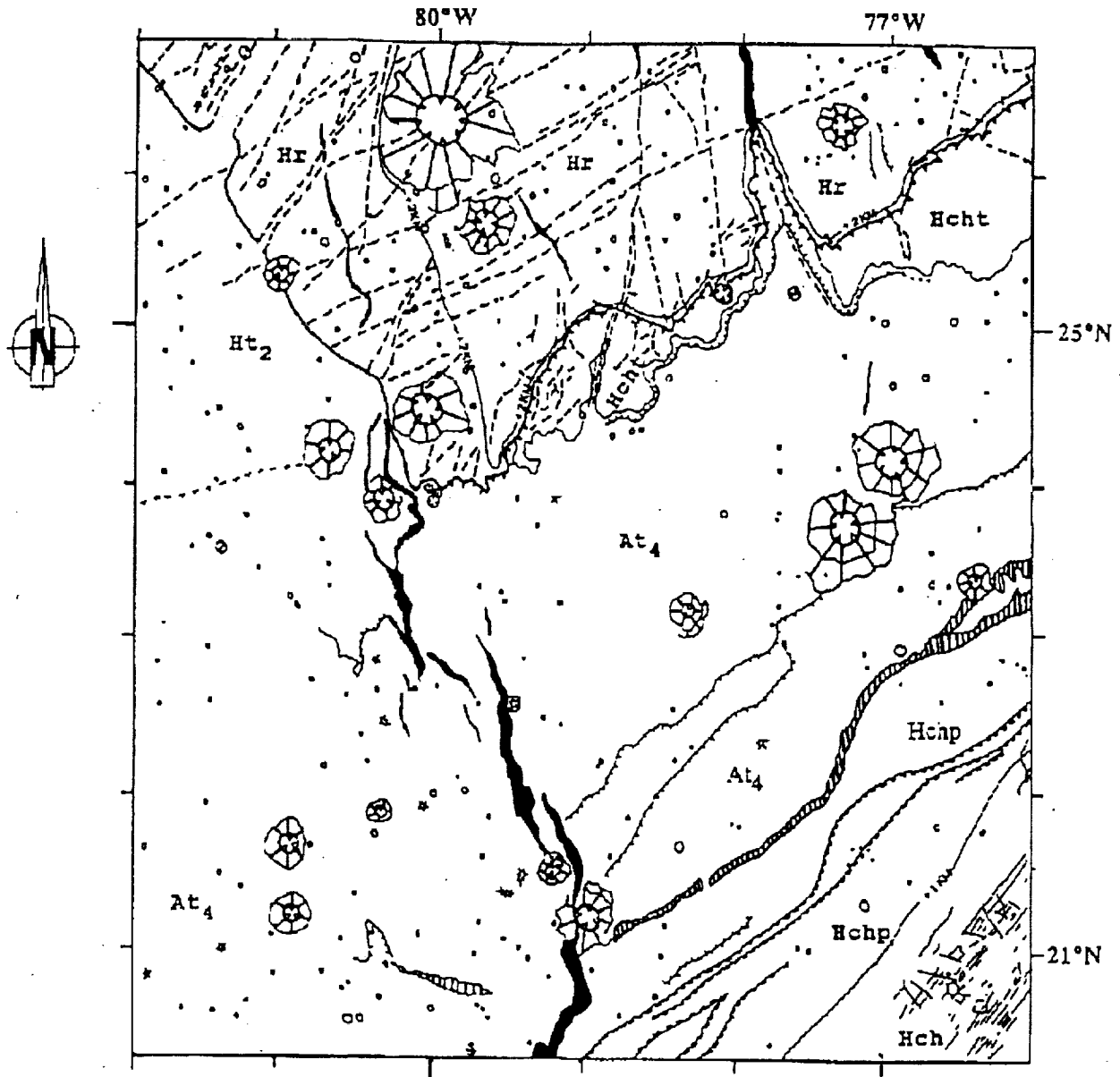
Latitude: 21 deg. N











Longitude: 77.5 deg.

Elevation: +1 km

Maps: MTM#20077, MTM#25077, MC-10 NW (I-1303)

Viking Orbiter Images: 555A03 through 555A28, 644A01 through 644A05, 2130A03 through 230A12



-  Limit of geological units
-  talus / scree (H: 500 m to 900 m)
-  fluvial terrace (H: < 10 m, slope 5° to 10°)
-  fracture / break (int. slope: 10°, max.: 30°, H: 300m)
-  wrinkle ridge (width: 5 km, H: 150 m to 300 m, slope: 10°, locally >20°)
-  possible fluvial bench (H: 200 m to 500 m, width: 3.5 km)
-  young lava flow (H: < 50 m)
-  valley floor (grooved terrain)
-  impact crater
-  rampart crater (slope: 5° to 15°, thickness < 75 m)



The Tempe-Mareotis region is of interest because (1) the rock units and landforms are the results of a variety of geologic processes that began billions of years ago and continue to the present day, (2) the volcanism contrasts with volcanism elsewhere on Mars, and (3) the volcanism is related to volcanism in Tharsis in space [1] and time. Processes include: (1) fluvial resurfacing of Noachian rocks in the Hesperian (or possibly Late Noachian), (2) northeast-trending graben with zigzag segments produced by extensional stresses after the fluvial erosion, (3) plains volcanism that began in the Late Hesperian and continued into Amazonian time, and (4) deposition of dusts and ongoing surface changes due to winds. The basaltic plains volcanism in Tempe-Mareotis is quite different than volcanic styles of the flood basalts of the plana and shields of the montes. Intense fracturing of the rocks in Tempe Fossae preceded the plains volcanism; this zone of fracturing lies along the northeastward extension of the Tharsis bulge and a great circle defined by the volcanoes atop the bulge (Arsia, Pavonis, and Ascraeus Montes and Uranus Patera). Volcanism in Tempe-Mareotis occurred in the Late Hesperian and Early Amazonian when many of the Tharsis volcanoes were forming, but eruptions from most of the great Tharsis shield volcanoes continued into more recent times.

Among the oldest rocks are those interpreted to be eroded layered deposits of Noachian age [eg. 2]; they probably include some combination of impact crater and basin ejecta, volcanics, and fluvial and eolian sediments. The oldest in-place crustal materials in the region may be present at the lowest elevations in Tanais Fossae where the relief of the layered deposits is near 1.6 km, but ejecta near the rims of large craters such as Reykholt must have come from depths near ten km.

Subsequent to the deposition of the layered deposits, the valleys of Tanais Fossae began to form -- possibly because of magmatic heating of ice-rich deposits within the layered deposits. Perhaps, water released during this heating resulted in a fluvial resurfacing event in the Hesperian (or possibly Late Noachian) Period. The flow of water etched terraces in the layered deposits, eroded impact craters, and left residual deposits in incised channels. The regional extent of this fluvial resurfacing event is unclear, but it could have been extensive. Enipeus Vallis, in the western part of the region and some 480 km long, may have formed during this fluvial resurfacing event.

Extensional stresses at right angles to the projected axis of the Tharsis bulge resulted in the formation of northeast-trending graben [3,4] with zigzag segments after the fluvial erosion event. Graben formation almost ceased and was followed by basaltic plains volcanism [3] in the Late Hesperian [2]. This volcanism produced low shields and lava fields. The magmas reached the surface along vents and fissures with a wide range of azimuths, but they were oriented chiefly in northeasterly directions; modal azimuths were near N. 47° E. and N. 62° E. Lavas continued to issue from local vents and fissures aligned in northeasterly directions from the Late Hesperian into the Early Amazonian.

Eolian processes, represented by windstreaks, bright-red surface materials with high albedos and low thermal inertias, and dune forms in graben, produced the most recent deposits and landforms. Eolian processes have been observed by spacecraft and are active today.

The volcanic landforms of the region are similar to landforms produced by basaltic plains volcanism [3] on Earth. Exemplified by the Snake River Plain in Idaho, basaltic plains volcanism is intermediate between flood or plateau basalt and Hawaiian volcanism [5]. Like plains and flood basalt volcanism on Earth, low shields and lava fields with flow fronts distinguish Tempe-Mareotis volcanism from Lunae Planum and Hesperia Planum volcanism on Mars. Like plains and Hawaiian volcanism on Earth, small shields distinguish Tempe-Mareotis volcanism from the great shields produced by Tharsis volcanism on Mars. Volcanic styles in Ceraunius Fossae and at high elevations in Syria Planum resemble the style of volcanism in Tempe-Mareotis [6].

In general, the appearances and dimensions of the shields in Tempe-Mareotis are similar to those of the Snake River Plain and suggest basaltic volcanism. The shields are typically near 5 km across, but one is near 60 km across. There are four types of volcanic edifices in Tempe-Mareotis: (1) low shields with summit depressions and smooth flanks, (2) low shields with summit depressions and radially textured or hummocky flanks, (3) low shields with summit knobs and hummocky flanks, and (4) domes. Reasons for the differences between the different kinds of shields are unclear, but radially textured flanks are probably the result of lava tube ridges, flows, and channels. Tumuli may give rise to hummocky flanks. Smooth flanks may result from pyroclastic eruptions, but lavas cannot be excluded. Height and flank-width ratios, which range from 0.011 to 0.097, are like those of low shields on Earth, which range from 0.010 to 0.067 [7,8]. Summit crater-diameter and flank-width ratios, which range from 0.211 to 0.931, are relatively large compared with those of low shields on Earth, which range from 0.032 to 0.54. Average yield strengths of lava flows in Tempe-Mareotis are near 1-2 kPa and consistent with basaltic lavas.

Volcanism in Tempe-Mareotis is chiefly Late Hesperian, about the same age as the paterae and tholi in Tharsis, but volcanism continued into the early Amazonian. Eruptions from the Tharsis montes continued well-beyond those in Tempe-Mareotis. Although the summit elevations of the large shields tend to increase with decreasing age, eruptions producing edifices with small relief at low elevations persisted in Ceraunius Fossae [6], Cerberus [9], and at the base of Olympus Mons [10] over the same interval of time as the large shields.

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**RATIONALE FOR IN-SITU EXPLORATION OF THE OLYMPUS MONS AUREOLE DEPOSITS FROM A NEW STRUCTURAL MODEL.** *P.J. McGovern\**, DTM, Carnegie Institution of Washington, Washington, D.C. 20015, mcgovern@dtm.ciw.edu.

**SUMMARY.** A new structural model of the large Martian shield volcano Olympus Mons [1-2] suggests a strong rationale for robotic exploration of the aureole deposits. This model for aureole and scarp formation at Olympus Mons involves repeated catastrophic flank failure along a pore-fluid-pressurized detachment between the volcano and the underlying terrain, analogous to detachment structures beneath Hawaiian volcanoes [3]. In this view, the aureole material consists of a series of highly fragmented landslides which fill a flexural moat surrounding Olympus Mons; the basal scarp is then the coalesced headwalls of these landslides. Material from a range of depths (ages) is thus potentially exposed in the aureole. Analysis of such samples would yield insight into volcanic processes, crustal formation, and planetary differentiation. Conditions in a basal detachment may provide favorable habitats for autotrophic organisms, perhaps up to the present day. Data from the Mars Global Surveyor (MGS) mission will help (and are already helping) to evaluate the basal detachment hypothesis and to identify candidate sites on the Olympus Mons aureole for a mobile lander or sample return mission.

**INTRODUCTION.** The Olympus Mons edifice is more than 600 km in diameter. A scarp defines the edifice base, which is surrounded by an aureole of disrupted terrain extending for hundreds of kilometers. The origin of the aureole deposits has been a matter of controversy; they have been attributed to mass movements of Olympus Mons flanks [e.g., 4-7] or to various types of volcanic deposits emplaced in-situ [e.g., 8-9]. Much of this work, however, preceded a radical re-assessment of volcano structure triggered by the discovery of large mass wasting events off the flanks of large ocean island volcanoes [10-11]. Exploiting this new information, McGovern and Solomon [1] proposed that a basal detachment, analogous to those beneath Hawaiian volcanoes [3], enabled the generation of large slumps and landslides that constitute the aureole deposits. In this view, these deposits partially fill a flexural moat around Olympus Mons [see 12] in a manner analogous to mass wasting events in the Hawaiian and Marquesas island chains on Earth [11].

**DETACHMENT MECHANICS.** A basal detachment model for Olympus Mons has important mechanical implications. Tanaka 1985 [7] proposed a basal detachment rooted in a weak ice-saturated layer. However, the formation of a basal detachment sufficient to cause volcano flank failure requires the generation of high pore fluid pressure in a low-permeability basal layer [2, 13]. For example, the detachment beneath Hawaiian volcanoes is rooted in the layer of abyssal clay sediment emplaced before volcano formation [3, 14]. A basal detachment model for Olympus Mons [1], therefore, implies the existence of an areally extensive layer of clay or other low-permeability material, as well as abundant subsurface water (as liquid, not ice) to act as the pressurized pore fluid [2]. The presence of clay minerals on Mars has been inferred from chemical analysis and spectroscopic studies of the surface [e.g., 15]. Heat flux from the interior of Mars allows the presence of liquid water at depths of a few kilometers [16]. Thus, the conditions required for a Hawaiian-style basal detachment may exist beneath Olympus Mons.

**LITHOSPHERE DEFLECTION AND MOAT FILLING.** The load of the Olympus Mons edifice is sufficient to cause depression of the lithosphere, resulting in an annular moat surrounding the volcano. Again by analogy with Hawaiian volcanoes, McGovern and Solomon [1-2] proposed that a flexural moat around Olympus Mons was filled with landslide material that constitutes the aureole deposits. A preliminary MGS/MOLA altimetry profile [12] suggests partial filling of a moat, as is the case at Hawaii and in contrast to the overfilling observed at volcanoes of the Marquesas chain [11]. The volume of material required to fill flexural moats around large volcanoes can be an order of magnitude greater than the volume of the topographically-defined edifice alone [17]. A similar corrective factor can thus be applied to estimates of the time required to build Olympus Mons based on edifice volume. This correction implies a longer history for the volcano than currently appreciated, a finding consistent with interpretation of possible flexural topography in Noachian terrain north of Olympus Mons [12]. The downward deflection of the volcano-lithosphere interface is deep enough to allow melting of water beneath the edifice and most of the aureole, thus favoring the formation of a detachment at that interface [2].

**IMPLICATIONS FOR LIFE ON MARS.** Conditions required for the existence of a basal detachment are also conducive to the existence of subsurface life. The discovery of possible remnants of Martian lifeforms in meteorite ALH84001 [18] has driven speculation about sites where life may continue to exist on Mars. The basal detachment model for Olympus Mons [1-2] requires the presence of liquid water deep within the volcano, where temperatures will be elevated due to the above-average thermal gradient and magmatic heat. Olympus Mons, and more generally the Tharsis region, have likely been a source of thermal and chemical energy for a large fraction of the planet's history. The deep flanks of Olympus Mons are shielded from exposure to ultraviolet radiation, extreme cold, and other surface conditions harmful to life. The flanks of Olympus Mons thus constitute a site favorable to the long-term maintenance of life on Mars, perhaps in the form of lithoautotrophic organisms such as those discovered in Columbia River basalts [19]. The proposed landslide structure of the distal flanks implies that evidence of this potential deep refuge for life may be found at or near the surface of the Olympus Mons aureole.

**SITE SELECTION.** Site selection in the Olympus Mons aureole will depend on complying with mission constraints and maximizing scientific return. Elevation and latitude constraints for the Mars 2001 mission rule out sites in the far north and distal southeast portions of the aureole. Allowable landing ellipses likely rule out sites within 100 km or so of the Olympus Mons main shield. The topographic roughness of many aureole lobes rule out a large fraction of aureole area. However, a preliminary MOLA altimetry profile indicates that relief in the outermost aureole lobe is much smaller than that of a younger inner lobe [12]. Thus, mission requirements favor a landing site near the edge of one of the outermost (oldest) aureole lobes.

Maximization of scientific return also favors a site near the edge of an outer aureole lobe. A site with access to multiple aureole lobes and aureole-covering flow units from the main shield could yield samples with a variety of ages and compositions. A site near an impact crater would allow access to deeper exhumed material of the chosen aureole lobe (or perhaps of an older lobe).

The most distal aureole deposits are most likely to contain evidence for a basal detachment, which might include signs of hydrothermal alteration, shear deformation, and clay minerals. As argued above, such a site would also be a favorable place to look for evidence of autotrophic organisms. Further data (topographic, image, and spectroscopic) from the MGS mission will allow a much more refined study of potential exploration sites in the Olympus Mons aureole.

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**MULTIPLE MANGALA VALLES LANDING SITES.** Mary G. Chapman<sup>1</sup>; US Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86001.

Mangala Valles is an outflow channel system about 850 km long and as much as 300 km wide that cuts the Martian highlands (lat 18.5° S. to 2.5° N. and long 149° to 157°). Mangala Valles originates at one of the northeast-trending Memnonia Fossae graben at lat 18.5° S., long 149.5° and ends at the highland-lowland boundary scarp (lat 4° S., long 152°). The debouchment area on Amazonis Planitia extends from lat 4° S. to at least lat 2.5° N. Mangala Valles channel floor deposits offer grab-bag collection areas as do most of the outflow channels. The channel has ponded areas where floods have accumulated over long periods of time similar to Ma'adim Vallis/Gusev Crater. The three unique characteristics of Mangala Valles are that it (1) heads at likely source of thermal water, (2) contains likely lava flow material (resistant material, see below) interbedded between Hesperian and Amazonian flood deposits, and (3) is mostly covered by recent detailed 1:500,000 scale geologic maps.

The length of Mangala Valles channel system and numerous sites of high scientific interest along it argue for a networked mission configuration with considerable mobility built in, such as a lander with a rover and balloon. However, there are at least 3 locations on or near the channel that have elevations less than 2.5 km above Martian datum and have relatively smooth 100-km-wide landing ellipses, providing access to potentially widely variable rock compositions within the traverse capabilities of the 2001 rover. Within the channel and its debouchment area, there are at least 2 areas to land having very smooth surfaced landing ellipses (centered at lat 14.1° S., long 149° and lat 2.0° N., long 152.5°). An additional highland landing site is located directly west of the channel (lat 9.0° S., long 156.5°). The highland site does not provide as smooth a landing ellipse as the channeled areas, but because the area may have been subject to broad sheetwash erosion during the earliest phase of Mangala Valles flooding, it is much smoother than the average highland locale.

**Site Justification**

(1) The search for life. Mangala Valles is a highly relevant area for exobiologic studies. The site offers access to recent and ancient rocks that can be sectioned and examined for evidence of fossils. Thermal systems are thought to have played a key role in the origin and evolution of life on Earth; areas with such proposed systems are thus important targets in searching for a Martian fossil record [1]. The Mangala channel may provide such a setting because it emanates from a likely volcano/tectonic graben of Memnonia Fossae and therefore may have been sourced by thermal waters [2,3]. Young channel outflows and lake beds are exobiologic targets, because recent water outflows may have exposed and deposited molecular evidence of extant life and ice-covered lakes might have been sites for life's "last stand" on the Martian surface [4]. Some channel deposits of Mangala Valles are as young as Amazonian in age [2,5-8] and the Mangala Valles channel contains several large craters where Hesperian and Amazonian episodic flooding ponded water and deposited lacustrine deposits [9]. The eroded highlands adjacent to Mangala Valles contain numerous small Noachian channels. In addition, Mangala Valles debouches onto Amazonis Planitia, a region that has been suggested to have been covered by a global circumpolar ocean [10-14].

(2) Resource assessment. The catastrophic flooding channel of Mangala Valles is a complex area containing terrains of variable type, composition, and age. Hesperian to Amazonian volcanic and sedimentary rocks are interbedded within a channel complex cut into Noachian highland materials.

(3) Geologic history. The understanding of localized volcanic/tectonic interactions, volcanic deposits, and nature of the highland-lowland dichotomy are primary geologic science goals for future missions [15]. Floods of Mangala Valles appear to emanate from a Memnonia Fossae graben [16] as do possible lava flows [2]. Detailed visual examination at the head of the Mangala channel may shed light on the nature of the Memnonia Fossa and its emanations. In addition, the highland-lowland boundary scarp terminates the Mangala channel and may be accessed by visual examination.

(4) Volatile and climatic history. Formation of outflow channels has been attributed to catastrophic flooding [17], glacial erosion [18], a combination of flooding and glacial processes [19], and debris flows [10]. Investigation of Mangala Valles by a networked set of vehicles (that include detailed camera visualization and sample-return capabilities) may determine the nature of channel formation.

#### **Specifics of Channel Sites**

**Landing Site lat 14.1° S., long 149°** Elevation ranges from 2.5-1.5 km above datum. Detailed geologic mapping [8] indicates that 6 material units crop out within the landing ellipse. The three most widespread deposits consist of Hesperian alluvial plains (unit Hmp) emplaced against highlands, an erosionally resistant unit interpreted as lava flows or highly indurated sediments (unit AHmp<sub>3</sub>), and an older channel floor material (unit AHmch). The east end of the ellipse contacts a cliff of Noachian hilly material (unit Nplh) interpreted to be weathered, brecciated highland terrain. Ejecta from a young 7-km-diameter impact crater occurs within the northernmost extent of the landing ellipse and about 8 isolated small hills (<2 km wide) of a topographically higher occurrence of resistant material (unit AHmp<sub>2</sub>) dot the landing ellipse.

**Landing Site lat 2.0° N., long 152.5°** Elevation <1 km above datum. This locale is hampered by low resolution Viking Image coverage and a lack of detailed geologic mapping. However, the landing site appears smooth in low resolution and its location in Amazonis Planitia in what appears to be a window in the Medusae Fossae Formation (thick, poorly indurated materials interpreted to be ignimbrite sheets or eolian deposits), suggests that the site might be floored by outwash and eolian deposits. The benefits of this site include low elevation and its location in a region that has been suggested to have been covered by a global circumpolar ocean [10-14].

#### **Specifics of Highland Site**

**Landing Site lat 9.0° S., long 156.5°** Elevation ranges from 2.5-1.5 km above datum. Detailed geologic mapping [6] indicates that 2 widespread material units crop out within the landing ellipse: Hesperian ridged plains (unit Hr; likely layered basalts and the Lower Hesperian Series referent) and Noachian knobby plateau material (unit Nplk) an eroded, localized mantle superposed on heavily cratered plateau material. Noachian channels (unit Nchd) occur throughout the knobby plateau material. This site has the advantage of being a relatively low elevation highland site, possibly somewhat smoothed by early Mangala sheetwash processes, easy rover accessibility to old Noachian channels, and a large part of the landing ellipse is covered by the smooth surface of ridged plains.

