JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. E4, PAGES 7785-7806, APRIL 25, 2001

Nomad Rover Field Experiment, Atacama Desert, Chile
1. Science results overview

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Abstract. Nomad was deployed for a 45 day traverse in the Atacama Desert, Chile, during the summer of 1997. During this traverse, 1 week was devoted to science experiments. The goal of the science experiments was to test different planetary surface exploration strategies that included (1) a Mars mission simulation, (2) a science on the fly experiment, where the rover was kept moving 75% of the operation time. (The goal of this operation was to determine whether or not successful interpretation of the environment is related to the time spent on a target. The role of mobility in helping the interpretation was also assessed.) (3) a meteorite search using visual and instrumental methods to remotely identify meteorites in extreme environments, and (4) a time-delay experiment with and without using the panospheric camera. The results were as follow: the remote science team positively identified the main characteristics of the test site geological environment. The science on the fly experiment showed that the selection of appropriate targets might be even more critical than the time spent on a study area to reconstruct the history of a site. During the same operation the science team members identified and sampled a rock from a Jurassic outcrop that they proposed to be a fossil. The presence of paleolife indicators in this rock was confirmed later by laboratory analysis. Both visual and instrumental modes demonstrated the feasibility, in at least some conditions, of carrying out a field search for meteorites by using remote-controlled vehicles. Finally, metrics collected from the observation of the science team operations, and the use team members made of mission data, provided critical information on what operation sequences could be automated on board rovers in future planetary surface explorations.

1. Introduction

The Nomad Rover Field Experiment took place in the Atacama Desert between June and July 1997. The test area centered at 23°S68°37'W was selected because of the variety of features and characteristics that provided an excellent analog to planetary landscapes. As shown by the Pathfinder mission that landed on Mars in July 1997, the presence of a mobile vehicle significantly extends the range of planetary surface investigation and therefore multiplies the potential of successfully achieving the mission objectives [*Golombek et al.*, 1999]. Future missions to Mars will explore the Martian highlands to document the climatic, hydrogeologic, and possibly biologic and/or prebiotic evolution of the planet. It will be then necessary to analyze and document surface material, such as rocks and soil, and to acquire and cache diverse samples for subsequent return to Earth. Achieving these objectives will require developing exploration techniques and strategies allowing the identification of materials critical to document these questions. Sojournor showed that rovers could provide a powerful platform to identify, reach, analyze, and (in the future) retrieve the samples that are needed to complete the Surveyor Program. It also emphasized the critical need of testing techniques and science protocols that will optimize the coming missions. Among the main issues to be resolved, critical ones are the navigation, the trafficability, the communication, the science instruments, and the appropriate science exploration strategies. This paper focuses on the science issues that were tested during the Nomad Field Experiment and on what they suggest for planetary exploration. The technical and engineering aspects of the experiment are addressed by *Whittaker et al.* [1997] and *Wettergreen et al.* [1997].

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Paper number 1999JE001166.
0148-0227/01/1999JE001166$9.00

2. Test Site Relevance to Planetary Surface Exploration

The Atacama desert has been predominantly hyperarid since the middle Miocene [*Alpers and Brimhall*, 1988]. Because of the lack of precipitation (1 cm/yr from fog) and the high mineral contents of the soil, the vegetation is virtually absent. The Atacama Desert includes features that we expect to find on Mars (e.g. impact craters, volcanic materials, rocks of various sizes, aqueous sedimentary deposits, playas, loose sands, and various types of slopes and terrains ranging from rough to smooth). Ancient episodes of floods carved channels, now dry, that exposed outcrops of Mesozoic ages and left salars in basins *[Monti and Henriquez*, 1970; *Stoertz and Eriksen*, 1974; *Eriksen*, 1983; *Chong*, 1984, 1988; *Berger and Grosjean*, 1995; *Cooke*, 1997]. The region is tectonically active, with fault systems and fractures and high Cordilleran range formations, including volcanoes. The average elevation of the site is above 2400 m. The Plateau area associates flats and knobby and hilly regions (Figure 1). The daily temperatures during the field experiment varied between 0° at night and +25°C during the day. By its geological contents and context the site was as close as possible to candidate landing sites targeted for the Mars Surveyor Program and to planetary surface conditions that automated vehicles will challenge. The barrenness of the site provided a suitable analog for the search for life on Mars. Few plants are known to currently survive in this harsh desert environment. However, Jurassic seas and lakes were hosts of diversified life-forms (animal and vegetal) that have left fossils. The varied topography provided a challenge for traverse planning and for testing the capacity of Nomad's mobility in the perspective of future deployments on planetary terrain.

3. Overall Project and Objectives

The test was designed to simulate a long-distance, long-duration robotic operation on planetary surfaces. This goal was successfully achieved, Nomad becoming the first rover to perform a 215-km traverse in 45 days of experiment. During this operation, 1 week was devoted to science. The science experiment was directed by the NASA Ames Research Center (ARC). The rover located in Chile was teleoperated from ARC in California. The objectives of the science experiment were to (1) simulate surface planetary missions to Mars and the Moon and missions in extreme terrestrial environment (evaluating control environments' appropriateness and developing and evaluating exploration strategies); (2) assess the importance of various imaging techniques in planetary landscape interpretation, including panospheric imaging, pan/tilt camera, stereo, and close-up imagery; (3) provide a realistic desert experience for remote rover operators through high-quality imagery and virtual environment interface; and finally (4) attempt to understand the reasons of data misinterpretation during previous field *experiments [Stoker and Hine*, 1996]. The difficulty for evaluating this question resides in the many variables that can lead to mistinterpretation. To constrain the source(s) of this misinter pretation, several investigations techniques were tested during the Nomad experiment, including engineering and instrument improvement, science protocols and exploration strategies.

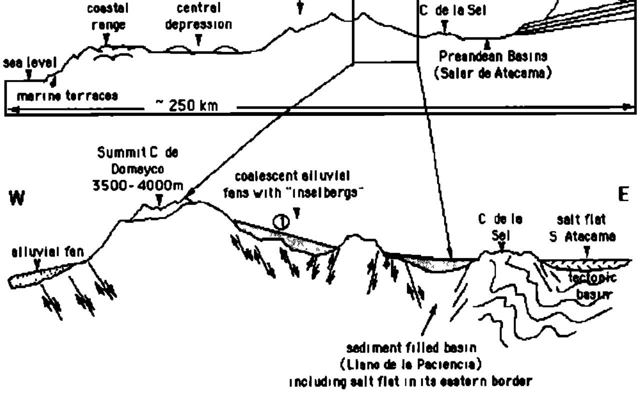

Figure 1. Geological setting of the test site area: 1 indicates the position of the rover on LS1, the first day of the science experiment.

4. Structure of the Experiment

The Nomad science experiment included four teams: (1) two science teams, one remotely located receiving the data at ARC and one in Chile with the rover (the role of the remote science team was to interpret, characterize, and reconstruct the current and past geologic, climatic, and possibly biologic history of the site from the data received from the rover. The field science team provided post-test ground truth. The results of the field investigation were communicated to ARC at the end of the week experiment for comparison.); (2) a rover operation team at ARC that was in charge of remotely teleoperating the rover; (3) a rover support field team that included engineers and technicians, and (4) technicians that supported the remote science team, including computing and network assistance.

4.1. Science Team Organization

Tasks and responsibilities were assigned to the ARC science team to optimize the information relay and operation effectiveness. The science team was composed of traverse planning specialists, a navigator, and several science team analysts (STAs). The STAs had to perform the imagery and instrument data interpretation, had to define the trafficability and navigation, and to keep the log of tasks and exploration strategies used to achieve the science objectives. The STAs reported to the science team leader. In Chile the field science team included three geologists who transmitted a daily report on traverses, stops, and targets investigated by the rover to the Lead Science Investigator located at NASA ARC. These daily reports were not communicated to the STAs until the end of the experiment. Designation of tasks and task contents are shown in Figure 2.

4.2. Nomad Rover

Nomad (Figure 3) is a robust 550-kg, four-wheel-drive/four wheel-steer rover. It was designed to perform long traverses in challenging terrain on Earth and/or on planetary surfaces. Nomad has an expendable/contractible chassis that makes it stable on steep slopes. Its characteristics are detailed in Table 1.

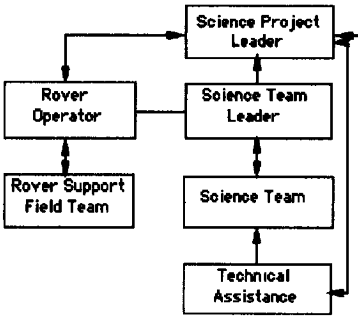

Fig. 2 CABROL ET AL : NOMAD ROVER FIELD EXPERIMENT, CHILE, 1

Figure 2. Structure of the science and rover teams. The science team did not have access to the field information. The field team communicated directly with the Project Science Lead, who was not involved in the science decisions.

4.3. Science Instrumentation, Communication, and Navigation

This science instrument package consisted of several imaging systems, which are detailed in Table 2. With no instruments enabling mineralogical or microscopic investigations, Nomad science payload provided an interesting challenge to test the ability of achieving science objectives with a limited instrumentation centered on imaging systems. The imaging systems were composed of four types of cameras: a human-eye high-resolution color stereoscopic camera pair identical to the one used in the 1999 Marsokhod Silver Lake field experiment [see *Stoker et al.,* this issue]; a monochromatic stereo pair; a wide angle monochromatic camera; and a panospheric camera. In addition to the imagery systems, the science instrumentation included a meteorological package described, in Table 2. During the meteorite search, Nomad was carrying magnetometers and a metal detector sled dragged behind the rover on a rigid tow-bar. The panospheric camera was an innovation compared to previous rover tests, where traditional cameras acquired panoramas and/or partial views of the test area. It provided views to the front and left side of the rover and horizon views to the right and back, generating a full panorama from 90° below to 30° above the horizontal [*Whittaker et al.,* 1997]. The panospheric camera gave the science team the possibility to observe the test area in any direction at anytime, even while the rover operator was driving. This capability gave to the science team and the rover operator the feeling of actually being in the field (Figure 4).

Figure 3. The Nomad rover crossing a channel. The ability of the rover to overcome difficult obstacles and challenging terrain allowed the science team to quickly reach distant science targets that proved to be critical for the overall understanding of the geological and biological history of the site.

Table 1. Nomad Specifications[a]

	Description
	Physical Characteristics
Mass, kg	550
Power consumption, W	2400
Size, m	1.8x1.8x2.4 stowed
	Locomotion
Wheel size, cm	76.2 diameter 50.8 width
Static stability, °	± 35
Obstacle, m	0.5 height, at least
Speed, m/s	0.5 maximum 0.3 average
	Sensors
Position estimation	IMU, GPS, gyrocompass, wheel encoders, skyline positioning from imagery
Navigation sensors	stereo cameras, laser scanner
	Computing
Real time computer	500 MHz 68040 and 40 MHz 68030 running Vx Works
Imaging computer	200 MHz Dual Pentium Pro running NT
Navigation computer	133 MHz Pentium running Linux
Safeguard teleoperation	remote driver, onboard safety Enabled
Autonomous	no human intervention
Direct teleoperation	remote driver, onboard safety disabled
	Communication
Data rate, Mbps	1.54 (total)
Equipment	wireless ethernet bridge using high-gain antenna for images and low bandwidth radio for status/command/control

[a]After *Whittaker et al.* [1997].

Images from the color cameras were retrieved as a single image or a stereoscopic pair (Figure 5). The color stereo pair produced the highest-resolution images available and were utilized for the final measurement of features. The best depth perception was obtained when the feature was ~5 m from the camera pair. The monochromatic camera pair produced images of lower resolution that were utilized for preliminary site characterization. Single images were used to produce 360° panoramas. The panospheric camera took a 360° image from a hemispheric mirror mounted on the rover and produced a dewrapped rectangular image projected on a screen. The rover operator could rotate the camera to view any 75° portion of the original panospheric image. The image was updated every second and received at NASA Ames with a 3-s satellite communication time delay. This frequency allowed the science team to gain a sense of motion. Images were utilized both for navigation and site characterization.

High data rate communication (shown in Table 1) was obtained using active pointing of the high gain antenna.

