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Life in the Atacama: Searching for life with rovers (science overview)

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[1] The Life in the Atacama project investigated the regional distribution of life and habitats in the Atacama Desert of Chile. We sought to create biogeologic maps through survey traverses across the desert using a rover carrying biologic and geologic instruments. Elements of our science approach were to: Perform ecological transects from the relatively wet coastal range to the arid core of the desert; use converging evidence from science instruments to reach conclusions about microbial abundance; and develop and test exploration strategies adapted to the search of scattered surface and shallow subsurface microbial oases. Understanding the ability of science teams to detect and characterize microbial life signatures remotely using a rover became central to the project. Traverses were accomplished using an autonomous rover in a method that is technologically relevant to Mars exploration. We present an overview of the results of the 2003, 2004, and 2005 field investigations. They include: The confirmed identification of microbial habitats in daylight by detecting fluorescence signals from chlorophyll and dye probes; the characterization of geology by imaging and spectral measurement; the mapping of life along transects; the characterization of environmental conditions; the development of mapping techniques including homogeneous biological scoring and predictive models of habitat location; the development of exploration strategies adapted to the search for life with an autonomous rover capable of up to 10 km of daily traverse; and the autonomous detection of life by the rover as it interprets observations on-the-fly and decides which targets to pursue with further analysis.

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1. Introduction

[2] Life in the Atacama Desert of Northern Chile (Figure 1) is sparsely distributed. It survives in localized habitats on scale of tens to hundreds of meters. A few of these habitats have been studied in detail (see references therein); however, little is known about the extent and distribution of microbial life and habitats across the desert, which was the focus of the Life in the Atacama (LITA) project. We conceived an approach to create biogeologic maps by making survey traverses across the desert with dedicated biologic and geologic instruments and sensors. We accomplish these surveys in a method that is technologically relevant to Mars exploration using an autonomous astrobiology rover (Figure 2).

[3] Using an autonomous rover to search for microbial life in the Atacama Desert provides information that can help design exploration strategies and life detection methods for

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Figure 1. Early morning fog (camanchaca) filling the Salar Grande basin, Atacama Desert. Image facing south with the Coastal Range to the west, at right.

terrestrial extreme environments and future missions on Mars. Previous rover field experiments in Mars analogue terrains focused on the methods and payloads to characterize past geology and climate as precursors to the Mars Exploration Rover (MER) mission as the goal of the MER mission was to understand if past environmental conditions on Mars were suitable for life [e.g., *Squyres et al.*, 2003]. Neither previous terrestrial rover field experiments [e.g., *Wettergreen et al.*, 1997; *Stoker et al.*, 2001; *Cabrol et al.*, 2001a, 2001b; *Arvidson et al.*, 2002; *Jolliff et al.*, 2002; *Moersch et al.*, 2002; *Stoker et al.*, 2002; *Stoker and Ashwanden*, 2002] nor the MER mission [*Crisp et al.*, 2003; *Squyres et al.*, 2003, 2004a, 2004b] were designed to search for life directly. However in a few instances, during experiments in terrestrial analogues to Mars, remote science teams stumbled onto life. In 1997, the science team using the rover Nomad in the Atacama Desert remotely detected a putative fossil [*Cabrol et al.*, 2001a], although the rover had visible imaging but no multispectral or microscopic capabilities. The remote scientists proposed three hypotheses that could explain the origin of the rock, one of them being a biogenic hypothesis which was based solely on morphological evidence from visible imagery and was not conclusive. The rock was manually collected and returned to the laboratory where fossils were found during the microscopic analysis of thin sections [*Cabrol et al.*, 2001b]. This finding was not entirely serendipitous since the remote science team directed the rover to a specific outcrop following a scientific rationale built upon previous observations. However the rock was sampled under an inaccurate assumption and the discovery was essentially the result of a speculative process not a deliberate life-seeking strategy. Two years later, another remote science team using the Marsokhod rover identified chlorophyll-based life during the 1999 Silver Lake rover field experiment [*Stoker et al.*, 2001]. A rock was sampled following the observation of a dip in a spectra obtained from the infrared spectrometer onboard the rover. The spectral signature was consistent with the presence of chlorophyll and provided a possible hint that life was present [*Johnson et al.*, 2001]. Life could not be confirmed in situ by other payload instruments since Marsokhod did not carry any microscopic imaging capabilities or discriminative spectrometers. Chasmolithic

Figure 2. Zoë rover in the Atacama Desert. The rover and its instrument payload were designed together to be able to conduct multikilometer survey traverses in desert environments. Sensor mast is at typical eye-level and optics match human foveal resolution. Wide-tread pneumatic tires, not suitable for Mars, are ideal for terrestrial deserts.