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# **MANGALA VALLES AS A POTENTIAL LANDING SITE FOR THE MARS SURVEYOR 2001 LANDER.** R. Anderson, Jet Propulsion Laboratory, M/S 230-235, 4800 Oak Grove Dr., Pasadena, CA 91109.

## ***Introduction***

Mangala Valles is an outflow channel in the Memnonia region of Mars. Although its origin is still under debate, most researchers believe they represent some form of catastrophic flood system which occurred early in the evolutionary history of Mars.

The scientific objective of the Mars Surveyor Program 2001 (MSP 01) landed mission is to examine the ancient climatic and geologic history of Mars; to characterize surface materials with respect to elemental and mineral composition of rock and soils; to identify the role water may have played with respect to evolutionary history of the surface; to look for samples which may contain possible evidence of ancient life; and to collect and store unaltered samples which may be eventually returned to Earth during a later mission (MSP 05 - 2005).

As with the Mars Pathfinder lander, the landing site will depend on several engineering constraints. Preliminary engineering constraints for MSP 01 landing site is that the landing site lies with 30° N and -15° S of the equator (due to solar power limitations) and below 2 km elevation. Both the scientific objectives and the engineering constraints can be accommodated with a Mangala Valles landing site.

## ***Geographic Location of the Mangala Landing Site***

Lower left hand corner: Long. -152° W; Lat. -10° S.  
Upper right hand corner: Long. -150° W, Lat. -6° S.  
Center location: Long. -151° W; Lat. -8° S.

Area elevation ranges from 1 - 2 km above mean elevation (based on Viking data).

## ***Geographic Setting***

This area is one of several Hesperian-age outflow channels. It is the only channel of any size located on the western side of and adjacent to the Tharsis Rise and dissects ancient Noachian plains materials. Units associated with and/or surrounding this valley include: Noachian plains material (Npl1) and ridge plains material (Nplr - west of the proposed area), several Hesperian channel deposits (Hchp and Hch), and younger Amazonian lava flows (AH3 - east of the proposed landing site) (Scott & Tanaka, 1986). Although the headlands are too far south of the proposed latitudinal guidelines, Hpl3 units (smooth plains unit) have been identified near the headlands and may be present in the outflow basin.

## ***Scientific rationale***

The Mangala Valles landing site is similar to the Mars Pathfinder landing site (Ares Valles) in that both are catastrophic flood channels and formed from the erosion of water. Ares Valles was chosen for the Mars Pathfinder landing site because it represented a "grab bag site" and contained a diversity of different rock types. This should also be true for Mangala Valles which may contain a similar diversity of rock types (volcanic, sedimentary, and impact origin), particle sizes and

shapes, and the possibility of subaqueous sedimentary deposits. Unlike the Ares Valles landing site, Mangala Valles cuts through a large region of identified older Noachian-age crater and ridge materials (Npl1 and Nplr). Both of these units should be represented in the valley system within the bedload component. Chemical analysis of these materials should give us valuable insight into the early formation of the Martian crust (Noachian crustal materials) and may also give us an indication of the amount of chemical and physical weathering that has taken place in this region of Mars. This material may also contain evidence for the presence and/or absence of early martian life.

Mangala valley is geographically close to some of the youngest Tharsis lava flow units (AH3). Identification of these materials will give several different compositions of martian lavas and a better understanding of the evolutionary history of the crust. This area resulted from the presence/erosion of water and may be an excellent location to search for past life in Noachian-age materials as well as containing large, Hesperian-age sedimentary deposits. Due to it's location adjacent to the young Tharsis volcanics, this region may contain deposits resulting from lakes, hot springs, and evaporates.



**POTENTIAL MARS SURVEYOR 2001 LANDING SITES NEAR APOLLINARIS PATERA.**  
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Landing sites near Apollinaris Patera are proposed for the Mars Surveyor 2001 lander/rover mission. Regions near the base of Apollinaris Patera provide a unique opportunity within the proposed  $-15^{\circ}$  to  $30^{\circ}$  latitude belt to sample outcrop lithologies ranging from highland Noachian basement rocks, to Hesperian aged lava flows, channel and flood plain materials, to Amazonian volcanic, ash flow, and channel deposits. Pristine impact craters exhibiting lobate ejecta blankets are found both on the volcano itself and on the surrounding terrain implying a ground water rich environment well into the Amazonian. Therefore its formation likely induced long-lived volcanic-hydrothermal systems, a high priority target for the mission.

Apollinaris is located on the highland/lowland boundary at  $8.5^{\circ}$ S and  $186^{\circ}$ W. The volcano itself has been mapped [1] as Hesperian in age, the highlands immediately to the south are Noachian. Ma'adim Valles is located to the south and water from the valley apparently flowed around the volcano before emptying into the Elysium basin to the north. A large fan structure emanates from the southern flank of the volcano. The fan is dissected by numerous valleys, which likely have been modified by fluvial processes [2].

This area is of particular scientific interest for a rover mission. The region contains a wide variety of rocks of different origins and ages. Erosional processes associated with fluvial, volcanic, and aeolian activity have shaped the surrounding terrain. In addition, the volcano is surrounded by extensive, relatively smooth areas at low elevations (0 to 1 km) which permit good access and rover mobility [1].

There is extensive evidence of ground water in the region. A 23 km diameter impact crater lies on the northwest flank of the volcano and exhibits a fresh lobate ejecta blanket. Ground water outflow resulted in chaos zones to the west of the volcano. The remaining isolated mesas likely reveal the pre-erosion stratigraphy. These mesas may expose either sediment from an ancient sea or highlands material. A narrow Amazonian channel emanates from the Medusae Fossae formation on the volcano's NE flank and broadens rapidly toward the north.

Volcanic hydrothermal processes have likely had a pervasive influence on shaping the surrounding regions as evidenced by the chaotic terrains on the volcano's western boundary and fluvial erosion of materials on its southern flank. The presence of impact craters with pristine lobate ejecta blankets, not only in the surrounding plains but also at the summit of the volcano, argues for the continued water-rich nature of the region until well into the Amazonian.

Using stereo photogrammetric methods, Robinson *et al.* [3] estimated a volume of  $10^5$  km<sup>3</sup> for the volcano. The main caldera is 85 km in diameter and 0.8 to 1.5 km deep. This implies a magma chamber volume during the late stages of eruption of 4,000 to 6,000 km<sup>3</sup>. Given the unmistakable evidence for persistent ground water in the region, it is inescapable that volcanic intrusions associated with the construction of Apollinaris would have been associated with long-lived hydrothermal systems. Gulick [4,5] and Gulick *et al.* [6] modeled hydrothermal systems associated with magmatic intrusions. They found that the lifetime of hydrothermal systems associated with 5,000 km<sup>3</sup> intrusions was  $10^7$  years. Assuming multiple intrusions over the lifetime of the volcano, it is likely that the hydrothermal activity associated with the growth of Apollinaris lasted in excess of  $10^8$  years. Hydrothermal fluids were likely discharged along the flanks of the volcano, particularly the western flank where a 500 m high basal escarpment defines the edge of the construct. Long-lived thermal springs would likely have been pervasive along these scarps as well as on other low regions of the volcano's flanks. Thermal springs would have been especially likely along the southern margin of the fan structure where sapping processes have eroded back into fault scarps at its base.

The basal scarp of Apollinaris may suggest that the volcano began forming in a water or ice rich environment. The small, pristine impact craters with lobate ejecta blankets that formed on the volcano may suggest that water may have remained in the subsurface until relatively recent times.

**Landing Site A.** A landing site at  $8.6^{\circ}$  S and  $187.5^{\circ}$ W (Figure 1) would provide the opportunity to sample the ejecta of the nearby

impact crater and allow sampling of the mesas from the nearby chaotic terrain. The mesa material would be in place while the crater material would be exhumed from depth. The buttes and mesas which form the chaotic terrain in this region would afford a 3 dimensional view of the surface to depths of hundreds of meters. The ejecta from the impact crater may provide samples from the deeper subsurface than that exposed in the walls of the mesas. The material from the greatest depth is expected to lie closest to the rim, however. It is likely that these mesa walls may be exposing Noachian age terrains. The lander would also be able to image the 500 m high western scarp of Apollinaris which lies about 10 km from the suggested landing site. This region lies at about 0 km elevation [3].

**Landing Site B.** A landing at 12° S and 185.5°W (Figure 1) would lie near the southern edge of the fan feature where sapping processes have eroded back into the fan along fault scarps. This area is dissected by incipient valleys which expose the stratigraphy of the fan. Numerous cliff forming scarps which mark the highland/lowland boundary cut through this area. This region is a likely site for thermal springs as it lies at the base of the fan which is both cut by scarps and incipient valleys. This region lies between the 0 and 1 km [3].

**Landing Sites C.** A landing site near the northeast flank of the volcano (Figure 1, C1) where the Amazonian channel appears to emanate from a fault scarp in the Medusae Fossae Formation. An alternate site in this region would be to land approximately 50-60km to the north (C2) where the channel abruptly widens and flows might have temporarily ponded.

Apollinaris provides an exceptional site for exobiological, geological, and climatological purposes. Fluvial (including ground water sapping) and associated processes were likely pervasive from the late Noachian, through the Hesperian, and into the Amazonian. Long-lived and large scale hydrothermal systems were certainly present throughout much if not all of this period. Thermal springs likely persisted for long periods. Water from the highlands via Ma'adim Valles and other smaller valley networks deposited highland-derived material in the area. In short, Apollinaris provides an excellent variety of rock types and ages and may preserve evidence of biologic or pre-biologic processes in associated thermal spring deposits.

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**Figure 1.** Apollinaris Patera. Potential landing sites labeled. Volcano caldera is about 80 km in diameter.

**SE ELYSIUM BASIN, MARS: A MARS 2001 CANDIDATE SITE OF LOCAL GEOLOGIC AND EXOBIOLOGIC INVESTIGATIONS.** J.M. Dohm, K.L. Tanaka, and J.H. Lias, U.S. Geological Survey, Flagstaff, Az, 86001; jdohm@flagmail.wr.usgs.gov

**Introduction.** The Elysium basin region of Mars, which extends for more than 2,500 km along the equatorial lowland plains between the cratered terrain of the southern highlands and volcanic rise that includes Elysium Mons, has been the site of numerous geologic investigations [1-4]; these investigations unanimously indicate that the basin served as a catchment basin for Amazonian channel and flood-plain deposits. Additionally, the basin may show the strongest evidence of a former lake on Mars [3,4]. With possible exception of the Chryse Basin, Elysium is the only depositional basin of regional extent that has been found on Mars from which an outflow of water can be established by direct evidence [4]. However, there is less agreement on the rock-stratigraphic, erosional, and depositional/emplacement histories of the Elysium basin-channel floor materials. Although Plescia [5] agrees that there was an episode of fluvial modification and deposition, he proposes that the emplacement of lava flow materials (Cerberus Plains Volcanic Plains) postdate any episode of fluvial erosion or deposition including lava flows that may have exploited pre-existing fluvial valleys. On the other hand, Scott and Chapman [3] suggest that the basin contains both lava flows and sedimentary deposits (lacustrine and fluvial) and that the emplacement of lava flows predates the fluvial episode.

Radar data obtained by Harmon et al. [6] show radar-bright areas on the basin floor and along the large outflow channel (proposed eastern drainage of Elysium paleolake into Utopia basin; [4]). These bright areas may be relatively fresh or eroded lava flows or boulder and cobble fields along the channel bed; thus the radar data are inconclusive as to the relative ages of the proposed lake and basin-floor materials. The basin-channel floor materials are marked by a large diversity of landforms. These include: (1) mesas, (2) relict channels, and (3) meander patterns. In addition to a volcanic and/or fluvial and lacustrine origin for the basin deposits [3,5], colluvial and eolian deposits and debris flow materials may have also partly infilled the basin. Additionally, some of the mesas could be erosional remnants of cratered highland materials. Materials of the Medusae Fossae Formation (interpreted to be pyroclastic material) occur within the region along part of the southern margin of the basin. Here, a putative former water level of about -1000 m can be recognized in places where possible shorelines and terraces have been eroded in relatively soft rocks of the Medusae Fossae Formation [4]. Thus, the SE-Elysium-basin deserves attention as a Mars 2001 site of geologic and exobiologic investigations.

**Scientific rationale for site selection.** The SE-Elysium-basin region is of special geologic interest for a rover investigation because of diversity in: (1) rock type (volcanic, sedimentary, and possible ancient crustal materials), (2) material ages (possible Noachian highland material and Amazonian lava flows and sedimentary deposits), and (3) landforms (indicative of erosional, sedimentary, and possibly other processes). By viewing the various landforms and sampling the rock materials that form the basin floor and high-standing outcrops and materials of the Medusae Fossae Formation, we might better constrain (1) whether or not a lake occupied the basin, (2) whether the basin floor materials are lacustrine or volcanic, and (3) whether or not the Medusae Fossae materials are pyroclastic or sedimentary. Additionally, the paleolake possibility, which may have existed intermittently, possibly for sufficiently long periods to promote and sustain life [4], may make this region suitable for future exobiologic investigations.

**Proposed traverses of the SE-Elysium-basin region.** We propose four traverses within the region that fall well within the mission constraints defined by the Athena investigation team; a representative traverse is shown in Figure 1 and described in Table 1. The proposed traverses, which occur within an elevation range of -2,000 to -1000 meters [7], are located near lat 2.5 N., long 184.8 (site A); lat 2.2 N., long 188.7 (site B); lat 5.1 N., long 188.9 (site C); lat 6.3N., long 185.5 (site D). Relatively smooth plains appear to dominate the proposed rover traverses. However, because radar reflectivity maps show areas of strong backscatter within the Elysium basin [6], MGS data should be utilized to determine more accurately the trafficability of the proposed sites.

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# SE Elysium Basin, Mars: A Mars 2001 Candidate: Dohm et al.

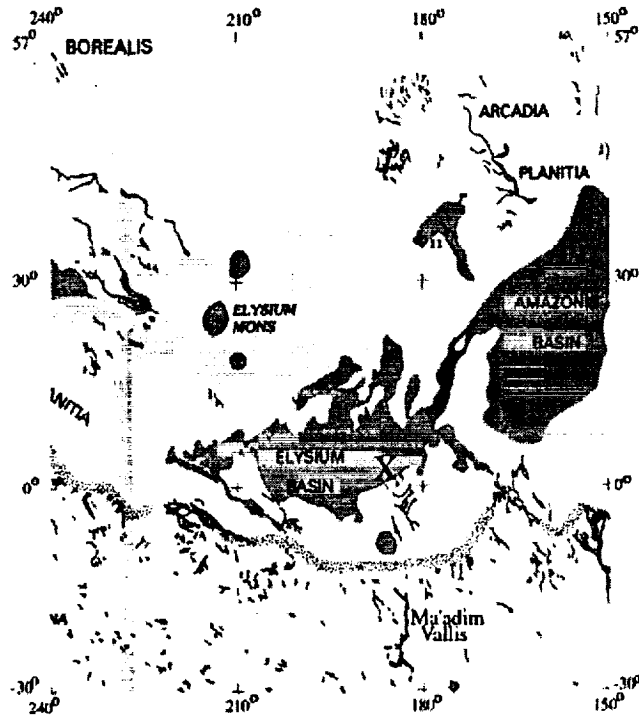


Figure 1. Part of map showing channels and possible paleolake basins of Scott et al [4]. X marks the SE-Elysium-basin region, a proposed site of local geologic and exobiologic investigations, which includes landing site A of Figure 2.



Figure 2. Traverse A of the SE-Elysium-basin region.

Table 1. Description of Traverse A.

SCIENCE SITES	DISTANCE	SCIENCE TARGETS	GEOLOGIC UNITS
<b>Traverse A</b>			
A <sub>1</sub>	0 km	Bright Elysium flood plain deposits (lacustrine/fluvial deposits or lava flows)	Ache (b)
A <sub>1</sub> -A <sub>2</sub>	15 km	Dark Elysium flood plain deposits (lacustrine/fluvial deposits or lava flows), possible channels and associated deposits	Ache (d)
A <sub>2</sub> -A <sub>3</sub>	12 km	Dark Elysium flood plain deposits; unfractured material (possibly crustal material) or eroded Medusae Fossae Formation (possible pyroclastic deposits)	Ache (d), IDNw Am (7)
A <sub>3</sub> -A <sub>4</sub>	30 km	Unfractured material or eroded Medusae Fossae Formation and dark Elysium flood plain deposits	IDNw/ Am (7), Ache (d)
	57 km		

\* Sites where samples and other data are collected to address geologic, exobiologic, and climatic issues.

**GUSEV CRATER PALEOLAKE: TWO-BILLION YEARS OF MARTIAN GEOLOGIC, (AND BIOLOGIC ?) HISTORY.** N. A. Cabrol<sup>1</sup>, E. A. Grin<sup>1</sup>, R. Landheim<sup>1,2</sup>, R. Greeley<sup>3</sup>, R. Kuzmin<sup>4</sup>, and C. P. McKay<sup>1</sup>, <sup>1</sup>NASA AMES Research Center, SST/CMEX, MS 245-3, Moffett Field, CA 94035-1000, <sup>2</sup>SETI Institute, Mountain View, CA, <sup>3</sup>Dpt. of Geology, Arizona State Univ., Tempe AZ 85287-1404, <sup>4</sup>Vernadsky Institute, Russian Academy of Sciences, 117975, Kosygin Street 19, Moscow, Russia. Email: ncabrol@mail.arc.nasa.gov.

**RATIONALE:** Ancient Martian lakes are sites where the climatological, chemical, and possibly biological history of the planet has been recorded. Their potential to keep this global information in their sedimentary deposits, potential only shared with the polar layered-deposits, designates them as the most promising targets for the ongoing exploration of Mars in terms of science return and global knowledge about Mars evolution. Many of the science priority objectives of the *Surveyor Program* can be met by exploring ancient Martian lake beds (see Table I). Among martian paleolakes, lakes in impact craters represent probably the most favorable sites to explore. Though highly destructive events when they occur, impacts may have provided in time a significant energy source for life, by generating heat, and at the contact of water and/or ice, deep hydrothermal systems, which are considered as favorable environments for life. In addition, impact craters lakes are changing environments, from thermally driven systems at the very first stage of their formation, to cold ice-protected potential oases in the more recent Martian geological times. Thus, they are plausible sites to study the progression of diverse microbiologic communities.

Table I: Science Objectives and Related Sites (adapted from Farmer and DesMarais, in Mars Landing Site Catalog)

Objective	Type of Sites
Diversified Geologic Record	- Paleolake beds* - Outflow/Runoff debouchment areas
Climate History	- Polar regions - Channels - Paleolakes*
Chemical Evolution	- Aqueous Sediments* - Lacustrine Sediments* - Deep Hydrothermal Systems*
Fossil Life	- Thermal Springs - Lake Beds*
Extant Life ?	- Current Hydrothermal Sites ? - Frozen in ice (poles, permafrost, frost mounds*) - Caves - Evaporite deposits* - Endoliths*

\* associated with, or possibly observed in impact crater-lakes.

**GUSEV CRATER:** Among the 160 impact crater lakes observed at the resolution of Viking [1], Gusev crater is probably one of the most promising sites for exploration. It is centered at 14°S/184.5°, at the mouth of the 1000-km Ma'adim Vallis, and its mean elevation is 0 m, providing favorable aerobraking conditions for the lander, and suitable latitudinal location for energy supply. Gusev crater has been

presented as a high-priority and exceptional site both from the geologic and the exobiologic standpoints [2-9].

1. *Geological Diversity:* as a receptacle for Ma'adim Vallis flows and numerous other fluvial valley networks of smaller dimensions, Gusev crater has been accumulating sediment from diversified parent-rocks on the cratered uplands from the Upper Noachian to the Middle Amazonian periods [8, 11, 12, 13]. The units crossed by Ma'adim Vallis and the regional hydrologic systems converging in Gusev represent crustal material, volcanic material modified by water erosion, and recent aeolian deposits [12]. Record of this rock accumulated during two billion years (see Fig. 1) was deposited in an aqueous sedimentary lens, which thickness was estimated between 500 to 780 m [3,11]. This thick and diversified geologic record is locally partially exposed both in a 300-500 m high delta structure and in the 20-km diameter Thyra crater. The 300-m high terraces of Thyra crater are carved in Gusev sediments, exposing most of the primary aqueous sedimentary deposits related to the first lacustrine episodes that could date back from the Upper Noachian [11, 12, 13].

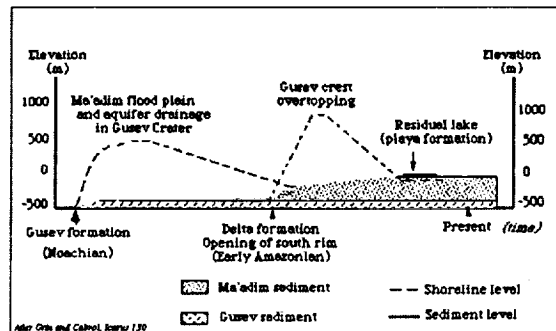


Figure 1: Gusev shoreline level and sediment evolution through time

2. *Exobiology Potential:* Gusev crater has been defined as a favorable location to sample potentially fossiliferous fluvial-deltaic sediment. Terrestrial deltas and lacustrine shoreline deposits are common sites for precipitation of carbonate cements and tufas, favoring preservation of fossils and organics [5]. The presence of carbonate rocks in Gusev has been proposed [3, 11]. A Recent study [15] has shown that light-colored carbonate sediments might be exposed in the deltaic region of Gusev. In the same study [15], isolated cone-shaped hills rising from the paleolake bottom have been associated with light-colored sediments, and have been suggested to be composed of carbonates, designating them as possible tufa-like mounds. In addition to the high potential for carbonate sediments in the deltaic region of the crater, the Thyra crater located 50 km northeast of the Ma'adim Vallis

mouth in Gusev shows a dark albedo spot which plausible interpretations are: hydrothermal, volcanic, or chemogenic deposits [7]. Since this spot is superimposed on the most recent aqueous sedimentary deposit, it must be Amazonian in age. Also in Thyra, high-albedo deposits exposed on the double-terrace oriented east-southeast were suggested to be composed of carbonate deposits or other chemogenic sediments [15]. Thus, Gusev has been a depositional area for approximately two billion years, and therefore has to be considered a site of high priority in terms of search for fossils and organic matter. Though the fossilization and preservation conditions have still to be studied for Mars, lacustrine sites are probably the most promising places to start, and provide the most likely sites to search for fossil evidence. In addition, the presence of a recent lake in Gusev during the Amazonian [11, 12] allows to suggest that water was still supplied relatively recently to the underground by infiltration at the bottom of the lake. This process may have occurred several times following the multiple-lake episodes in Gusev, and generated a water/ice-rich underground, which coupled with the heat associated with cratering and possible magmatic activity could have provided a suitable environment for the inception of life and its survival through time. Finally, following the waning of the last lake in Gusev during the Amazonian, formation of late playas in topographic lows, like Thyra crater, are likely to have occurred, thus providing another potential environment for microorganisms [16].