Table 2. Nomad Navigation and Science Package

	Description
Navigation and Science Imaging Systems	
Panospheric camera	1 k x 1 k at 6 Hz
Rear camera	1 k x 1 k grayscale, occasional
Compression	100:1; DSP based wavelet compression
High-resolution camera	3 CCD color camera with a pan/tilt mechanism for remote geology
Science Instruments	
Weather sensors	temperature, wind velocity, humidity
Magnetometers	meteorite search
Metal detector	meteorite search

Nomad could ascertain its position using an odometer, inclinometers, a gyrocompass, the inertial measurement unit (IMU), and the Global Positioning System (GPS). It also demonstrated new positioning technology by using panoramic skyline images to determine its position in the terrain map [*Whittaker et al.*, 1997]. At ARC the rover operator could assess the rover position and state using a virtual dashboard (Figure 6). The rover position plotted on aerial images was rendered in 3-D and updated in real time [*Wettergreen et al.*, 1997]. This innovative visualization system proved to be extremely efficient for localization, navigation, and science exploration.

During the week of science operation, Nomad was teleoperated from ARC. Although not applicable currently to the exploration of Mars, where science teams are directing rovers through command sequencing and time delays because of the communication windows and distance, this operation mode will become highly relevant when human crews land on Mars and use rovers as scouts to investigate the surroundings of their habitat [*Cabrol et al.*, 1999]. Therefore developing teleoperation strategies that make this type of exploration productive should be regarded as an important goal to achieve for the robotic program. Teleoperation is also highly relevant for lunar exploration, where communication delays are almost nonexistent (3 seconds roundtrip signal).

5. Mars Experiment

The overall goal of the different experiments during the week of science operation was to prepare near-term surface planetary missions by testing exploration strategies including (1) a Mars sample caching/retrieving mission, (2) a "science on the fly" mission, (3) visual and instrumental methods to remotely identify meteorites in extreme environments, and, finally, (4) a panospheric camera capability experiment, associated to a Mars time-delay simulation.

The Mars Experiment took place during the first and second days of the science experiment. The first day was initially planned to characterize the site and to select samples that better represented the geologic, climatic, and biologic history of the test site. The second day was planned to simulate a later retrieval of these samples by a subsequent mission (N. A. Cabrol, science plan, unpublished,1997) using GPS positioning and rover navigation from a new "landing site." In addition to the science objectives and navigation, another goal was to document the types of obstacles that Nomad was able to overcome in order to assess its trafficability potential.

5.1. Landing Site 1

The rover test site was located on the east flank on the Domeyco Range in the Chilean Precordilleran Range (see Figure 1) at ~2400 m elevation. The geological setting of the landing site 1 (LS1) included superimposed drainage systems cutting across ancient and recent alluvial plains. Ravines up to 10 m in height (average 2-4 m) were cut in the alluvial plains. The drainage was reactivated through active tectonism. Several inselbergs outcropping from the alluvium and mudflows were visible from LS1, as well as the salt flat of Llano de la Paciencia in the far ground.

5.2. Mars Experiment Day 1

At the start of the experiment the science team was provided a set of simulated orbital images acquired by an aircraft at 4000-m altitude with a Mars Global Surveyor Mars

Figure 4. On the left, wrapped panospheric image. On the right, the same image dewrapped as it appeared on the giant screen in the science control room at NASA Ames Research Center. The frequent update of the images provided the sense of being in the field, and in some instances, proved critical in helping characterize the environment.

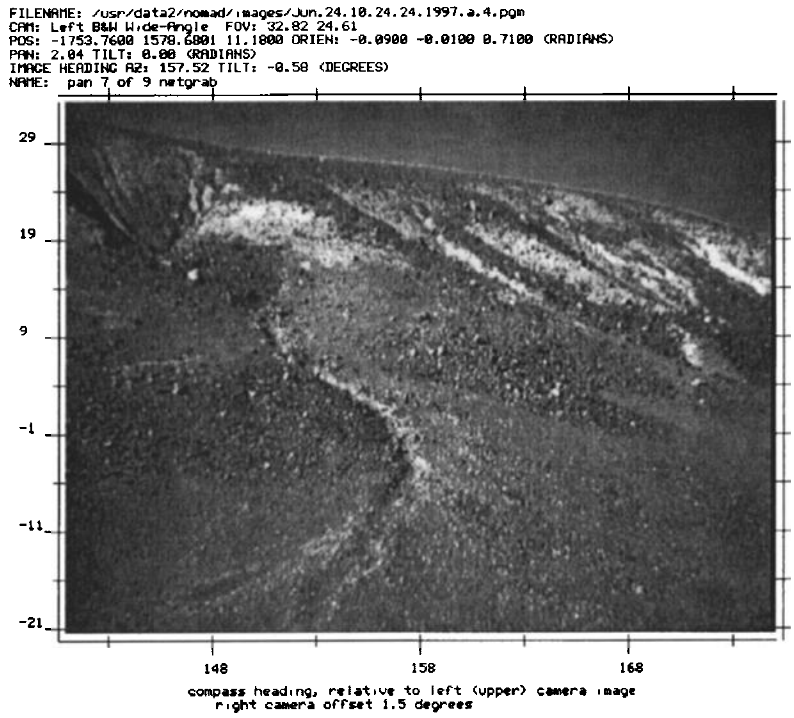

Figure 5. Example of image product delivered to the science team. The image was time-stamped. It also showed which camera was used, the heading, the position, and the pan and tilt orientation.

Orbiter Camera (MOC)-equivalent high-resolution of 1 m/pixel, and a stereo color panorama of LS1. An offset between the aerial imagery coordinates and the GPS on board the rover confused the science team members who were unable to localize the rover position at LS1 better than ± 200 m. This situation resulted in a significant loss of time (55 min) and further lack of orientation during the first day that required the initial plan to be revised. The reason of the offset was finally attributed to lateral movements, and/or pitch, of the aircraft while acquiring the images.

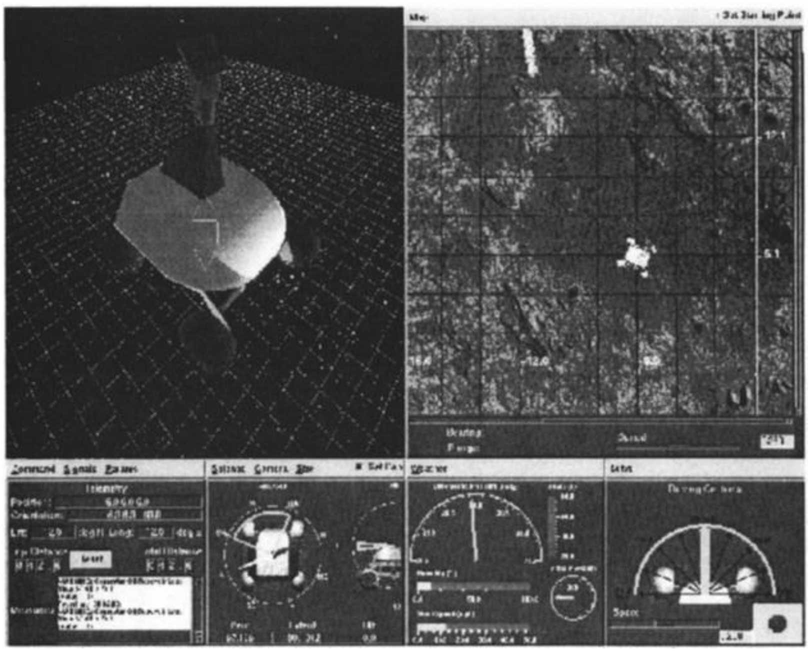

Figure 6. The virtual dashboard developed by the Intelligent Mechanisms Group at NASA Ames Research Center and used by the remotely located rover operator. The objectives of the virtual dashboard are to simplify the assessment of the current rover state, to develop the understanding of the environment, and to provide the operator the sense of being present at the site. It displays from left to right the telemetry panel, the science panel, the weather panel (pressure, temperature, wind direction, wind speed, and humidity), and the driving control. On the upper part, it displays the map panel, which shows the movement of the rover on the site map's background.

From the panorama and aerial imagery the science team members first documented LS1, which they described as relatively flat and gravelly, with scarps and local breaks in slope within a few hundred meters of the rover, the far horizon being characterized by higher-elevation terrain and mountains. Stereo images of the scarp were obtained in order to determine trafficability constraints. The science team planned then to investigate the geology to the south, southwest, and southeast of the assumed rover landing site position. Because of the offset and difficulty in reconciling the landscape as seen on the panorama with the aerial images, the science and rover teams were faced with serious trafficabi lity obstacles, the rover path being blocked by a series of unexpected (because they were not supposed to be in the vicinity of the rover) deep channels. Therefore most of a frustrating first morning of teleoperation and navigation was used to find a clear path with stereo imaging and panoramas to determine where Nomad could cross and reach the potential science targets identified by the science team. The science team then decided to split in two, one group studying the aerial photographs and panospheric images for navigation purposes, in an attempt to reconstruct the previous rover traverses and positions, the other studying the close-up images of the surface immediately adjacent to the rover for geologic analysis. This decision proved to be beneficial for the science investigation during the remainder of the day, the navigator providing landmarks to the science team for a better orientation. At the end of the day the Nomad's position was confirmed by the field to be ±100 m from the prediction of the science team.

After a 100-m traverse along a channel edge, a crossover was possible in a location where the scarp was a few tens of centimeters high. The rover then entered the channel, and the science team was able to analyze the geology close up (~5 m) in front of the rover. Using the panospheric cameras and stereo images, the science team members described the environment as "alluvium deposits showing possible aeolian reworking." A prominent mesa was then located on the horizon a few hundred meters southeast of the rover and targeted by the science team as a potential source of exposures that could help unravel the past geology of the region. This landmark was also used by the science team to ascertain the rover position. The last objective of the first day operation was to reach the identified outcrop. The rover was first directed to cross the streambed instead of continuing to move down the channel. However, the material was apparently loosely consolidated, and the team was constrained to moving down the channel instead of crossing.

5.3. Lessons Learned From Day 1

The sample caching strategy planned for the first day could not be tested because of the discrepancy in the rover positioning systems and the aerial map coordinates. This situation led to the modification of the objectives for the following day. However, the science team was able to acquire some information about the rover environment during the traverses and stops. They undertook the reconstruction of the sequencing of ancient channel activity and tried to estimate the contribution of the aeolian processes. The nature of the rocks and grain-size material was analyzed during the stops. The science team took advantage of the images acquired for orientation to perform science analysis. They correctly identified the paleochannel environment and, as a result, proposed the presence of four types of material: sorted rocks of uniform size located on the edge of the channel bench that Nomad followed before crossing the channel; alluvium deposits with aeolian reworking; fine-grained albedo deposits; and unconsolidated material on channel slopes that were later confirmed by the field team (G. Chong, field report, unpublished 1997).

Data relative to Nomad's trafficability abilities were also collected. The science team could test the ability of Nomad to overcome obstacles in different terrain. The total traverse length for day one was 150 m in particularly challenging terrain. The rover proved to be very efficient in climbing slopes of nearly 30° in smooth terrain and 17° slopes in unconsolidated terrain. Nomad was also able to overcome steep channel edges tens of centimeters high. This ability allowed the rover to traverse channels and obstacles that would have been traps for smaller rovers.

The panospheric camera that provided 360° images displayed on a large screen at NASA Ames was also an important asset, especially in the situation of lack of orientation, as at the beginning of the mission. The science team navigator could take advantage of the panospheric camera at any time to target landmarks and take bearings.

5.4. Mars Experiment Day 2

With no cached samples to retrieve, the following day was replanned and became an exploratory mission, where the science team had to reconstruct the past geology, climate, and biology. A new "landing site" was selected from the aerial photographs. The site was designated as LS2 and marked on the aerial images. These images were accessible by the field team via the Web. The field team positioned the rover where the science team requested the starting point for day two to avoid the discrepancy in positioning as encountered during the previous day. LS2 was located ~500 m southwest of LS1 (Figure 7). The science team made preliminary interpretations of the area around LS2 from the aerial photographs and from panoramas. Initial interpretation (before moving the rover) suggested that the area was composed of gravelly channel deposits immediately west of LS2, possible volcanic constructs ~500 m northwest of the site, erosion features at the base of the surrounding mountains, and sapping channels intersecting a main channel. A traverse including five stops was then designed by the science team to document the proposed interpretations.

5.4.1. Observation and interpretation from the science team and comparison with ground truth. The following section compares the observations and interpretation of the remote science team at Ames and the ground truth for the same sites as obtained from the field science team after the end of the field experiment (G. Chong et al., unpublished field report, 1997).