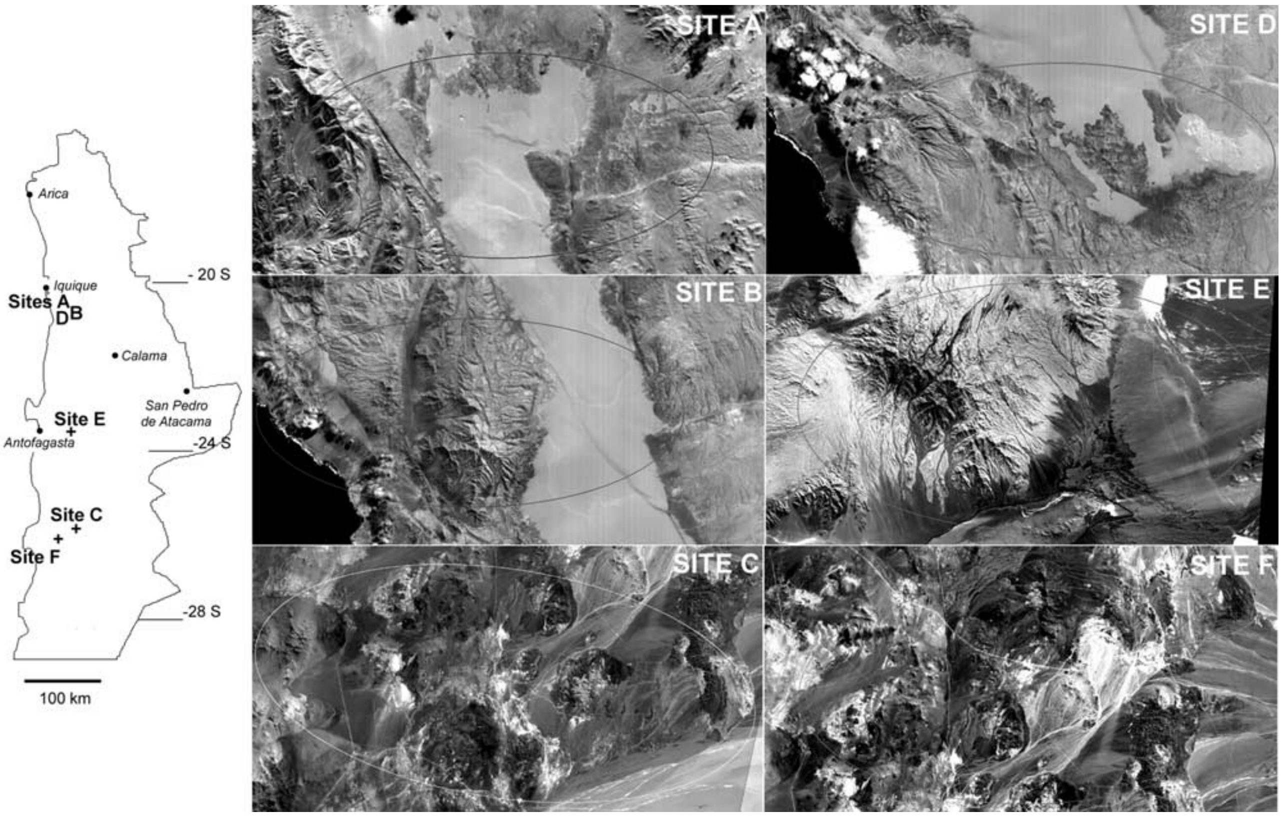


Figure 3. (b–f) ASTER images of the five sites investigated by the LITA project between 2004 and 2005 and (a) Site A chosen for component testing in 2003. A 20-km wide "landing" ellipse is marked on the orbital image, and the geographical location of each site is indicated to the left on the map of Northern Chile.

organisms were found on the sample during ground-truth [*Grin et al.*, 2001]. On Mars, where no sample return or ground-truth is yet possible, similar observations of biosignature would remain inconclusive.

