1-1-2001

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JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. E4, PAGES 7665-7682, APRIL 25, 2001

Observation of the geology and geomorphology of the 1999 Marsokhod test site

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Abstract. The Marsokhod rover returned data from six stations that were used to decipher the geomorphology and geology of a region not previously visited by members of the geomorphology field team. Satellite images and simulated descent images provided information about the regional setting. The landing zone was on an alluvial apron flanking a mountain block to the west and a playa surface to the east. Rover color images, infrared spectra analysis of the mountains, and the apron surface provided insight into the rock composition of the nearby mountains. From the return data the geomorphology team interpreted the region to consist of compressionally deformed, ancient marine sediments and igneous rocks exposed by more recent extensional tectonics. Unconsolidated alluvial materials blanket the lower flanks of the mountains. An ancient shoreline cut into alluvial material marks a high stand of water during a past, wetter climate period. Playa sediments floor a present-day, seasonally, dry lake. Observations made by the rover using panoramic and close-up (hand specimens--scale) image data and color scene data confirmed the presence of boulders, cobbles, and fines of various provinces. Rover traverses to sites identified as geologically distinct, such as fan, channel, shoreline, and playa, provided useful clues to the geologic interpretations. Analysis of local rocks was given context only through comparison with distant geologic features. These results demonstrated the importance of a multifaceted approach to site interpretation through comparison of interpretations derived by differing geologic techniques.

1. Introduction.

The 1999 Marsokhod Field Experiment was designed to simulate the operational environment of an instrumented Mars rover and its support team. *Stoker et al.* [this issue] describe the overall structure and objectives of the field trial. This experiment is one of a series of field trials employing the Marsokhod platform outfitted with a variety of instruments and deployed in different geologic settings. Previous field experiments with Marsokhod rover were conducted at Amboy, California [*Greeley et al.*, 1994], Kilauea, Hawaii [*Stoker*, 1998], and Tuba City, Arizona [*Christian et al.*, 1997]. The Marsokhod rover and instrumentation used in this field test are described by *Stoker et al.* [this issue]. This experiment employed orbital data, simulated descent images, a rover mounted color, stereographic panoramic imaging system, and near- and midrange infrared spectrographic instrumentation [*Johnson et al.*, this issue]. Part of the field test simulated a manipulator arm capable of trenching and positioning a camera for close-up imaging (Robotic Arm Camera Experiment) [*Keller et al.*,2000], and part of the field test was devoted to testing the interaction of an astronaut and rover (Astronaut-Rover (ASRO) Project) [*Cabrol et al.*, 1999]. Science teams conducted remote observations though interaction with an engineering team which translated and uplinked instructions to the rover in the field. Actual programming of instructions was transparent to the science team.

The geomorphology team consisted of fifteen members (Table 1). Ten geologists began the experiment at NASA Ames, Moffett Field, California. After working together and with the staff at Ames for the first 3 days of the field trial, these investigators returned to their home institutions for the remainder of the experiment. Five additional geologists participated from their home institutions as members of the Distributed Science Team. Communication was established via telephone conferences and the Internet. Data from Marsokhod rover were posted on a Web site for all to share. The team had no prior contact or group training before the start of the experiment. The number of active participants at any one time during the mission tended to vary from a maximum during the early part of the experiment to a bare minimum as individual investigators drifted away to more pressing duties and obligations once they returned to their home institutions.

The field trial was designed to simulate a Mars Lander/Rover by using available orbital data, simulated descent images (Figures 1a-1d), surface data returned by telemetry from a rover, and samples collected and returned from the field. The assignment to the geomorphology and mineralogy teams was to characterize the locality in terms of landforms and materials, to select targets for detailed observation, and to determine geological history. The teams were provided with Landsat and SPOT orbital data of the Marsokhod study area prior to the start

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Paper number 1999JE001167.
0148-0227/01/1999JE001167$09.00

Table 1. Members of the Geomorphology Team

Team Member	Home Institution
Jayne Aubele	New Mexico Museum of Natural History
Nadine Barlow	Central Florida University
E. Art Bettis[a]	University of Iowa
Mary Chapman	USGS Flagstaff
Stephen Clifford	Lunar and Planetary Institute
Robert Craddock[a]	National Air and Space Museum
Larry Crumpler	New Mexico Museum of Natural History
Rene De Hon[a]	University of Louisiana at Monroe
C. Tom Foster[a]	University of Iowa
Virginia Gulick	NASA Ames Research Center
Jeff Johnson	USGS Flagstaff
Horton Newsom	University of New Mexico
Gian Gabriele Ori	Universita' d'Annunizo
Mark Reagan[a]	University of Iowa
Kenneth Tanaka	USGS Flagstaff

[a]Distributed Science Team.

of the field test. Simulated "descent images" and a color composite image derived from the Thermal Infrared Multispectral Scanner (TIMS) [*Kahle and Goetz*, 1983] were supplied at the start of the exercise. The TIMS image that was initially posted was not the band 5/3/1 RGB image that was intended owing to a processing error. After some initial confusion the problem was recognized, and the correct TIMS image was posted a week later. Marsokhod acquired color and monochrome image frames, and mosaics were assembled during the field test. Rover instruments acquired thermal and visible/near-infrared (VIS/NIR) spectra of both near-field and far-field objects of interest. Data were used in their acquired format, and secondary products were produced by team members during the test to provide additional insights. Data manipulations included production of stereo pairs from the descent image and from the Pan Cam images as well as assembly of digital terrain models. The mineralogy team provided rapid, preliminary interpretations of spectra.

The chronology of events and data availability are shown in Table 2. The actual location of the landing site at Silver Lake, north of Baker in southern California, was not revealed to the science team members until the end of the mission. This experiment was as much a test of team dynamics [*Thomas et al.*, this issue] and interaction with a rover as it was a geologic investigation. Therefore this paper will include a more chronological approach to observations than normally is provided in many geologic reports.

The following sections describe placement of the rover and the geomorphology and geology as viewed during the active phase of the field test. These observations were used to construct a geologic history of the region. For comparison, see on-site geologic mapping [*Grin et al.*, this issue] and thin section analysis of simulated returned samples [*Johnson et al.*, this issue].

2. Observations

2.1. Regional Geomorphology

Orbital images were used to establish a regional geomorphologic context, and descent images (Figures 1a -1d) were used for the geologic and geomorphologic analysis of the landing site area. Science team members conducted rock abundance and size distribution data and constructed preliminary geologic maps from descent images (Plate 1) prior to deciding the initial rover traverses. On the basis of analysis of vegetation and erosional patterns seen in these images, the science team determined that Marsokhod rover was located in a rocky desert region where rainfall is scarce and discharge in streams and gullies occurs only after occasional thunderstorms. The region, as seen in descent image 1 (Figure1a) and in the digital elevation model, consists of a mountain block and adjoining intermountain basin. Rugged hills west of the landing site are flanked by an eastward sloping alluvial apron that merges with the surface of a dry lake (playa) located east of the landing site. Small, isolated, dark hills are scattered to the east and northwest of the landing site. Dark material comprises the major part of the mountains; however, the slope nearest the landing site is predominantly light colored. The alluvial apron varies in color depending on the local supply of rock debris or differences in the degree of rock varnish development. Two large stream courses drain from the interior of the mountains. One channel, south of the landing site, drains south and east out of the hills toward the playa. Another channel separates the lower light colored hills from higher-standing dark material along the northwest edge of the image. This channel emerges from the mountains and dissects a large, dark alluvial fan in the northern part of the area. A third channel has cut a steep-sided gorge into the rolling surface of dark material north of the playa. A set of anastomosing channels drains eastward across the landing site. Many small, intermittent channels and washes (arroyos) cut apron materials and drain toward the playa.

Descent images and a surface panorama imaged by the rover (Plate 2) were used to determine the initial location of the lander and to analyze local geomorphology. From the descent image, major channels and smaller arroyos could be identified in the vicinity of the landing site. Arroyos were primarily revealed by concentrations of dark vegetation. Comparing features shown in the color panorama with features from the descent images allowed triangulation of the rover's position.

We developed a system of nomenclature based on the *Star Wars* movies for the features that could be viewed from the rover, with a few exceptions to this rule. Acorn Hill and White Rock were named after prominent characteristics in shape and/or color of these features. The names of features visible in the first panoramic image are shown in Plate 2.

2.2. Traverse Planning.

Although choice of the landing site was not at the discretion of the geomorphology or the mineralogy teams, the site was a logical place to begin a remote survey. Each rover move during initial traverses was based on data acquired at the previous rover position. This extremely slow process, which resulted in short traverses (tens of meters), was abandoned after the first three moves when we were allowed to direct the rover to travel to sites of prominent features hundred's of meters to kilometers away. Traverses after Station 3 were targeted for more distant sites. Six sites were eventually visited during the simulation (Figure 2).

From the initial location (Station 1) a Pan Cam survey allowed the science teams to characterize the surface near the rover and locate the rover in relationship to the surrounding terrain. The panoramic view showed the rover located on a cobble-covered slope. A distant mountain block and scattered hills broke the skyline. A rock cairn was seen in the middle ground upslope from the rover.