5.4.1.1. Site 1 : The science goal at site 1 was to obtain information on a ravine immediately southeast of LS2. Images were taken of the ground and the ravine, including black and white, mono color, and stereo color of the ground. Stereo images were also taken of the ground and wall southwest of LS2. The wall appeared to be highly eroded with a high-albedo surface material. The channel floor materials were well-sorted. Close-up views provided images showing layering of the high-albedo material. No interpretation of the geology was made at site one.

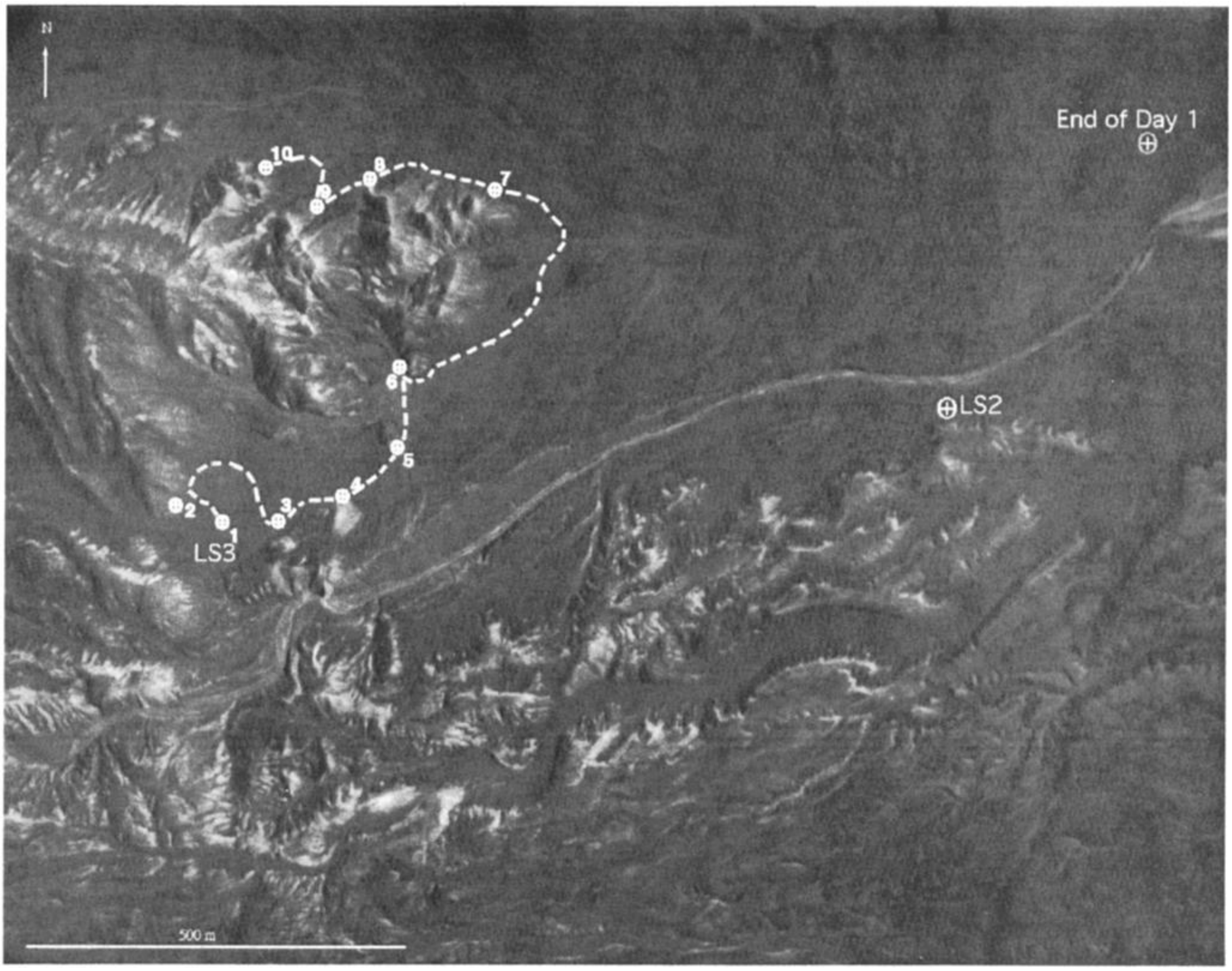

Figure 7. Aerial image of the test site area. These images were acquired at 4000 m of altitude by an airplane. They have a resolution of 1m/pixel. They were provided to the science team as simulated orbital images. They show the landing sites of day 2 and day 3 (LS2 and LS3) and the traverse completed during the science on the fly experiment (day 3). During day 3 alone, the rover covered a 1.3-km traverse.

5.4.1.2. Site 2: A close-up high-resolution stereo image was made of the channel floor (Figure 8a). It appeared to be well-sorted. The walls of the channel mouth southeast of LS2 are dissected and contained a high-albedo surface deposit. No layering was observed. Black-and-white images revealed cobbles, interpreted to be of volcanic origin (basalt). Following is the ground-truth as it appears in G. Chong (unpublished field report, 1997). The site is located in a 16-m-wide ravine made of alluvial material showing predominant boulders of volcanic rocks, some limestone, colloidal silica, chert, and sandstone. The clasts range from subangular to subrounded. Their size is between ≤ 1 cm and 40 cm. Exceptionally, a boulder reaches 80 cm. Some boulders are very well rounded, not because they have been transported but because they are eroded from former conglomerates. Their color is predominantly due to stained iron oxides. This site contains also an alluvial friable deposit covering the summit of the mound in the horizontal position and discordantly underlying red sandstone. It is composed mainly of conglomerates with moderate rounded boulders and a gypsiferous horizon. The gypsum is the main component together with friable sandstone of light color.

5.4.1.3. Site 3: Stereo and color images were taken of a surface layer unit on the channel floor located ~30 m from LS2. This layer appeared to be dissected and consisted of moderately sorted material, which was interpreted to be channel floor deposits from a high-energy environment. A stereo image of this unit and images of two structures on the horizon were taken to triangulate and determine the location. A third image was also taken of the geologic structures in front of the rover to confirm the exact location. A panoramic view of possible volcanic constructs on the horizon in front of the rover was also acquired. A large rock, initially interpreted to be possibly a volcanic bomb, was observed in front of the rover. There was a general consensus after closer study that the rock could be a volcanic bomb or possibly a large rock carried by high-energy floods. High-resolution images showed that this rock was fractured and possibly vesicular in nature. On the basis of the erosion pattern, the putative "volcanic bomb" appeared to have been transported for some distance. Following is the ground truth. Site 3 is located 26 m from LS2. To the left of the rover, major boulders of highly silicified (dacite?) subrounded volcanic rocks are visible. They are light gray in color. To the right of the rover and 6 m

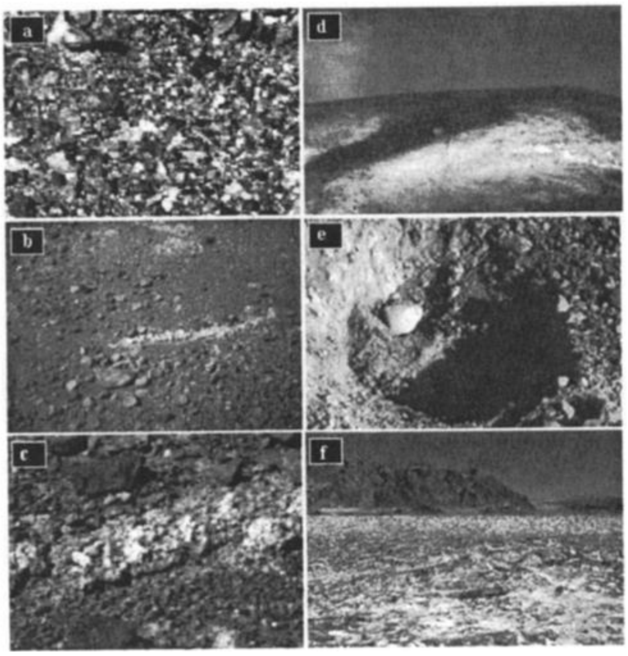

Figure 8. Gypsum exposed in the test site area: (a) in alluvial deposits mixed with volcanic material, (b) on the channel floor, (c) on the channel bench, and (d) as a light-colored material outcropping on the hills. (e) The spinning of the rover's wheels allowed the exposition of the subsurface material composed of fine-grained sediment containing rounded to subrounded pebbles and cobbles of mixed sedimentary and volcanic origin. (f) Ancient salar exposing bright white gypsum deposit.

away from the dacite, another reddish boulder of porphyritic andesite origin (50x30x40 cm) was proposed by the remote science team to be a volcanic bomb.

5.4.1.4. Site 4 and site 4a (in the continuation of site 4 exploration): This site is located approximately 30 m west-northwest of site 3. The science goal with site 4 was to study smooth channel deposits and a rock outcrop. A three-dimensional 3-D image was obtained of a massive terrace deposit that exhibited differential erosion and undercutting at the base. The science team also requested close-up high-resolution color images of another rock that appeared to be highly eroded. This particular rock was interpreted to be of pyroclastic origin. The walls of a mound in the vicinity of site 4 contained a high-albedo material (Figures 8b and 8c). Its nature and origin raised controversy among the team members. On the basis of image analysis, this material was proposed to consist of ash-fall deposits, salt (gypsum, nitrate, carbonate), or lag deposits. The material was also present on the floors of channels (Figure 8d) that dissected a mound at the site. Owing to trafficability obstacles, the rover was not able to come close enough to the outcrop at the initial site 4, so this stop was moved farther to the north and designated as site 4a. It was also noticed that at site 4 stereo images were not very useful when taken straight down at the ground, the rocks being relatively small and well sorted. Following is the ground truth. To reach site 4, Nomad drove to the east along the explored ravine and in some places drove along a slope of 22°. All materials observed within the channel are alluvial. Horizontal debris flows show boulders up to 50 cm that are subangular to rounded. Their origin is mostly volcanic with rare limestone. Following is the site 4a ground truth. This site was a second site explored in the vicinity of site 4 and is located along in the same ravine. At this site the science team raised a question about the difference of color between an underlying lighter colored horizon and a darker overlying. The science team assumed that they were two different units, which they actually are not. All profiles correspond to alluvial material, locally friable-clast supported, mainly debris flows with alternation of fine-grained material (sandstone) and coarser grain material (breccias and conglomerates). Gypsum is abundant. Exotic blocks can reach up to 80 cm or more. The reason for the lighter color in the basal part is a film of mud covering the wall, which was produced by a recent mudflow.

5.4.1.5. Site 5: Along the traverse to site 5, high-resolution stereo color images were taken of the rover track to acquire an understanding of the composition of the fine-grained sediments at the site. The right rover track exposed light material. The operation was then called at 15:30 LT without reaching site 5, the Sun setting in Chile.

5.4.2. Conclusions from Day 2. Overall the day 2 mission was a success, the new objectives being reached and the re-planned exploration strategy tested. The results obtained during day 2 were satisfying at various levels: (1) the science team made preliminary interpretations of the LS2 area from the aerial photographs and attempted to verify them by taking increasing advantage of both the imaging systems and mobility of Nomad; (2) 250-m traverse total was achieved by the rover to visit and document the five sites (including site 4a) designated by the science team; (3) the ability of Nomad to overcome significant slopes (22°) was confirmed. Also confirmed was the fact that Nomad had difficulty overcoming lower gradient slopes (17°) when the material was loose (see site 4 description).

From the science standpoint, interesting observations were made regarding the interaction between the science team and the rover and the mental process from which the experiment is run. On day 2, the science team started with preliminary interpretations of the LS2 area from aerial images (e.g., gravelly channels, possible volcanic constructs, erosion features, and sapping channels). The rover explored site 1 to document these hypotheses. However, no science interpretation of the site was made, and important information was overlooked, as if the science team thought that the images acquired from site 1 were not teaching anything new from the preliminary interpretations made from aerial photographs. However, as shown by the field report, important data could have been acquired by a detailed study of the material grain size and grain shape in the channel. This study would have been possible with the various imagery systems on board. A closer look at some of the rocks (volcanic clasts) would have provided support to some of the science team's preliminary interpretations made on aerial photographs concerning the proximity of the "possible volcanic constructs." It seems that in the overall goal of the day 2 operation (reaching and documenting five sites), reaching the targeted sites sometimes became more important than documenting them and shadowed the science investigation. At the following sites the decision on how long to stay at a target and when to leave became more associated with the science that could be achieved at the targets.