[4] As part of its integrated exploration program, NASA is now planning autonomous missions that will document more directly Mars' biological potential starting with the Mobile Science Laboratory (MSL), scheduled to launch in 2009. It is, therefore, important to understand our ability to detect and characterize biosignatures from a robotic platform. This was a primary motivation of the LITA project. The project was a three-year collaboration of roboticists and scientists working together to conduct remote investigations of the Atacama Desert. Field investigations devoted approximately one week to each of six sites: Three in the Coastal Range, two at high altitude in the arid core of the desert, and one site in a lower altitude transitional region (Figure 3).

[5] From the technology standpoint, the first year (2003) was focused on component testing (Table 1). That year, a preliminary field experiment used the rover Hyperion to test and calibrate instruments in the field and assess operational requirements for the 2004 and 2005 field seasons [*Wettergreen et al.*, 2005a, 2005b; *Cabrol et al.*, 2005]. As a result of the 2003 experiment, Zoë (Greek for "life") was designed and deployed for the 2004 and 2005 field investigations in the Atacama Desert. The second field season was dedicated to the integrated operation of all the rover and payload elements, and in the third year, we had created an operational astrobiology rover.

[6] In this article, section 2 explains the objectives of the scientific and technologic investigation. In section 3, we describe the rover Zoë and particularly the elements of its scientific instrument payload. The remote science operations center, tools, and process are explained in section 4. Then, we detail the exploration strategies that we developed in section 5. An overview of the scientific and technical results of the field investigation is given in section 6. For detailed results on the geological mapping, mineralogy and biology, see *Warren-Rhodes et al.* [2007a, 2007b], A. Hock (Life in the Atacama: A scoring system for mapping habitability and the robotic exploration for life, submitted to *Journal of Geophysical Research,* 2007, hereinafter referred to as Hock et al., submitted manuscript, 2007), J. Piatek et al. (Surface and subsurface composition of the Life in the Atacama field sites from rover data and orbital image analysis, submitted to *Journal of Geophysical Research,* 2007, hereinafter referred to as Piatek et al., submitted manuscript, 2007), and S. Weinstein et al. (Application of pulsed-excitation fluorescence imager for daylight detection of sparse life in tests in the Atacama Desert, submitted to *Journal of Geophysical Research*, 2007, hereinafter referred to as Weinstein et al., submitted manuscript, 2007). Finally in sections 7 and 8 we discuss and conclude on the main

Table 1. Field Investigation Metrics

Year	Activities	Duration (50% Ops)	Distance	Observations	Location
1	Component Testing	30 days	10 km	10 Survey Observations	Coastal Range A
2	Functional Integration	60 days	50 km	100 Survey Observations 10 Focused	Coastal Range B Hyper Arid C
3	Operational Science	100 days	180+ km	160+ Survey Observations 16+ Focused	Coastal Range D Transition Region E Hyper Arid F

results of the field investigations and how the lessons learned could inform future planetary exploration and serve the exploration of extreme terrestrial environments.

2. Goals and Objectives

[7] The primary goal of the LITA project was to investigate the regional distribution of life in the Atacama Desert. Specific objectives (Table 2) addressed both the scientific and technical challenges in this goal.

[8] Identifying microbial organisms and/or fossils where life's density is amongst the lowest on our planet is informative in many ways and can help us prepare missions that will seek life on other planets. The LITA project was supported by the NASA Astrobiology Science and Technology for Exploring Planets (ASTEP) program. The ASTEP program's dual objectives are to study extreme environments on Earth to understand the prospects for life beyond our planet and to enable future astrobiology missions by developing the necessary technologies for exploring planets and moons in search of life. The selection of the Atacama Desert was in part a response to the dual intentions of the ASTEP program. The Atacama is Mars-relevant for both scientific investigation and technology experimentation.

[9] Another ASTEP project "Long Term Extreme Environment and Mars Analog Studies in the Atacama Desert" searched for and characterized microbial life and habitats in the Atacama using nonrobotic field geology and biology methods with a science team exploring and manually performing experiments in the field [see *Quinn et al.*, 2007]. The two approaches provide basis for comparison and a way to assess human and robotic performance in the same environment.