An initial traverse was planned upslope toward the rock

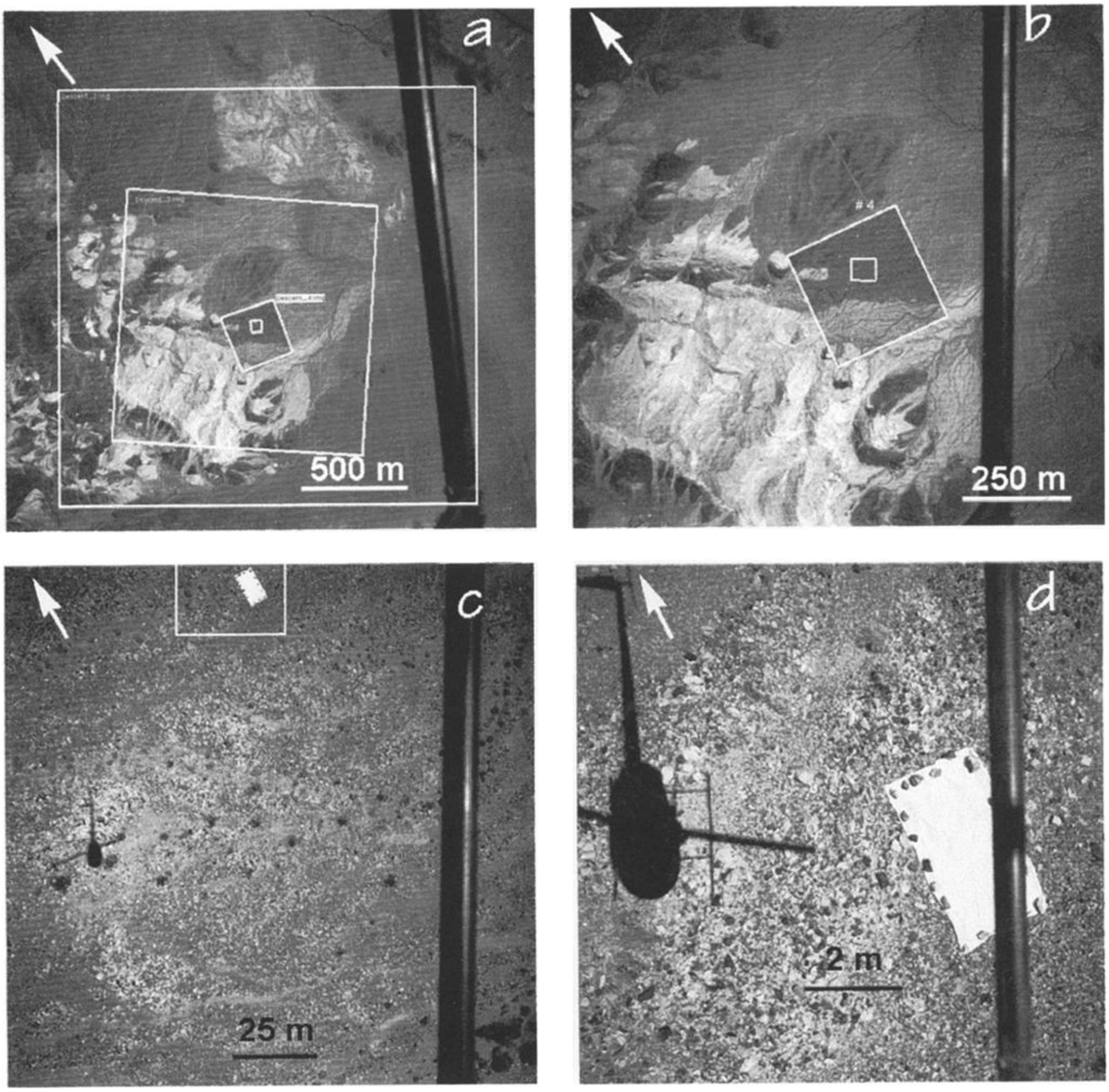

Figure 1. Simulated descent imagery of landing site. These four images show the landing site at increasingly higher resolutions. All images were simulated from a helicopter [*Stoker et al.*, this issue]. (a) Descent image 1 was taken at an altitude of 1888 m above the surface. The image has a resolution of 2.79 m/pixel. This image was used to determine regional geomorphology of the landing site area. (b) Descent image 2 was taken at an altitude of 1541 m and has a resolution of 2.33 m/pixel. This image provides higher resolution of the landing site area and was used in the creation of geologic maps. (c) Descent image 5 was taken at an altitude of 42.7 m and has a resolution of 0.05 m/pixel. The local distribution of rock versus sandy areas can be easily discerned. The landing site is located off the top right of this image. (d) The helicopter was only 10.57 m above the surface in descent image 6. The 0.01 m/pixel resolution available on this image allowed determination of the size-frequency distribution of rocks and permitted the team to begin traverse planning. The white rectangle is 2 x 3.5 m in size.

cairn, visible in the panoramic image and descent image 4, to obtain a better view of the nearby hills and mountain ridge (Boba Fett Peaks, Han Peaks, White Rock, and Acorn Hill). A view from this location (Station 2) would allow production of stereographic images and would reveal whether a traverse closer to the White Rock or mountains would be possible.

The rover was moved 10 m along this path to Station 2 next to the cairn (Emperor). After taking a panoramic image at this location (Plate 3), it was determined that further traverse upslope would be impractical. The rover was then directed to move 25 m downslope to Station 3 on the edge of an arroyo. A partial pan image was acquired, and a scuff test was performed

Table 2. Chronology of Availablity of Data to Remote Team

Date	Notes
Feb. 6	descent images available
Feb. 8	
0800 UT	Station 1 panoramic camera mosaic received
1700 UT	panoramic images posted with rock labels
1730 UT	sharp images of hills posted
Feb. 9	
0900 UT	more images of hills posted; oral presentation pf near- and mid-ir results
1100 UT	incorrectly processed TIMS image posted
1200 UT	full-resolution close-up images of rocks at station 1; preliminary geologic map overlays of descent images and sharp images of hills
1330 UT	IR results posted
Afternoon	Station 2 black and white panoramic mosaic
Feb. 10	
Morning	VIS/NIR spectra of "Valentine" orally communicated (desert varnish coating on siliceous rock: wrong rock?); near-IR spectra of dark rocks suggested to be desert varnish coated silicic rocks (quartzite, not basalt; incorrect based on later information
Feb. 11	
1100 UT	First-pass geologic history
Feb. 12	
Morning	Oral communication of mid-IR spectra indicating dark rocks are basalt, light rocks are dolomites (near-IR as well); Valentine: feldspar-rich (silicic plutonic or crystalline volcanic, probably plutonic)
Feb. 13	Station 3 abbreviated pan imagery
Feb. 15	Station 4 black and white panoramic imagery
Feb. 16	Station 4 shallow scoop imagery including near-IR correctly processed TIMS band 5/3/1 RGB image posted
Feb. 17	Station 5 color panoramic imagery
Feb. 18	Station 5 trench location imagery
Feb. 20	Station 6 color panoramic imagery
Feb. 25	geologic map and geologic history posted
Feb. 26	structural geology map posted
March 5	TIR of rocks at Station 1 posted; alternate geologic history posted
March 7	VIS/NIR of rocks at Station 1 posted
March 9	revised geologic map after review of spectral data and close-up rock images

using the rover wheels to scrape away the top few centimeters of soil. A soil sample was collected from the results of this test.

At this point it became permissible for the team to direct the rover to a new location, not limited by rover traverse time considerations, and the team selected several, long-range science sites. Station 4, northwest of Death Star Hill (Figure 2), was chosen because it is located on banded materials interpreted as a possible relic shoreline or banded outcrops of steeply dipping sediments. Station 5 was sited at the confluence of drainage east of the banded materials. The science team also selected two possible sites on the playa.

The field test for which the geomorphology team had originally been assembled ended with the observations at Station 4; however, the Robotic Arm Camera (RAC) [*Keller et al.*, 2001] and Astronaut-Rover (ASRO) field experiments continued to conduct observations with different instrumentation and emphasis [*Cabrol et al.*, 1999]. Inasmuch as these later field tests were performed at sites selected for rover stations in the original plan, we have included observations at the confluence of drainage (Station 5) and the northern shoreline of the playa (Station 6) in our final summary and interpretation of the geology.

2.3. Rover Observations

2.3.1. Stations 1-3: Alluvial apron. Stations 1, 2, and 3 were located on the alluvial apron not far from the foothills of Boba Fett Peaks mountain block (Figure 2). Panoramic images revealed that the highland west of the landing site is composed of interbedded light and dark colored rocks (Plate 4). In addition, outliers of bedrock materials are located as low topographic rises northwest of Station 1. The landing site is on one of at least four apparently active alluvial fans emanating from the highland. The fans have different surface tones produced by different mixtures of rock types and, perhaps, different degrees of desert varnish development. At Station 1 the rover was located on a low rise capped by cobble-sized desert pavement. The rise is one of many on a slightly rolling surface formed by cobble-covered interfluves and intervening sandy, anastomosing washes (Figures 1c and 1d). The fan surface served as a grab bag site of blocks, cobbles, and pebbles carried in from the mountains to the west. Rocks in the rover's near field (Plates 3 and 5) consisted of at least two principal rock types and perhaps as many as five. The most obvious distinction was between light and dark rocks. A detailed survey of rock sizes and colors was conducted to better characterize the surface and the probable source areas of the materials [Folk, 1968]. Color distinctions included white, tan, pink, multicolored, and dark rocks. Brown and tan rocks on the fan probably represented units with brownish hues in Acorn and Han Peaks.