At site 2, good interpretation results were achieved. The science team used the close-up imagery to assess the origin of several rocks. A basaltic origin was proposed for a rock, and the volcanic origin was confirmed by the field science team. High-albedo surface deposits were observed by the remote science team, who proposed three hypotheses, among them the presence of salt (gypsum). Without instrument for mineralogical investigation on board, the science team did not, and could not, go further in the interpretation. These deposits were confirmed to be gypsum horizons by the field team. At this stage it seems that an accurate knowledge of the environment acquired during the previous stops, as well as the frequent use of the panospheric camera to constantly test the hypothesis about the environment, helped the remote science team members to stress the correct hypothesis.

At sites 3 to 4a the science team took increasing advantage of all of the capabilities on board Nomad and started to describe in greater detail the overall geologic setting of each site. At site 3 the interpretations proposed by the remote science team report were close to the field science team report. At site 4 the science team identified an interesting target on a slope of ~20°. Because of the unconsolidated nature of the slope material, the rover could not reach the target, its wheels starting to spin. However, the science team transformed this unfavorable situation into a productive, not preplanned science operation. They asked the rover operator to move back 2 m and to take a high-resolution image of the hole dug by the wheels to assess the characteristics of the slope material (Figure 8e). The success of day 2 can be related to two main factors: (1) the science team was able to locate the rover with respect to the aerial images and thus better assess the environment, as the entire operation time was devoted to science and traverse planning instead of orientation, and (2) the science team was becoming more acquainted with the rover's capability and the test site environment.

6. Science on the Fly Experiment

The goal of this experiment was to develop and assess a potential exploration strategy for long-traverse reconnaissance missions and determine whether or not successful interpretation is related to the time spent on a science target. Caching and retrieval of samples deemed critical was authorized.

The requirement of the experiment was to keep Nomad traversing 75% of the operation time, 25% (2 hours total) being devoted to stops on science targets. The operation was an association of navigation, trafficability, and science interpretation skills. The objectives of the mission were (1) to select science targets representative of the area in the range of the rover daily trafficability (this selection was done using aerial photographs.); (2) to send the rover to the targets; (3) to acquire as much information as possible about the local geology, biology, and climate while traversing to the targets using the imaging systems on board Nomad; and, once on the target, for the science team (4) use no more of 25% of the day operations to document the study site (e.g. stratigraphy, geology, climate, biology) during stops. A third "landing site" designated as LS3 (see Figure 7) was selected for this operation.

The goal was to perform a long reconnaissance traverse including a small number of major stops. After the analysis of the aerial photographs, the objectives of the science team were (1) to determine the origin of white outcrops, light colored units, and aligned promontories observed on aerial images (can sedimentary or volcanic origin be distinguished?); (2) to determine wether bedding and/or flow structures be identified; and (3) to determine whether or not the promontories were actually structurally controlled.

The planned traverse initially included eight stops. Two more stops were added on the fly to reach targets of significant science interest. At the end of the day, Nomad had covered a 1.3-km-long traverse, setting the record for a rover traverse during science operation and allowing the science team to achieve significant progress in its knowledge of the test area, including a cached-sample containing evidence of paleolife activity [see *Cabrol et al.*, this issue].

6.1. Science on the Fly and Comparison With Ground Truth

The following section compares the results obtained remotely by the science team during day 3, field notes during the experiment, and the post field test ground truth investigation of the site.

6.1.1. Sites 1 and 2 (at the landing site, a few meters apart). The science team requested a series of 360° black-and-white wide-angle panoramas to document both the surface around the rover and the landscape near the landing site. Outcrops of bright and dark material already identified on the aerial images were observed. In some places, darker boulders were visible at the bottom of the slopes. The panorama of the surface nearby the rover showed that the area consisted of alluvial material including regularly spaced larger rocks. The science team requested the rover to move several meters to acquire a close-up image. The close-up image requested of the floor revealed the presence of angular and flat clasts mixed with more rounded gravel-like material. From these images the choice to go to site 3, as selected from aerial images, was confirmed. Following is the ground truth. The rover was standing on an alluvial plain facing west with a slope of 2°-4°. Outcrops were visible ~15 m away to the south of the landing site. Alluvium materials of light colors (yellow, pink, and reddish) were predominantly of volcanic origin, with minor limestone, chert, conglomerates, and red sandstones. They were locally well rounded (G. Chong, unpublished field report, 1997). The hill corresponds to outcrops of a block conglomerate, polimictic at least 250 m thick, poorly sorted, with boulders up to 0.80 m. It is composed of predominantly volcanic rocks, angular to well rounded, plus sandstones, silica, breccias, boulders, and a matrix of coarse sand with volcanic components. Interbedded sandstones are present.

6.1.2 Site 3. The snapshots taken while the rover was approaching site 3 revealed light colored outcrops with float covering darker slope-forming material. Rocks and blocks of mixed bright and dark material covered the slope. A high-resolution color image revealed dark angular rocks, possibly of volcanic origin, that were contained in a matrix of fine-grained material of a lighter reddish color. There was a possible mixture of volcanic and sedimentary material. Following is the ground-truth. The rover stands looking to the south. The outcrop corresponds to a sequence of red sandstones 15-20 m thick. The sandstones are coarse-grained, partly conglomeratic. They are overlaid by horizontal, friable conglomeratic sediments with a wide range of lithologies: fluidic tuffs, volcanic rocks, silicific acidic intrusive rocks, intrusive tonalite, rhyolite, and calcarous rocks. Colluvium are observed along the slope.

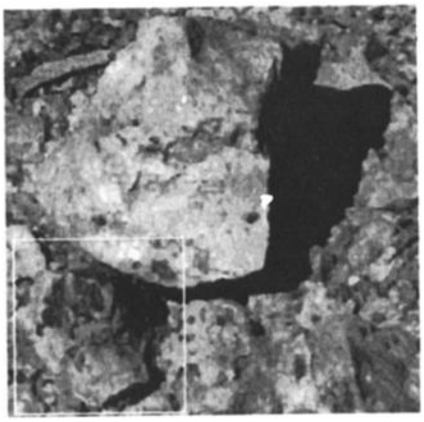

Figure 9. The box shows sample I-250697 in place in the field. The rock is ~18 cm high. The characteristic shape and albedo of the dark feature were what caught the attention of the science team. The rock looked different from the other rocks present in the field.

6.1.3. Site 4. An image of the outcrop was taken using the panospheric camera. Several boulders and rocks were observed along the slope. Among them, one rock showed a dark feature on its upper side. A high-resolution stereo image was requested. Compared to the surrounding rocks, the sample was noted to contain an "anomalous clast...possible fossil" by the ARC science team. Three hypotheses were proposed by the science team: (1) a possible fossil (ammonoid or algal mat structure), (2) a chert nodule, and (3) iron-rich conglomerate clasts. The fossil hypothesis was supported by the shape of the anomalous clast (Figure 9), and by the remotely interpreted environment in the vicinity of site 4. The rock was selected for sampling and numbered by the field team. Following is the ground-truth. The rock resembles a lacustrine limestone and is conglomeratic. It was probably formed in the proximity of an ancient coastline. The "anomalous clast" (possible fossil) designated by the science team is similar to other reworked fossiliferous material from the Jurassic Age found in the outcrop and in its surroundings. The fossiliferous material found at site 4 resembles corals, and algae-carpet material in places, with remains of shells. Most of these fossiliferous remains are associated to concretions (G. Chong, 1997, unpublished field report, 1997). Field hand-sample inspection of the sample I-250697 confirmed the presence of chert. Regarding the anomalous clast on sample I-250697, fossil algae mat material was the interpretation made by the field science team. The chertification process was so advanced that field observation could not verify the existence of any fossil remnants. The sample was shipped back to ARC and then to the University of Iowa for analysis, where the presence of fossils was confirmed. For a detailed description of sample I-250697, see *Cabrol et al.,* [this issue]. The age of the outcrop where this rock was found is Tithonian to Neocomian, at the margin of the Jurassic and the lower Cretaceous (140-100 Ma). The analysis of the returned rock provided a considerable amount of new geologic, climatic, and biologic information about a succession of environments in which the rock evolved. All of these aspects are discussed in detail by *Cabrol et al.,* [this issue].

6.1.4. Sites 5 and 6. Low conical hills were observed at these sites. The science team noted that the hills were covered with alluvium. No evidence of dikes, structure, or volcanic material was discovered. A soil experiment was performed by looking at the track of the rover as it backed off the hill. On its way to site 6 the rover crossed a drainage system to investigate structurally controlled volcanic terrain. From the observation of monochromatic black-and-white wide-angle image observation, the floor of the drainage system was proposed to be possibly cemented alluvium. One high-resolution color requested by the science team showed a rock massive, defined as possibly dense from image observation, with a possible dike contact of cross cutting dike.Todocument this preliminary interpretation, a close-up view image was requested. From this image the science team proposed that the material was possibly basaltic dike material. Further imaging of the drainage system was then abandoned because of the experiment time constraint and Sun angle on the slope, which resulted in poor-quality images. Following is the ground truth. Sites 5 and 6 were on the same outcrop, which was composed of friable conglomerates. Outcrops are obliterated because of the colluvium eroded from the outcrops. The rover was facing a large feature, which was first temporarily interpreted also as a possible dike by the field team but later confirmed as a volcanic rock boulder of dacitic-andesitic lithic tuff.

6.1.5 Site 7. A light colored outcrop was visible with float covering a darker slope-forming material. The outcrop was ~4.5 m-thick and medium-grained. It was interpreted as possible matrix-supported conglomerate at the base, middle beds of fine-grained sandstone interbedded light red to white, with top beds of coarse-grained clast supported conglomerate. Large float clasts were present at the base of the hill. Images were requested from two large boulders. Boulder 1 was proposed to be a conglomerate of fine-grained matrix, poorly sorted. Boulder 2 was also fine-grained with one stretched clast visible in the left middle part of the boulder. At the same site the science team described layered rocks. Their interpretation for the whole area was interbedded conglomeratic and fine-grained layers, possibly sandstone and conglomerate, or lahar and tuffaceous deposits. Following is the ground truth. Red sandstones interbedded with thin horizons of calcareous sandstones and conglomerates. The red sandstones can display cross bedding. Boulders in the colluvium can also include fossiliferous reworked septarean concretions. A dike is observed at site 7.

6.1.6. Sites 8-10. At site 8 the outcrop was ~1-m thick (calculation from 3-D model obtained from stereo images). It was described as fine-grained, indistinct bedding. Although not clearly visible on the first image, a possible disrupted bedding was visible on the second image of the site and was interpreted possibly as a massive exfoliated sandstone. Site 9, just a few meters away, presented several drainage systems, with a possible dip slope consisting of material similar to that at site 8. The science team requested a close-up view that showed medium-sized clasts in matrix-supported material. Fine-grained material outcrop as a dipping material was also noted. Finally, at site 10 a different type of material was observed and was described as horizon with light midslope material capped with dark material. The rock material was described as large clast bimodal, fine-grained matrix with very angular clasts, differing from previous conglomeratic material. No further interpretation was attempted. From the ground truth investigation, we learn that the material is composed of conglomerate, marl in the matrix, and rounded boulders. Isolated 40-cm blocks, which correspond to sandstones, red sandstones, and volcanic rocks.

6.2. Results

From the traverses and stops the science team was able to partially document most of the questions and preliminary interpretation raised by the survey of the aerial photographs at the beginning of the experiment. One of these questions was to determine the origin of the various light colored units.

Although a detailed description of the images was achieved, in some instances the imagery alone did not allow the science team to distinguish between sedimentary and volcanic material. This gap in interpretation would have been resolved by the presence of a spectrometer on board Nomad. The interpretation was also complicated by the fact that volcanic and sedimentary materials were both present on these units. However, in other instances, the science team was able to positively identify sedimentary structures such as bedding and grading at site 7 or volcanic materials. Combined with close-up images, which revealed the texture of the rocks, their interpretation of the presence of sandstones was correct, and the overall site characterization was close to the one provided by the field science team.

Another question raised by the aerial images was to understand if the light colored peaks in a linear strike observed in the aerial images were volcanic, which they were not confirmed to be. Instead, the suspect volcanic cones were later positively identified as outcrops of layered beds. The science team was able to confirm that they were structurally controlled and composed of dipping beds.