[10] Although the climate evolution and geology of the Atacama are fairly well documented [e.g., *Alpers and Brimhall*, 1989; *Grosjean et al.*, 1995; *Grosjean*, 1996; *Scheuber and Chong*, 1996; *Betancourt et al.*, 2000; *Hartley and Chong*, 2002; *Rech et al.*, 2002; *Bao et al.*, 2004] the characterization of microbial life in this desert, including its abundance, distribution, diversity and that of potential habitats, is still in its infancy [e.g., *Arrieta*, 1997; *Navarro-González et al.*, 2003; *Oren et al.*, 2003; *Warren-Rhodes et al.*, 2006; *Wierzchos et al.*, 2006]. Therefore, our primary science objectives were to document and characterize life in the Atacama along geographical and ecological transects, going from the relatively more "humid" Coastal Range where precipitation is 10 mm/yr from fog to the dry core of the desert ($\ll$5 mm/yr). We also intended to map the gradient of life and habitats along these traverses. We expected to make genuine discoveries contributing to the body of knowledge about the Atacama Desert despite, if not because of, the technologic developments and methodology begin concurrently developed.

[11] These science objectives implied the mapping of habitats, whether morphological, mineralogical, textural, or physical. The rover was also used to characterize the mineralogical properties of rocks and soils; document life and how it modifies its environment through the identification of biosignatures; and identify survival strategies, deriving them from the interaction between life and its environment.

[12] Since the LITA project objectives were in areas of both science and technology, to achieve the goals of the science investigation we had to create a robotic astrobiologist that could navigate over the horizon, use resources efficiently, and enable autonomy with self-awareness. To enable the robot to perform long survey traverses, it must be able to navigate beyond its field-of-view (>1 km). This means it must model the environment and detect obstacles at necessary scales, localize based on odometry, sun position, and local feature/global landmark tracking (but not

Table 2. Science and Technology Objectives

	Objectives	Significance
1.	Understand Habitat	Identify and characterize the diversity of habitats and understand the strategies used by life to survive in arid environments.
2.	Seek Life	Establish whether the hyper arid region of the Atacama represents an absolute limit to life and understand the gradient of biodiversity and environments.
3.	Relevant Science	Design an instrument payload capable of identifying life and test science exploration strategies enabling the positive identification of habitats.
4.	Over-the-Horizon Navigation	Exhibit productivity of traverse achieving 1 km per command cycle.
5.	Efficient Resource Utilization	Enable science rovers to reason about resources and make on-the-fly decisions to optimize productivity.
6.	Autonomy and Self-Awareness	Engage science rovers in remote exploration, surviving with minimal communication, while fully aware of themselves and their surroundings.

Table 3. Zoë Rover Specifications

Mass	198 kg
Dimensions	1.63 m width (axles), 2.00 m length (between axles), 1.80 m height 0.35 m ground clearance
Wheels	0.75 m diameter
Turning	2.50 m radius
Speed	0.90 m/s nominal, 1.10 m/s maximum
Power	72 V bus 120 W steady-state + 90–260 W locomotion
Solar	Triple junction, GaAs, 23% efficiency (average), 2.40 m^2
Battery	Lithium-Polymer, $\sim$1500 Whr capacity ($\times$2)
Computing	2.4 GHz Pentium4, 1GB RAM ($\times$2) 800 Mhz Celeron, 256MB RAM

artificial satellites), and register observations to orbital data sets. It must also employ traverse planning and sequence execution that reasons about solar and battery energy limitations, communication cycles, delay, data volume, science instrument use, and sampling frequency. We had to establish variable rover autonomy and effective remote investigation (telescience) over low-bandwidth, long-latency communication links. This required development of limited rover self-awareness, monitoring hardware and software for fault detection and recovery in order to achieve long duration science investigation operations.

[13] Other operational objectives of LITA were to test exploration strategies relevant to the remote, autonomous, search for life and to maximize science operations productivity. Therefore, Zoë was designed to be an astrobiology robot that responded to (a) specific operational requirements dictated by the investigation of microbial life in the Atacama, and (b) constraints relevant to Mars exploration, specifically limited bandwidth communication (150 Mb/day), sustainable energy use, and long-duration autonomy (1 command cycle/day). The search for life in the Atacama included both surface chlorophyllic microbial organisms unlikely to be relevant to Mars, and shallow subsurface habitats that could be accessed by a mechanism for overturning rocks and plowing soils. This mechanism enabled the investigation of subsurface habitats protected from UV radiation and exposure to desiccating extremes of winds and temperature, conditions that could be relevant to early Mars or putative present-day localized Martian oases.