TIMS data (Plate 5) indicated that light materials of Boba Fett and White Rock consisted largely of carbonates. Much of the dark rock around Boba Fett Peaks appeared to be mafic igneous rock, which makes up a large portion of the dark fans.

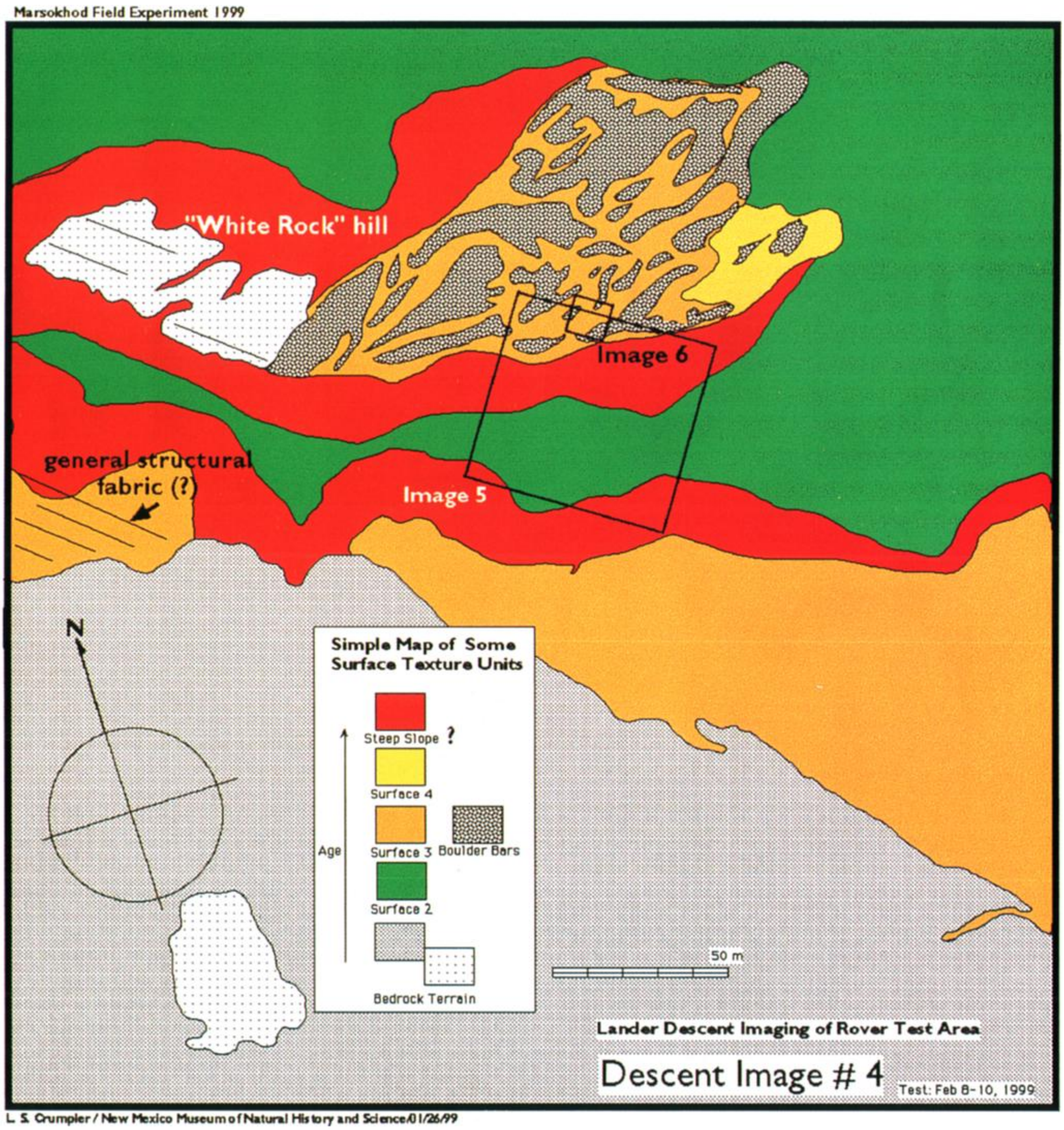

Plate 1. Preliminary photogeologic map. Immediately prior to the first day of the field exercise and on the first day, geology team members at Ames produced preliminary geologic maps at various scales from descent images. These maps allowed the team to begin their analysis of the geologic setting and plan targets for further study. This photogeologic map produced from descent image 4 (see outline in Figure 1b) records the location of bedrock materials and various alluvial surfaces in the landing area.

Plate 2. Station 1 color panorama. The Marsokhod cameras produced this 360° color panorama at Station 1. The names of the geographical features discussed in the text are shown. This image was used to determine the location of the landing site (when compared to descent images 4 and 5) and to plan subsequent traverses. Emperor is a rock cairn ~10 m from Station 1. White Rock is a low relief outcrop visible beyond Emperor, and Princess Leia Ridge comprises the foothills nearest the landing site.

Pink and tan rocks were originally interpreted as either silicic igneous or sedimentary rocks.

The mineralogy team, using infrared spectral data [*Johnson et al.*, this issue], identified the light colored rocks as carbonates consisting largely of dolomite and perhaps some calcite, whereas the dark rocks were interpreted as desert varnished silicic rocks. Additional spectra obtained at Stations 1 and 2 indicated that dark rocks of the fan were variably varnished and weathered mafic rocks. All light colored rocks were predominantly dolomite although some calcite and silicates (clay) or organic material may have been present. Finally, pinkish rocks, as Valentine, clearly were feldspar-rich, and may be either silicic plutonic or highly crystalline volcanic rocks.

2.3.2. Station 4: Banded terrain. This station is located on a flat surface just west of Death Star Hill, next to two mounds called Wedge and Biggs. In descent images this site exhibited a banded appearance caused by subtle variations in color and tone. Banding is parallel to the playa shoreline and has a weakly developed trellis drainage pattern. Fan deposits and drainage tend to be diverted around this patch of ground.

Panoramic imaging at Station 4 (Figure 3) shows the rover to be sitting on a flat, pebble-armored surface. A light colored hill breaking the skyline to the east was called Death Star Hill. A 50-cm-deep test pit dug at this station (Plate 6) revealed fine-grained, sandy materials beneath the armor.

The TIMS image indicates that alternating bands consist of quartz-rich material separated by areas with colors matching the alluvial fans [*Johnson et al.*, this issue]. Based on the descent and TIMS images as well as Pan Cam images of the trench, we interpreted the site as a paleoshoreline consisting of quartz-rich, sandy, beach materials alternating with erosional bands.

2.3.3. Station 5: Confluence of drainage. Station 5 was at the confluence of drainages, roughly 100 m from Station 4 at the southeast edge of the banded materials. Presumably, the drainage contains a sampling of material from upstream, including debris derived from the nearby Death Star Hill and from the more distant dark fan material.

A panoramic image from RAC revealed a sandy surface with low pebble abundance. Fines trapped in the lee of bushes on this image clearly indicated a wind direction from the north-northwest, which was consistent with directions of apparent wind-generated streaks on the TIMS image. Images of a trench (Figure 4) at this locality revealed a gravel-rich substrate, which was interpreted as alluvial material.

2.3.4. Station 6: Playa surface. Station 6 was visited by as part of the ARSO Experiment [*Cabrol et al.*, 1999], which tested the interaction between an astronaut and the rover as a field assistant. The geomorphology team included data collected during this experiment in their analysis. The station was near the shoreline at the north end of the playa ~1 km from Station 5. The rover imaged the hill slope adjacent to the playa (Plate 7) and the nearby playa surface. A steep slope capped by a resistant, dark layer of material overlooks the north shore of the playa. Large angular blocks of dark float litter the slope. The material subjacent to the dark material is not well exposed.

No spectral data were obtained at this site. Compositional inferences are derived from the TIMS image. Dark material north and east of the shoreline is blue in TIMS imagery and presumed to be mafic.