3. *Climate Record:* The detrital clastic components of lake sediments reflect the relief, climate, and the rock types present in the drainage area of the lake [17]. Lakes are particularly sensitive depositional environments which respond immediately to local, regional, and global changes. The size and shape of the clasts, and the composition of sedimentary rocks will tell about the atmosphere and climate changes through the history of lacustrine activity in Gusev, which, thus, provide an exceptional open-window on two billion years of martian climatic changes.

4. *Resources:* the global inventory and the distribution of near surface materials and volatiles is an important part of the Surveyor Program. Because of its long hydrogeologic history, Gusev is a favorable site to start the assessment of the martian environment and its potential utilization: (a) its location as a collector site provides stratified samples of rocks from various sequential, physical and chemical origins that will unveil the martian past environment, (b) the presence of ice-cored mounds have been proposed as evidence of potential subsurface stored water/ice in the Thyra region [18], and could provide accessible resources for manned outposts.

5. *Candidate Landing Sites in Gusev:* Two candidate-landing sites present the most potential for science return. They are: (a) the Thyra crater 14.5°S/186°W, for which models of traverses and science activity planning projects are already designed [7], thus allowing a rapid definition of targets for high resolution imaging in 1999 (MOC), and topog-

raphy assessment for trafficability purposes (MOLA), (b) the second site is the Ma'adim Vallis delta (15°S/184.6°W).

SCIENCE RETURN POTENTIAL: As a conclusion, we propose a table (see Table II) that summarizes the worthiness of a mission in Gusev crater, and the expected science return relative to the objectives to be met by the Surveyor Program.

Table II: Merit and Expected Science Return

Science	Merit	
Diversified Geology	⊕	- crustal mat. - volc/hydroth. mat. - fluvio-lacust. mat. - aeolian mat.
Climate History	⊕	- fluvio-lacust. dep. - lacustrine varves
Exobiology	⊕	- 2Gyr fluvio-lacustrine activity - aqueous dep. envir <sup>1</sup> - possible hydrothermal activity in Thyra
Sampling Diversity	⊕	- sedimentary rocks - igneous rocks - soil - extinct/extant life (?)
Engineering	Merit	
Latitude	within limits	- Site #1: Thyra crater: 14.5°S/186°W - Site #2: Delta: 15°S/184.6°W
Elevation	⊕	- 0 m mean elevation
Trafficability	TBD	- Good at Viking Res. - Good prediction on lake bed. Need MOC/MOLA resolution data

⊕ high ∅ moderate ⊗ low

References: [1] Cabrol (1998) *29th LPSC* (submitted), [2] Cabrol et al., (1991) *Astron. Vest.* 25, [3] Goldspiel and Squyres (1991) *Icarus* 89, [4] Greeley (1994) *Landing Site Catalog*, Site 112, [5] Farmer and Landheim (1994) *Landing Site Catalog*, Site 138, [6] Cabrol and Grin (1995) *Plan. Space. Sci.* 43, [7] Cabrol (1995) *MESR report*, [8] Landheim (1995) *Master Thesis*, [9] Cabrol et al., (1996) *Icarus* 123, [10] Cabrol and Grin (1997) *Orig. Life*, 26 (3-5) [11] Grin and Cabrol (1997) *Icarus* 130 (2), [12] Kuzmin et al., (1998) *US. Geol. Surv.*, 1-500k, [13] Cabrol et al., (1998a), *Icarus* (TBP), [14] Cabrol et al., (1998b) *Icarus* (TBP), [15] Kempe and Kazmierczak (1998) *Plan. Space. Sci.* (in press), [16] Rotschild (1990) *Icarus* 88, [17] Einsele (1992) *Sedimentary Basins* (Springer-Verlag), [18] Cabrol et al., (1998) *Icarus* (TBS),

**SOUTHERN UTOPIA PLANITIA: GEOLOGY AND PROPOSED 2001 ROVER TRAVERSE NEAR THE LOWLAND/HIGHLAND BOUNDARY.** J.S. Kargel, U.S. Geological Survey, Flagstaff, AZ 86001; jkargel@flagmail.wr.usgs.gov

***Introduction.***

A 2001 landing site in southern Utopia Planitia is proposed near N Lat 28° 52', Long. 270° 29' [1], at an elevation of -400 m (interpolated from [2]), in an area where thermal inertia data [3] suggests a moderate rock abundance. The landing site is an area of so-called "thumbprint terrain." The primary geologic objectives of this mission would be to investigate (a) the nature of the lowland/highland boundary, (b) the physical processes responsible for modifying this boundary, and (c) the petrology and origin of deposits that fill much of the northern plains. We would address hitherto intractable questions as to the possible roles of eolian, volcanic, marine/lacustrine, mud/debris flows, and glacial processes operating regionally and mass wasting, mud volcanism, and periglacial processes acting locally. Widely suspected of being an area where water or ice once was abundant, this could be a possible exobiological site.

***Geologic overview.***

The Martian lowland/highland boundary includes, in close proximity, rock units of diverse origin and wide ranging ages [4]. This globe-circling geologic boundary probably is the most striking first-order geologic contact on the planet. Although not as visually stunning as the equatorial canyons, major shield volcanoes, or polar caps, the boundary zone nevertheless includes some dramatic and enigmatic landforms-- naturally sculpted knobs towering hundreds of meters (e.g., the so-called "face"), fretted canyons bearing glacier-like and lobate mass flow units, and variety of plains deposits.

Interpretations vary, but any origin must have involved processes that acted on a globe-girdling scale, because the stratigraphic contacts along the boundary circumscribe virtually the entire northern plains, except where younger volcanic deposits overlap [4-8]. This important set of stratigraphic contacts and the rock units involved may hold a key to the nature of depositional processes in the northern plains. According to Mars Observer Laser Altimeter measurements [9], these processes appear to have filled and leveled huge expanses of the northern plains basin. Much of the sedimentary component was derived by widespread erosion of the highlands and the lowland/highland boundary zone. The highland/lowland boundary zone evidently contains a rock record of processes whose collective reach was truly global.

Parker et al. [6, 7] the boundary zone encompassing their Units A and B, Contact 2 between these units, and the fretted or gradational boundary itself. Contact 2 and Units A and B occur within the landing site area. Parker et al. [7] showed and described an image of the very site proposed here for the 2001 mission (Fig. 12, above and left of center, in ref. [7]). This type of contact occurs along perhaps 50% of the periphery of the northern plains but inward from (downward in elevation, generally north of) the boundary feature described as being either fretted or gradational [6, 7]. Contact 2 at the landing site occurs between the two basal units, where Unit B overlies and onlaps Unit A, which in turn extends to the very edge of the northern plains at a somewhat fretted, somewhat gradational boundary with the Noachian cratered plains. Unit B is dominated by hummocks and whorled or subparallel ridges constituting thumbprint terrain; in the immediate landing site thumbprint terrain degenerates into its hummocky form.

Parker's Contact 2 coincides with what Jöns [5] mapped and interpreted as the edge of a northern plains "mud ocean," an interpretation that lately has drawn new support in terms of a debris-flow model [10]. In the vicinity of the proposed landing site, Contact 2 also coincides with what Scott et al. [11] mapped as the western shore of a long, narrow lake west of Elysium. Thumbprint terrain and associated plains deposits making up Unit B have been variously interpreted as debris flows perhaps with aligned mud volcanoes [5, 10], lava flows perhaps covered with eolian deposits [4], ancient shorelines or nearshore marine deposits [6, 7, 13], or glacial moraines [8]. There is no consensus on the interpretation of these features, but there is agreement that this Contact 2 circumscribes much of the northern plains and represents a dramatic geologic event central to an understanding of deposition in the northern plains. This contact generally occurs between 0 and -2 km. MOLA data [9] suggest that in this area Contact 2 occurs at or near a profound change in the gentle slopes of the northern plains (Unit A is relatively steeply sloping, Unit B is almost horizontal), although this requires confirmation.

***The landing site and rover traverse.***

The Syrtis Major quadrangle, containing the landing site and the boundary zone, has been mapped geologically at 1:5 million by Meyer and Grolier [12], and the area was mapped as part of a global geologic map at 1:25 million by Scott and Carr [4]. The landing site occurs on a terrain mapped alternatively as (a) "plains material" of unclear origin, perhaps involving eolian, volcanic, sedimentary, impact, and/or ground-ice processes, and an unspecified though relatively young age [12], or (b) "cratered plains material" consisting of possible lava flows blanketed by eolian deposits of Amazonian age [4].

The landing site nominally occurs on Parker's Unit B and is within roving distance of Contact 2, west of which lies Unit A. (See Fig. 12 of [7]). The landing site is expressed locally as a fairly smooth landscape grading into a somewhat rougher area to the east comprising scattered hummocks and whorled to parallel ridges-- somewhat subdued and disordered thumbprint terrain. North of the landing site, thumbprint terrain occurs in spectacular form, so there is little question that Unit B at the landing site is closely related to thumbprint terrain. Contact 2 occurs as a discrete, lobate contact of Unit B onlapping Unit A along a lobate scarp-like contact, convex toward Unit A; the scarp is of order 50 m high. The surface of Unit A dips to the northeast, and so it appears that Unit B thickens in the same direction. A visit by Athena to Contact A stands a good chance of settling the argument over the depositional origin of Unit B and whether there were oceans/big lakes, glaciers, mud seas, sand seas, or lava seas in this part of the northern plains. Reaching Contact 2 is the primary geologic objective.

For the following proposed traverse, which is merely illustrative of the possibilities in this area, I assume a precise landing at the coordinates specified above. Less precise landing accuracy would entail changes to the specific traverse, but the same type of geologic features occur over a much wider area, so landing accuracy of  $\pm 30$  or 40 km would allow the basic objectives to be achieved.

(1) Rover investigations start with morphologic, sedimentologic, and petrologic investigations of Unit B in the immediate vicinity of the lander (N Lat  $28^{\circ} 52'$ , Long.  $270^{\circ} 29'$ ) (coordinates based on [1]).

(2) The rover would then drive 4 km west to Contact 2 (N Lat  $28^{\circ} 52'$ , Long.  $270^{\circ} 33'$ ), the overarching goal of the mission.

(3) Drive 3 km northeast to a nearby knob that locally diverted deposition of Unit B (N Lat  $28^{\circ} 54'$ , Long.  $270^{\circ} 31'$ ). Drive around east side of the knob where Unit B was deposited onto the knob. Study knob's lithology and indications of possible mud volcanism, wave or current activity, and mass wasting due to ice processes or arid-climate mesaland processes (ground-water sapping, avalanches, and eolian erosion).

(4) Drive 7 km northwestward to an 8-km-long ridge and drive 2 km along its edge (N Lat  $29^{\circ} 01'$ , Long.  $270^{\circ} 33'$ ). This feature is a possible tombolo, a compressional ridge in a debris flow, an esker, or some other structure— but whatever it is, such ridges are common in Unit B.

(5) Drive 33 km to the edge of the ejecta blanket of a double-lobe 10-km-diameter rampart crater (N Lat  $29^{\circ} 26'$ , Long.  $270^{\circ} 57'$ ); this crater would have excavated rocks from over 1000 m deep, with complete penetration through Unit B and possible penetration through Unit A into Noachian-age basement material of the boundary zone. Examine ejecta for flow characteristics, evidence of aqueous chemical and physical weathering of rocks; investigate igneous, sedimentary, and shock metamorphic petrology.

Other geologic features in this area include: (6) a butterfly ejecta crater (Lat  $30^{\circ}$  N, Long  $273^{\circ}$ )— this crater measures  $32 \times 48$  km and is a possible source for some of the SNC meteorites; ejecta from this crater may be within driving distance of the nominal landing site. (7) Knobs and Contact A similar to what is present at rover stops 2 and 3. (8) Terraced knobs and flat-topped mesas. (9) Secondary crater field from the ejecta of a distant, unknown crater— a possible navigational obstacle, but an interesting geologic objective, with possible SNC meteorites, if navigation is possible. (10) Eroded ghost crater partly buried by Unit A. (11) A sharp contact between Unit A and heavily eroded Noachian-age rocks of the gradational form of the boundary zone— a region where periglacial ice processes are believed to have been active.

The knobs pose a small but significant landing hazard, since they occupy ~2-3% of the surface area in this region. Boulders are a more likely and unavoidable hazard, since thermal inertia data suggests a moderate (10-15%) rock abundance [2]. In general, the smooth terrain and moderate rock abundance suggests that this area should be easily navigable and a relatively safe landing site. The combination of safety, geologic interest, and difference with respect to earlier landing sites makes this area worth serious consideration for the 2001 mission.

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**Introduction.** We propose two traverses in southwestern Isidis Planitia, Mars, as candidate sites for the Mars 2001 Surveyor lander/rover mission. Investigation of these sites would address geoscience and exobiologic issues of current interest, including: How were highland materials degraded and northern plains materials emplaced? What is the composition of Hesperian lavas? Can fossils be found in materials formerly making up shallow aquifers?

**Site setting.** The proposed traverses occur on relatively smooth plains marked by ridges, hills, and impact craters and distant plateau and highland terrains, mostly within the range of lats 6-9° N., longs 256-279° W. The plains are within a topographic basin at an elevation of about -2,000 m or lower, based on the USGS elevation model [1], the Smith and Zuber model [2], and a Goldstone radar profile at lat 9.48° N. [3].

**Regional geology.** The 1,000-km-diameter Isidis basin (Fig. 1) formed as the result of a huge impact during the Early Noachian [4]. The surrounding crust was uplifted and fractured; surviving remnants of the crust form part of Arabia Terra northwest of Isidis and Libya Montes, a broad chain of massifs along the south margin of Isidis (unit Nplh in Fig. 2). At the end of the Noachian, the highland/lowland dichotomy boundary zone was degraded [4], during which the eastern rim of Isidis may have been eroded, resulting in patches of knobby plateau material in Arabia Terra (unit plk). Later, during the Hesperian, outpourings of lava formed Syrtis Major Planum (unit Hs). Initially, the flows were in the form of broad, planar sheets. Then, lobate flows issued from large calderas in the center of the planum [3] and about 600 km west of Isidis Planitia. At about the same time, ridged plains material (unit pr) of sedimentary or volcanic origin infilled at least parts of Isidis basin. During the Late Hesperian or Early Amazonian, according to crater densities [5], a circular deposit of plains material (unit AHi) covered most of Isidis Planitia (Fig. 2). This material includes distinctive arcuate ridges made up of chained, pitted cones that have been interpreted as pseudocraters [6], glacial moraine features [5], or mud volcanoes [7]. Along the northern edge of the unit occur a few troughs containing medial ridges. Such features can be seen elsewhere in the northern plains of Mars and have been interpreted as glacial tunnel valleys and eskers [8], deformation features within ice streams [9] or mass flows [7]. Much of the north and eastern edge of the Isidis plains unit (unit AHi) can be traced in Viking images, indicating that it may have originated at least in part by degradation of the east edge of Syrtis Major Planum, which produced knobby and hummocky plains material (unit pk).

**Traverse descriptions.** Assuming that the Mars 2001 rover will be able to navigate a few tens of kilometers across smooth plains, we have selected two

traverses that visit the following science targets (Fig. 3): (1) Isidis plains material, (2) ridges made up of pitted cones, (3) Syrtis Major Planum material in the form of knobs and possible colluvium transported basinward from the edge of the planum. In addition, rover and lander cameras may image the nearby degraded margin of Syrtis Major Planum and Libya Montes.

**Scientific objectives.** The site includes diverse rock types and ages (Noachian crust, Hesperian lavas, Hesperian/Amazonian sedimentary deposits) and unusual landforms (including the pitted ridges and degraded plateau margin). Pitted cones are common in the northern plains of Mars [e.g., 5-7], and recent geologic mapping indicates that they generally occur in what appear to be huge mass flow deposits [10]. If the cones did form by mud volcanism, they would have originated from water-saturated, perhaps gas-rich material. On Earth, such material may originate at depths of hundreds of meters to kilometers [e.g., 11]. Knobs of Syrtis Planum material may have also been water-rich, to help explain how the plateau margin may have become so highly degraded. Thus the pitted cones and knobs may expose material previously wet (unfrozen) and at depth. Such material would be ideal for exobiologic sampling. Additionally, geomorphic investigation of high-standing landforms may reveal whether lakes or glaciers once existed within Isidis basin.

**MGS data.** Additional data may be gathered by Mars Global Surveyor for this region and help constrain some of the geologic interpretations pertinent to the traverses. For example, mineralogic spectral signatures from TES may determine if the Isidis plains material is derived from Noachian crust and Syrtis Major lavas. High-resolution MOC images and MOLA data may reveal smaller landforms and broad topographic relations that favor the occurrence of particular sedimentary and erosional processes in the areas of the traverses.

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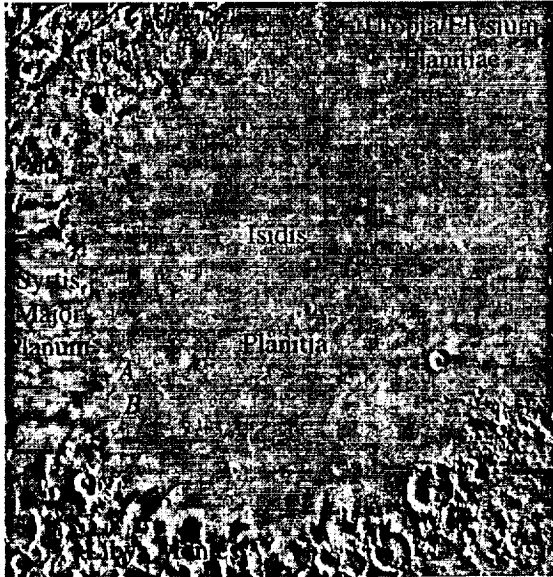
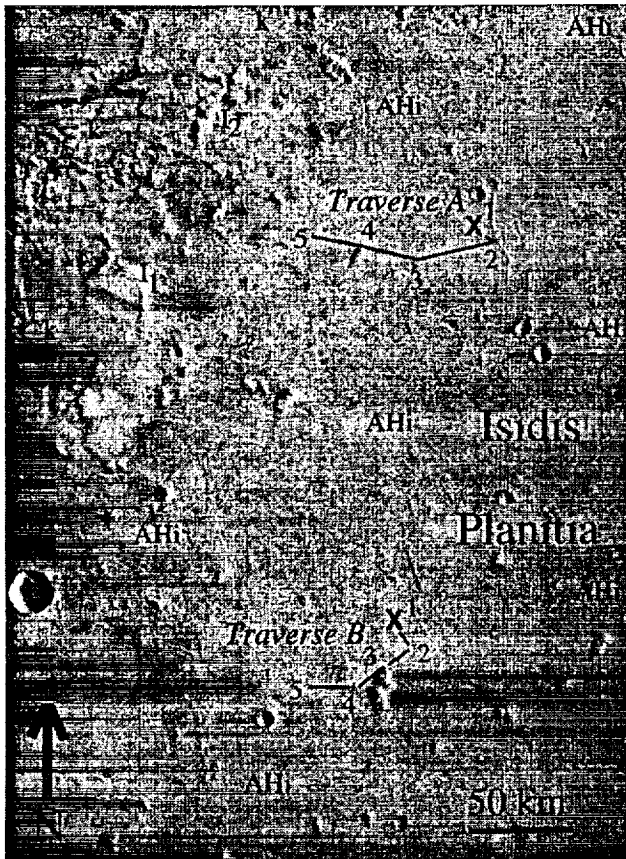


Fig. 1. Isidis basin, Mars, showing locations of traverses A and B. Fig. 2. Geologic map of Isidis basin (see text for explanation).



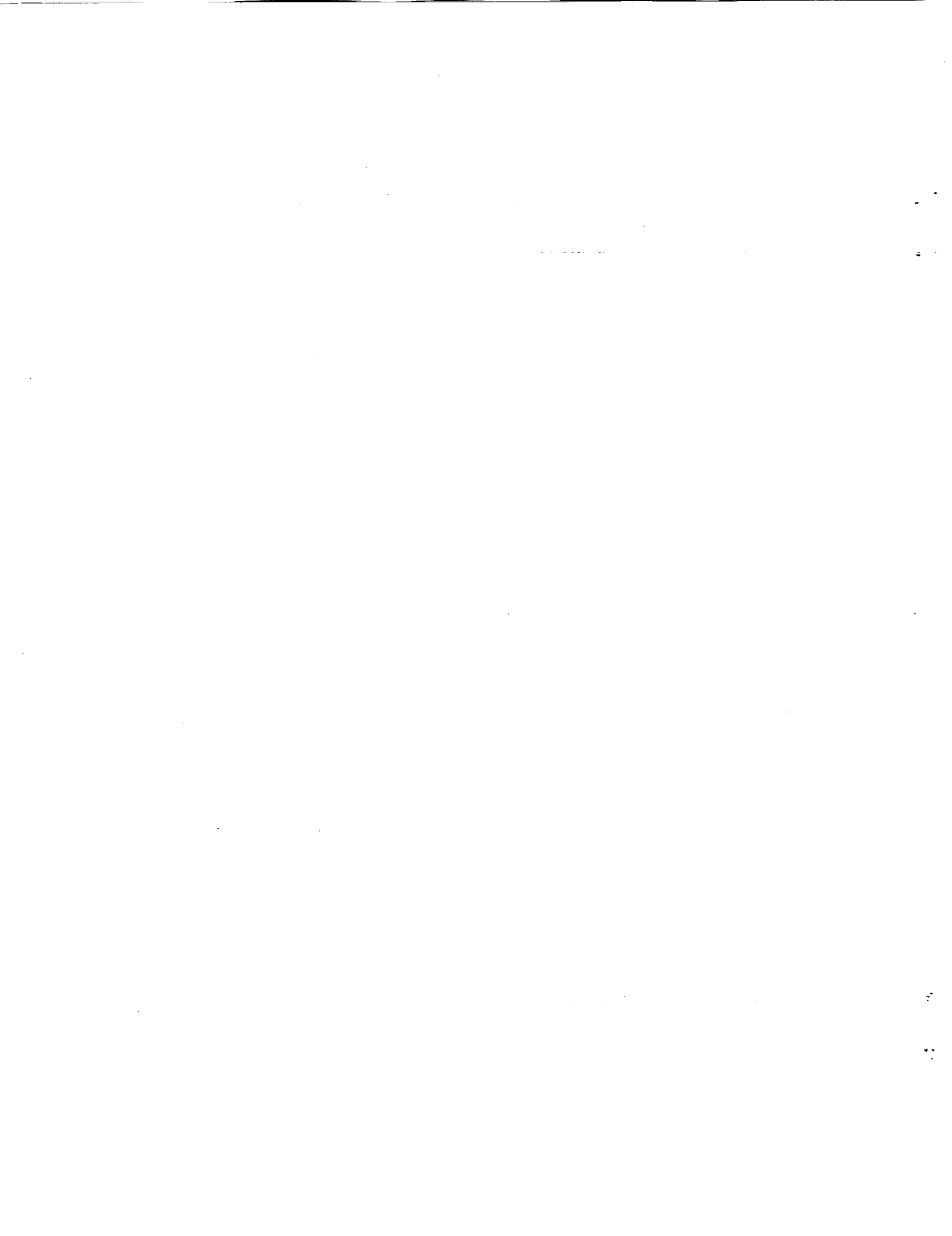
*Traverse A*

SCIENCE SITES	DISTANCE	SCIENCE TARGETS	GEOLOGIC UNITS
A <sub>x1</sub>		Isidis plains unit (probable sedimentary deposit)	AHi
A <sub>x1</sub> -A <sub>2</sub>	5 km	Isidis plains unit; ridge consisting of conical hills with summit craters (possible mud volcanoes)	AHi
A <sub>2</sub> -A <sub>3</sub>	18 km	Isidis plains unit; knob (volcanic or ancient crustal material)	AHi, k
A <sub>3</sub> -A <sub>4</sub>	14 km	Isidis plains unit or colluvial material; knob	AHi, k
A <sub>4</sub> -A <sub>5</sub>	11 km	Isidis plains unit or colluvial material	AHi
	48 km		

*Traverse B*

SCIENCE SITES	DISTANCE	SCIENCE TARGETS	GEOLOGIC UNITS
B <sub>x1</sub>	0 km	Isidis plains unit (probable sedimentary deposit)	AHi
B <sub>x1</sub> -B <sub>2</sub>	8 km	Isidis plains unit; ridge consisting of conical hills with summit craters (possible mud volcanoes)	AHi
B <sub>2</sub> -B <sub>3</sub>	8 km	Isidis plains unit; knob (volcanic or ancient crustal material)	AHi, k
B <sub>3</sub> -B <sub>4</sub>	10 km	Isidis plains unit; knob	AHi, k
B <sub>4</sub> -B <sub>5</sub>	11 km	Isidis plains unit; possible landslide material and (or) ejecta from nearby impact crater	AHi
	37 km		

Fig. 3. Detail of proposed traverses and description of science targets (tables).