[14] These distinctive characteristics established, LITA and future robotic exploration of life on Mars have an essential component in common: The necessity for an unambiguous detection of sparsely distributed biogenic material. Whether the rover payload is intended to identify organic compounds such as proteins, amino acids, and other acids and bases that attach to carbon like MSL, or other evidence of life, like carbohydrates or building blocks of life including lipids, this evidence is unlikely to be uniformly distributed and easy to find on Mars. Neither is life readily identifiable in the Atacama. While life ‘‘follows the water’’ in the desert, it is scattered and its distribution follows the subtle reaches of the fog or that of invisible aquifers, which are dictated by complex geographical and topographical parameters. It can be abundant in a localized patch (millimeters to a few hundreds of meters in size) and then disappear for many kilometers. It can be present on one wall of a small gully and absent from the opposite wall only ten centimeters away. Keys to finding microscopic life are critical at all scales. They are found at the megascale (regional geology, morphology, topography, and climatology); at the mesoscale (a slope, a rock, a type of soil, a specific size of sediment); and at the microscale (a crack in a rock, pore and joint spaces, grain translucence). The success of finding life while exploring the desert on foot depends on integrating all of this information, a task which robotic exploration needs to achieve as well.

[15] In both the Atacama and Mars cases, a remote science team is faced with searching for evidence that is scarce at best and oases (extant/extinct) associated with very localized microclimates (at meter scale, a slope, a rock, or a crack in a rock), and widely spaced (<1 km–100s km). Success depends on directing the rover and its payload to those rare spots efficiently. LITA has showed that this is possible with an autonomous rover in one of the most scarcely populated deserts on Earth, and in the process validated new exploration strategies.

3. Rover and Science Payload

[16] Zoë is a four-wheel drive, dual-axle steered rover of approximately the same scale as Sprit and Opportunity, the twin Mars Exploration rovers. Zoë is 2.2 m long, 1.63 m wide and has a mass of 198 kg (Table 3). Stereo cameras located on top of her mast are 1.80 m above the ground giving a perspective on the landscape that is equivalent to what scientists would see if they were in the desert themselves. Zoë can carry out two types of moves: traverse and positioning. Traverse moves string together one to hundreds of waypoints to navigate long-distances between locations in the orbital data; positioning moves are used to adjust position when the rover reaches a site of interest. They are used to place remote sensing and in situ instruments on a target and used with the plow deployed to trench the soil.

[17] Zoë is powered by a 2.4 m^2 solar array made of triple-junction gallium-arsenide cells. A power tracker collects energy from the solar array to maintain the rover’s 72-volt buss made up of two 1500W/hr lithium-polymer batteries. [*Calderón et al.*, 2007] The batteries charge when there is excess power and are drawn down when energy is needed, either from low production (sunlight) or high consumption, as when climbing slopes [see also *Wettergreen et al.*, 2005a, 2005b]. The rover has four independently driven wheels on two passively articulated axles attached to the chassis by joints that are free to rotate in both roll and yaw. This maintains four-wheel contact with the terrain, providing superior traction (Figure 4) [*Wagner et al.*, 2005].

[18] The science payload (Table 4) was designed as a suite of science instruments allowing for both the search for habitats and life [*Cabrol et al.*, 2005]. The payload reflects this transition by combining complementary elements, some directed towards the remote sensing of the environment (geology, morphology, mineralogy, weather) for the purpose of detecting habitable conditions along traverses, and others directed toward the in situ detection of life’s signatures, such as biological constructs and physical patterns. It was designed to detect surface and shallow subsurface microbial organisms and chlorophyll-based life. Whether life on Mars (if any) ever used photosynthesis has yet to be established. However, from our current knowledge of the evolution of