Mud cracks are apparent in the fine-grained materials of the playa surface (Plate 7). We infer that standing water, supplied by intermittent streams draining onto the basin floor after infrequent rains, periodically covers the surface. Mud cracks are

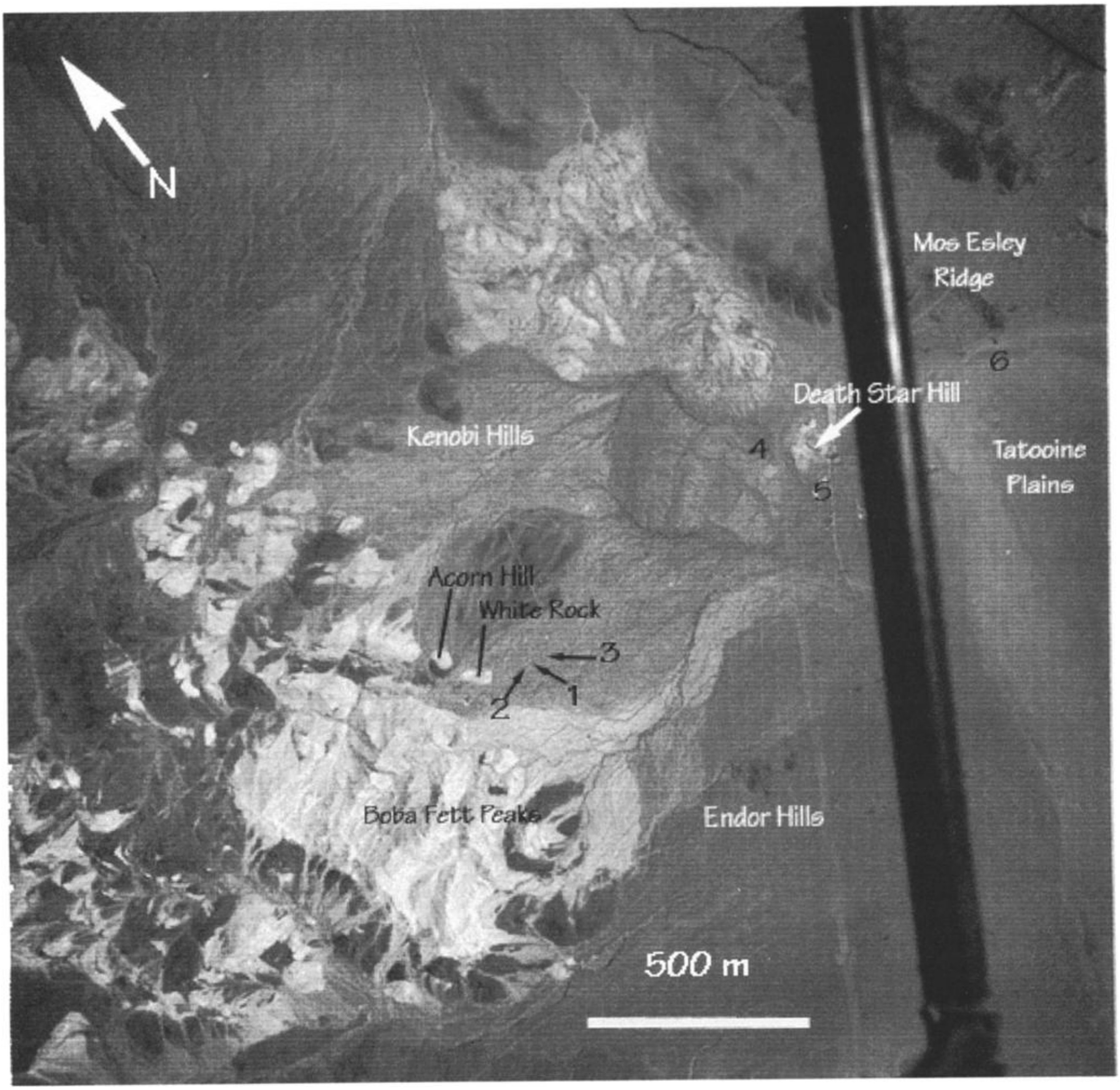

Figure 2. Station locations. Locations of sites visited by rover are marked on this descent image. Prominent landmarks referred to in the text are named.

consistent with a playa material grain size of mostly silt and clay. There is no direct evidence of evaporitic material, but it may be presumed to be present.

Light and dark surfaces are present within the playa. The tonal differences may indicate compositional variations or grain-size variations. The dark band parallel to the shoreline appears to be a gravel bar. Purple/magenta tints of the playa in TIMS imagery are consistent with a surface mixture of fine-grained silicates and, most likely, clays. Images of the surface by the rover give confidence to the opinion that the material is silt and clay-rich sediment.

2.4. Stratigraphy

Data acquired from orbit and by Marsokhod rover permitted determination of the major stratigraphic relationships of the region and allowed a reconstruction of a broad-stroke geologic history. Several members of the geomorphology team produced geologic maps at different stages of the exercise. Observations recorded in preliminary geologic maps were used to plan rover traverses and to provide a hypothesis that could be tested by new data received from the rover. Maps constructed later in the trial summarize geologic observations and illustrate relative age of

Plate 3. Station 2 color panorama. This partial panoramic mosaic was taken from Marsokhod after the traverse near the cairn (Emperor). This location provided a closer view of the nearby peaks. Talus can be seen at the base of the ridge. Cobbles of a variety of colors comprise the surface rubble and offer abundant targets for infrared reflectance determination of compositions. The scorpion replica on the cairn was placed there by the field team.

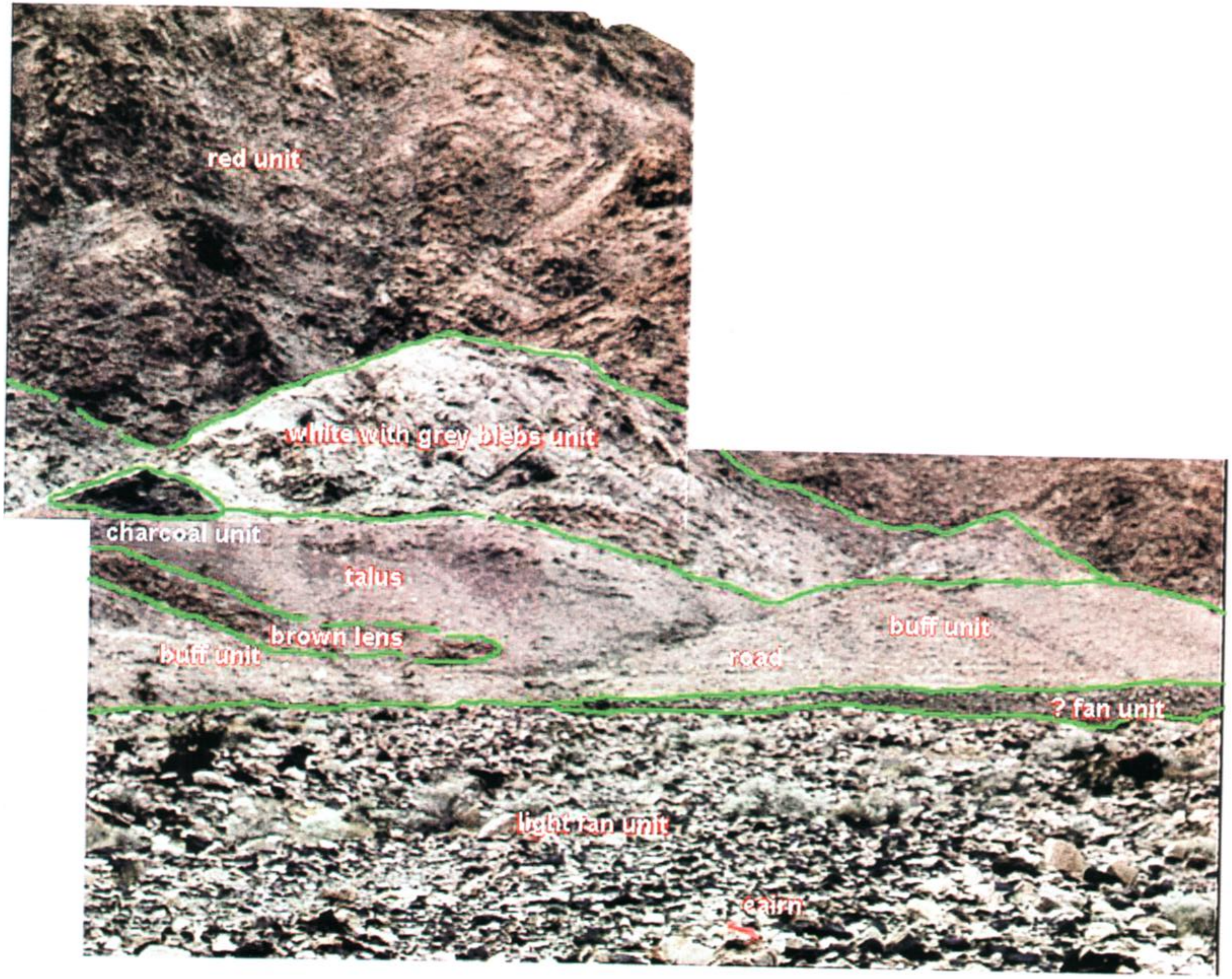

Plate 4. Mountain view. A variety of materials of Boba Fett Peaks were delineated in the mosaic obtained at Station 1. These materials are probably the source of cobbles at the landing site. They provided targets for long-range infrared study.