Overall, the comparison between the remote science team log and the field team ground truth shows that at the end of the day, although not all the preliminary interpretations were confirmed, most of the main components of the site geology had been captured by the science team, including the potential of this site to bear evidence of paleolife activity with the identification of sample I-250697. By what they discovered and what they missed, the science team members showed both the potential and limitations of the imagery. From this experiment it appears to be obvious that the aerial (so-called orbital) images and their MOC-like resolution of 1m/pixel allowed the science team to raise the correct issues and subsequently to send the rover to appropriate science targets in order to document them and reconstruct, sometimes very accurately, the environment. The high-resolution color images were sometimes used to assess the texture of the rocks and blocks, leading to a correct proposition of the presence of sandstones and enabling a detailed description and correct interpretation of the presence of fine-grained matrix clasts and conglomerates. In other instances it was insufficient to determine whether the rock was volcanic or sedimentary. This answer would have certainly been provided by a spectrometer. However, why in some instances the same imager enables the science team to go into such detailed texture and morphologic description and why sometimes it fails to provide basic answer are important questions to resolve for planetary surface exploration. Part of the answer is certainly related to the degree of confidence reached by the science team about the regional geological context. For instance, the volcanic nature of some of the features and structures had been proposed by the science team but could not be definitely confirmed. This might be the reason why the science team members were reluctant to put as a unique interpretation that some of the observed rocks were volcanic. On the other hand, the context of past flows, drainage systems, and ancient lakes had been well established both that day (e.g., with the presence of drainage systems and alluvial deposits) and during the two previous days of exploration. Therefore the science team probably felt more confident to go into a much more detailed description and interpretation (e.g., sandstones) of rocks found in the proximity of such an environment. What this issue teaches us is that there was a "mental map of the site" already acquired by the science team after the survey of the aerial images. This mental map was actually driving the investigation of the team members with an unconscious set of likely, or less likely, interpretations. It demonstrates how the quality of orbital and/or descent images and other science instruments will be important in the coming surface exploration of Mars and how much our ability to interpret their results is going to affect the decisions made during the surface exploration. It is therefore critical that rovers should be equipped with a set of science instruments able by their complementary performance to minimize the effects of "preconceived" ideas of what should be found at one site.

Another interesting aspect was related to some of the decisions of the science team that led to significant miss. For instance, after the discovery of the first potential fossil candidate (I-250697) and its sampling, the science team decided to leave for the next site, while a thorough investigation of site 4 seemed to be the next operation to undertake, as it would likely be the case during a Mars mission. Although the time spent on science sites was limited to 25% of the day by the protocol of this experiment, there was no constraint on how these 25% should be used. The science team failed in the ability of replanning the mission and reassessing its priorities. Had it undertaken the thorough investigation of site 4, obvious fossils of shells and coquinae would have been exposed nearby the rover (G. Chong, unpublished field report, 1997). By leaving site 4, they left behind the possibility of finding even more evidence of paleolife and the possibility to document thoroughly the environment in which the fossil had been found. Instead, the science team left for the next site to complete the morning program.

Another example of missed fossils that could have been identified on images (by opposition to I-250697, which required laboratory analysis to be confirmed) happened at site 7. Another fossil being missed was both the result of a technical problem that was recurrent since the start of the operation in the morning and the result of the science team decision. Because of a mechanical problem with the tilt of the camera, some routine operations had to be performed by hand by the field team. The science team would send a command for an image and provide the exact desired positioning of the camera, and the field team would position the camera as requested. The science team instructions were followed accurately, up to the point that on one image half of a rock was captured. While the science team attempted the interpretation of this half-rock image, fossils of shells were out of the field of view on the other half. On this particular example, the science team should have asked the image to be recentered and recaptured to include the entire rock. It was not possible for the remote science team members to know that there was a fossil on the other part of the rock; however, the missing part could have held important clues for the interpretation of the rock's origin, and the image should have been recaptured.

7. Meteorite Search

Rover exploration could benefit the meteorite search program in regions like Antarctica, where sustaining human presence is associated with risks. To test the ability of identifying meteorites from a rover, Nomad used the onboard imagery, a metal detector, and magnetometers. Visual (imaging system) and instrumental (magnetometer) approaches were tested in two experiment runs in a search area of 500 m^2. During the visual search, meteorites were planted randomly in the area. Their number, size, composition, and position were not known by the remote science team. The tested strategy was to first characterize the local geology in order to identify the meteorites (e.g., possible contrasting morphology, texture, and color). Once the geology was characterized, the science team conducted the search following the standard strategy adopted by the U.S. Antarctic Search for Meteorites program, by performing a grid search and examining the ground in the immediate vicinity of the rover with the panospheric camera while traversing the search area in a zigzag pattern. Forward facing high-resolution images were acquired at each stop, and every image was examined for any unusual object. Given the limited time of the experiment, the stopping interval was relaxed to stopping only when a candidate meteorite was spotted while roving continuously.

The vision system allowed precise refinement of surface meteorite locations, and the pointed antenna enabled the remote science team to view detailed images of the search area. Three rocks, designated M1, M2, and M3 (Figure 10), were encountered during the second track. The rocks were first seen in the forward direction in panoramic scenes and then scrutinized using the close-up high-resolution color imagery for shape and texture characteristics. They appeared as relatively large and dark objects contrasting with the smaller sized, and/or lighter colored background. M1 was revealed to be a dark brown object, about 10 cm across, with relatively planar facets, rounded angles, and distinct thumb-sized (1-2 cm across) dimples on the facets, suggesting the possibility of an iron meteorite, the dimples being reminiscent of regmaglyphs (shallow depressions characteristic of iron meteorites, formed by erosion of their surface by turbulent vortices during atmospheric entry). Then, M2 was examined with a single monochromatic high-resolution image, which revealed a planar-cleavage morphology and roundness, characteristics that are unlikely to correspond to a meteorite. A basalt interpretation was tentatively proposed for M2. The M3 candidate, a dark and large rock with a mat, grayish brown surface, appeared in the high-resolution full-color imagery, not unlike those observed in chondrites such as Allende. However, the presence of a body-wide facet with apparent angular edges suggested that the dark appearance was likely due to a shadowing. The visual mode search was then discontinued.

Ground truth from the field science team confirmed the conclusions of the NASA ARC team: M1 was one of the planted meteorites (iron-type). M2 (basalt) and M3 (sedimentary rock) were naturally occurring local rocks. The key parameters of the success of this operation seemed to have been the imagery capabilities of the rover, especially its ability to go from large scene to high-resolution color close-up and a favorable terrain for operation. The results of the visual teleoperated mode search are obviously encouraging, though the use of this technique is subject to limitations related to the access to the site: for instance, the flat area of

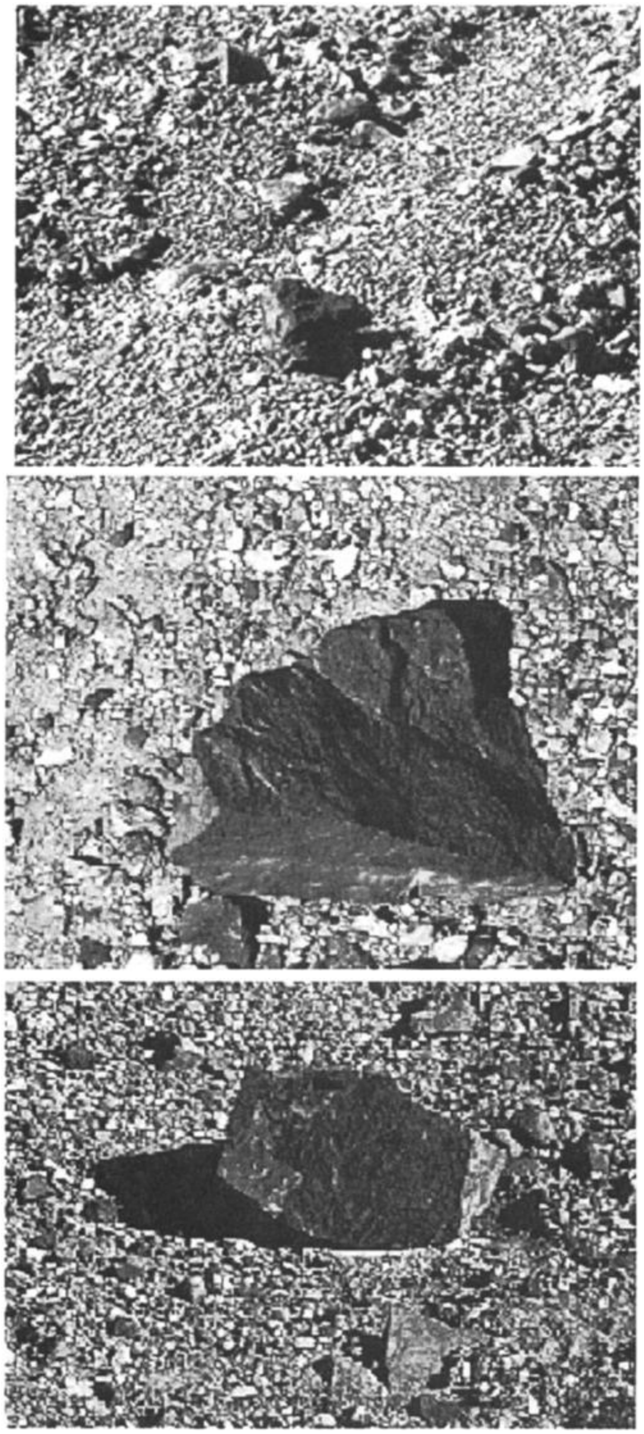

Figure 10. Rocks targeted by the science team during the meteorite experiment. M1 (top), is an iron-type meteorite that had been planted randomly in the field by the field team; (middle) M2 is a basalt; and (bottom) M3 is a sedimentary rock. Using the imaging systems on board Nomad, the science team provided the correct interpretation for each of the encountered rocks.

the Atacama was a favorable environment, as could be icy-plains in Antarctica or the Arctic. However, it is known that meteorites can be found in blocky, boulder-rich environments, in which case the use of a rover might be limited or even precluded.

During run 2 the magnetometers successfully located some magnetite samples. The metal detector gave more ambiguous results, having registered noise, among which was the interference of the VHF radios used by the field team to communicate. The meteorites were randomly buried 20 cm deep in the search area for the instrumental search run. The rover pulling the metal detector was sent on linear traverses to detect signals from the instrument. The numerical data were received with a delay at ARC, while the rover was still moving along. A spike was interpreted as a possible evidence of a buried meteorite. The position of the candidate meteorite was reconstructed using the time spent between the reception of the data and the average speed of the rover. Both interpretation of the spike and its origin were confirmed by the field team. There was not enough operation time left for this experiment to search for the other meteorites.

Although more runs will be necessary in the future to test this exploration strategy, this type of meteorite search tested for the first time during the Atacama field experiment and renewed since with Nomad in Antarctica suggested the feasibility, in at least some conditions, of carrying out a field search for meteorites by remote control. Data of sufficient quality and diagnostic content (spectral range, color, spatial resolution, and magnetic sensitivity) are proved to be critical for the remote identification of the candidate meteorites. Integrating the range of diagnostic information into an automated system will also be critical to the implementation of an automated meteorite search.

8. Panospheric Camera and Time Delay

The primary objective was to test the contribution of a panospheric camera to a remote-controlled geologic field investigation. The secondary objective was to evaluate the influence of a time delay between command sequences. The first task was to operate a geologic investigation without using the panospheric camera. The second task was, starting from the same starting point (designated as LS4), to conduct a second geologic investigation using the panospheric camera. Both tasks were conducted with a command sequence time delay of 15 min to simulate a transmission during Martian missions.

The method of investigation for the first task not using the panospheric camera was to utilize the wide-angle low-resolution monochromatic camera to take a series of images to produce a single panorama. This method was used in previous tests with the Marsokhod rover [*Stoker and Hine*, 1996]. The acquisition of such panorama requires about 30 min. The panorama was analyzed to determine appropriate action: further image acquisition and/or motion. High-resolution images were acquired of either distant geomorphic features or local clasts. A similar method of investigation was used for the second task, but using panospheric images.

Higher-resolution stereo color or black-and-white images were taken of geomorphic features and rock clasts. Geographic locations chosen were based on distant features, geologic expectations, and rock clasts that stood out within the environment.