## STRATEGIES AND RECOMMENDED TARGETS FOR MARS SURVEYOR PROGRAM LANDING

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### Introduction

The two major constraints for selecting the Mars Surveyor Program (MSP) 2001 landing site at the time of this meeting are latitude (30°N to 15°S) and elevation (< 2.5 km). The latitude belt will be narrowed down to a 15° sector after this workshop. This mission will demonstrate the capability to perform a precision landing, with the goal of achieving an accuracy of approximately 10 km, 3-sigma. There will be at least two different landing sites ('01 and '03) selected in the MSP. However, there should be an option of having the '05 sample return mission land in a different site and the '05 mission should be equipped with a rover for two reasons. The reasoning behind this follows: '05 lander/rover package should have the option of going to an independent site from either '01 or '03 because predecessor missions (orbital) may locate the "Ultimate Site"; '05 needs a rover to either: (A) explore and sample this "ultimate site" for sample return; (B) retrieve samples from '01 or '03 rovers, as a contingency, in case these rovers malfunction and can't negotiate the trek back to the sample return vehicle.

### Site Selection Rationale

Ideally, the landing site should be located where a suite of rocks and soils is readily accessible to the sampling vehicle. The rocks should be in place and have a wide range in age, lithology, composition, and mode of origin. One crucial requirement is that the samples be correlative with other major geologic units in the global time-stratigraphic system. Some of the materials should be associated with important volcano-tectonic episodes and magmatic histories, others with fluvial, aeolian, and periglacial processes that are indicators of climate and atmospheric history. Ultimately, the ideal site would also be in an area where evidence of extant or extinct biological activity would most likely be found. One caveat regarding the sampling of Martian crater ejecta deposits for stratigraphy should be noted: namely ejecta mixing and destruction of the systematic pattern seen on the Moon due to the Martian atmosphere. The present day atmosphere can cause this affect to occur (1) and a thicker earlier atmosphere would only accentuate this process.

**Uniform Geology or Compact Geology.** The two major competing strategies for selecting this landing site are: geologically uniform simple sites vs. geologically diverse complex sites. Simple sites contain regions with extensive, uniform surface materials that are a typical representation of a widely occurring type of terrain of clear global importance (Hr: Hesperian ridged plains material). Complex sites contain regions with compact geology, which is defined as regions with a wide variety of surface materials in terms of age and origins (Avf: Amazonian Valles Marineris floor material). The obvious advantage of a site with compact geology is the availability of a maximum variety of materials and ages. However, the geologic history of a complex site might prove to be very difficult to decipher.

*Without dates one can not get rates.* Simple sites have the advantage of containing terrain where unambiguous samples can be collected, returned to Earth, and radiometrically dated that relate directly to extensive regional / global geologic units with sufficient crater density so as to provide precise calibration of cratering ages. The critical unit to date will be Hesperian ridged plains material (Hr) because it is the basal rock-stratigraphic unit of the Hesperian System (2). This attribute of simple sites makes them very important for the correlation and calibration of Martian geologic episodes, processes, and rates of volcanism, channeling, and tectonism.

### Candidate Landing Sites

Site	Site Name	Location (lat; long)	Elev (km)	Rock Units
1	Terra Sirenum Highland Lowland Scarp	4°- 5° S; 145°-149° W	1 - 2	N ridged plateau: early crust, H intercrater plains: lava flows, AH Tharsis Montes Fm: lava flows, A lava flows, AH valley network fluvial deposits (deltas at Abus and Isara Vallis)

- 2 Memnonia Outflow Channel 11° S; 173° W 2 H ridged plains: lava flows, sediments?, A Medusae Fossae Fm: ash flow tuffs, ancient polar deposits, A outflow channel, hydrothermal?

#### Candidate Landing Sites

Site	Site Name	Location (lat; long)	Elev (km)	Rock Units
3	Maja Valles Fan Delta Complex	18° - 22° N; 53° - 56° W	0 - 1	N basement complex: early crust, N hilly plateau: early crust, H ridged plains, H deltas, flood plains, lacustrine sediments (Dixie, Northport crater, Chryse Planitia)
4	Xanthe Terra Highlands	10° - 15° N; 45 - 54° W	0-1	N hilly plateau: early crust, N lava flows, H ridged plains, NH valley networks
5	Lunae Planum	23.5° N; 59° W	2	H ridged plains with layering visible in walls of canyons
6	Olympica Fossae	23° N; 123° W	2 - 3	H Alba Pater Fm lava flows; A Olympus Mons Fm lava plains, channels originating at grabens: hydrothermal
7	Labeatis Fossae	24° - 27° N; 80° - 81° W	1 - 2	Sharp contact between H ridged plains, H Tharsis Fm lava flows, and A Tharsis Fm lava flows
8	Ganges Chasma	7° - 9° S; 47° - 52° W	0	NH wall material of canyon, H layered material 100's m thick on floor of Ganges: lacustrine deposits, volcanic ?, H Chasma channel materials, A alluvial deposits, landslides, mafic volcanic material, dune fields
9	Libya Montes	0° - 4° N; 270° - 280° W	0 - 2	N hilly plateau material interbedded lava flows, NH valley networks, A smooth plains: aeolian, fluvial ?
10	Arabia Terra	5° S - 25° N; 310° - 342° W	1 - 2	N ridged plains, plateau volcanic materials; H plateau material: fluvial, volcanic, aeolian, Schiaparelli basin floor deltaic deposits from Brazos Valles
11	Elysium	5° S - 10° N; 170° - 220° W	0-2	N crustal material, H plateau material, A fluvial (Marte Vallis) and lacustrine sediments, shorelines, hydrothermal channels (Athabasca Vallis) emanating from fissures

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**SW ISIDIS PLANITIA, MARS: VALLEY NETWORK SEDIMENTS, HIGHLAND ROCKS, AND INTERMEDIATE-AGE LAVAS.** L. S. Crumpler, New Mexico Museum of Natural History and Science, 1801 Mountain Rd NW, Albuquerque, NM 87104.

**INTRODUCTION.** Four basic themes identified repeatedly for the Mars Surveyor program of sample return are life, climate, crater count calibration, and resources [1]. Sample themes repeatedly discussed that address these four issues are sediments, ancient highland rocks, volcanic plains, and ices. Geological settings that will enable these types of sample to be collected include lake beds (and spring deposits,) valley networks, volcanic plains, and polar deposits. This study evaluates potential Mars Surveyor lander/rover sites on the southwestern western and southwestern margins of the Isidis impact that contain these three of these geologic settings (lake beds and spring deposits, valley networks, and volcanic plains).

The margins of the Isidis basin were selected for study because the Isidis basin has been a topographic sink for volatiles [3], runoff of an area of high drainage density [4], and possible subsurface flow and spring emergence [1]. In addition, there are many sites along the margins that both fit within engineering constraints and address realistic field science objectives of a Mars Surveyor program rover.

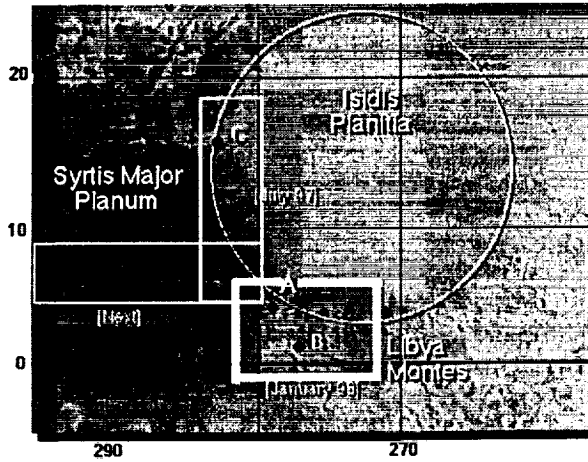
Two sites along the transition between Syrtis Major and Isidis Planitia have been discussed previously [2]. A secondary site along the western boundary has been discussed previously on the basis of theoretical arguments for spring discharge there [2]. In this discussion, I review direct observations in support of a third and prime site (3.4°N and 277.8°W) located at the terminus of a major valley network. The proposed site is of particular interest because it lies at the geologic junction between the intermediate-age lavas of Syrtis Major Planum, the valley networks of Libya Montes, and the late basin-fill materials of Isidis Planitia [Figure 1]. Geologic opportunities at this site include a thick

stratigraphic section of sediments, macroscopic exposures of sedimentary features, altered highland materials, and potential fragments of intermediate age lavas derived from Syrtis Major. The site is chosen such that these goals are attainable with a simple geotraverse between 15 and 25 km over terrain with relatively benign slopes.

**MAP DISCUSSION.** The areas of interest have been geologically mapped digitally at scales up to 1:300K, using specially mosaicked and digitally enhanced Viking EDRs [Figure 2]. Spectral data [5] were also considered. Eight units are mapped and span ages from middle Noachian to late Hesperian-early Amazonian: Nm, ancient highland massifs interpreted to be heavily eroded Isidis basin ejecta; Nf, fluviially dissected foothills and lower slopes of massifs and rolling inter-montane plains; Hi, intermontane and crater-interior plains interpreted as sediments; Hd, plains bearing high density valley networks with meandering characteristics; Hv, Syrtis Major lava flows, Hk, knobby, Isidis-marginal plains; and Hr, plains with ridges and aligned-mounds of the Isidis basin interior.

**THE LANDING SITE.** The proposed site lies in the terminal fan of a large valley network (Fig.3). The terminal valley networks deposits here are locally cut by a small valley enabling direct access to sediments; a geotraverse from this valley to the east would move up a possible stratigraphic succession of terminal deposits over 15 km. Highland rocks, many probably weathered and altered, occur in adjacent hills and may be accessible. The nearby impact crater *Syrtis Ee* is the largest and youngest in the area and is located on the margins of the Syrtis lava flow. Dispersed samples of these intermediate-age lavas may randomly litter the surface and be available for sampling and analysis.

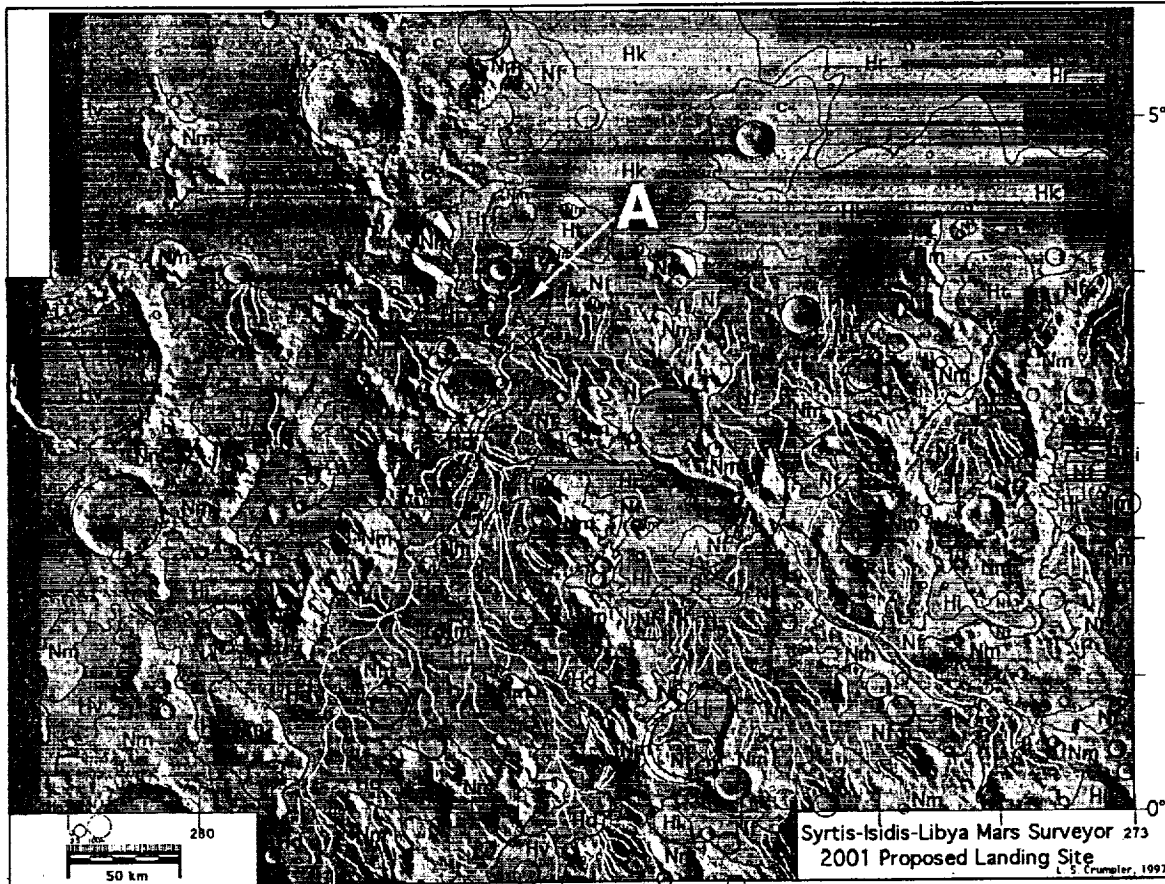
**REFERENCES.**[1] Mars 2005 Sample Return Workshop, LPI Tech Report 97-01; [2] Crumpler, 1997, *LPSC XXVIII*, 231; [3] Grizzaffi and Schultz, 1989, *Icarus* 77, 358-381; Meyer and Grolier, 1977, *U. S. Geol. Survey Misc. Invest. Series Map I-995*:[4]



**Figure 1.** Regional image showing area of study. Three sites are proposed as part of this work, all on the western margin of Isidis. Sites A and B are discussed in this report.



**Figure 3.** High resolution view of proposed site showing a traverse route across fluvial sediments at the terminus of a large valley network. Lines highlight morphologic features. Merged Viking EDRs 377s77 & 78.



**Figure 2.** Geologic map prepared on digital mosaic base showing the regional setting of the proposed Mars Surveyor landing site (A). Site is located at the terminus of a significant valley network draining the highland massifs on the southwestern margin of the Isidis basin. In addition to the fluvially-laid sediments deposited at the terminus of this valley network, a large impact crater (northwest map) could have distributed intermediate-age lavas of Syrtis Major across the proposed landing site.



**CONSIDERATIONS FOR SELECTING THE 2001 MARS LANDING SITE.** Robert A. Craddock<sup>1,2</sup>, Ted A. Maxwell<sup>1</sup>, Alan D. Howard<sup>2</sup>, and Olena A. Krawciw<sup>1</sup>, <sup>1</sup>Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560 (craddock@ceps.nasm.edu), <sup>2</sup>Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia 22903

It's somewhat ironic that the site of the first sample return from Mars may be in the martian highlands. Although these materials represent over 65% of the surface area of Mars [1], in comparison to features such as the Tharsis volcanoes, outflow channels, or Valles Marineris relatively little research effort has been devoted to the highlands. Because the highlands are extremely old, they have been subjected to most of the geologic processes that have occurred on Mars through time, so geologically they are extremely complicated. On the other hand, they are so vast that it's difficult to identify very many traverses 10 km long that will have access to more than one geologic unit. Although the impetus for exploring the highlands comes from the putative evidence of nanofossils in the ALH 84001 meteorite [2], which is thought to have come from the cratered highlands [3], many scientists still cling to the idea that the early martian climate was cold and dry. If this hypothesis is true, then the surface of the highlands might be one of the worst places to look for evidence of life. However, there are several key geologic settings that could assure we get as diverse a sampling as possible, settle the long-standing debate about the nature of the early martian climate, and increase our chances at finding evidence of extinct or extant life. The landing should occur in an area that is (1) as dust-free as possible (i.e., high thermal inertia), (2) as low an elevation as possible, (3) within traversing distance of (Hesperian) ridged plains materials, and (4) near both an ancient valley network and a degraded impact crater. When these criteria are taken into account along with the engineering constraints imposed on the lander, the latitudinal bin with the most viable landing sites occurs from the 0° to 15°S latitude, primarily within the Mare Tyrrhenum (MC-22) and Margaritifer Sinus (MC-19) quadrangles.

**High Thermal Inertia (Dust-free) Considerations.** Fresh crater populations indicate that many of the features that characterize the martian highlands, such as ancient valley networks [e.g., 4] and degraded impact craters [5], date back to between the early Noachian (~4.4 Gy) to early Hesperian (~3.5 Gy). These features are usually present in most of the geologic units that have been identified in the highlands at the 1:15M scale [6, 7]. However, a majority of the units mapped in the martian highlands also contain materials that probably post-date the formation of the ancient valley networks or crater degradation. Late-stage flood volcanism, (Nplr) for example, may have covered some of the intercrater regions [6, 7, 8]. The most ubiquitous materials within the latitudinal constraints of the 2001 lander (30°N to 15°S), however, are aeolian deposits (e.g., Nple). Based on thermal, radar, and visual remote sensing observations [9, 10], the Arabia (MC-12) Memnonia (MC-16), and Aeolis (MC-23) quadrangles will be especially problematic and may contain 0.1-2 m of dust [9]. Obviously, such extensive deposits will make sample collection and interpreting the surface geology extremely difficult, and these areas should be avoided. Areas of higher thermal inertia are probably dust-free [9], and they may contain bedrock exposures or large rock populations, which would be ideal sites for exploration.

**Low Elevation Considerations.** Although the 2001 lander will be capable of landing up to 2.5 km above Mars datum, the lower the elevation at the landing site, the more atmosphere the spacecraft will pass through and the more efficiently the parachutes will work. Thus, it is an engineering benefit to have as low a landing site as possible. In addition, analyses of superposed fresh crater populations located in highland material between ±30° latitude suggest that crater degradation ceased at higher elevations (e.g., 3-4 km, middle Noachian) before it did at lower elevations (e.g., 1-2 km, early Hesperian) [5]. This observation is consistent with the cessation of fluvial activity due to desiccation of a volatile reservoir with time or with decreasing martian atmospheric pressures that caused cloud condensation--and thus precipitation--to occur at progressively lower elevations with time. This age-elevation relationship is also seen in age dates of the ancient valley networks [4]. These observations suggest that fluvial processes were active later and longer in martian history at lower elevations. The implication is that our chances of finding evidence of life should be better at lower elevations.

**Hesperian Ridged Plains Considerations.** Dendritic ancient valley networks in the equatorial highlands show evidence of drainage into smooth, intracrater basins. Such areas have been interpreted as containing sedimentary deposits [11]. In many instances, comparisons of the fresh impact crater populations contained in these basins with those in the surrounding degraded highlands concur with this interpretation [8]. These analyses indicate that extensive sedimentary deposits may have resulted from highland degradation, implying that materials eroded from impact craters were transported great distances (tens of kilometers), which requires overland flow of water. (It also implies that the ancient valley networks are the

result of surface runoff and not sapping alone.) Many potential depositional basins, however, have also been interpreted as volcanic plains [6, 7, 8]. Although age dates based on total crater populations suggest these materials are Noachian in age [6, 7], fresh crater age dates suggest that resurfacing and/or the final period of deposition ended by the Hesperian [8, 12], which is contemporaneous with the widespread volcanic resurfacing event that occurred during this period in martian history [12]. If volcanic, a sample of Hesperian ridged plains materials from the highlands would be critical for deconvolving the absolute age dates of the martian periods [13]. A traverse to the edge of this material could also allow us to obtain samples of highland rock. If the ridged plains materials are sedimentary deposits, then they represent ideal locations for obtaining a "grab bag" selection of rocks (similar to the Mars Pathfinder landing site [14]). Whether these materials are the result of sediment transport or flood volcanism, landing in or around ridged plains materials increases our chance of obtaining as diverse a sampling as possible.

**Ancient Valley Networks/Degraded Craters Considerations.** Both ancient valley networks [e.g., 15] and degraded impact craters [5, 16] record a period in martian history where both geologic and probably climatic conditions were much different than the present. Recent photoclinometric analyses of craters in the Sinus Sabaeus and Margaritifer Sinus regions [16] and two dimensional computer simulations of a variety of erosional processes indicate that a combination of diffusional creep and fluvial erosion and deposition is capable of describing the observed degraded crater morphology. However, extensive seepage and backwasting are also needed to explain the enlargement in crater diameter (up to 30%) observed at the terminal stage of degradation. These results argue that early Mars experienced wide-spread precipitation, fluvial processes, and near surface groundwater flow. Although the formation mechanism(s) for the ancient valley networks is a contentious issue (i.e., sapping versus surface runoff), inarguably they required that some water be released to the surface in order for erosion to occur. Even if MGS data are not able to identify carbonate deposits or evidence of a potential hot spring, both ancient valley networks and degraded impact craters required that some liquid water be present during their formation. An unmodified ancient valley network, in particular, should be in any candidate landing in order to search for evidence of life.