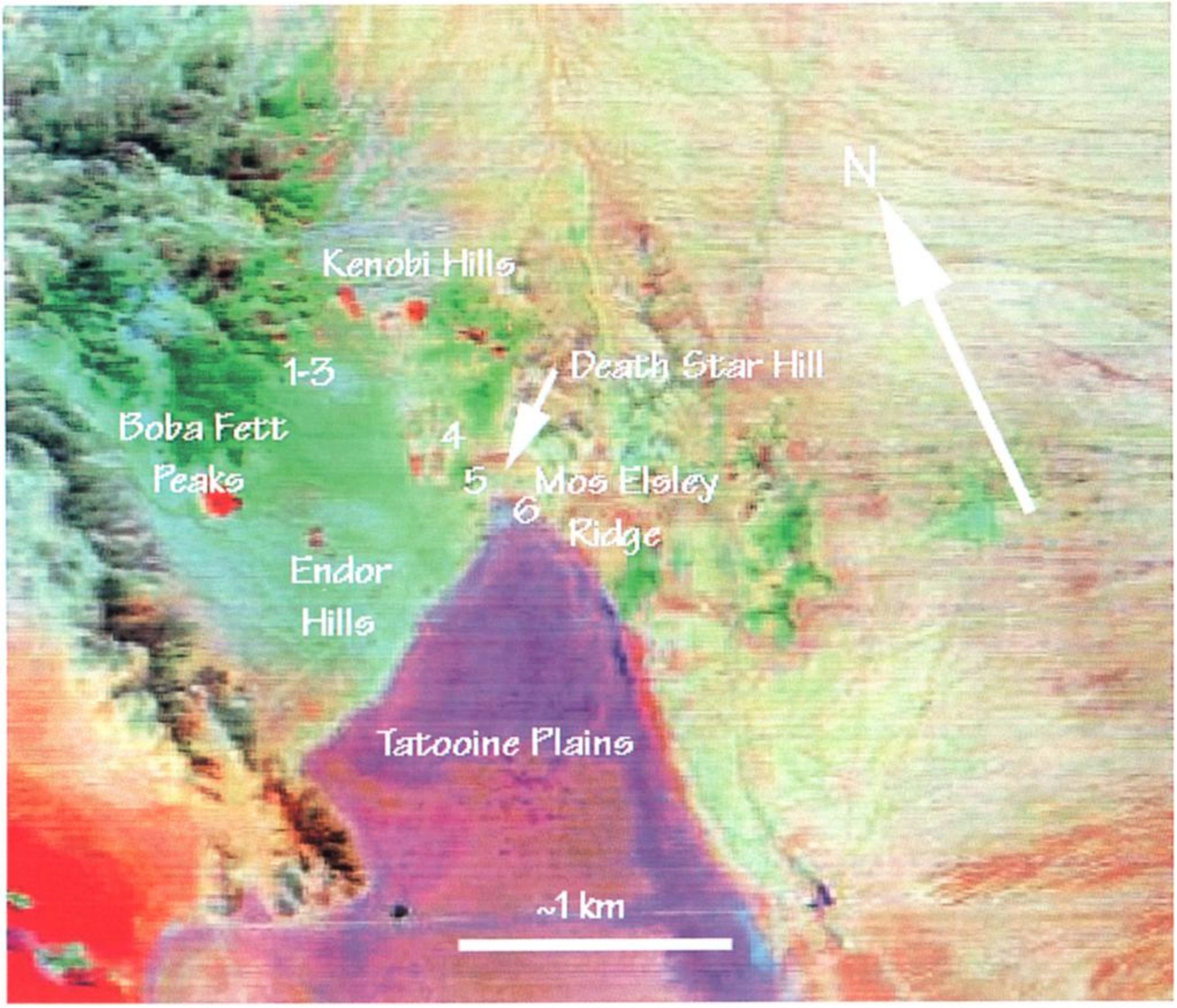

Plate 5. TIMS Image. Thermal infrared data have been coregistered with a SPOT image, providing a regional overview of rock compositions. Band 5 (10.2-11.1 nm) is red; band 3 (9.0-9.4 nm) is green; and band 1 (8.2-8.6 nm) is blue. Colors are indicative of rock compositions where silica-rich rocks are red; carbonate-rich rocks are green; and mafic or clay–rich rocks are blue. Major landmarks are annotated on this image.

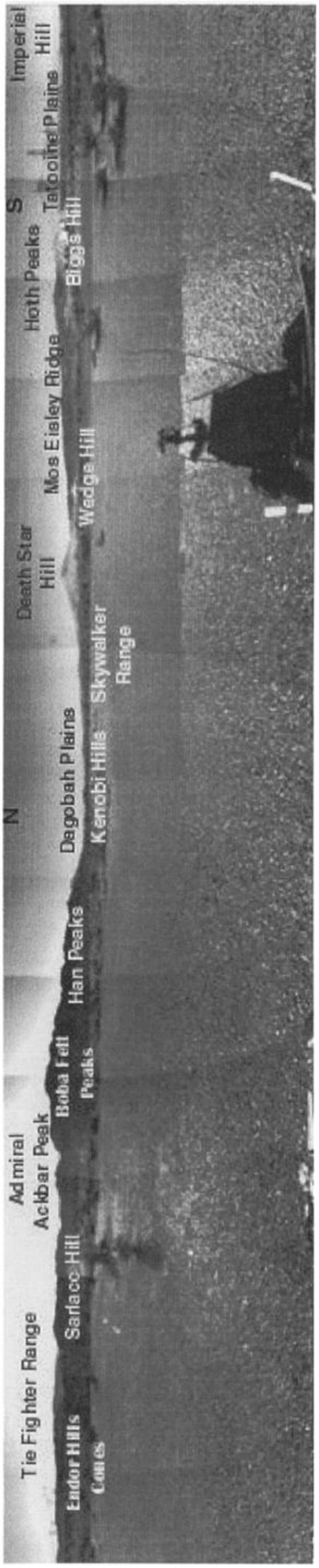

Figure 3. Station 4 panorama. Station 4 was located just west of Death Star Hill on a potential paleoshoreline. The panorama includes identification of major features discussed in the text. This site is characterized by a flat level surface with a uniform size distribution of surface materials.

events responsible for materials and structures. Two maps constructed near the end of the field trials are included here as Plate 8 and Figure 5.

Geologic materials in the area consist of older consolidated or crystalline materials and younger unconsolidated surficial materials. The oldest materials occur as stratified and deformed materials of the mountains. Deformed materials are probably pre-Cenozoic in age and consist of materials exposed as outcrops of consolidated sediments or metamorphic rocks and intrusive igneous materials. These materials include carbonates, silicic materials, and mafic materials.

Carbonates consist of coarsely crystalline dolomite and lesser calcite. They include the Boba Fett Peaks, White Rock, Death Star Hill, Hoth Peaks, and Alderaan Range. Carbonates apparently make up most of the hills nearest the landing site as well as light colored outcrops east of the landing site (including Death Star Hill, Wedge, and Biggs).

Intermediate tones on the descent images and red colors on the TIMS image represent quartz-rich units. These materials appear to be interbedded with carbonates in the mountains near the landing site. Conical knobs northeast (Kenobi Hills) and southwest (Sarlacc Hill and Endor Hills) of the landing site have the morphology of cinder cones, but their bright red color on TIMS data indicates a high quartz content.

Mafic materials are recognized as dark tones in descent imagery and blue hues in TIMS imagery. This material makes up the bulk of the mountains to the west of the landing site (i.e., Millennium Falcon Range) as well as dark patches within the region of predominantly carbonate material (i.e., within Skywalker Range to the east). Mafic material was interpreted to be intrusive mafic materials and/or amphibolite in the mountains.

Data from Thermal infrared (TIR) and VIS/NIR spectroscopy of rocks such as Valentine were interpreted as rich in feldspar and lesser quartz [*Johnson et al.*, this issue]. Assignment of outcrops for these rocks is somewhat problematical. Apparently, source regions are intermediate tone materials in scattered outcrops in the hills near the landing site. This material was interpreted as probably silicic igneous material and is probably plutonic rather than volcanic.

Resistant, dark material, capping the surface north-northeast of the playa (Dagobah Plains), appears dark in descent images and bluish in the TIMS image. No VIS/NIR or TIR spectra were obtained for these materials. The material is cut by a deep valley but otherwise appears relatively undissected. This material was interpreted to be relatively young basalt on the basis of its apparent position of capping light materials above the playa shoreline (Plate 7).

Alluvial materials consist of an unconsolidated alluvial apron formed by coalescing alluvial fans and recent channel materials that flank the east side of the mountains. Either the older fans derive a larger part of their lithology from predominantly dark materials or the material may be light material that has been highly varnished. Playa materials, materials of active channels, and minor eolian materials are among the youngest of the region.

3. Geologic History

We suggest that the earliest recorded geologic event in the region was the deposition of carbonate sediments in warm shallow seas, perhaps with interstratified quartz-rich sediments. The high proportion of dolomite in the carbonate rocks