Results show that panospheric imagery is helpful in three areas: trafficability, near-field imagery, and topography relationship. The 360° field of view allows trafficability decisions to be made more easily. The advantages were the short update time and the capacity to view the rover surroundings. These two features allowed the science team to observe the changes in landforms and construct a mental terrain map of the traversed area. A terrain map, in the geologic sense, contains relationships between the topography, differential erosion, rock type, clast size range, and soil formation. This mental map provides an extremely important sense of scale and allows the team to quickly determine the best motion and image commands for site investigation. Panospheric imagery also provides images of objects close to the rover for preliminary examination, allowing the user to determine if high-resolution investigation is appropriate. The overall effect of using the panospheric camera was a significant improvement in the characterization and interpretation of the site and significant reduction in the time required to investigate the specific site. This effect was one of the major results emphasized by the remote science team during the science on the fly experiment. The wide-angle camera was helpful in navigation and far-field imagery. The panoramas created by successive single images from either the color or the monochromatic camera pair worked well for triangulation purposes. The stereoscopic camera pairs produced the highest resolution and were utilized as the main analytical tool to characterize rock clasts and outcrops.

The time delay affected the way in which rover commands were issued. The most conservative approach was to send a list of imagery commands, wait for the images to return, analyze them, and decide if further image acquisition or motion command was appropriate. This method seems to result in most careful data acquisition, maximizes the amount of time spent at each site, and is similar to a detailed field investigation. The next approach is to give the rover a series of image commands followed by a motion command and order a panoramic (or panospheric) image at the new location. The sequence for the rover is then to take the images, move to next site, take another image, and wait for further commands. This method does not allow the information gained by the analysis of incoming images to serve in the determination of the next appropriate motion or image acquisition command. The rover might be sent back to a previously visited site for further study. However, it minimizes the effect of time delay and is similar to a rapid field reconnaissance. The first method seems to be more appropriate where locations had been previously identified for detailed geologic mapping or where unexpected features are discovered that justify further investigation. The second method proves to be appropriate for a reconnaissance survey over a large area.

8.1. Run 1: Science Operations Without Panospheric Camera

The first part of the test did not utilize the panospheric camera for guidance or for preliminary geologic investigation of the landscape. A panorama mosaic of wide-angle monochromatic images was used to determine possible investigation sites. Rover commands were given as a series of imagery and motion commands to the rover operator. Four image/motion orders were given during the course of the experiment which resulted in three sites occupied by the rover and four sets of commands, which produced one panorama mosaic, 16 color or monochromatic images, and two motion commands.

Command sequence 1 included one 360° panorama of wide-angle images. The angle of inclination was set to include the horizon. From these images, seven clasts were identified for high-resolution monochromatic images.

Command sequence 2 was a request for the series of seven high-resolution monochromatic images of the seven clasts. After reviewing the images, the science team decided to move closer and take new images of the clasts with the color stereoscopic cameras. A heading and a distance of 5 m were determined to locate the rover in the optimum position for depth perception.

Command sequence 3 included one 5-m forward motion and five high-resolution color images from clasts A to E. These color images were determined by the science team to be the best characterization of the area that they could obtain. It was then decided to move to a site located about 15 m away to take an image of two outcrops with stereo color images.

Command sequence 4 included a 15-m forward motion and two images of the outcrops to obtain different angles from the one captured in the preliminary panorama. This command was the final order given for the first part of the test. The rover was then returned to the starting point in preparation for the second portion of the test.

After the acquisition of the data and the completion of the command sequences, the science team proposed that the outcrop possibly consists of sandstone or conglomerate and they requested the sampling of five rocks. Their description of these rocks ranged from possible limestone clast with chert, to red clast with conglomerate, to white clast. The ground truth confirmed the presence of conglomeratic limestone and sandstone with the presence of chert nodules.

8.2. Science Operations With Panospheric Camera

The purpose of this second experiment was to determine how the panospheric camera affected the science investigation. The rover was returned to the same starting point at the end of run 1. The science team immediately commented that the effect of the panospheric camera on the ability to conduct geologic investigation became apparent as soon as it was turned on. Because of the field of view of the camera, erosional features were visible that were not previously apparent, and clasts not previously seen were chosen for imaging. To maintain the time delay, an 8-min break between image arrival and command sequences was maintained. This allowed the science team to analyze the imagery prior to issuing command sequences. Four image/motion orders were given during the course of run 2, which resulted in four sites surveyed by the rover and four sets of commands, which produced 15 color or monochromatic images and three motion commands.

At the end of run 2 the conclusion of the science team was that the panospheric camera greatly assisted in the geologic field investigation. It allowed the team members to build a mental terrain map of the area traversed by the rover, providing a sense of scale of geologic relationships. It also allowed the site investigation to be completed more quickly and thoroughly. The time delay produced a conflict between the detailed geologic investigation and the reconnaissance traverse. Images could be more thoroughly examined, and the knowledge could be reapplied to the next command. However, a hierarchy of importance of the data received was difficult to establish.

9. Utilization of Data and Metrics Obtained During the Various Exploration Strategies

The week of science experiments allowed the science team to collect important information on how the remote science team could actually use the rover and its science package. The overall objective was to address the following questions: For how many tasks does the science team use the images? Is there a regular pattern of utilization per task or is it random? How often does the science team use a specific image product and in what specific circumstances? Does the science team use a specific suite of image products for a particular exploration strategy (e.g., Mars experiment, science on the fly, meteorite search, and time delay)?

Our goal was to possibly identify patterns of utilization and exploration that could help in planning rover missions in advance and possibly identify repetitive suites of commands for specific science tasks that could be automated on board rovers during future planetary surface missions. To address this issue, the activity of the science team was surveyed, and its daily logs of activity during the week of science experiment were collected. In addition, to help the survey, every image requested by the remote science team and sent back by the rover was archived during the mission and included a time stamp (time of acquisition), type of image, camera, and orientation.

9.1. Imagery Systems, Image Products, and Their Utilization

During the week of this experiment a total of 121,000 panospheric images were collected and archived. The images were acquired every second to give a sense of motion and they were received with a 3-s delay at NASA ARC, where they were recorded and archived later on CD-ROMs. A total of 1412 images were also requested and used from the varied imaging systems on board Nomad. Table 3 shows the utilization of the different imagery systems and resulting image products used by the science team per day of experiment.

9.1.1. Panospheric images. These images were mainly used for teleoperated navigation by the rover operator, and by the science team navigator. The science team analysts used them to ascertain the context of the study sites, rock samples, and/or outcrops. Because of their resolution, these images could not be used for determinant science interpretation. The panospheric images were critical during the meteorite search, allowing the science team to have a complete vision of the surveyed area around the rover, thus covering more surface at once than any other imager could have.The conclusion reached is that the panospheric camera is a critical instrument for navigation and science context. It had not enough performance for science interpretation with the resolution used during the Atacama experiment. It will be a powerful asset in planetary surface operations for reconnaissance missions both on the Moon and on Mars. On the Moon it can be used for teleoperation, the communication time delay of 3 s being equivalent to the one that was experienced during the Atacama experiment. On Mars, because of the longer time

Table 3. Utilization of Nomad's Imagery Systems

	Images per Day of Experiment					
Image product	June 23	June 24	June 25	June 26	June 27	Cumulative
Black-and white wide-angle panorama (and partial	2 runs 12 5 (3)[a]	0 runs 0	0 runs 0	0 runs 0	0 runs 0	2 runs 17 (1)
Black-and-white wide-angle panorama (and partial)	3 runs 18 9 3 (5.5)	2 runs 9 7 (5)	3 runs 36 12 12 (25)	0 runs 0 (0)	0 runs 0 (0)	8 runs 106 (7.5)
High-resolution stereo color panorama (and partial)	3 runs 120 15 11 (28)	4 runs 12 10 13 39 (23)	0 (0)	0 (0)	0 (0)	7 220 (15.6)
Black-and-White wide-angle single frame	187 (36)	200 (62.3)	103 (43)	87 (61)	111 (57)	688 (48.7)
Black-and-white wide-angle pair	41 (8)	0	0	0	3 (1.5)	44 (3)
High-resolution stereo color pair	18 (3.5)	16 (5)	19 (8)	7 (5)	27 (14)	87 (6)
High-resolution color single frame	17 (3)	6 (1.8)	17 (7.1)	15 (10.6)	13 (6.7)	68 (4.8)
High-resolution stereo black-and-white pair	4 (0.7)	1 (0 3)	2 (0.8)	0	0	7 (0.5)
High-resolution balck-and-white single frame	2 (0.3)	1 (0.3)	37 (15 5)	32 (22.7)	40 (20.6)	112 (8)
Lost data (communication failure)	56 (10.1)	7 (0.2)	0	0	0	63 (4.5)
Total images (other than panospheric)	518	321	238	141	194	1412
Panospheric camera images	28,000	21,600	32,400	25,200	14,000	121,000

[a]The number without parentheses indicates the number of images. The number in parentheses indicates the corresponding percentage compared to the daily total of images. This percentage is calculated on the total number of images other than panospheric.

delay of 15 to 40 min, the panospheric camera will not be as effective for exploration in the current Surveyor Program mission configuration. However, it will become an important science tool as soon as humans land on Mars and can teleoperate scout rovers from their lander to explore remote areas [*Cabrol et al.*, 1999]. This instrument will help save precious operation time by enabling the fast localization of potential science targets.

9.1.2. Panoramas and partial panoramas. Three types of panoramas, partial panoramas, and mosaics were used by the science team. They are high-resolution stereo color, stereo black-and-white, and mono black-and-white wide angle panoramas. As shown by Table 3 and Plate 1, each of these panoramas was used for different tasks. Among the three, the high-resolution stereo color panorama contains the most information: color that provides indications about the geologic diversity; topography that can be reconstructed using the stereo pairs; and high resolution that helps identify the rock nature, texture, and, to some extent, mineralogy. The counterpart to the amount of information is the time and volume of data necessary to acquire this type of panorama. High-resolution stereo color panoramas and partial panoramas were often requested during the first day of operation. They represented 28% of the total number of science images (percentage excluding panospheric images). This number can be explained by the fact that the science team was having its first contact with the test site area and needed information to make preliminary interpretation. However, later requests of partial high-resolution stereo color panoramas during the day (see Plate 1) are clearly related to the fact that the science team could not orient itself, and was at the same time trying to find geologic landmarks and to acquire science information.

A stereo black-and-white panorama was provided to the science team as part of the initial data along with the complete high-resolution stereo color panorama and the aerial images. This type of image product provided the context, the morphology, some geological information, and topographic information used both for navigation and for science. However, the science team used it only once more and prefer to use either the high-resolution stereo color for complete information or the mono black-and-white panoramas, partial panoramas, and/or mosaics for a quick assessment of the context.

9.1.3. Black-and-white wide angle single frames . As seen in Table 3, this image product represents the main category of images (48.7% over the entire experiment). The amount of images recorded is related first to regular snapshots taken by the rover operator during traverses, which make this image product the best navigation tool along with the panospheric camera. They are also counted as science images because they were archived and available for the science team members to view and analyze. The science team members increasingly used them to preselect potential interesting science targets (see Tables 4 to 8).

9.1.4. Single frames and pairs . Few stereo black-and-white wide-angle pairs were used for science interpretation. They were mostly requested by the science team during the first day of operation (see Table 4), to assess the topography and the trafficability. Later during the week of experiment, the color high-resolution stereo pair was preferred to this data product. Containing potentially the same topographic information, the color added the potential for mineralogical assessment, and the high-resolution allowed better study of the rocks and outcrops structure and texture. The high-resolution color single frame was the most utilized data product for science interpretation.

As the experiment proceeded, the science team appeared to use faster obtained information and what we call "replacement" products, which could provide the science team member with enough science information in less time. For instance, a thorough survey starting with a high-resolution stereo color panorama was likely replaced in the following days of experiment by a fast black-and-white panorama (or partial mosaics) used for the designation of potential targets and utilization of high-resolution color (mono or stereo) only once on target. The comparison between the science team interpretation and the field team science report shows that the science team interpretation was also increasingly accurate. The use of "replacement" imaging strategies does not appear then to induce more interpretation errors and could have the potential to save operation time, at least in some circumstances that will need to be identified in further tests. One such test could be to ask two science teams to use each one of these imaging sequences during the first day of experiment, and observe what results are obtained in term of science interpretation and time for reaching significant conclusions. Figure 11 shows the request and use of the various data products by the science team per day of the experiment.