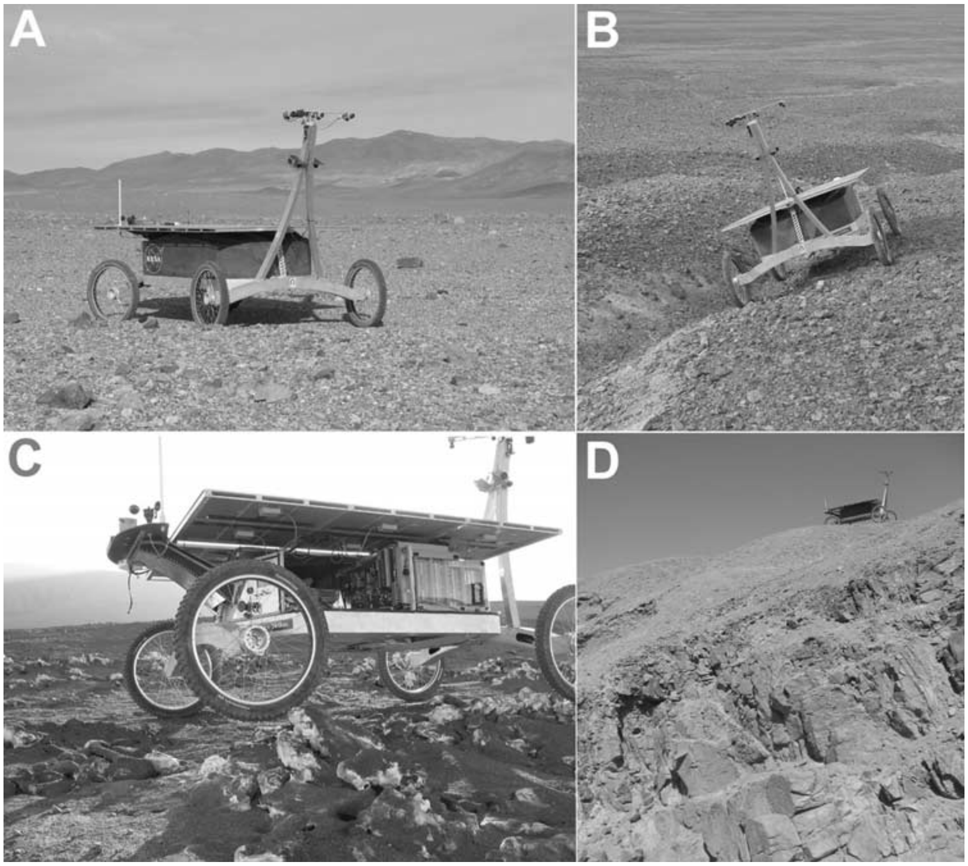


Figure 4. Zoë traversing various types of terrain in the desert. (a) Flat, gravelly desert pavement. (b) Alluvial fans with repetitive small channels, which presented a particularly challenging terrain for the rover. Most of the time, when in autonomous mode, Zoë would choose another path and drive far out to go back to a waypoint on the other side of the obstacle and reach her targeted stop via another route. (c) "Salar" with high density of halite constructs. (d) Mountainous terrain. On such hard terrain, the rover could climb ∼20 degree slopes. On soft soil, her climbing abilities were reduced to ∼10 degrees.

environmental conditions of the red planet [e.g., *Christensen et al.*, 2003a; *Squyres et al.*, 2004a, 2004b; *Mustard et al.*, 2005; *Bibring et al.*, 2005] it can be hypothesized that detecting life's signatures will necessarily involve accessing sheltered, isolated, oases scattered over large areas. LITA focuses on demonstrating such capability.

[19] The payload elements are shown in Figure 5. They consist of onboard cameras, instruments, sensors, and additional independent instruments. Onboard instruments were designed and integrated with the rover and worked automatically from rover commands. Additional instruments were operated manually but measurements were acquired as if these instruments were onboard the rover. The science payload aimed at addressing: (a) The habitability potential along extended traverses; (b) environmental and paleoenvironmental conditions, and (c) the identification of life in situ through converging evidence of various science payload elements. The presence of life within samples was evaluated by the science team using visible imagery, microscopy and fluorescence imager capabilities (Weinstein et al., submitted manuscript, 2007) including chlorophyll, proteins, lipids, carbohydrates, and DNA dyes.

3.1. Stereo Panoramic Imager (SPI)

[20] Searching for habitats and life, whether past or present, requires an accurate understanding of the environment and its evolution that begins with identifying critical clues and potential targets with imaging systems [e.g., *Bell et al.*, 2004, 2006]. On Zoë, the Stereo Panoramic Imager (SPI) played that role (Figure 5a) SPI is a high-resolution, color, trinocular camera rig, which provided information about regional context and allowed an in-depth geological reconnaissance, including the assessment of rock and soil distribution, morphological and structural diversity, texture, albedo, and lithology. Color allowed a first order evaluation of mineralogical diversity. Operational use of SPI included the collection of high-resolution science imagery, the reconstruction of 3D models and the planning of local traverses and science operations on a tactical (short term) and strategical (long term) basis. SPI provided the intermediate scale in contextual imaging, between the global satellite imagery and the local-to-microscopic scale obtained from the fluorescence imager. This scaling continuum and nested imagery was critical in the evaluation of the presence of oases at metric to micrometric scale [*Warren-Rhodes et al.*, 2007a, 2007b]. The SPI imager was also used