**Potential Sites in Mare Tyrrhenum and Margaritifer Sinus.** Although a large number of sites are available that meet the engineering constraints of this mission and satisfy the scientific arguments presented above, the Mare Tyrrhenum and Margaritifer Sinus quadrangles, in particular, contain many suitable locations. Examples of potential landing sites are presented in Table 1. Perhaps some of these locations will be considered as candidate sites for the 2001 or 2003 missions. In general, however, the optimal working latitudinal for designing the thermal protection on the 2001 lander is between 0° to 15° south latitude.

Table 1. Potential landing sites in Mare Tyrrhenum and Margaritifer Sinus.

Latitude	Longitude	Elevation	Viking Frame No.	Geologic Units
-6.4	253.3	~2.5 km	379S43	Npld/Hr
-2.2	255.0	~2.0 km	379S42	Npld/Hr
-10.0	245.0	~3.0 km	629A01	Npld/Hr
-4.0	242.0	~2.5 km	381S61	Npld/Hr
-1.5	8.5	~0.5 km	367A27	Npld/Npl2/Hr

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From a scientific viewpoint there are a multitude of fundamental questions regarding the evolution of Mars which warrant serious consideration for guiding future lander and sample return missions. For brevity's sake one can group scientific objectives into three broad categories. First there are many assumptions and inferences regarding the last 20 years of geologic mapping on Mars which need to be verified at the earliest possible opportunity. Validation of lithostratigraphic work is essential for future mission planning and should be a primary component of any sample return mission. Second, the evidence for water on the Martian surface in the past is unequivocal, but has yet to be placed in its proper hydrologic setting. While hypotheses regarding the ancient Martian hydrosphere are numerous, all remain highly speculative in nature. A lander site should be chosen which has a high prospect of advancing our knowledge of the ancient Martian hydrosphere. The third issue is the possibility for life, or past life, on Mars. This issue, no matter how tenuous or speculative it is believed to be, is of such fundamental concern to humanity that it must, despite the odds, be given serious consideration.

The 6 potential lander sites listed below contain scientific components that provide opportunities for advances on all three of the objectives above. The first 3 were selected on the basis of providing the highest probability of a successful return of samples which will yield the most knowledge on the ancient Martian hydrosphere, and yet still provide information fundamental to verification of lithostratigraphic models, and a reasonable opportunity for exobiologic investigations. All six sites are Noachian-early Hesperian(?) drainage basins where evidence is available to support the past presence of water having collected and evaporated/sublimated back to the Martian atmosphere. The six are grouped into two categories. The first category are basins with a high prospect for exposures of chemical sediment that accumulated by the evaporation and/or cooling of surface or near surface ground waters. These are grouped together because each provides an opportunity to collect and return chemical and/or biological deposits which can provide direct evidence of Mars' ancient hydrosphere and atmosphere. Mineralogy and geochemistry of these deposits (e.g. the stable isotopic composition of minerals and fluid inclusions) should provide hard evidence on the ancient Martian hydrosphere and atmosphere.

**Group 1. Potential Evaporite deposit sites:**

Site 1. 'White Rock' Crater Basin,

Sinus Sabaeus NE  
335 Long., -8 Lat.  
Elevation: basin floor less than 2500 m  
Geology: evaporite basin in old regolith with "White Rock", an inselberg of potential evaporite or carbonate sedimentary rock

Site 2. Becquerel Crater Basin,

Oxia Palus, NE  
7 Long., 22 Lat.  
Elevation: 0 - 1000 m  
Geology: another potential evaporite basin with another not so white 'White Rock' inselberg, of a potential evaporite deposit

Site 3. Crommelin Crater Basin,

Oxia Palus, SE  
10 Long., 5 Lat.  
Elevation: 0- 1000 m  
Geology: concentrically zoned facies of basin infill deposits, possible salts.

Lander investigations (with the potential for sample return) of these three Noachian drainage basins provide a reasonable probability for discovery of chemical and biological sediments.

Lake, playa, salina, and sabkha depositional environments are all possible to have existed in the early history of Mars; a period for which evidence leads many to believe that water flowed and ponded on the Martian surface under a warmer and wetter climatic regime. Given the prospects for these environments to have been analogous to the Earth's arid and hyperarid regions, low lying basins would have been relatively poor in clastic inputs, and have had a dominance of chemical (and/or biological) deposits. On earth these basins have carbonate, siliceous, or iron mineral accumulations (in dilute lakes), and carbonate, evaporite, and silicate (e.g. zeolites where volcanic glass falls into alkaline lakes) minerals in more saline environments. Because of the systematic chemical hydrogeology of such closed drainage basins, deposition or post-depositional precipitation of chemical sediment (or cement) is usually along one of several distinct paths. Invariably, saline minerals form after deposition of Ca and Mg carbonates. Sulfates (typically gypsum) are the mineral group to most commonly follow carbonate deposition, but only if alkaline earth elements have been depleted by carbonate deposition. Chloride-rich deposits are typically the last to form. Precipitation can occur from lake brines under going both cooling, and evaporation, and commonly have an episodic history leading to some manner of rhythmic bedding. It can also occur within subsurface environments as capillary forces allow evaporation to several meters of depth. Internal cementation within these dry basins (playas or salinas) will typically lead to a more massive and disruptive bedding structure. Each of the three sites above has attributes which are consistent with the evaporite basin model, and have prospects for accessible exposures of chemical deposits for sample return.

The other three sites are also ancient closed drainage basins which collected surface and ground waters and must have also been sites of evaporation/sublimation of water back to the atmosphere. However these sites do not have any direct evidence for exposures of chemical deposits like the first group. What makes this group appealing is that each has opportunities to address other fundamental lithostratigraphic problems. Site 4, for example provides the opportunity to sample basin deposits formed in part under a fluvial regime, but also to sample regolith of the southern Highlands, and that of the Medusae Fossae Formation. It, and Site 5, are both located along the 'dichotomy' boundary, and thus provide an opportunity to collect materials of dramatically different geologic origins and perhaps age. Site 6 is a site at the southern limits of the landers' proposed latitudinal range (~30°S) and is also of a closed drainage basin. What is

most interesting about this crater basin site is that it provides an opportunity to sample deposits from three temporally discrete periods of basin infilling, as well as investigate up to 2 kilometers of layered Highland 'regolith' stratigraphy that appears to be exposed along the southern crater rim and inflowing stream channel.

**Group 2. Closed Drainage Basin sites in the Memnonia and Aeolis Regions with significant other lithostratigraphic opportunities**

Site 4. Labou Vallis, Memnonia NE

156 Long., -7.5 Lat.

Elevation: ~2500 m

Geology: mouth of outflow channel, potential exposure of Medusae Fossae Fm. Noachian crust,

Site 5. Medusae Fossae area, Memnonia, NW

159.5 Long., -9 Lat.

Elevation: 1000-2000 m

Geology: fluvial/alluvial/eolian basin deposits on edge between Noachian highlands and Medusae Fossae Fm., fault scarp uplifts basin fill, small channels dissect marginal highland crater walls

Site 6. unnamed basin, Aeolis, NW

217.5 Long., -14 Lat.

Elevation: probably 2000-2500 m

Geology; exposed alluvial basin fill strata, side canyon of possible layered regolith.



Figure 1. Viking photo mosaics of 6 sites in close Noachian to early Hesperian drainage basins which offer excellent science opportunities for future lander missions to Mars.

**A REASON TO LAND IN THE DARK.** W. M. Calvin, U. S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001, wcalvin@flagmail.wr.usgs.gov.

In spite of many years of both remote and in-situ observations, we still know very little about the actual surface mineralogy of Mars. The current presumption from the spectroscopic community is that bright regions represent altered (i.e. oxidized) materials and that dark regions must be relatively unaltered volcanic material such as pyroxene. A number of recent observations, both of the geology and spectroscopy of dark regions suggest that the picture is not nearly so simple. Evidence which counters these previous assumptions includes the lack of pyroxene absorptions in the dark material at the Pathfinder landing site and remote observations which suggest the most hydrated regions appear to be low or moderately low albedo areas [1,2].

Here I examine the potential for ferrous clays, a spectrally distinct class of minerals, to be consistent with the visible, near-infrared and thermal infrared spectra of Mars, the geology and past presence of water, and their tantalizing association with organic materials and biotic precursors which suggest that some dark regions may be the best sites for exobiological exploration. Within the landing constraints for the 2001 mission, the best exobiological sites consistent with the ferrous clay model are in Margaritifer and Meridiani Terra.

### **Spectral Properties**

Ferrous clays are black or dark green in color and the visible and near-infrared spectra are dominated by a broad  $\text{Fe}^{2+}$  absorption which extends from 0.6 to at least 2  $\mu\text{m}$  or beyond [3]. These minerals are unique in that they lack absorption features at 1.4 and 1.9  $\mu\text{m}$ , associated with OH overtones and common to all other clay mineral spectra that I know of. These clays also typically lack absorptions in the 2.2 to 2.5  $\mu\text{m}$  region associated with metal-OH vibrations, unless they have a large amount of Al in the structure [3]. We measured one sample with a weak Fe-OH feature near 2.3  $\mu\text{m}$ . All measured samples have the 3- $\mu\text{m}$  absorption associated with water of hydration though the shape and depth of this feature varies substantially between samples.

In the thermal infrared (5 to 25  $\mu\text{m}$ ) our ground samples exhibit very little spectral contrast. However, most samples exhibit a 10% feature that should appear in emission as an absorption between 5 and 8  $\mu\text{m}$  (2000 and 1250  $\text{cm}^{-1}$ ). Given the number of weak atmospheric features on Mars in this region [e.g. 4] these clays may be difficult to identify in data from the Mars Global

Surveyor Thermal Emission Spectrometer (MGS-TES). The advantage is that these clays have no obvious spectral features that are inconsistent with previous thermal infrared observations.

I have recently shown [5] a spectral model for the visible and near-infrared spectrum that is consistent with abundant ferrous clays in some dark regions on Mars. It should be noted that this model does not eliminate the presence of pyroxene nor is it expected that a single mineralogical and spectral model will be valid everywhere on the surface. In particular, dark regions such as Syrtis Major, are not consistent with the ferrous clay model.

### **Geological Associations**

In developing the ferrous clay spectral model, I noted the strong correlation between martian drainage densities mapped by Carr and Chuang [6] and the low-latitude, low-albedo zone that circles the planet. In earlier work, Pieri [7] also found a nearly direct correlation between the sub-equatorial low albedo belt and small channels observed in Mariner 9 images. Much of the dark low-latitude belt is heavily cratered suggesting that it is quite old.

The ferrous clay model is consistent with dark regions that may be ancient lakes or sub-aqueous sedimentary deposits [8,9]. In this case it would suggest that minerals formed early in the history of the planet are preserved on the surface. On Earth, ferrous clay minerals such as greenalite, chamosite and berthierine are commonly found as sedimentary deposits in Precambrian banded iron formations (BIF). In BIF, these minerals are often found alternating with magnetite, siderite or pyrite and are formed in shallow marine basins where their stability and occurrence was presumably aided by the high proportion of  $\text{CO}_2$  in the early terrestrial atmosphere and a lack of available oxygen in the depositional environment [10,11]. Other terrestrial marine environments include precipitation in association with a calcitized volcanic ash [12], and off shore from major river discharge areas where the dissolved iron load is high [13].

It should be noted that these minerals need not be formed in a sub-aqueous environment. These high-iron clays also occur as low temperature hydrothermal alteration of an ultra-mafic dyke [14], diagenetic cementing agents in Appalachian red beds [15], and in volcanogenic massive sulfide deposits [16]. These minerals can either form directly with hematite or undergo subse-

quent weathering to hematite and are also associated with detrital carbon. They are common low-temperature aqueous alteration products in carbonaceous chondrites [17]. In these cases the spectra would be consistent with inferred exobiology sites on Mars through the common requirement for the presence of water both for potential life and for the formation of these serpentines.

### Biological Associations

The role of microbial organisms in the precipitation of ferrous clays is not clearly established. Particularly for BIFs significant controversy seems to exist regarding the role and extent of biomineralization in the earliest formations. However, it has been argued that carbon isotope information in Archean iron formations indicate autotrophy and that the sulfur isotopes suggest dissimilatory sulfate reduction, though abiotic mechanisms are also plausible [11].

The occurrence of ferrous clays in carbonaceous chondrites is also of interest as these meteorites contain amino acids and polycyclic aromatic hydrocarbons, abiotic building blocks for life. It is possible that ferrous clays reflect early chemical processes that may have led to eventual biotic evolution, though this is purely speculative at this point. At the very least their association with the era when life emerged on Earth and their occurrence with organic materials in primitive meteorites make them interesting target areas for exploration should they be confirmed on Mars.

### Implications for 2001

The ferrous clay model has not yet been confirmed through observation of unique spectral properties. At this point I intend only to provide an alternative to the Yellowstone "hydrothermal" model of where to look for life on Mars. It is quite likely that the best exobiological sites will be noted by their low albedos, whether in regard to hydrous ferrous silicate precipitation or through the presence of Fe-sulfides as at "black smokers" at the terrestrial sea floor. Within the elevation and latitude constraints placed on the '01 mission, the dark areas which exhibit the most channels and evidence of former water lie in the Margaritifer and Meridiani regions.

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**STUDIES OF POTENTIAL MARS SURVEYOR 1998 LANDING SITES.** K. E. Herkenhoff, Jet Propulsion Laboratory, California Institute of Technology (Mail Stop 183-501, 4800 Oak Grove Drive, Pasadena, California 91109; Ken.Herkenhoff@jpl.nasa.gov).

**Introduction:**

The 1998 lander payload consists of a descent imager, the Mars Volatiles and Climate Surveyor (MVACS) instruments (lander stereo camera, arm-mounted close-up imager, meteorology package, thermal and evolved gas analyzer), and a LIDAR instrument. The mission focuses on assessment of near-surface water ice in the south polar region, and the volatile and climate history of Mars. In order to achieve these objectives, the landing site must allow access to polar layered deposits by the robotic arm, which may be able to dig as much as 0.5 m below the surface. Hence, the presence of recent aeolian debris at the landing site may adversely affect the ability of the MVACS instruments to gather the samples and acquire data needed to properly address the science objectives. The studies described here include mapping surface units in the landing region (73°S - 77°S, 140°W - 230°W) to infer the distribution of aeolian debris and to identify potential landing sites where mantling is minimal. Because the '98 lander will not be able to survive very low temperature conditions, this study also includes mapping of south polar seasonal frost retreat based on Viking Orbiter images. The results of this work, in conjunction with complementary studies by other investigators, will facilitate the selection of the Mars Surveyor 1998 landing site (and backup) by the summer of 1998.

It is widely believed that the Martian polar layered deposits record climate variations over at least the last 10 to 100 million years [1-9], but the details of the processes involved and their relative roles in layer formation and evolution remain obscure [10]. Variations in axial obliquity and orbital eccentricity are thought to influence the climates of both Earth and Mars, but are of greater amplitude in the Martian case [11-13]. The Earth's hydrosphere and biosphere do not have a current counterpart on Mars, so that it should be simpler to determine the causes and history of climate changes on Mars. Analysis of Martian climate history will enhance our understanding of climate change in general, and therefore may contribute to the understanding of Earth's complex climate system. Knowledge of the geology of the Martian polar deposits is essential in deducing the processes responsible for their formation and erosion, and the mechanisms by which climatic variations are preserved. A common presumption among Mars researchers is that the layered deposits are the result of variations in the

proportions of dust and water ice deposited over many climate cycles [4-6], but their composition is poorly constrained [14].

**Surface age:**

Using medium-resolution Viking imagery, Plaut *et al.* [9] found several craters in the southern layered deposits. Their counting of craters down to the size barely resolved in the best Viking images indicates that some areas of the layered deposits are at least 120 million years old. The observed crater size-frequency distribution is consistent with low sedimentation or erosion rates over many of the quasi-periodic orbital/axial variations that are theoretically responsible for the layering in the polar deposits. In contrast, Cutts *et al.* [3] found no craters larger than about 300 meters in summertime images of the north polar layered deposits, which indicates much higher resurfacing rates. Neither have any likely impact craters been found on the north polar layered deposits in excellent springtime images [15]. This result confirms the paradoxical difference in surface ages between the north and south polar layered deposits, and suggests that the inferences of geologic evolution of the north polar layered deposits may not necessarily apply to the south polar deposits. Further study of the south polar layered deposits is therefore required to properly select a landing site for the Mars Surveyor 1998 lander and interpret observations made at the site.

**Color and albedo:**

Herkenhoff and Murray [16] identified and mapped five surface units in the vicinity of the south polar residual cap based upon their color (red/violet ratio) and albedo, as deduced from a color mosaic of Viking Orbiter 2 images. A similar technique has been used in conjunction with Mariner 9 images to map the geology of three 1:500,000 scale quadrangles: MTM -90000 [17], MTM -85080 [18], and MTM -85280 [19]. In some areas, changes in the extent of albedo features have been observed between the Mariner 9 and Viking missions, and even during the Viking mission. Much of the layered deposits and surrounding terrains appear to be mantled by bright dust, presumably deposited from atmospheric suspension. The dust mantle has been removed from some areas, exposing the darker, less red layered deposits.

Some areas adjacent to the residual frost cap are brighter and less red than the layered deposits,

indicating that frost is present below the limit of resolution of the images. Comparison of Mariner 9 imaging and IRIS data suggests that CO<sub>2</sub> frost was present in these areas, cooling the surface below its radiative equilibrium temperature [20]. In some areas, the presence of frost late into the southern summer appears to stabilize dust deposits, resulting in net deposition.

#### **Topography:**

By combining stereophotogrammetry and a new photoclinometric technique, Herkenhoff and Murray [21] showed that the layered appearance of an exposure of the south polar deposits is due mainly to "staircase" topography rather than albedo variations. It was possible to determine both topographic and albedo variations along photoclinometric profiles using two images of the same area that were taken with different illumination directions. This photoclinometric technique is useful in the (common) case where surface albedo is variable. The results of this study, using Mariner 9 images with resolution as good as 80 meters/pixel, show that slopes between layers range up to 20°.

#### **MOC observations:**

Recent images of the south polar layered terrain with resolutions of 15-30 meters/pixel acquired by the MGS MOC show that exposures of layered deposits are considerably rougher than expected in the vicinity of the residual cap. Observations of the preferred landing area for the 1998 lander appear to be blurred by atmospheric haze, so MOC images outside of the landing area will be used to evaluate topographic slope variations in the south polar layered deposits. These images also show dark spots on the layered deposits that are 1 km or smaller in diameter. In places, these spots merge into what appears to be a resistant unit within the layered deposits that has undergone significant erosion. The dark spots are probably not duneforms, as they are mostly circular in plan, variable in size, and are arranged in linear and sinuous patterns. However, they may represent the source material of the dark dunes that are found in both polar regions. Preliminary studies of these features indicate that they form a rather rough surface, perhaps hazardous to the 1998 lander. Analysis of these new MOC images as well as Mariner 9 and Viking Orbiter images of the south polar region continues, and will result in recommendations to the Mars Surveyor 1998 project regarding landing site selection.

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**DA VINCI CRATER: POTENTIAL LANDING SITE FOR THE MARS 2001 MISSION.** *D.M. Nelson<sup>1</sup>, R. Greeley<sup>1</sup>, H.P. Klein<sup>2</sup>*. 1. Dept. of Geology, Arizona State University, Box 871404, Tempe, AZ 85282-1404. E-mail: nelson@dione.la.asu.edu. 2. SETI Institute, 2035 Landings Dr., Mountain View, CA, 94043.

Da Vinci, a large crater in Xanthe Terra which indicates fluvial modification and is a potential exobiology site, is proposed as a possible landing site for the Mars 2001 mission. Da Vinci is ~90 km diameter and located on the west margin of Hydraotes Chaos, at 2°N, 39°W; the floor is +1 km planetary datum (Figure 1). Associated fluvial features in conjunction with its proximity to Hydraotes Chaos suggest that this crater was subject to one or more high energy floods. Being an enclosed system, and having the potential for containing standing water, Da Vinci could have sustained an environment capable of supporting life. Additionally, if biotic communities were present in the aquifer below Hydraotes, and, with its disruption the organisms were brought to the surface, exobiology indicators from this source could be located in Da Vinci.