9.2. Exploration Strategies, Sequences of Imaging, and Science Outcome

The survey of requested images shown in Plate 1 illustrates the variations in imaging sequences and imaging strategies chosen by the science team during the different experiments. Because of the localization problem and loss of a significant amount of data because of communication failures, day 1 is not regarded as significant. Despite the aerial images and the full stereo color high-resolution panorama, it appears that the science outcome expected from such operationally time-consuming data product was not reached at the end of the day. Although the science team members had reached some correct conclusions about the first site, they did not take advantage in full of all the information they had requested or were

Table 4. Type of Images and Their Utilization by the Science Team: Mars Day 1[a]

	Panoramas (or Partial Pans)			Image Pairs			Single Frames		
	HR Stereo Color	Stereo B&W (WA)	Mono B&W W/A	Stereo HR Color Pair	Stereo B&W (WA) Pair	HR Stereo B&W Pair	HR Color Single Frame	HR B&W Single Frame	B&W (WA) Single Frame
Total images	146	17	30	18	41	4	17	2	187
Localization/ orientation	[120][b] (82)[c]	5 (29.4)	[27] (90)	0	[31] (75.6)	4 (100)	0	1 (50)	3 (1.6)
Science context	[120] (82)	5 (29.4)	[30] (100)	2 (11)	16 (39)	0	0	2 (100)	1 (0.5)
Navigation	0	5 (29.4)	0	0	10 (24)	3 (75)	0	1 (50)	[187] (100)
Trafficability	[120] (82)	5 (29.4)	[27] (90)	1 (5)	21 (51)	4 (100)	0	1 (50)	4 (2)
Topography	[120] (82)	5 (29.4)	0	0	14 (34.1)	4 (100)	0	0	0
Preselection of science target	[146] (100)	0	[27] (90)	0	0	1 (25)	1 (5.8)	0	0
Geology	[146] (100)	0	[30] (100)	[18] (100)	14 (34.1)	4 (100)	[17] (100)	2 (100)	17 (9)
Rock texture/ mineralogy[d]	26 (17.8)	0	0	[18] (100)	0	2 (50)	8 (47)	1 (50)	18 (9.6)
Biology	0	0	0	0	0	0	0	0	0

[a]HR, high-resolution, B&W, black and white; WA, wide angle
[b]Numbers between brackets show a significant use of the data type.
[c]Numbers in parentheses show the percentage this occurrence represents over the total number of images per image type. Numbers without parentheses show the occurrence of utilization per image type.
[d]No spectrometers being on board Nomad, the science team evaluated possible mineralogical contents using close-ups with high-resolution color imagery. Rock texture was evaluated using high-resolution, black-and-white and/or color images.

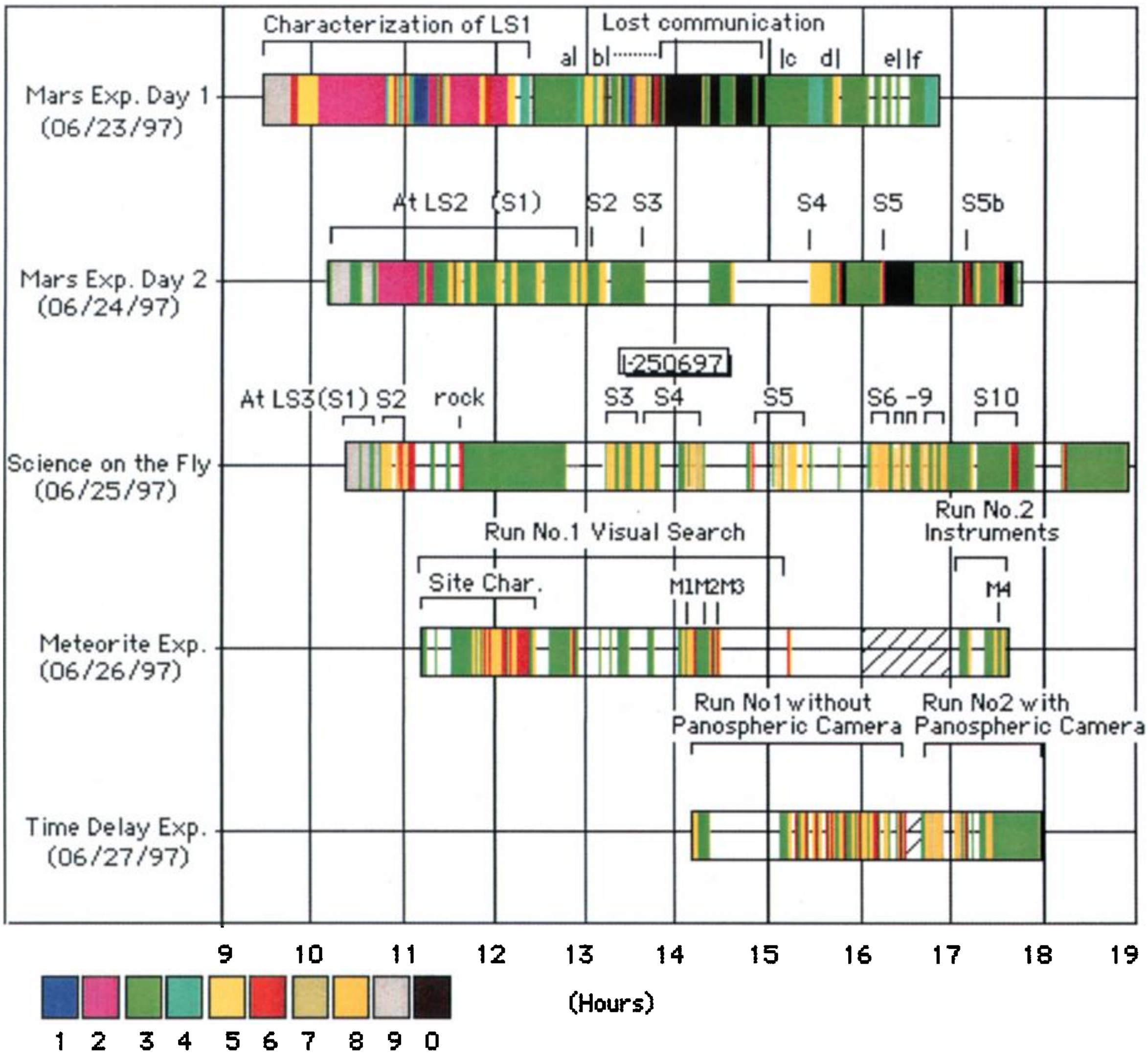

Plate 1. Sequence of image requests per experiment. 1, stereo black-and-white wide-angle panorama; 2, stereo color high-resolution panorama; 3, mono black-and-white wide-angle single frame; 4, stereo black-and-white wide-angle image pair; 5, stereo color high-resolution image pair; 6, mono color high-resolution image; 7, stereo black-and-white high-resolution image pair; 8, mono black-and-white high-resolution single frame; 9, mono black-and-white wide-angle panorama; 0, lost data (communication failure).

Table 5. Type of Images and Their Utilization by the Science Team: Mars Day 2[a]

	Panoramas (or Partial Pans)			Image Pairs			Single Frames		
	HR Stereo Color	Stereo B&W (WA)	Mono B&W W/A	Stereo HR Color Pair	Stereo B&W (WA) Pair	HR Stereo B&W Pair	HR Color Single Frame	HR B&W Single Frame	B&W (WA) Single Frame
Total images	74	0	16	16	0	1	6	1	200
Localization/ orientation	0	0	[16] (100)	0	0	0	0	0	110 (55)
Science context	31 (41.8)	0	10 (62.5)	0	0	0	0	1 (100)	50 (25)
Navigation	0	0	0	0	0	0	0	0	[200] (100)
Trafficability	0	0	0	1 (6)	0	0	0	0	0
Topography	14 (19)	0	0	5 (31)	0	0	0	0	0
Preselection of science target	0	0	7 (43.7)	0	0	0	0	0	5 (2.5)
Geology	[74] (100)	0	0	[15] (93.7)	0	1 (100)	6 (100)	0	3 (1.5)
Rock texture/ mineralogy	19 (14)	0	0	5 (31)	0	0	6 (100)	0	0
Biology	0	0	0	0	0	0	0	0	0

[a]Same symbols and legends as in Table 4.

provided. One main reason might have been the localization problem that kept the focus away from science interpretation for a significant part of the day.

During day 2, the science team used an exploration strategy closer to the one currently used by the Surveyor Program: long stay at the "landing site" (about half a day), thorough science inspection of the area around the rover at the landing site, rare traverses (total of 250 m), and intense use of high-resolution color images to document science targets. This pattern was even increased during the time-delay experiment (see Plate 1), when the science team investigated a reduced area. The science outcome was in both cases a good

Table 6. Type of Images and Their Utilization by the Science Team: Science on the Fly[a]

	Panoramas (or Partial Pans)			Image Pairs			Single Frames		
	HR Stereo Color	Stereo B&W (WA)	Mono B&W W/A	Stereo HR Color Pair	Stereo B&W (WA) Pair	HR Stereo B&W Pair	HR Color Single Frame	HR B&W Single Frame	B&W (WA) Single Frame
Total images	0	0	60	19	0	2	17	37	103
Localization/ orientation	0	0	[60] (100)	0	0	0	0	0	15 (14.5)
Science context	0	0	[60] (100)	3 (16)	0	0	7 (41)	27 (73)	13 (12.6)
Navigation	0	0	0	0	0	0	0	0	[94] (91.2)
Trafficability	0	0	[60] (100)	0	0	0	0	0	1 (0.9)
Topography	0	0	0	3 (16)	0	0	2 (11.7)	0	0
Preselection of science target	0	0	0	1 (5.2)	0	0	1 (5.8)	3 (8)	20 (18)
Geology	0	0	20 (33)	[16] (84)	0	2 (100)	8 (47)	18 (48.6)	15 (14.5)
Rock texture/ mineralogy	0	0	0	10 (52.6)	0	2 (100)	1 (5.8)	2 (5.4)	0
Biology	0	0	0	5 (26)	0	0	1 (5.8)	3 (8)	0

[a]Same symbols and legends as in Table 4.

Table 7. Type of Images and Their Utilization by the Science Team: Meteorite Experiment[a]

	Panoramas (or Partial Pans)			Image Pairs			Single Frames		
	HR Stereo Color	Stereo B&W (WA)	Mono B&W W/A	Stereo HR Color Pair	Stereo B&W (WA) Pair	HR Stereo B&W Pair	HR Color Single Frame	HR B&W Single Frame	B&W (WA) Single Frame
Total images	0	0	0	7	0	0	15	32	87
Localization/ orientation	0	0	0	0	0	0	0	2 (6)	23 (26.4)
Science context	0	0	0	7 (100)	0	0	6 (40)	6 (18.5)	37 (42.5)
Navigation	0	0	0	0	0	0	0	1 (3)	[78] (89.6)
Trafficability	0	0	0	0	0	0	0	0	15 (17.2)
Topography	0	0	0	0	0	0	0	0	8 (9)
Preselection of science target	0	0	0	0	0	0	4 (26)	3 (9.3)	14 (16)
Geology	0	0	0	7 (100)	0	0	9 (60)	29 (90)	32 (36.7)
Rock texture/ mineralogy	0	0	0	7 (100)	0	0	6 (40)	0	0
Biology	0	0	0	0	0	0	0	0	0

[a]Same symbols and legends as in Table 4.

characterization of the immediate surroundings of the "landing sites" compared to the ground truth. However, it provided only a small amount of information about the geological context at a larger scale. This exploration strategy seemed to enable the science team to point towards correct hypotheses, ask correct questions, but not necessarily to verify them.

During day 3 the almost reverse strategy was used, emphasizing strongly the mobility. The resulting sequencing of images requested by the science team is also different: complete panoramas are avoided; emphasis is put on partial mosaics, repetitive use of mono black-and-white images to preselect targets and assess the trafficability, and use of stereo color high-resolution images when finally on target. This

Table 8. Type of Images and Their Utilization by the Science Team: Time Delay Experiment[a]

	Panoramas (or Partial Pans)			*Image Pairs*			*Single Frames*		
	HR Stereo Color	Stereo B&W (WA)	Mono B&W W/A	Stereo HR Color Pair	Stereo B&W (WA) Pair	HR Stereo B&W Pair	HR Color Single Frame	HR B&W Single Frame	B&W (WA) Single Frame
Total images	0	0	0	27	0	0	13	40	111
Localization/ orientation	0	0	0	2 (7.4)	0	0	0	0	39 (35)
Science context	0	0	0	2 (7.4)	0	0	3 (23)	[29] (72.4)	12 (11)
Navigation	0	0	0	0	0	0	0	1 (2.5)	[75] (67)
Trafficability	0	0	0	6 (22)	0	0	0	0	14 (12.6)
Topography	0	0	0	0	0	0	12 (5)	0	31 (28)
Preselection of science target	0	0	0	0	0	0	1 (7.6)	1 (2.5)	12 (10.8)
Geology	0	0	0	14 (52)	0	0	[13] (100)	[30] (75)	35 (31.5)
Rock texture/ mineralogy[c]	0	0	0	14 (52)	0	0	[10] (77)	3 (7.5)	0
Biology	0	0	0	0	0	0	0	0	0

[a]Same symbols and legends as in Table 4.