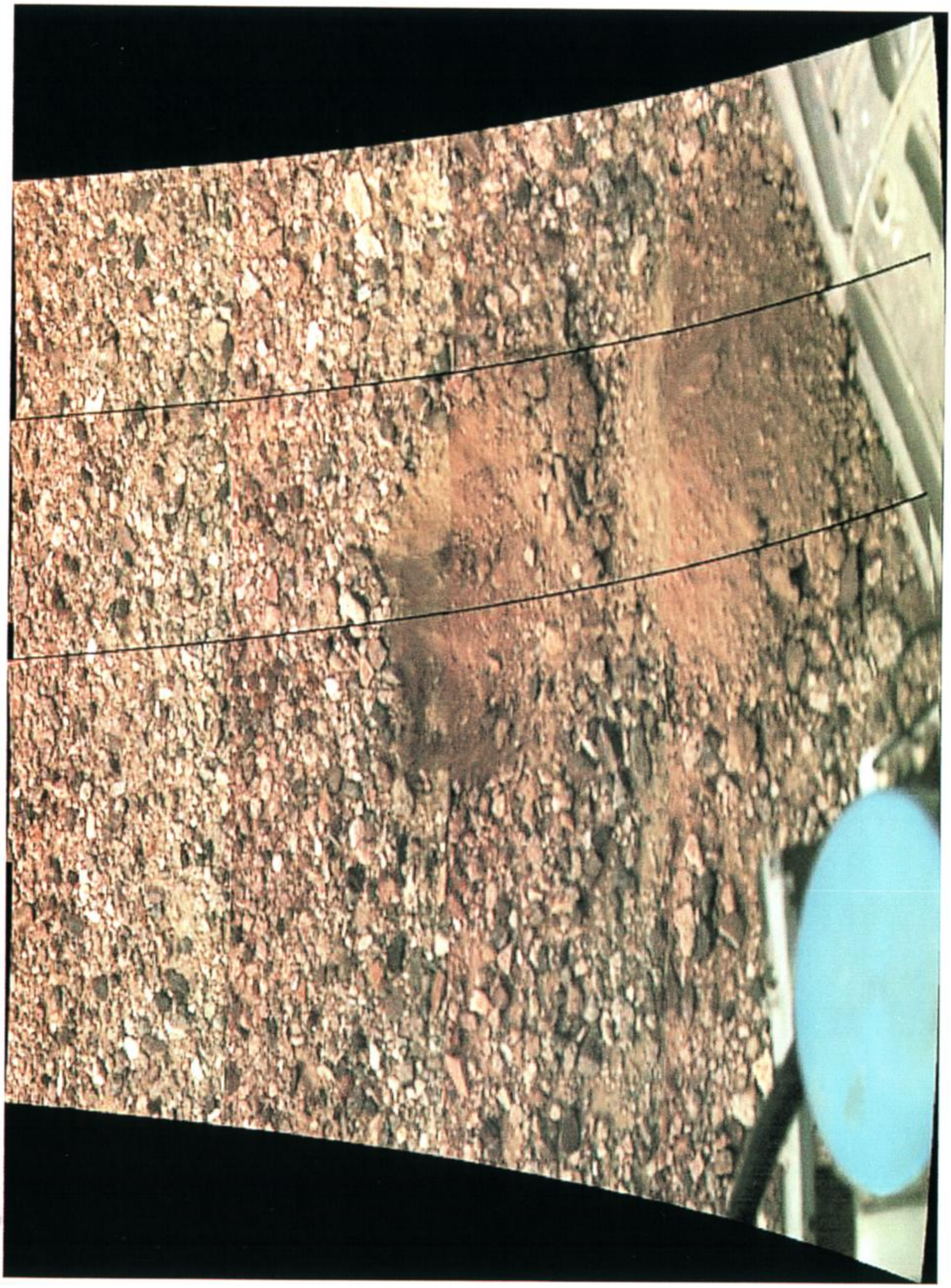

Plate 6. Test pit at Station 4. Fine-grained material comprises the substrate beneath the armored surface. The ability to dig beneath the surface added to the geomorphology team's ability to interpret local geology.

Figure 4. Trench at Station 5. The RAC experiment included a trench and "hand lens" imaging of materials retrieved from the trench. A gravel-rich substrate is consistent with alluvial materials.

indicates that the brines from which the carbonates were deposited were high in Mg/Ca ratios or that these sediments were originally deposited as limestones and diagenetically altered.

These sediments were buried and metamorphosed. They may have been metamorphosed through contact with intermediate to silicic plutonic bodies. Alternately, they may have been buried deeply by an ancient compressional tectonic event and have undergone regional metamorphism. Intermediate-to-silicic magmatism occurred in the area after the original sedimentation and before a portion of the subsequent tectonism and erosion.

Extensional tectonism and erosion exhumed the metasedimentary units and igneous materials. Normal faulting created mountain blocks and intermountain closed basins. Erosion (mass wasting and fluvial) generated an alluvial apron that blanketed the lower slopes of the mountains and the basin floor. Differing surface albedos of alluvial fans are produced by different mixtures of rock types and, perhaps, different degrees of desert varnish (Figures 1a and 1b). Erosion of the highlands and deposition of alluvium in channels on these fans is intermittent and ongoing, but it is less active than in the past. Reasonably fresh fault scarps along the mountain front are evidence that extensional tectonics remain active.

Channels emptying out of higher regions onto the floor of the basin supplied water, which ponded in the closed basin to form a lake. A paleoshoreline provides evidence that the lake levels in the past were much higher than the present-day seasonal lake. This high stand of the lake represents a climate regime wetter and probably cooler than that of the present. Continued fan growth partially buried much of this early shoreline. Mafic volcanism and plutonism occurred during extension. Deformed mafic materials to the west of Princess Leia Ridge clearly preceded extension. Undifferentiated mafic units proximal to the playa appears to be truncated by paleoshorelines. Therefore most or all of the mafic magmatism preceded playa lake development and at least a portion of the extension.

Even in the much more arid climate of the present, the playa continues to periodically fill with water, as indicated by the presence of fresh mud cracks in unconsolidated sediments. Fine sediment trapped in the lee of bushy vegetation indicates an average wind direction of approximately north-northwest. This is consistent with streaking visible on the TIMS image and indicates an active eolian regime.

Although there is no way to assign absolute ages and despite the fact that no index fossils were observed [*Newsom et al.*, this issue] to assist placing these materials into a time-stratigraphic context, it is reasonable to assume that the rocks and landforms imaged by Marsokhod rover record a long and involved geologic history. Carbonate sediments commonly imply marine sedimentation in warm, shallow seas. These materials provide excellent candidates for close scrutiny in the field and in the laboratory in the search for signs of ancient life. Sandstone represents a more energetic environment, but it should not be overlooked as a possible host for fossils, especially if it represented a nearshore facies. Because the sediments are strongly deformed, they and the accompanying igneous materials were presumed to be older than Cenozoic. On the other hand, basalt north of the playa, alluvial fan material, and playa material were presumed to be young. Basaltic volcanism probably occurred prior to and during regional extension. Preservation of surface morphology of paleoshorelines associated with the high stand of the lake probably correlates to pluvial lake formation during the more humid climate associated with Wisconsinan Glaciation [*Harden*, 1998].

4. Discussion

Orbital image data of the region were necessary to place the landing site in a geomorphologic and geologic context. Landing

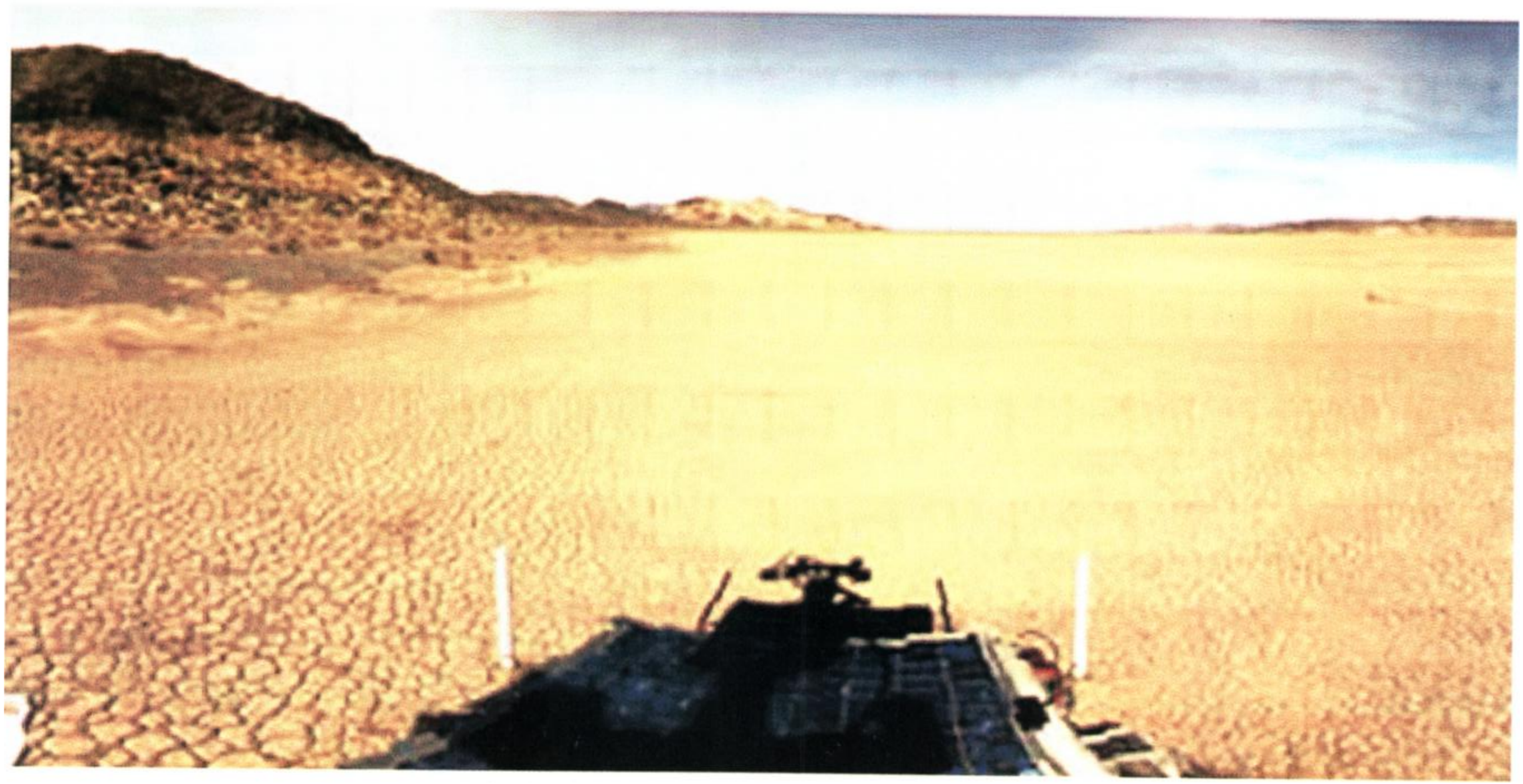

Plate 7. Partial pan at Station 6. The rover field team visited Station 6 as part of the ASRO experiment. Located near the shoreline at the north end of the playa ~1 km from Station 5, this image reveals a resistant dark layer of material capping the slope above the shoreline. Mud cracks on the playa surface indicate that the area continues to be affected by periodic saturation.