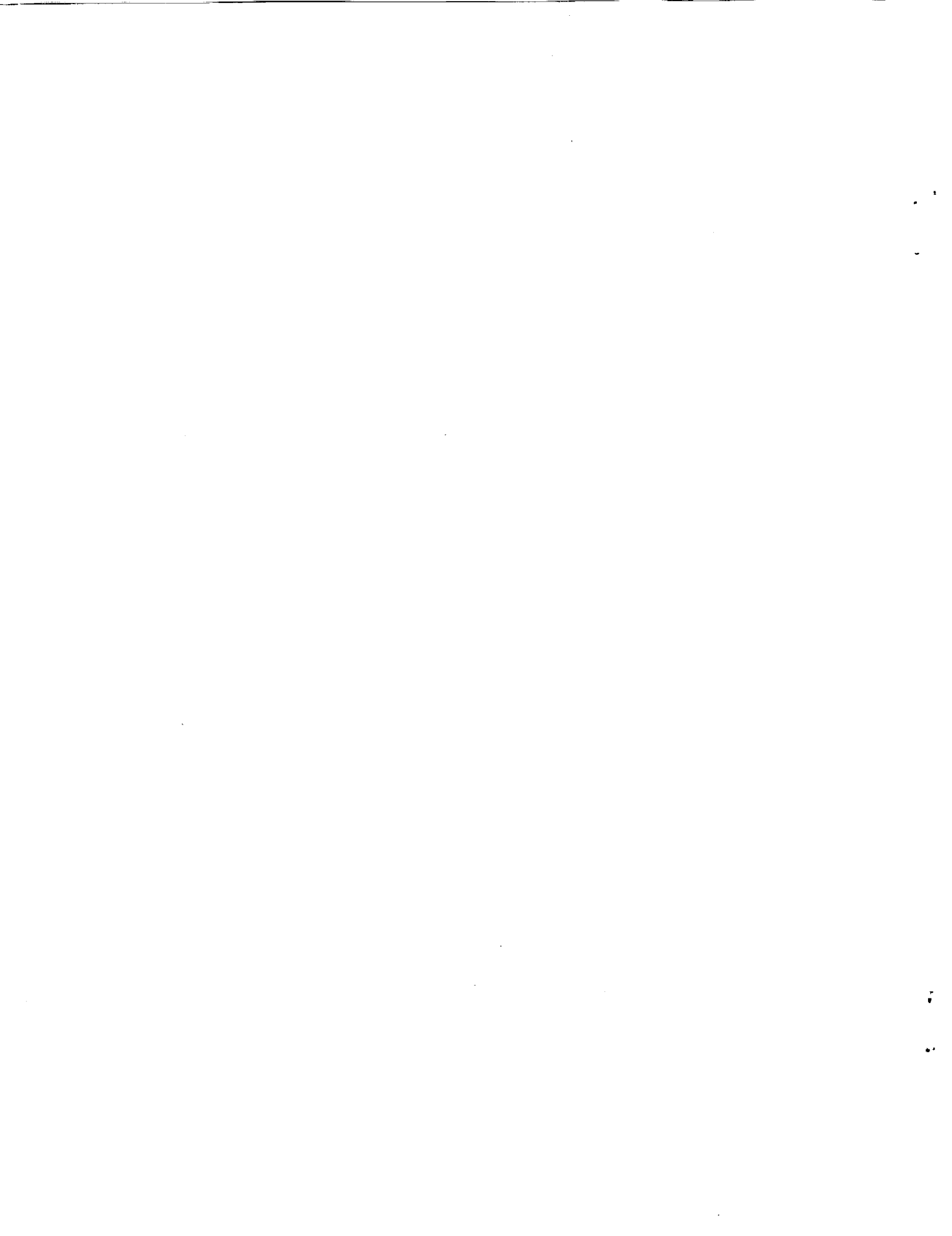
The crater is situated on smooth plateau material (Hpls) [1], interpreted to be brecciated volcanic materials (likely Noachian [2]) later modified (in the Hesperian) by fluvial processes. Evidence for volcanism are north-south trending mare-like wrinkle ridges in the plains to the north as well as subdued ridges within the crater. The southeastern and northern rims of the crater have been breached by flows discharging from Hydraotes Chaos, passing north through the crater and forming a narrow channel ~120 long in the Xanthe Terra plain north of Da Vinci. Because the southern breach adjacent to Hydraotes is ~10 km wide, this might have allowed standing water to drain quickly. Therefore, the duration of a prolonged lacustrine environment is

uncertain. The floor of the crater is smooth except for a ~12 km diameter superposed crater. The crater ejecta is lobate, suggesting that the ground likely contained water (liquid or ice) at the time of impact.

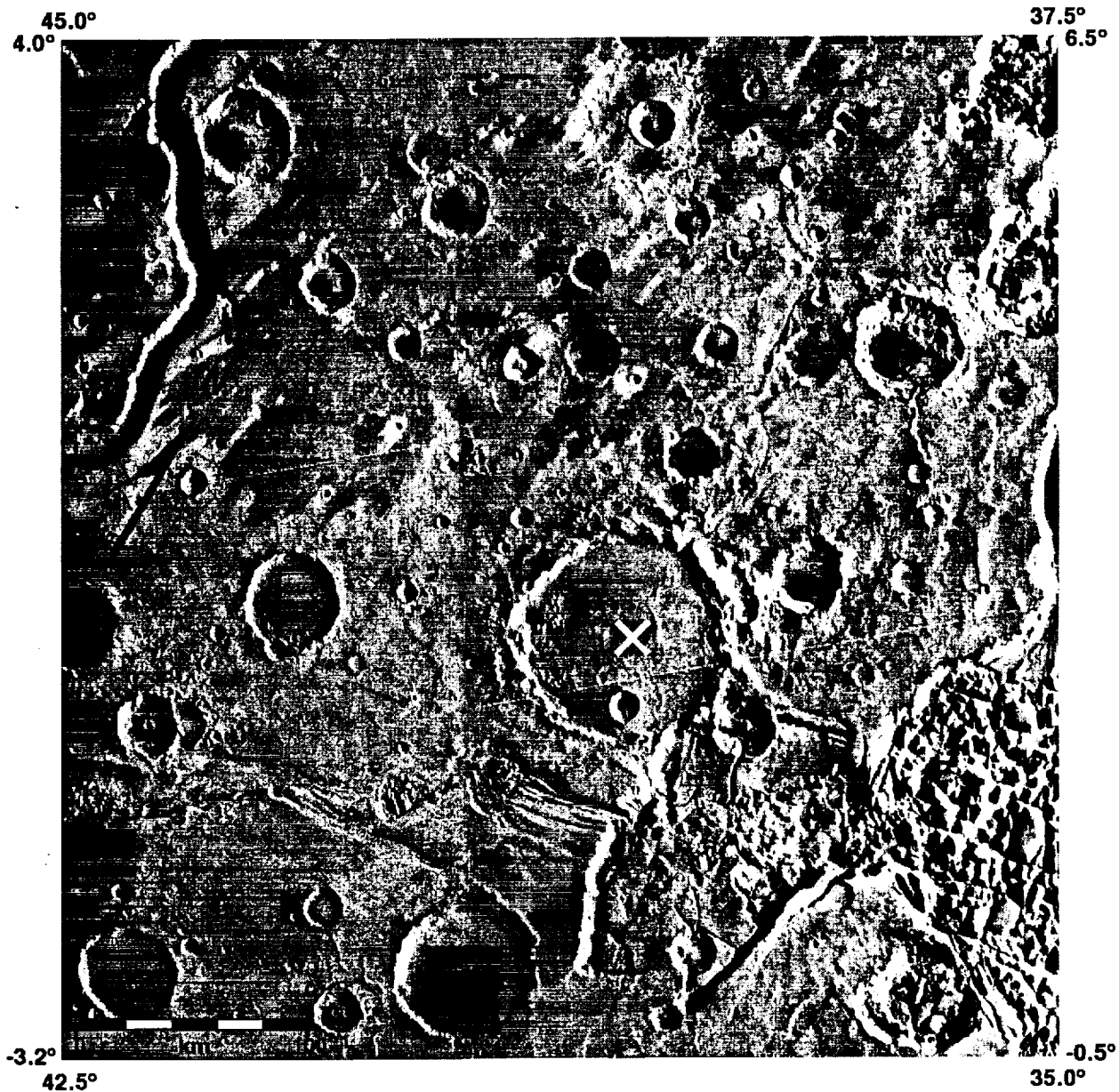
The exobiology potential for this crater was examined, based on methods outlined by *Farmer et al.* [3]. In a stable environment, life requires water, heat, and organic minerals. Although there is evidence for the former presence of water in Da Vinci, a stable environment is less certain. If standing water (akin to ponds and/or tide pools) endured in these areas, biotic communities could have developed.

Materials within Da Vinci crater could provide an interesting suite of rocks to be examined by the 2001 rover. The crater which impacted inside Da Vinci, penetrated through the upper rock layers and overturned materials, redistributing them over the surface. Sampled brecciated material would include the upper-most fluvial sediments, possibly containing exobiologic materials, uncovered volcanic materials, and possibly basement rock.

In summary, Da Vinci crater is a proposed site for the Mars 2001 mission, which provides the potential for sampling multiple geologic units, including volcanic and fluvial materials which have been brecciated and distributed over the surface by impact cratering. In addition, the proximity to Hydraotes Chaos, a zone of potential exobiology, as well as the possibility of Da Vinci being a former lacustrine environment, also makes this site a viable candidate for exobiology.

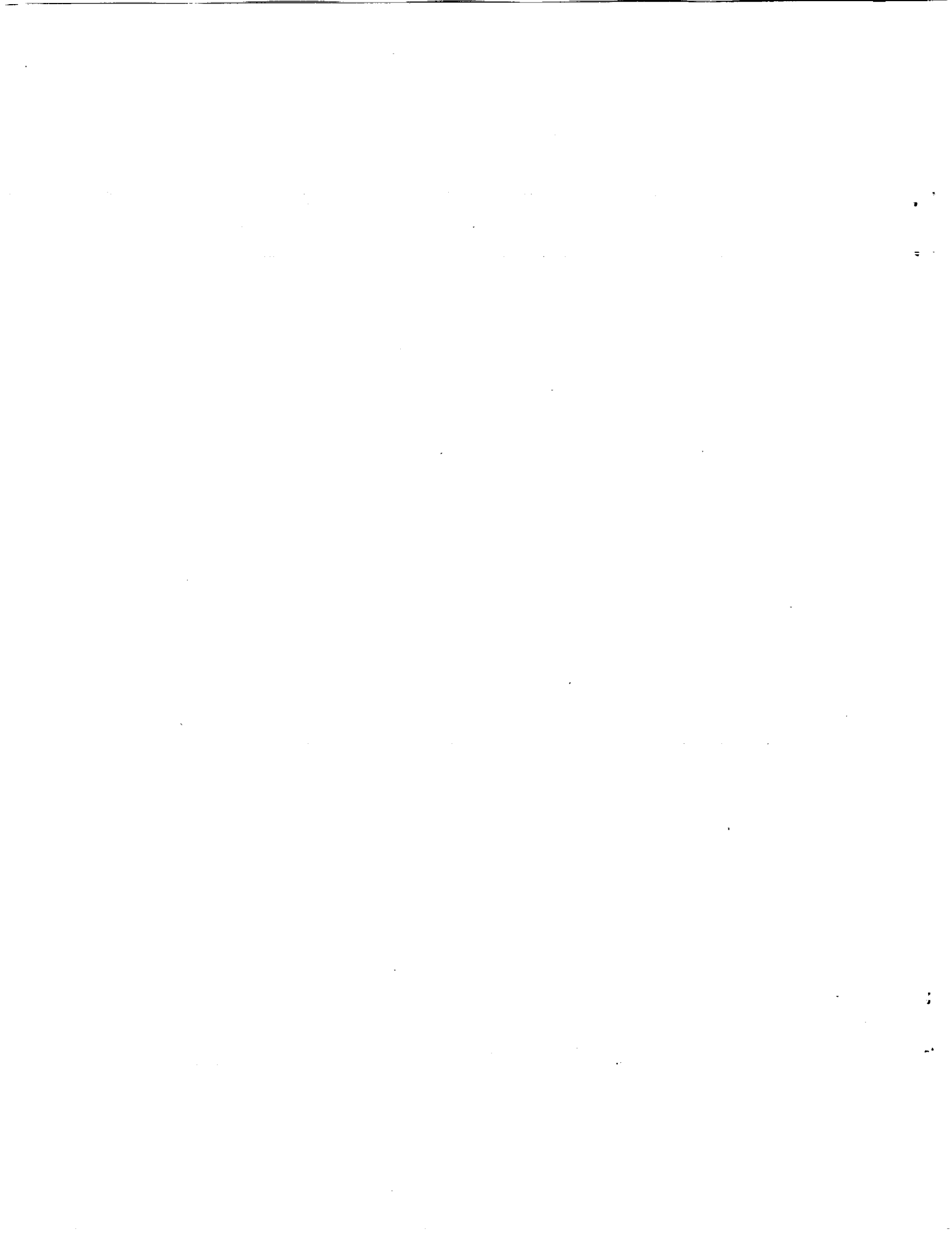


DA VINCI CRATER. *D.M. Nelson, R. Greeley, H.P. Klein.*



**Figure 1.** Da Vinci crater ( $2^{\circ}\text{N}$ ,  $39^{\circ}\text{W}$ , at +1 km) is located in Xanthe Terra, adjacent to Hydraotes Chaos (lower right) and Ravi Vallis (lower left). A breach in the northern rim allowed flow to continue over ridged plains (which are presumed volcanic). Potential landing site is indicated by cross-hairs.

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**GALILAEI CRATER AS A POSSIBLE LANDING SITE FOR THE MARS 2001 MISSION.** *D.M. Nelson<sup>1</sup>, R. Greeley<sup>1</sup>, H.P. Klein<sup>2</sup>*. 1. Dept. of Geology, Arizona State University, Box 871404, Tempe, AZ 85282-1404. E-mail: nelson@dione.la.asu.edu. 2. SETI Institute, 2035 Landings Dr., Mountain View, CA, 94043.

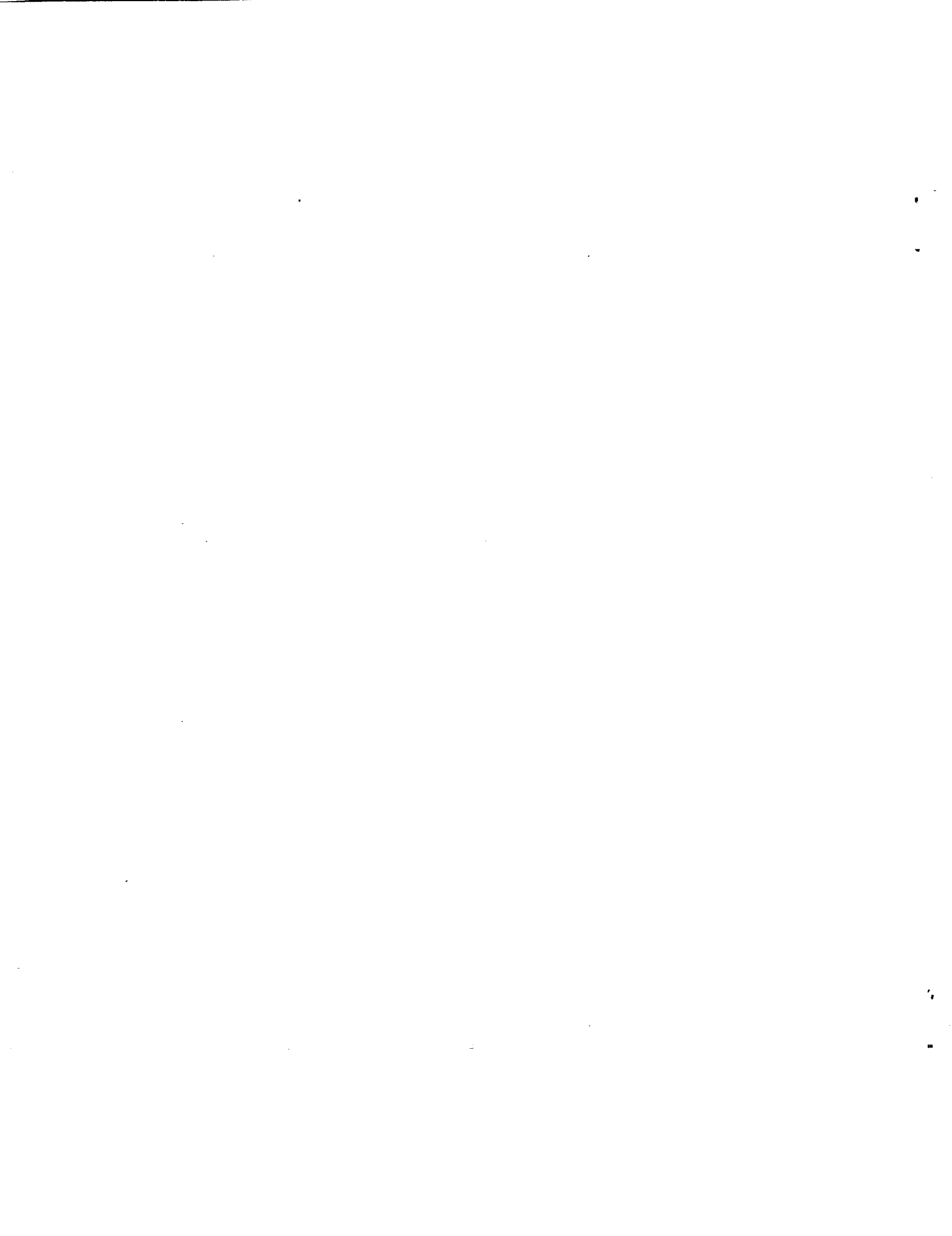
Galilaei is a ~130 km diameter crater, located at 6°N, 27°W, and ~0 km planetary datum, between two outflow channels extending from Hydaspsis Chaos (Figure 1). This crater is proposed as a potential landing site for the investigation of both geology and exobiology. The smooth crater floor, fluvial scour features, and drainage valley suggest that this crater was subject to multiple floods. As a site presumed to have contained liquid water, possibly for significant periods of time, it is considered as a potential exobiology site.

Galilaei crater lies within the cratered highland region of Xanthe Terra consisting of smooth plateau material (Hpls), interpreted to be volcanic flows which had been modified during the Hesperian by broad sheetwash from Valles Marineris [1]. Along its southeast margin is an undeveloped channel, which leads to Ares Vallis. Hydaspsis Chaos lies to the south of the crater and a strip of grooved terrain, trending to the northwest from the Chaos, indicates flow into Tiu Vallis. Galilaei has a smooth floor with many small hills (<5 km) near the crater wall. The hills on the crater floor could be remnants of material eroded from the crater walls. These hills cluster to the greatest extent near a narrow valley which drains from the crater to Tiu Vallis. The severely degraded crater rim and scour features south and west of the crater, suggest that flooding from Hydaspsis Chaos over-topped the crater

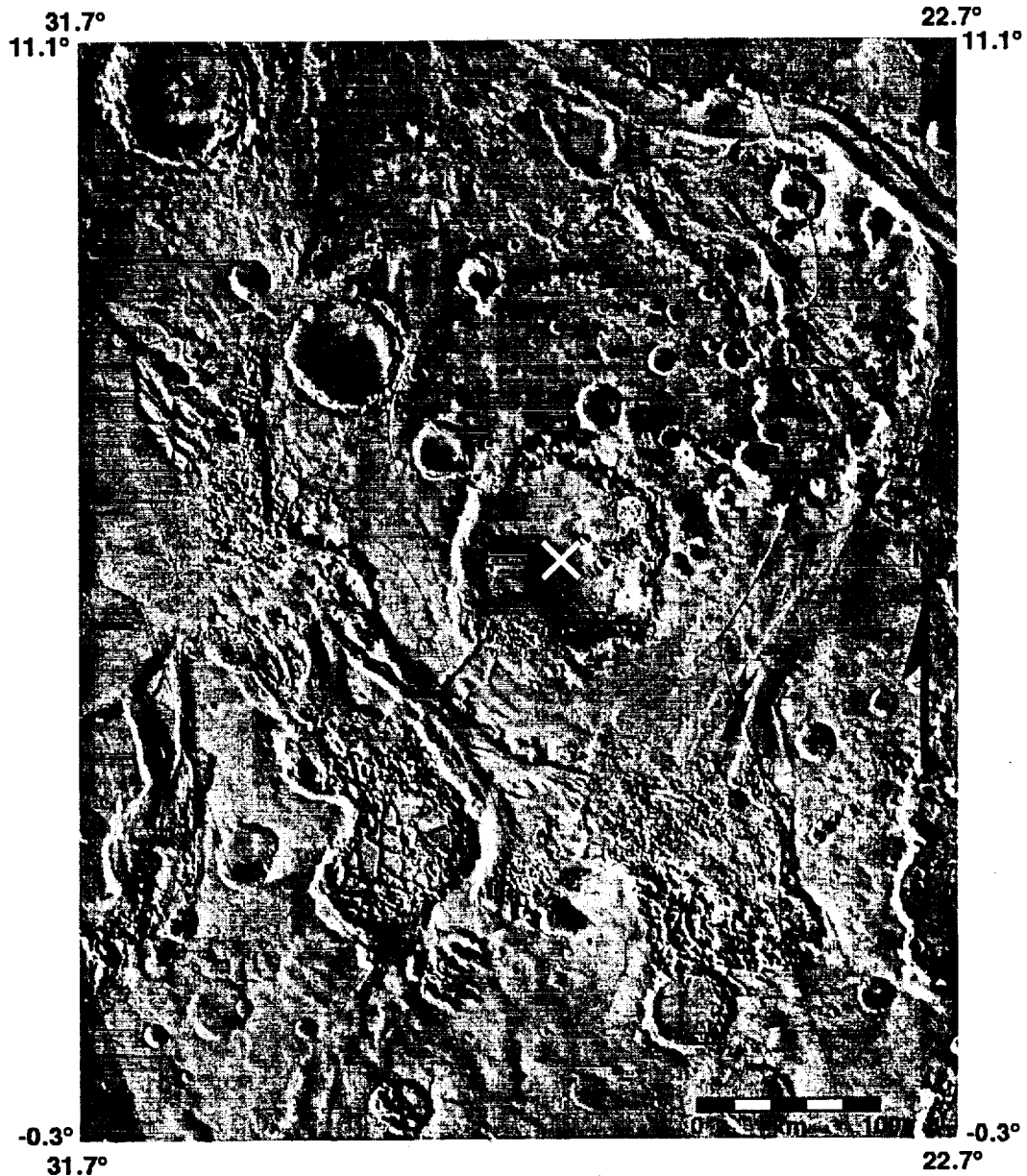
rim more than once and drained into the basin.

This site was assessed for exobiological potential following the method outlined by *Farmer et al.* [2]. The proximity of Galilaei crater to the inferred water source of Hydaspsis Chaos, scour features between Hydaspsis and the crater, the thick smooth floor deposits, and drainage valley leading out of the crater all suggest that this crater was likely to have been the site of a lacustrine environment. Although it is uncertain how long this environment remained stable before the water evaporated or turned to ice, because the crater had been subject to multiple events, the environment could have endured long enough for potential life to arise. Additionally, if Hydaspsis overlies a former hot spot, which precipitated the outflow of water, possible biotic communities could have developed within the aquifer beneath Hydaspsis before disruption. Following the release of water, the organisms, or other exobiology indicators, could have been carried into the crater.

Sediments examined by the 2001 rover at this site could include materials excavated from the highland plateau surrounding the crater by flooding events from Hydaspsis. Reworked sediments and potentially hydrated minerals could also be present. In addition, fossil-bearing sediments and/or organic materials could also be located at this site for examination and collection.