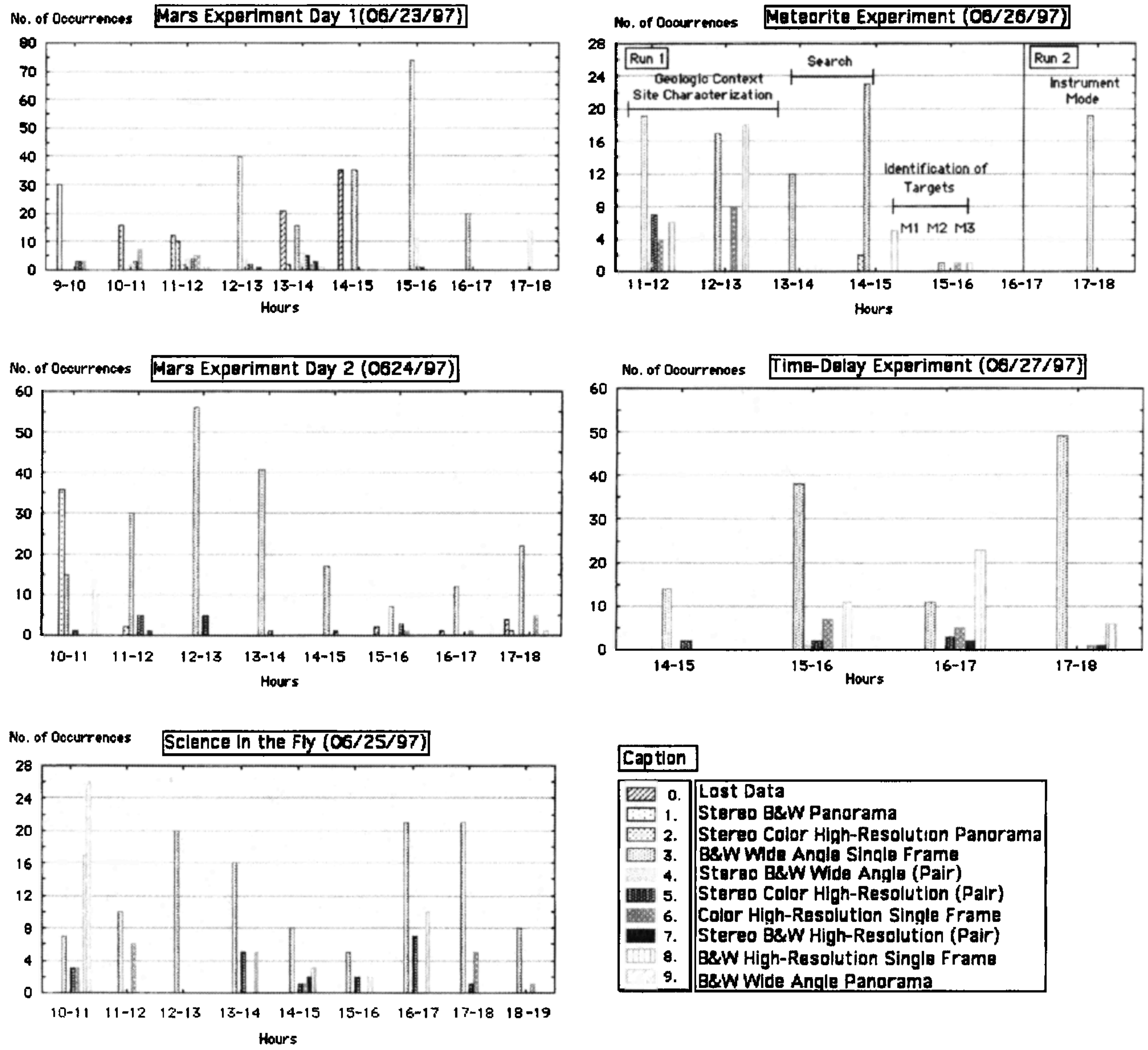

Figure 11. Utilization of image products during the different experiments.

repetitive pattern is clearly visible in Plate 1 and could provide an example of task sequencing that could be automated on rovers in the future. This exploration strategy gave the science team the opportunity not only to make preliminary hypotheses but to reach distant and critical science targets to obtain answers. More was learned about the environment of the test site during that particular day than during the two previous, although the number of images requested was by far lower. It seems then that there is no relationship between what can be learned about a site and the volume of data acquired from this site. However, there is a relationship between the type of data, the sequence in which these data are used by the science team, and how fast the team members reach the proper conclusions and/or go to the critical targets. Day 3 showed that it is not necessary to always have a stereo-color high-resolution full panorama of a landing site at the beginning of a science operation to have a sense of where the critical targets are. The morphology, shape, texture, and topographic information are contained in the black-and-white panoramas. The time/power saved on the acquisition of these data (by comparison with a high-resolution stereo-color full panorama) was used later on during the day by the science team to survey more thoroughly distant science targets that they were able to reach. The time saved at the beginning of the operation enabled them to go farther away from the starting point (LS3) than any day before, thus acquiring more critical information about a larger geological context. In the end, it led the science team to investigate an outcrop of sedimentary material from site 4 to site 10 and to collect sample I-250697 as a potential fossil, later confirmed by laboratory analysis [*Cabrol et al.*, this issue]. Mobility and fast data acquisition seem to have been the key of this particularly successful experiment.

The meteorite search on day 4 used two exploration strategies. Run 2 involving instrument measurement readings (metal detector and magnetometers), the imagery system was used only once to confirm a potential target. During run 1, the characterization of the search area was made using the high-resolution color images, with a sequencing of image request comparable to the one made the previous day at the beginning of the science on the fly experiment. During the search the sequence was one of navigation and preselection of targets (snapshots of mono black-and-white wide-angle images and panospheric images) and mono- and stereo-color high-resolution images to assess the nature of the candidate-meteorite. As a conclusion to this section, Tables 4 to 8 show the various types of image products used by the science team during the different science experiments.

10. Conclusion

The Nomad rover field experiment demonstrated significant and promising achievement in the perspective of planetary surface exploration. A definitive improvement in science interpretation accuracy compared to previous rover field experiment was achieved. Although ambiguities remained in some instances, the overall geology of the test site was generally properly identified. It can be proposed that the combination of the panospheric camera and the high resolution of the pancam system were critical in this improvement, as well as the ability to reach distant science targets. The role of the high resolution should be emphasized, since the same imager was subsequently used during the 1999 Marsokhod rover experiment in Silver Lake, where the pancam system was used without the association of the panospheric camera. The science team also globally successfully interpreted the test site geology [see *Stoker et al.*, this issue]. The experiment demonstrated the importance of the panospheric images in providing to the science team the feeling of being actually in the field and in helping the construction of a mental map of the test site that led to a faster understanding of the environment. The importance of mobility in robotic exploration during the science on the fly experiment was clearly shown. A significant sum of knowledge about the site was accumulated using a limited science payload during a day where only 25% of the operational time was devoted to science at selected sites. This result seems to indicate that quality orbital images coupled with the use of the mobility of the rover should enable future missions to Mars to identify and reach critical sites. In the case of Nomad it allowed the science team to reach sample I-250697, located about a kilometer away from the simulated landing site. During the overall science mission, the Nomad rover covered a total 2.1-km science traverse.

This field experiment also emphasized the importance of having instruments that enable a mineralogical interpretation of the rocks on board rovers. These instruments were not present during the Atacama field experiment and their presence would have proved critical for interpretation in some instances. The science team suggested as concluding remarks that microscope capabilities would be most important, Nomad offering only the possibility of close-ups. In 1999 the Marsokhod rover was carrying these capabilities [*see Stoker et al.*, this issue], and the geological interpretation gained much insight.

The week of science operation also pointed out a pattern of how the rover is used. In at least two instances the science team failed to reassess its mission priorities following interesting observations and discoveries. The concept of successful mission seemed to be sometimes attached only to the completion of the morning science briefing objectives (e.g., reaching the 10 identified targets, reaching a particular outcrop), while an important discovery, like the fossiliferous outcrop of site 4 during the science on the fly experiment, and what it could teach about the past environment was significant enough to justify a replanning of the experiment. Three important lessons were also learned from this particular day: (1) flexibility and ability to replan are critical for a mission completion and success; (2) when a potential fossil is found, thorough investigation of the site should be mandatory before leaving; otherwise the science team will usually leave with more questions than answers; and, finally, (3) rocks on close-ups should be always imaged entirely. Critical pieces of information can also be located on the hidden part.

The discovery of sample I-250697 teaches us also the critical importance of visible imagery for the coming exobiology exploration of Mars. It can be argued that a sophisticated imagery system will be a most effective tool to identify life on Mars, and is an important strategic and tactical tool, the utility of which cannot be denied in a reconnaissance of surface fossil records that could have been exposed by cratering processes. In the context of Mars exploration with probably very similar environments (lake shoreline, altered iron-rich carbonate units), the primary tools for the rover reconnaissance and selection of potential study areas will remain the imagery system. Using only the imagery system, correct area characterization of the geology and stratigraphy led the science team to site 4 and to sample 1-250697 on the fossiliferous unit. Powerful rover-mounted cameras will likely be the tools that first identify likely fossiliferous units and any "suspicious rocks" within them..

It is also important to understand how, and why, sample I-250697 was identified. The reconnaissance mode using wide to narrow field-of-view imagery systems allows documentation and characterization of the environment in which the rover moves. This notion of becoming familiar with the explored environment is fundamental. Both in the case of sample I-250697 and in the case of the meteorite search, the science team found them because they looked different from the surrounding environment that the science team was then familiar with.

This field experiment showed the potential of Nomad or Nomad-type rovers as platforms for planetary surface exploration. Nomad provided excellent performance for traverses and an ability to go quickly from one target to another and to overcome challenging obstacles. This ability has certainly played a significant role in the science interpretation, in helping reach targets that would have been otherwise impossible to reach with smaller rovers. The presence of the panospheric camera was also critical. The Nomad field experiment also demonstrated the importance of teleoperation as a valid planetary surface exploration strategy. Nomad could be teleoperated on the Moon as it was during the Atacama field experiment. In addition, the way Nomad was operated will also become highly relevant to the Mars exploration when humans land there and teleoperate scout rovers from their lander. A highly mobile and robust rover like Nomad is a promising technology to develop in this perspective along with new exploration strategies, such as the reconnaissance mode (science on the fly) that was tested during the Atacama field experiment.

Acknowledgments. This experiment was supported by the NASA Space Telerobotics Program, David Lavery, Program Manager The

Nomad project is led by the Carnegie Mellon University (CMU). We thank R. Whittaker, E Rollins, M. Maimone, J Murphy, M. Sibenac, D. Bapna, J. Teza, M. Parris, B. Shamah, A. Foessel, and G Thomas (telepresence interface) for enabling our participation in this project. The Atacama Field Experiment was a joint effort of the CMU Field Robotics Center (FRC), the NASA Ames Research Center Intelligent Mechanism Group (IMG), and the NASA Ames Research Center Space Science Division (SST). We are very thankful to our Field Science Team in Chile from the Universidad Catolica del Norte (UCN), Antofagasta, for its dedicated collaboration. Special thanks to Ted Bunch, Rocco Mancinelli (NASA Ames Research Center), Jack Farmer (Arizona State University), and Dan Lowe (Stanford University) for their contribution in their first assessment of the origin of sample I-250697 when it first arrived at Ames. Our gratitude goes to Julia Golden, Kay Saville, and Greg Ludvigson of the Geology Department at the University of Iowa for hosting I-260697 in their department, processing it, and providing the analysis that is reported in this article. Their contribution to this work has been critical. The first author is particularly thankful to Nicole Masjedizadeh for help in navigating the data archival system and for always keeping a back-up copy of these archives.

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(Received February 4, 2000; revised August 23, 2000; accepted September 12, 2000.)