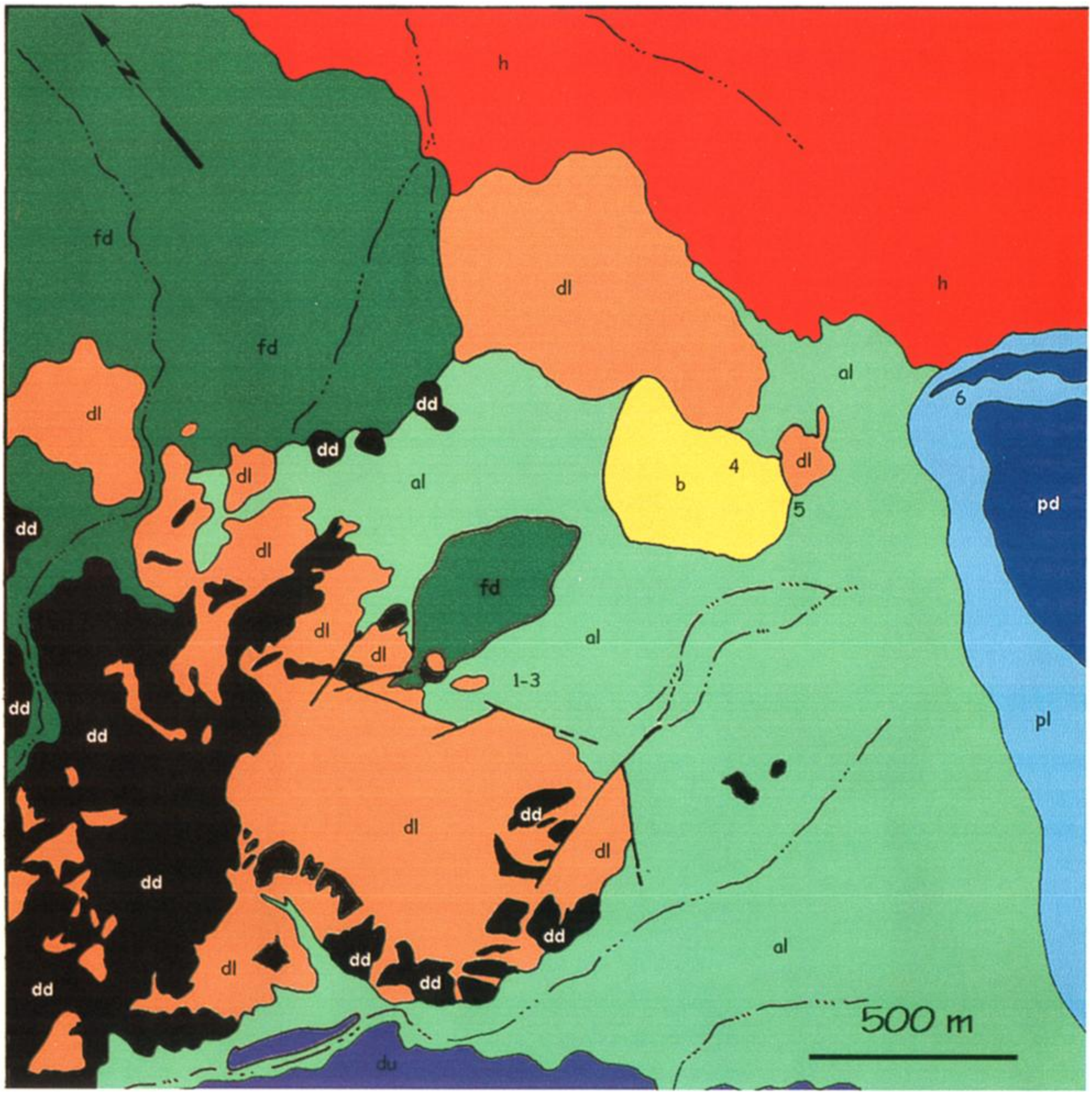

Plate 8. Geomorphologic sketch map. This map represents one attempt to summarize the geology of the region using tonal and geomorphologic characteristics as the primary criteria for subdivision. The surfaces from oldest to youngest are as follows: du, undivided deformed material; dd, dark deformed material; dl, light deformed material; b, banded material; h, horizontal (dark) material; al, alluvial apron material; fd, dark fan material; pl and pd, playa material. Mapping is based on descent image 1.

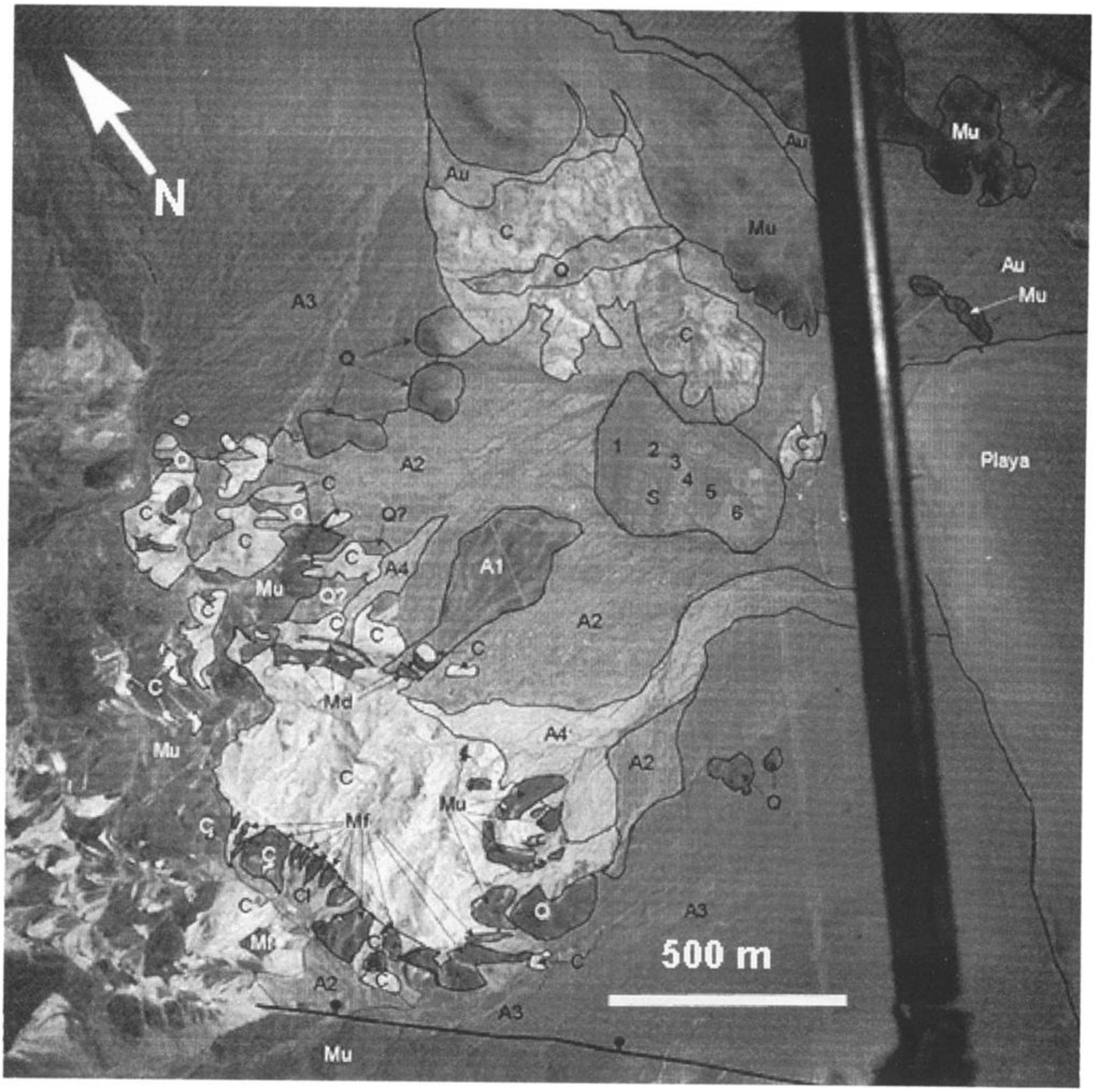

Figure 5. Geologic sketch map. An interpretation of the geology of the region emphasizes the compositional interpretation of the materials. Units in order of apparent age are as follows: Mu, mafic volcanic or plutonic units undifferentiated; Md, mafic dikes or sills; Mf, mafic lava flows; C, carbonate rock; Q, silica rich rock; A1-A3 and Au, alluvial materials; S, paleolake shorelines; Cl, colluvium; and playa materials.

sequence images provided a view of the surface otherwise unavailable from orbit or lander perspectives. In a similar fashion, the TIMS data provided important compositional information that helped direct observations and that influenced construction of a geologic model of the region.