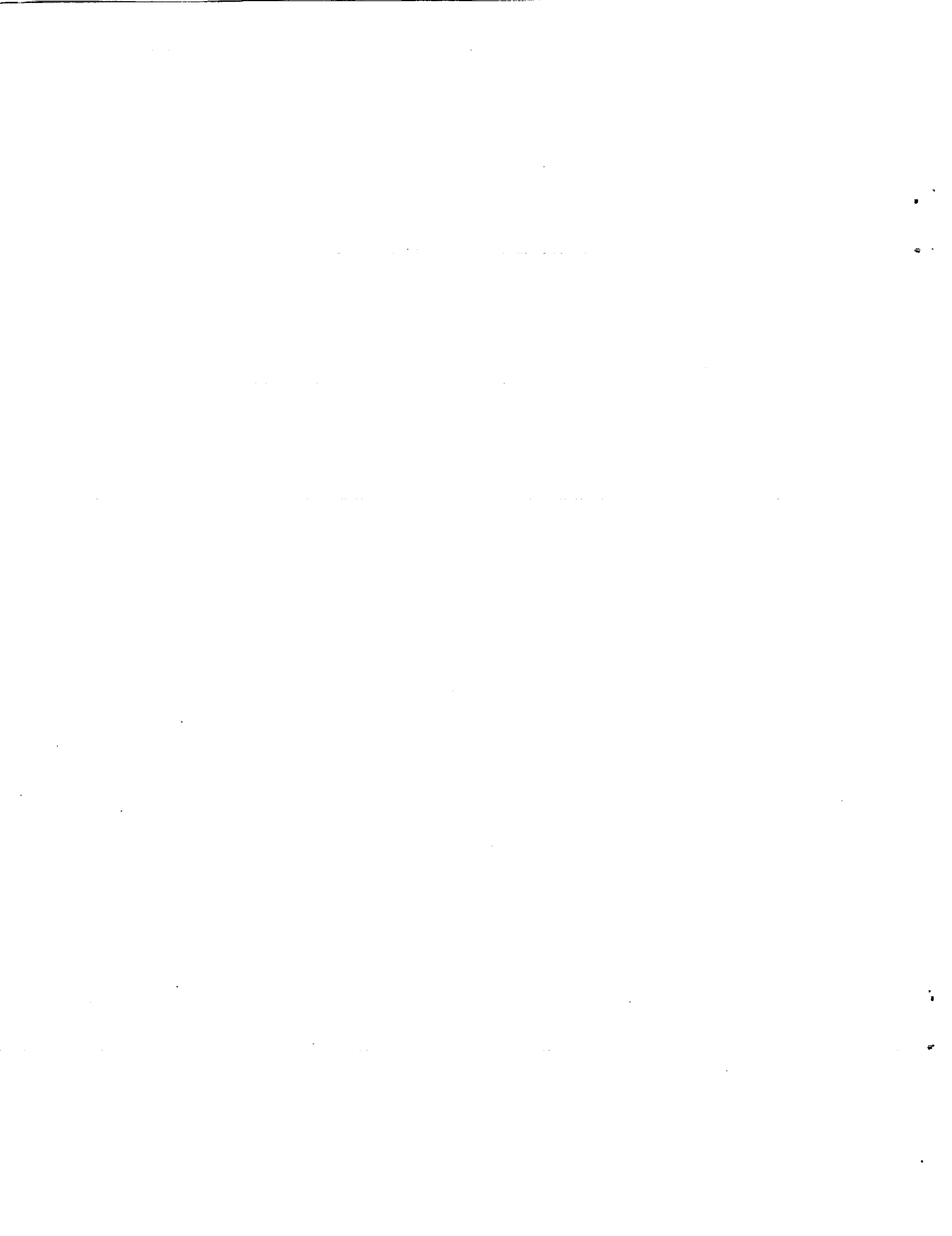
**GALILAEI CRATER.** *D.M. Nelson, R. Greeley, H.P. Klein.*



**Figure 1.** Galilaei crater ( $6^{\circ}\text{N}$ ,  $27^{\circ}\text{W}$ , at  $\sim 0$  km), located at the conjunction of Tiu Vallis (left) and a tributary to Ares Vallis (right), north of Hydaspiis Chaos (bottom). The landing site is indicated by cross-hairs within Galilaei.

**References.**

- [1] Nelson, D.M., Geology of Outflow Channels at the Mars Pathfinder Landing Site (M.S. Thesis), 1997. [2] Farmer, J.D., et al., Mars Landing Site Catalog, 11-16 pp., 1994.





**GALE CRATER: AN AMAZONIAN IMPACT CRATER LAKE AT THE PLATEAU/PLAIN BOUNDARY.** N. A. Cabrol and E. A. Grin, NASA AMES Research Center, Space Science Division, Center for Mars Exploration, MS 245-3, Moffett Field, CA 94035-1000. Email: ncabrol@mail.arc.nasa.gov.

**GALE CRATER DESCRIPTION:** Gale is a 140-km diameter impact crater located at the plateau/plain boundary in the Aeolis Northeast subquadrangle of Mars (5°S/223°W). The crater is bordered in the northward direction by the Elysium Basin, and in eastward direction by Hesperian channels and the Aeolis Mensae [1,2].

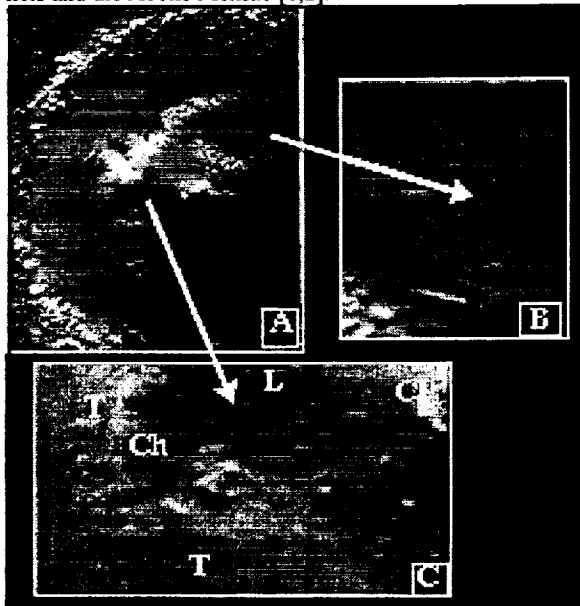


Figure 1: A: Gale crater (140-km diameter), B: stream-lined terraces on the northeast part of the central sedimentary deposit, C: detail of a south-exposed slope: CP: part of the central peak remnants, L= exposed layering, T= terraces, Ch= young channel cutting through the terraces.

The crater displays a rim with two distinct erosion stages: (a) though eroded, the south rim of Gale has an apparent crest line visible from the north to the southwest, (b) the west and northwest rims are characterized by a strong erosion that, in some places, partially destroyed the rampart, leaving remnant pits embayed in smooth-like deposits. The same type of deposits is observed north, outside Gale, it also borders the Aeolis Mensae, covers the bottom of the plateau scarp, and the crater floor. The central part of Gale shows a 6400 km<sup>2</sup> subround and asymmetrical deposit: (a) the south part is composed of smooth material, (b) the north part shows spectacular terraces, streamlines, and channels. The transition between the two parts of the deposit is characterized by a scarp ranging from 200 to 2000 m high. The highest point of the scarp is at the center of the crater, and probably corresponds to a central peak. Gale crater does not show a major channel directly inflowing. However, several large fluvial systems are bordering the crater, and could be at the origin of the flooding of the crater, or have contributed to. One fluvial system is entering the crater by the southwest rim but cannot be accounted alone for the volume of sediment deposited in

the crater. This channel erodes the crater floor deposit, and ends in a irregular-shaped and dark albedo feature.

1. A GRAB BAG SITE (*origin, distribution and age of the sediment*): Gale crater shows the morphology of a crater filled during sedimentation episodes, and then eroded [3,,4]. Part of the lower sediment deposition contained in Gale might be ancient and not only aqueous in origin. According to the regional geologic history, the sedimentary deposit could be a mixture of aeolian and pyroclastic material, and aqueous sedimentary material [1, 3, 4] that can originate both from drainage of the regional subsurface aquifer, and/or from surface flood. The central deposit shows three main levels: (a) the current crater floor (north of Gale), (b) an ancient level about 200 m higher (south of Gale), and (c) the massive terraced deposits (Fig. 1). A crater statistics on the 15,400 km<sup>2</sup> area of the crater floor and deposit [3,4] gave: 259±12.4 craters, most of them partly embayed in the sedimentary deposit, and all inferior to 5-km diameter. For superimposed crater population only, the result is 194±112. The deduced relative ages ranges from Early to Middle Amazonian. The population of craters are comparable for the three levels, implying that the last sedimentation/erosion episode on Gale was recent and affected the whole crater.

2. HYDROGEOLOGIC AND LACUSTRINE ACTIVITY: The streamlined morphology of the border of the deposit, the layering, the channels, and the terraces (see Fig.1) are compatible with a significant fluvio-lacustrine history of the site. Multiple levels may suggest different episodes, but the common statistical age of the three levels shows that the last episode involved the whole crater. The origin of the lake water in Gale may have varied in time. Three major contributions have been proposed [4]: (a) the drainage of the regional underground aquifer by Gale crater over an area of 110-km radius around the crater which would have provided approximately 1,600 km<sup>3</sup> of water, (b), surface drainage entering Gale by the south and north rims. In the south, a 250-km long system originates in the cratered uplands in a Noachian crater material plain (Nc), and crosses Hesperian and Amazonian crater material plains (AHc) northward [1]. Several fluvial systems originate in the Aeolis Mensae, east of Gale. They may had two functions in time: to recharge the underground aquifer in the region of Gale, and to supply surface water in the crater by overspilling the northern rim, and (c) surface floods that originated from the rising of the water level in the Elysium Basin. According to the Amazonian age of Gale's floor, and the erosion direction in the crater, a flood from Elysium Basin is the most likely event to explain the material observed in Gale, and the formation of the last lake. This last flood may have been important enough to flood the central deposit up to about 1400 m above the crater floor, leaving two islands (non stream-

lined features) at the center of the deposit. Terrace spacing suggests a regular drop of the lake level in time. Fractures in terraces perpendicular to the shoreline can be interpreted either as: (a) the result of the drainage systems during the waning of the lake, or (b) traces of the pressure of an ice-covered sheet associated with subglacial drainage.

3. CANDIDATE LANDING SITES:

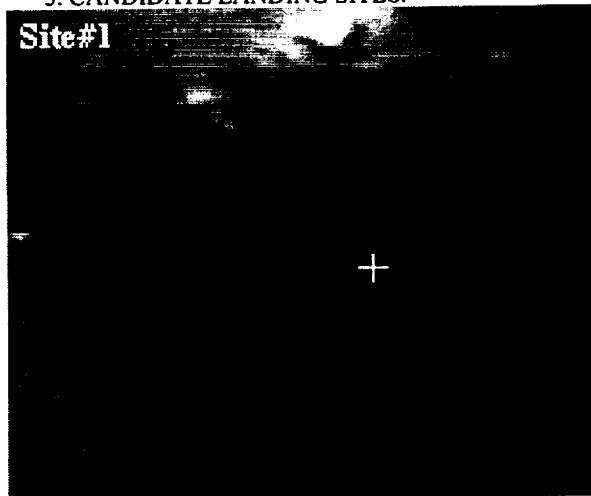


Figure 2: Landing Site at the bottom of the central peak to sample potential rocks associated with hydrothermal processes. Local terraces, channels, and exposed sediments on the central peak, will allow a diversified (type and ages) sampling.

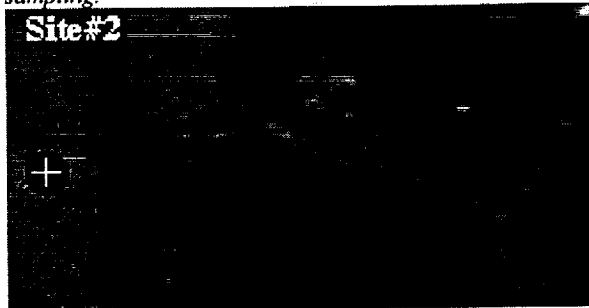


Figure 3: Site #2 at the debouchment of a channel that collected sediments from the different levels of the central deposit, and from the central peak.

The presence of a lake of such volume during the Amazonian period is one more evidence that water was still active on Mars relatively recently. Gale crater offers the rare opportunity to unveil a key-period of the martian history. The Amazonian might proved not as cold and dry as previously thought. The presence of large lakes and basins (Elysium Basin is large as the Mediterranean Sea), reinforces the model of an extensive water activity during the Amazonian that has still to be understood in the context of an assumed cooling and drying planet. The sediments and rocks that were left of this period in Gale keep the record of the climatic conditions of the Amazonian and the clues that are missing to understand the climatic evolution of Mars. In addition, Gale crater presents the advantage to be located at the pla-

teau/plain boundary, which has never been studied and contains information about the two main martian geological units.

SCIENCE RETURN POTENTIAL: As a conclusion, we propose a table (see Table I) that summarizes the worthiness of a mission in Gale crater, and the expected science return relative to the objectives to be met by the Surveyor Program.

Table I: Merit and Expected Science Return in Gale

Science	Merit	
Diversified Geology	⊕	- crustal mat. - young plain mat. (Elysium Basin) - volcanic (Medusae Fossae system) - hydroth. mat. (central peak in lacust. envir.) - fluvio-lacust. mat. - aeolian mat.
Climate History	⊕	- fluvio-lacustrine deposits. (recent Elysium activity) - lacustrine varves
Exobiology	⊕	- fluvio-lacustrine activity - aqueous dep. envir' - possible hydrothermal systems near the central peak
Sampling Diversity	⊕	- sedimentary rocks (N, H, Am) - igneous rocks - soil (bright and dark albedo material). - extinct/extant life (?)
Engineering	Merit	
Latitude	within limits	- Site #1: 5°S/222°W. Region of central peak and terraces. - Site #2: 5°S/223°W. Outlet of a channel crossing the central deposit from the central peak to the lateral terraces.
Elevation	⊕	- (-1000/-2000 m mean elevation)
Trafficability	TBD	- Good at Viking Res. - Good prediction on lake bed. Need MOC/MOLA resolution data

⊕ high ⊖ moderate ⊗ low

References: [1] Scott and Chapman., (1995) *USGS Map I-2397*, [2] Greeley and Guest (1987) *USGS Map I-1802-B*, [3] Cabrol (1997) *28th LPSC*, [4] Cabrol and Grin (1998) *Icarus* (TBS)

**MA'ADIM VALLIS ESTUARINE DELTA IN ELYSIUM BASIN AND ITS RELEVANCE AS A LANDING SITE FOR EXOBIOLGY EXPLORATION ON MARS.** E. A. Grin and N. A. Cabrol, NASA Ames Research Center, Space Science Division, Center for Mars Exploration. MS 245-3, Moffett Field, CA 94035-1000. Email: egrin@mail.arc.nasa.gov

**RATIONALE:** The debouche of Ma'adim Vallis in the Elysium Basin generated a transitional transported sediment structure, which planimetric shape is controlled by the enclosing topography of a deep re-entrant gulf of the Basin into the highland. We defined it as an estuarine delta. The location and the importance of this estuarine delta is supported by the theoretical model of graded profile constructed for Ma'adim Vallis [1], and by two approaches: (i) the reconstruction of Ma'adim Vallis downstream course from Gusev to Elysium Basin (figure 1), and (ii) the survey of the sediment deposit in the alleged estuary. The longitudinal graded profile of Ma'adim Vallis finds its base-level in the Elysium Basin, at a -1000 m elevation [1], which is in agreement with the observed Basin shoreline [2]. This model is supported by observational evidence of flow between the northern rim of Gusev crater, and the Elysium Basin shoreline. This downstream course of Ma'adim Vallis can be divided into three hydrogeologic regions.

**HYDROGEOLOGIC REGIONS:** (a) The first region is a flooded plain (Zephyria Mensae), consisting in chaotic terrain formed by highland rocks, and disintegrated lava of the western flank of Apollinaris [2,3]. Morphologic indicators of the flood process are (see figure 1): (1) the sediment deposit over the Gusev crater northern rim that reflects the overspilling of the crater-lake water through a 40-km wide gap provided by an ancient impact crater [4], (2) the tear-drop shaped feature on the northeastern flank of Apollinaris Patera, and (3) the chaotic terrain that suggest the emergence of ground water generated by the seepage of the crater lake through high-permeable broken rampart material [2]. This underground water circulation sustained by the hydrostatic pressure of the crater-lake has likely generated a hydrothermal system in the volcanic environment of Apollinaris Patera. The stratigraphy of the flooded area is identified as Hesperian age, with occurrences of Noachian hilly individual features [2], and as Amazonian flooded plain and chaotic material [3], (b) The second region is located on the western flank of Apollinaris Patera. It is surrounded by relics of deep valleys that suggest a former downstream course of Ma'adim Vallis. The geologic setting of this region (Lucus Planum) is interpreted to be an Amazonian formation [2,3] composed by the middle and lower members of the Medusae Formation., c) The third region corresponds to the convergence of the west and east branches of Ma'adim Vallis into a deep re-entrant wide gulf that penetrates about 100 km into the highland. This topographic depression is delineated by the -1000 m elevation contour. This gulf has formed an estuarine configuration centered at 3°S/190°W within the Elysium Basin. This configuration has favored the

formation of a estuarine sedimentary delta, because of topographically controlled lateral migration. This estuarine structure is strongly dominated by the incoming supply of Ma'adim Vallis fluvial sediment extracted from Zephyria Mensae and Lucus Planum.



Figure 1: Downstream course of Ma'adim Vallis from Gusev to Elysium Basin. The ¥ symbol shows underground water emergence.

**ESTUARINE SEDIMENTOLOGY:** The obtuse-angle geometry of the estuary increases the sedimentation rate, which is higher than in the course of the channel. The sediment deposition process is governed by the estuarine water circulation. The inflowing loaded fluvial water enters the estuary as a bottom current, and mixes with the relatively less-loaded water of the receiving basin. When they mixed, the inflowing fluvial material, and the landward basin circulating water generate an accumulation of highly-diversified estuarine deposit stratification. This accumulation of material is mostly centered in the transitional zone of the delta (labeled B in figure 2). The sediment trapping efficiency of the estuary is function of the energy bal-

ance between the inflowing fluvial water, and the incoming basin current. The submergence of the delta by the rising of the water-level increases the estuary water-depth, and consequently the sediment entrapment is favored. The locus of sediment accumulation moves landward in the zone of inflowing fluvial water (labeled A in figure 2). This results in the rising of the channel base-level, thus in the increase of the length of the longitudinal graded-profile.

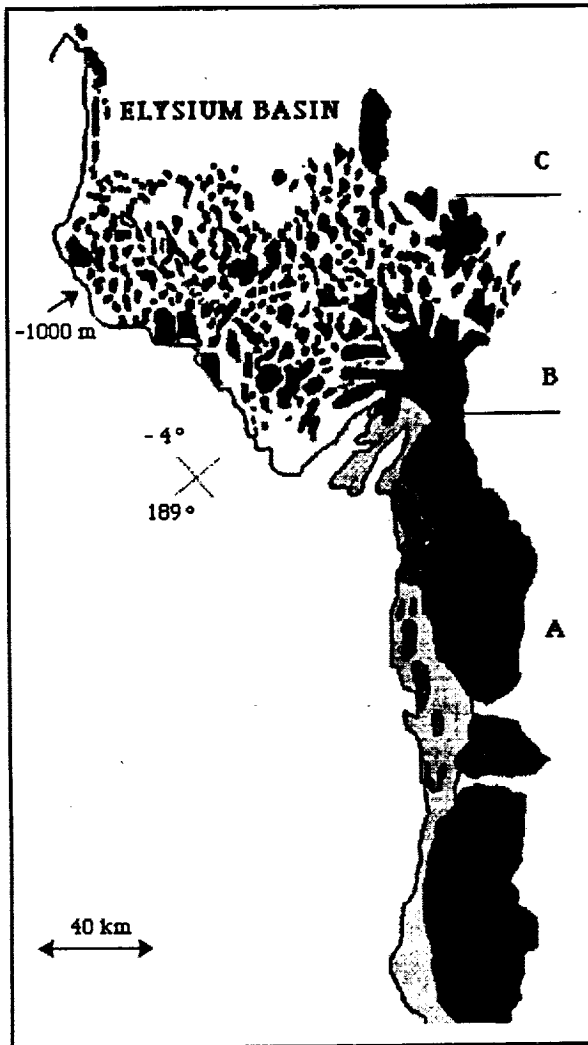


Figure 2: Estuarine Delta Model for Ma'adim Vallis de-bouche in Elysium Basin. ((A) Fluvial estuarine sediment deposition, (B) Basin estuarine sediment accumulation, and (C) Delta estuarine shoreline sediment deposition.

The sediment deposit facies of the zone A (figure 2) shows a generally smooth surface. The longitudinal deposit is bordered by alluvial terraces that reflect the variations of the channel level. The waning of the Elysium Basin caused the erosion of the Basin estuarine zone by small channels (see zone B in figure 2), this episode being characterized by dissected tear-drop shaped mesa-like morphologies in the delta. Our estuarine delta model predicts a lithostratigraphic deposi-

tional sequence associated with the water submergence and the transgression of Elysium Basin. The thickness of the estuarine sediment corresponds to the Elysium Basin levels changes relatively to the bed floor of the estuary. The depositional sequence of Ma'adim Vallis are described (figure 2): (1) a pro-current filled region (A), where fluvial are longitudinally accumulated by the inflowing water, (2) inverse current from Elysium Basin (B), where fluvial and lacustrine sediments are accumulated, and (3) zone of current equilibrium (C), where the sediments are distributed as a shoreline at the boundary of the estuarine delta.

**RELEVANCE TO MARS EXPLORATION:** The estuary sedimentology dynamics collects and keeps the record of the geologic unit material crossed by Ma'adim Vallis, and those of the lakebed deposit of Elysium Basin. The predicted mixed stratigraphic sequence from fluvial and lacustrine sediment makes this site an exceptional environment to concentrate potential multi-origin biologic records. We envision four possible strategies to explore this sedimentologic record: (1) longitudinal surface and subsurface traverses in region A to investigate outcrop levees, (2) exploration of the mesa walls in region B, (3) deep drilling hole lodging of the sequential deposits in the zones A and B, and (4) surface and subsurface exploration of the shoreline delta. The expected results for each of these strategies are: (1) in the deepest layers of region A are predicted frequent and abundant coarse material, sandy lenses lamination grading downward from sand to cobbles. Volcanic debris from the Noachian crustal Plateau unit material, hydrothermal altered rocks, carbonates, Hesperian and possibly Amazonian volcanic material, from Apollinaris Patera, altered rocks and carbonates from Zephyria Mensae are expected. As a favorable environment for inception of life, possible biological records are expected in transported rock, (2) At the surface, and subsurface ( $\leq 100$  m), large deposits sandy to silted material from Elysium paleolake basin mixed with fine-grained sediments from Ma'adim Vallis are expected mostly in the upstream part of region B, (3) on the shoreline of the estuarine delta, abundant fine material from Elysium paleolake basin (evaporites, carbonates), mostly Amazonian in age are expected. The Ma'adim estuary is a favorable landing site for all the above mentioned science aspects, and for its location. The site lies near the equator, which is favorable for the rover solar power supply, and at -1000 m elevation, which is a favorable configuration for the descent system braking. Another advantage is the extent of the area of high scientific interest ( $33,000 \text{ km}^2$ ), which provides a good ellipse, and potential long study traverses.

[1] Cabrol *et al.*, 1996. *Icarus* 123, 269-283 [2] Scott and Chapman 1995. USGS Geol. Map I-2397, [3] Kuzmin *et al.*, 1998 *in press*. [4] Grin and Cabrol 1997, *Icarus* 130. This study is supported by the NRC grant for the second author

**DEEP BASALT AQUIFERS IN ORCUS PATERA, ELYSIUM BASIN MARS: PERSPECTIVES FOR EXOBIOLGY EXPLORATION.** E. A. Grin and N. A. Cabrol, NASA Ames Research Center, Space Science Division, Center for Mars Exploration, MS 245-3. Moffett Field, CA 94035-1000. Email: egrin@mail.arc.nasa.gov.

**Introduction:** Direct indicators of shorelines, spillways, and terraces allowed to determine the extent of the Elysium Paleolake between the contour-lines 1000 and 500 m below the Martian datum [1]. The Elysium Paleolake is bordered north by Orcus Patera (14°N/181°W), which lies west of the Tartarus Montes and Tartarus Colles (see figure 1). The Orcus Patera displays an ellipse-shaped collapsed caldera of 360-km long and 100-km wide. Viking topographic data show that the bottom of the caldera is located at 2500 below the Martian datum, and surrounded by a steep-walled rampart, which crest is located at about 0 m elevation.

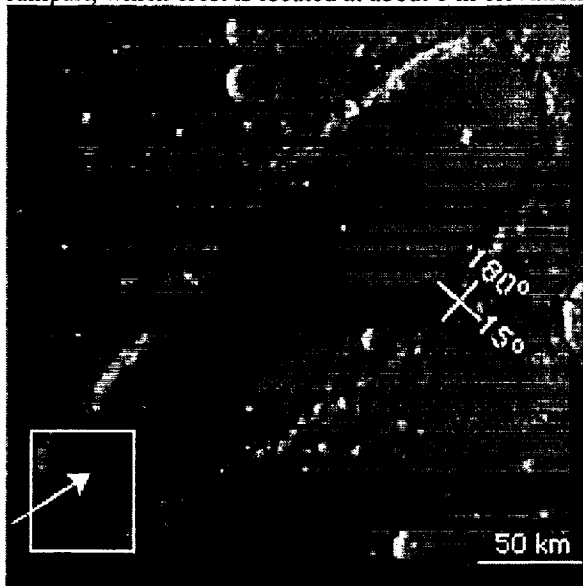
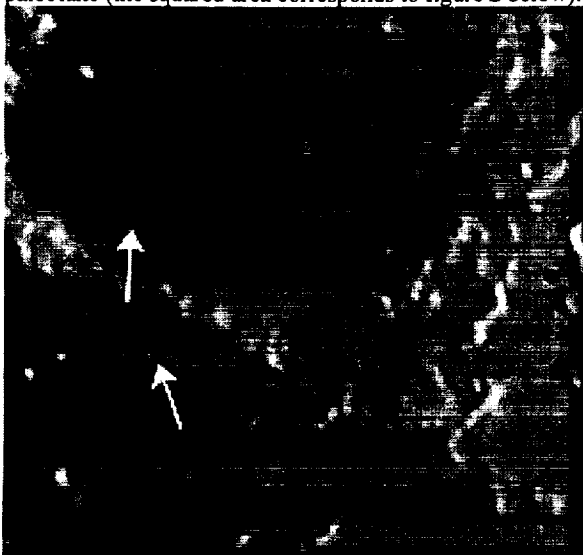


Figure 1: Orcus Patera in Elysium Basin. The arrow shows a possible spillway for the water from the Elysium paleolake (the squared area corresponds to figure 2 below).



Considering the localization of Orcus Patera in the Elysium paleolake, its altimetry, and the magmatic origin of this caldera, we propose the existence of a paleolake in Orcus Patera generated (a) by juvenile water from magma during the Noachian period, and (b) by intermittent influx of the Elysium Basin from Hesperian to Amazonian. Results are encouraging to consider this site as a potential high-energy source environment for microbial communities.

**Orcus Patera:** The outward walls of Orcus Patera are circumscribed by a 50-km wide lava field mapped as Noachian material [1]. The structure of Orcus Patera represents the record of material erupted from a magmatic reservoir. The caldera is enclosed by steep inner walls (25% measured from topographic data), values which could be in agreement with the presence of a deep magmatic reservoir, as suggested by the typology of *Crumpler et al.*, [2]. The depth of the caldera might be due to the collapse of the magma reservoir, and the release of gases accompanying the magma thermal evolution [3].

**Origins of water for the paleolake(s):** The water that generated a paleolake in Orcus Patera may have come from two origins: (1) *Juvenile water:* *Plescia and Crips* [3] estimated a magma H<sub>2</sub>O content by weight between 0.5% and 1.5% using for the first value a comparison with terrestrial basalt, and for the second values from a Martian meteorite. The amount of H<sub>2</sub>O can be estimated by the volume of erupted lava, and the lava content of the caldera. In this study, we adopt a water content of 1% [4]. The total volume of magma that has been contained in the caldera, and the volume of lava contained in the observed lava field is about  $110 \times 10^6 \text{ km}^3$ , that gives a total volume of  $1.10 \times 10^6 \text{ km}^3$  of water. The juvenile water expelled by the overpressure within the magma chamber charged with desolved water-vapor may have moved into the crust. The decrease in overburden pressure led to bubble formation. The ascent of these bubbles generated a pressurization of the magma, which was sufficient to fracture the overlaying magma layer, (2) *Water from Elysium paleolake.* During the Amazonian, the rise of the Elysium paleolake level generated an overspilling that supplied the caldera with water. The southern portion of the crest shows a deep gap 12-km wide at -1500 m elevation, locating the gap between 500 to 1000 m below the assumed water of Elysium paleolake, thus facilitating the influx of Elysium paleolake water into Orcus Patera. Bathymetric calculations give a floor area of  $25,500 \text{ km}^2$  at -2000 m elevation, and a water volume of  $42,000 \text{ km}^3$ , with a lake-level at -1500 m [1]. A substantial amount of water may have percolated through the fractured lava, and part of the volume may have overspilled the northern crest of Orcus

Patera [1] to debouch in the Tartarus Montes region. **Deep subsurface basaltic aqueous environment:** We envision the formation of a subsurface aqueous environment in basaltic rocks at the contact of the two water-source origins, possibly the percolating surface lake water, and more likely the juvenile water [5]. Similarly to terrestrial calderas, Orcus Patera might be surrounded by ring-fractures caused by the collapse of the magma chamber that followed the release of gases. These ring-fractures may have been covered later by sedimentation in the caldera (lacustrine, aeolian, and volcanic), and by mass wasting (figure 3).

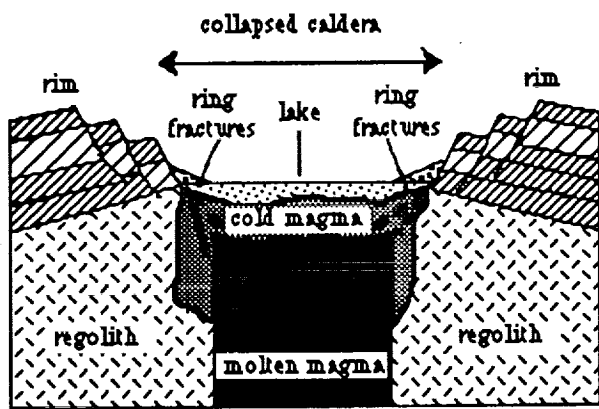


Figure 3 : Stratigraphic model of Orcus Patera

The detumescence of the magma in the caldera, and the vesiculation of the juvenile water may have operated simultaneously [6]. Comparatively to terrestrial melts, Martian iron-rich melts are denser. This greater density implies greater effusion rates (eight-times terrestrial values), and larger fissuration widths (two-times terrestrial ones) [7]. With increasing vesiculation of magma, the bubbles interact with one-another because there are of similar pressure. They make a magma froth at the contact with the caldera surface, and on the walls of the fractures [8]. In the saturated magma, froth, where the volume ratio of gases-to-liquid is about 4:1, the bubbles form a huge surface area of interconnected spaces. Bubbles near the caldera surface disrupt the magma, and fragmentation takes place, which moves downward through the magma column. (figure 4). On Earth, the bubbles are likely to grow between 1 and 50 mm in diameter due to the difference between the magma surface tension, and the bubble supersaturation pressure [9]. The Martian low-pressure at surface level is likely to accelerate the expansion of the bubbles, and increase their final diameter and number, creating more voids in the magma. The strong magma froth with enclosed juvenile water

bubbles interconnected with exsolved gas bubbles constitute a potential geothermal environment for geochemical energy production from basalt and water that does not require excessive temperatures. This process can start at +20°C.

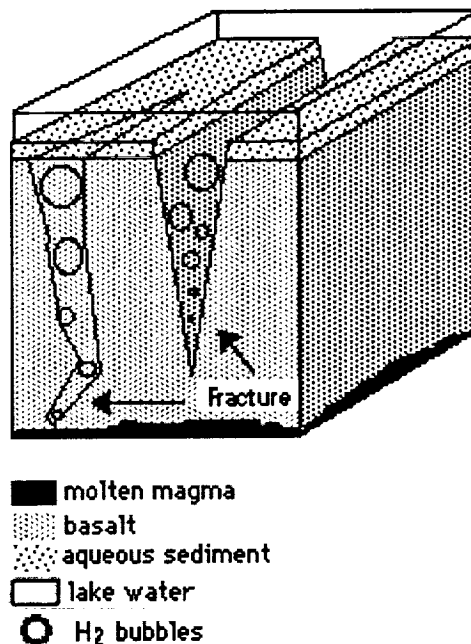


figure 4: vesiculation of juvenile water

**Conclusion:** Similar types of environments have been shown on Earth as potential energy sources for microbial metabolism [6], and could have provided deep aqueous basaltic niches for possible Martian microorganisms, even geologically recently. During the Amazonian, combination of volcanism and water activity still existed on Mars. Moreover, this type of potential niches open ways for investigation of possible oases of extinct or extant life, not only on paleolakes, and surface hydrothermalism spring areas, but also all large systems of *fossae*, which combine hydrologic and volcanic activities, and which provide an energy source, and an underground shelter to prevent surface UV bombardment .

References: [1] Scott and Chapman 1995. *USGS Map I-2397*, [2] Crumpler *et al.*, 1994. *LPSC 25th*, [3] Plescia and Crips 1992. *LPSC 23th*, [4] Greeley 1987. *Science* 236, [5] Cave 1993. *JGR 98-E6*, [6] Steven and McKinley 1995. *Science* 270, [7] Bertka 1992. *LPSC 23th*, [8] Sparks 1978. *J.Volc.Geo.Res.* 3., [9] Francis 1995. *Volcanoes*, Oxford U.Press.

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## POSSIBLE LACUSTRINE DEPOSITS ON CRATER FLOORS AS TARGETS FOR MARS SURVEYOR SAMPLE RETURN MISSIONS

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A high priority for a sample return landing site is a location where liquid water may have flowed and/or ponded early in Martian history. Such a site could potentially provide samples that would address water chemistry and availability during Martian history, as well as provide a possible site for accumulation of any microfossils that might accompany any sedimentary deposit. There is abundant evidence that water played a crucial role throughout Martian history, but it is often difficult to find many features that unambiguously indicate a fluvial or pluvial contribution to the local geologic story. Lacustrine deposits within large craters in the highlands of Mars represent a possible target that might provide a sample return mission with access to materials from the ancient cratered terrain as well as water-borne sediments that accumulated within the crater at some time after heavy bombardment.

The case has been made that the cratered highlands of Mars include numerous pluvial lakes, as evidenced either by erosional shorelines within a crater or by high albedo deposits on the crater floor [1]. The erosional features representing possible lake shorelines are distinctive, but they lack clear evidence that the liquid involved was water (as opposed to a possible fluid lava or some other geologically reasonable liquid). A compelling case for evidence of water-borne sediments can be made for distinct high-albedo deposits within some highland craters. Viking imaging does not reveal clear layering in these deposits, although erosional patterns in some of them suggest that the material is variably indurated and may be vertically inhomogeneous.

Two candidates for possible lacustrine deposits are the crater Bequerel (N22, W7) [1,2,3] and an unnamed crater near the Schaparelli basin that includes the unusual feature called "White Rock" (S8, W335) [1,3,4]. Both are located within the cratered highlands, which is the prime target area for the sample return missions. Bequerel is approximately 80 km in diameter, located in the Arabia Terra highlands with a rim height above the 0-km elevation contour but a floor that is mostly below the -1-km elevation contour [5]. Assuming the landing ellipse is small enough to fit within the crater and miss the eroded (possible lacustrine) deposit, this crater deserves consideration as a possible target for a sample return mission. The White Rock crater is about 70 km in diameter, located within Terra Sabaea, but it is more problematic as a potential target since its rim corresponds to an elevation between the 4 and 5-km contours and its floor is below the 3-km contour [5]. The flow or elevation may exceed the final engineering constraints, so this particular crater may not be a satisfactory target, even though the White Rock deposit has a strong possibility of being a sizeable lacustrine deposit [3,4]. An alternative target near the White Rock crater is the 150 km diameter Schaparelli basin (S3, W343), whose floor is below the 2-km elevation contour [5]. If Schaparelli is assumed to have experienced conditions similar to those that led to the formation of the White Rock deposit, then this basin should be considered for a sample return landing.

Knowledge of the topography and elevation of features on Mars is currently rather imprecisely known. Elevations based on Viking data can be in error by up to a couple of

km [5]. Earth-based radar gives substantially better topography, but only for isolated tracks scattered within the N25 to S25 latitude band [e.g., 6]. The Mars Orbital Laser Altimeter (MOLA) experiment [7] on the Mars Global Surveyor (MGS) spacecraft will generate the first well-constrained topographic data set for Mars during its two-year mapping mission, which should officially commence in March 1999. Preliminary MOLA data described in press releases and made available on the Internet make it abundantly clear how poorly constrained are some portions of the Viking-based elevation data set. It is anticipated that MOLA data may show that crater floors with possible lacustrine deposits currently thought to be at too high an elevation (e.g. the White Rock crater) may yet turn out to be within the engineering constraints of a lander mission. Also, high-resolution images from the Mars Orbital Camera (MOC) [8] and compositional information from the Thermal Emission Spectrometer (TES) [9] on the MGS spacecraft may be able to test the viability of a lacustrine interpretation for the high-albedo intracrater deposits prior to final selection of the landing site for the 2001 mission, as well as subsequent Mars landing missions.

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**VOLCANIC INTRUSIONS ON MARS: HEAT SOURCES TO MAINTAIN VIABLE ECOSYSTEMS?**

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**Introduction:** We analyze long-term heat input into the martian crust from volcanic sources and use this as a basis for developing criteria for potential landing sites that might have maintained thermally viable ecosystems in the past history of Mars. Candidate sites that meet these criteria are described.

**Structure of volcanoes:** Centers of basaltic activity located over mantle hot-spots on both Earth and Mars produce the same basic pattern of a shallow magma reservoir (commonly marked by a collapse crater or caldera) located beneath the summit of a shield volcano (1-8). Near-vertically oriented dikes (pressurized magma-filled cracks) propagate mainly laterally away from the reservoir whenever it becomes excessively over-pressured by the arrival of batches of magma from the mantle beneath. These dikes either stall within the body of the volcano as intrusions or, if they grow vertically by a great enough distance, erupt at the surface to feed lava flows or explosive eruptions. The growth of many shield volcanoes is influenced by pre-existing regional stresses in such a way as to concentrate dike injection into relatively narrow zones — rift zones — oriented radial to the summit. Intrusions outnumber surface eruptions by a factor of several to one.

The main difference between terrestrial and martian volcanoes is caused by the lower acceleration due to gravity on Mars (9-11). The interplay between stresses arising due to gravity and stresses linked to the elastic properties of rocks causes all martian magma reservoirs to be centered at greater depths and to be larger in both horizontal and vertical dimensions (1, 6,11). The greater magma volumes housed by these reservoirs cause laterally propagating rift-zone dikes to be both horizontally and vertically more extensive and also wider (i.e. thicker) than those on Earth; Table 1 shows typical values of vertical height and width.

Any shield volcano grows as a stack of interleaved, sub-horizontal layers of volcanic ash from explosive eruptions and vesicular lava from effusive eruptions cut, at any given level within the pile, by the near-vertical dikes feeding later eruptions. Once the products of any one eruption have cooled, the pore spaces between ash particles and the vesicles within lava flows form natural locations for the near-surface accumulation of water ice and solid carbon dioxide. The very low atmospheric pressure on Mars causes more exsolution of magmatic volatiles (mainly water and CO<sub>2</sub>) than on Earth; this means that explosive eruptions were more common on Mars than Earth (3,12) and that lava flows were more vesicular, both factors enhancing the trapping of volatiles from the atmosphere.

**Thermal consequences of dike injection:**

There are several ways in which the intrusion of new dikes influences the thermal structure of the old eruptives into which they are intruded and thus the state (solid or liquid) of the H<sub>2</sub>O trapped in these rocks. If a dike is intruded into a region which has seen no activity for a long time, then close to the new dike the heat pulse will raise the temperature first above the melting point of H<sub>2</sub>O and then above the boiling point; further away only the melting point will be exceeded. The time scale  $t_1$  over which such a heating event lasts is of order  $5(w^2/\kappa)$  where  $w$  is the dike width and  $\kappa$  is the thermal diffusivity of the magma; for  $w = 5$  m and  $\kappa = 10^{-6} \text{ m}^2 \text{ s}^{-1}$ ,  $\tau_1 \approx 4$  years. The lateral width of the region affected is  $\sim 6w = 30$  m.

Where successive dikes are intruded near to one another in a rift zone, part of the region between any two dikes can stay at a temperature such that H<sub>2</sub>O is a liquid for a much longer time provided that new dikes arrive on a time scale comparable with  $\tau_1$ . We can estimate the time interval between intrusions by noting that to assemble the typical volume of a large martian volcano ( $\sim 10^6 \text{ km}^3$  for the Tharsis shields) in 1 Ga (i.e.  $3 \times 10^{16}$  s) by randomly intruding dikes 50 km in horizontal extent, 13 km in vertical extent and 6 m thick (c.f. Table 1), implies that the time between events is  $\sim 4000$  years. However, if these dikes are confined to a rift zone, the time interval between events is less. The Hawaiian shield volcanoes on Earth have active rift zones which at any one time are only a few hundred meters wide and occupy only about 1/200 of the horizontal cross-sectional area of the volcano. Preliminary estimates from Viking Orbiter images suggest that the ratio is similar for Mars, reducing the mean interval between nearby intrusions to  $4000/200 = 20$  years. This value is close enough to the 4 years found earlier to suggest that significant local "warm zones" can exist down to depths of several kilometers in volcanic rift zones.

**Regional heat flow effects:** An alternative assessment takes account of the fact that, over the whole extent of a rift zone, the net effect of the intrusions is to increase the regional heat flow and locally raise the geotherm toward the surface on the time scale over which the rift zone remains the preferred site of activity. The total amount of heat,  $H$ , available from cooling the magma required to build a shield volcano of volume  $V$  is  $H = (V \rho S \Delta\theta)$  where  $\rho$  is the mean density of the edifice,  $S$  is the specific heat of the magma and  $\Delta\theta$  is the temperature interval through which the magma cools. Substituting typical values of  $V \sim 10^6 \text{ km}^3$ ,  $\rho \sim 3000 \text{ kg/m}^3$ ,  $S \sim 1000 \text{ J kg}^{-1} \text{ K}^{-1}$  and  $\Delta\theta \sim 1000 \text{ K}$ , we find  $H \sim 3 \times 10^{24} \text{ J}$ . The time scale for release of this heat is, as before,  $\sim 1 \text{ Ga} = 3 \times$

$10^{16}$  s and the total surface area of the volcano with diameter 500 km is  $\sim 8 \times 10^{11} \text{ m}^2$  implying a mean heat flux  $Q_v$  of  $\sim 1.3 \times 10^{-4} \text{ W m}^{-2}$ . If the fractional area of rift zones at any one time is again taken as 1/200 of the surface area of the volcano, the local heat flux is more like  $Q_v = 2.5 \times 10^{-2} \text{ W m}^{-2}$ . This is comparable to the present day planetary average geothermal heat flux  $Q_g$  estimated at between 3 and  $4 \times 10^{-2} \text{ W m}^{-2}$  (13).

We are mainly concerned with the influence of volcanic heat sources at some time part-way through martian geological history when the geothermal heat flux was higher than the current value by a factor of, say, 2 or 3, i.e.  $\sim 8 \times 10^{-2} \text{ W m}^{-2}$ ; the volcanic flux would then have represented a 30% increase in the heat flow. Estimates of the depth to the base of the cryosphere based on the current geothermal heat flow range from about 2 km near the equator to about 5 km near the poles. With the higher earlier flux these depths would have been  $\sim 800$  m and  $\sim 2000$  m, respectively and the 30% increase in heat flow would have changed them to  $\sim 615$  and  $\sim 1540$  m, respectively. Thus, the vertical extent of the zone within which  $\text{H}_2\text{O}$  could be present as liquid water could have been extended by at least 200 to 400 m, depending on the latitude.

**Summary:** The above calculations suggest that the local volcanic heat sources inevitably present in the rift zones on the flanks of large martian volcanoes could have very significantly extended the sizes of regions within which water could persist as a liquid for time periods of at least tens and probably hundreds of millions of years. These latter intervals are long enough, by analogy with what happened on the Earth, for significant biological development (14). It is possible that the ultimate limitation on the lifetime of such favored regions is not so much the availability of heat but rather the need to prevent water from leaving the regions too rapidly as a result of the imposed thermal gradient (15) or to re-supply water from deeper levels in the hydrothermal system of the volcano to compensate for that lost. Typical geological environments on Mars where such conditions might have persisted include volcanic rift zones, graben and edifice annuli. We outline several such candidate sites for the Mars 2001 opportunity.

**Table 1.** Widths (w) and vertical heights (h) of dikes centered at neutral buoyancy levels in the rift zones of volcanoes on Earth and Mars for a range of plausible driving pressures,  $P_0$ , defined as the amounts by which the pressure in the dike at its mid-point exceeds the external compressive stress.

$P_0/\text{MPa}$	Earth		Mars	
	h/km	w/m	h/km	w/m
5	0.95	0.45	4.8	1.4
10	4.7	2.3	12.9	5.7
20	9.7	8.7	28.0	22.6

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