Returned samples from the field for petrographic analysis, which we did not consider in this study, provide ground truth and a check on the accuracy of interpretations based on remotely sensed data [*Grin et al.*, this issue]. Petrographic analysis adds an entirely different dimension to the project. Long range rock identification, even with the help of infrared instrumentation, is tenuous at best. Rocks interpreted as mafic during the mission are primarily dioritic intrusive rocks, metadiorite, and a variety of amphibolites *[Grin et al., this issue]*. Rocks identified as silicic rocks are altered monzonites, quartz monzonite, and granite. Rocks identified as calcitic to dolomitic were identified correctly. However, we were not able to detect whether some of these rocks are siliceous and contain forsterite and periclase, which would indicate very high-grade metamorphism. The prevalence of metamorphism in the region greatly decreases the possibility of finding fossils in these ancient rocks.

Visible/near-IR and TIR data posted during the exercise indicated the presence of hornblende in some dark rocks [*Johnson et al.*, this issue]. In retrospect, these clues should have alerted the geomorphology team to the dominance of amphibolites rather than basalt in rocks at the landing site [see *Grin et al.*, this issue]; however, the first look at spectral data was interpreted by the mineralogy team to indicate the presence of altered basaltic rock. This interpretation and the close-up imagery caused the geomorphology team to interpret these rocks as hydrothermal altered intrusive basaltic rocks. Continued exchange of information between geomorphology and mineralogy teams after the field test would have greatly improved geological interpretation.

The roughly 2-week period during which the field test was conducted constitutes the equivalent, in most respects, of a very brief field reconnaissance in which a geologist took a lot of photographs and attempted to determine the geology at a later date. In effect, the rover acted as a surrogate field assistant set down at a random location in the middle of the field area. It looked around, examined nearby rocks, and viewed distant scenery. It strolled to two other nearby sites to get a look at the terrain, local geology, and rocks underfoot. At one site it stopped and "kicked" the surface to get a better idea of the material on which it was standing. It then traversed to a new site, a kilometer away, without the benefit of looking at the geology along the way. At each new site it scanned the horizon for a distant view as well as looked down at the surface. It dug a shallow trench and examined the excavated material with a hand lens.

In many respects the rover operated as a semi-intelligent field assistant. It served as the eyes of a geologist not present at the site. Some observations were an improvement over those of a human geologist. For example, the rover had the ability to look at the scene in near-infrared and mid-infrared wavelengths. It could determine some of the mineralogical components that comprise the rocks in the distant hills without the necessity of hiking to the mountains and climbing steep slopes.

Although the rover was able to replicate some actions of a field geologist and it excelled in a few capabilities, it was at a disadvantage in most other respects. One disadvantage was limited movement. Whereas a human can climb over rocks, traverse steep slopes, and cross rugged terrain, the rover was simply unable to move as fast and as far as a geologist could. Nor could the rover pick up a rock, turn it around, view it from different perspectives, and then scratch it with a knife or break it with a hammer to determine its hardness or to view a fresh inside surface. It could not "feel" the texture of a fine-grained sediment as with a human hand or scrape a sedimentary rock gently against a tooth to determine if it was composed mostly of clay, silt, or sand-sized particles. The robot camera was not able to match the detail of the human eye, which resulted in a critical loss of useful geological information. Another disadvantage was the rover's inability to look at geology while traversing from one location to another. The final limiting factor is the extremely long time lapse involved in transferring information back and forth between the geologist and the rover in the field. Often, the rover management team had to develop commands for the rover for the next observational period before information was received from the previous command sequence. A geologist in the field has the ability to make real-time decisions about what to do next. Even more critical was the need for multiple command cycles to obtain requested data at a given site. A single science objective had to be achieved through many iterations of a basic command cycle. First, data taken in the field was transmitted to the science team. Next, the science team selected new targets from this data, and the necessary information was requested from the appropriate instruments. New commands were then uplinked and executed by the rover and, in some cases, by the associated field team. A portion of the resulting data was returned, and the science team was then provided the data that had been obtained. Discussions began again as to whether we should finish getting the originally requested data or change our near-term objectives. Finally, new requests were uploaded and the process was repeated. Experience has shown with past rover tests [*Stoker et al.*, 1998] that this time- intensive process cannot be substantially shortened given the limited data downlink bandwidth and command cycle opportunities. New technologies [*Gulick et al.*, 1999, this issue; *Gazis and Roush*, this issue] may help provide some onboard science understanding that will improve the prospects. This problem is even more severe during planetary missions. The resulting bottleneck severely decreases the mobility of the rover, and thus, science objectives have to be modest and continually reevaluated throughout the mission.

The operational difficulty thus imposed suggests that in real rover traverses of planetary surfaces, a better integration of proposed activities and actual downlink results will be necessary, or that long-range "alternative" plans may be needed for action during subsequent uplinks. However, an effort is underway [see *Gulick et al.*, this issue] to develop a system of fast, autonomous image analysis algorithms to enhance science return, decrease data volume, and reduce the number of command cycles required to obtain data to address this problem. An experimental prototype system was tested during the field test [*Gazis and Roush*, this issue; *Gulick et al.* in this issue].

In the early days of geologic exploration of the western United States, a geologist would go into the field with a crew of field assistants who would be sent out in all directions from a central base camp to observe, collect samples, and report back. In a reversal of that technique, a crew of geologists (and engineers) sent forth a single robotic field assistant to observe, collect, and report back. We need to recognize the limitations that this reversal places on scientific inquiry.

References

Cabrol, N.A., J.J. Kosmo, R.C. Trevino, and C. R. Stoker, Astronaut-rover interaction for planetary surface exploration: 99' Silver Lake first ASRO experiment, *Lunar Planet. Sci.* [CD-ROM], *XXX*, abstract 1069, 1999.

Christian, P.R., D.D. Wettergreen, M. Bualat, K. Schwer, D. Tucker, and E. Zbinden, Field experiments with the Ames Marsokhod rover, paper presented at 1997 Field and Service Robotics Conference, Aus. Robotics and Autom. Assoc., Canberra, Australia, 1997.

Folk, R.L., *Petrology of Sedimentary Rocks*, Univ. of Texas Press, Austin, 170 pp., 1968.

Gazis, P. R., and T.L. Roush, Autonomous identification of carbonates using near-IR reflectance spectra during the February 1999 Marsokhod field tests, *J. Geophys. Res.*, this issue.

Greeley, R., A.T. Basilevsky, R.O. Kuzmin, C.R. Stoker, and G. Taylor, Science results from the Marsokhod test, Amboy lava field,California, paper presented at International Planetary Rover Symposium, Vernadsky Institute, Moscow, Russia, May, 1994.

Grin, E.A., M.K. Reagan, N.A. Cabrol, E.A. Bettis III, C.T. Foster Jr, C.R. Stoker, and T.L. Roush, and J.E. Moersch, Geological analysis of the Marsokhod Field Test from ground-truth sampling and mapping, *J. Geophys. Res.*, this issue.

Gulick, V.C., R.L. Morris, M. Ruzon and T.L Roush, Autonomous science analyses of digital images for Mars sample return and beyond, *Proc. Lunar Planet. Sci. Conf. 30th*, abstract 1994, 1999.

Gulick, V.C., R.L. Morris, M.A. Ruzon, and T.L. Roush, Autonomous image analyses during the 1999 Marsokhod rover field tests, *J. Geophys. Res.*, this issue.

Harden, D.R., *California Geology*, 479p, Prentice Hall, Englewood Cliffs, N. J., 1998

Johnson, J.R., et al., Geological characterization of remote field sites using visible and infrared spectroscopy: Results from the 1999 Marsokhod field test, *J. Geophys. Res.*, this issue.

Kahle, A.B., and A.F.H. Goetz, Mineralogic information from a new airborne thermal infrared multispectral scanner, *Science, 222*, 24-27, 1983.

Keller, H.U., et al., The MVACS Robotic Arm Camera, *J. Geophys. Res.*, in press, 2001.

Newsom, H., J.L. Bishop, and J.R. Johnson, Search for life on Mars in surface samples: Lessons from the 1999 Marsokhod rover field experiment, *J. Geophys. Res.*, this issue.

Stoker, C.R., The search for life on Mars: The role of rovers,*J. Geophys. Res. 103*, 28,557-28,575, 1998.

Stoker, R.C., et al., Marsokhod rover mission simulation at Silver Lake, California: Mission overview, data sets, and summary of results, *J. Geophys. Res.*, this issue.

Thomas, G., M.K. Reagan, E.A. Bettis III, N.A. Cabrol, and A. Rathe, Analysis of science team activities during the 1999 Maroskhod rover field experiment: Implications for automated planetary surface exploration, *J. Geophys. Res.*, this issue.

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(Received August 20, 1999; revised August 29, 2000;
Accepted October 13, 2000)