Table 4. Rover Science Payload

Payload Element	Location	Primary Science Objectives
Stereo Panoramic Imager (SPI)	*Rover Mast*	Geology, morphology, large-scale texture, topography. Assist navigation. High-resolution close-up.
Stereo Navcam	*Rover Mast*	Context and traverse.
Workspace Cams	*Rover Underbody*	Context imaging for samples.
Vis/NIR Reflectance Spectrometer	*Rover Mast*	Geology and Habitability: Iron-bearing minerals, silicates, carbonates, sulfates, clays and oxides. Identification of secondary alteration minerals and other minerals for form in the presence of liquid-water.
Fluorescence Imager	*Rover Underbody*	Identification of life.
Dyes	*Fluoresence Imager*	Identification of biosignatures (Chlorophyll check, DNA, lipids, proteins, carbohydrates)
Wheels/Power Sensors (WPS)	*Rover*	Surface strength and soil properties
Subsurface Access Mechanism (SAM)	*Rover Underbody*	Subsurface Habitats: Structure and properties of the subsurface. Overturn rocks.
Environmental Sensors (EnviS)	*Rover Tail*	Weather and incident sunlight for possible correlation with biological processes and habitat localization. Temperature, pressure, wind, insolation, UVA and UVB. A separate meteorological station was also installed at the "landing" sites. Dew sensor.
Thermal IR Spectrometer	*Independent*	Geology and Habitability: Determines the mineralogical composition of geological targets.
Neutron Spectrometer	*Independent*	Near-surface deposits of hydrogen-bearing compositions (water and hydrated minerals).

to detect atmospheric changes, specifically the presence of morning and late afternoon fog events in the Coastal Range (as shown at Site A in Figure 1), which signaled the location of potential water accumulation on the ground and, possibly, the concentration of life.

[21] The imager was composed of three cameras with 400–700 nm sensitivity obtained from 1280 × 960 pixels with a horizontal field of view (HFOV) of 21.1 degrees (Table 5). The imager yield a 0.28 mrad/pixel resolution, resolution equivalent to that of Pancam on the MER rovers Spirit and Opportunity [*Bell et al.*, 2003; *Squyres et al.*, 2003]. The use of three cameras allowed stereo reconstruction of both near-field and far-field scenes. Each camera was separated from its neighbors by 30 cm, so range maps could be with either a 30-cm or a 60-cm baseline. The 30-cm baseline was useful for measuring range to objects less than 10 meters away while the 60-cm baseline could measure the range of objects much further away. Data products included images from the left, middle, or right cameras captured in less than 5 seconds. Panoramas covered ±180° degrees horizontally with 10-degree steps and −45° to +15° vertical with 10-degree steps. Depending on the request, one, two, or three images could be taken at once. A complete trinocular panorama required 10 minutes to collect. Other data products included mosaics of limited sectors and selected quad-image sets. These quads were regularly requested to obtain context and ground images along traverses and typically covered a limited field-of-view in the four cardinal directions. They accommodated operational low-bandwidth restrictions and were the base for homogeneous regional mapping. This method developed during the first field investigation in April 2003 proved a productive mapping tool and an efficient method to detect targets of interest (i.e., local oases) in between detailed investigation sites.

3.2. Stereo Navigation Camera

[22] Zoë used stereo cameras to detect obstacles a few meters ahead. The landscape was visible from approximately one meter beyond Zoë's front wheels up to the horizon. The rover's obstacle avoidance software processed 320 × 240-pixel grayscale images from the navigation cameras at roughly 5 Hz. However, color images at this resolution could also be saved as a science data product. Since each image was only a few kilobytes in size, sequences were assembled into a movie that showed the rover's approach to a waypoint or entire traverses. These movies were extremely useful to the science team in the identification of transitions in the geological, morphological, and mineralogical environment related to changes in life habitats. The navigation cameras were fixed to Zoë's front axle, so they rotated as the vehicle steered, giving a number of views of the terrain. Periodic navigation camera images could therefore be useful in providing a better perspective of the landscape traversed by the rover.

3.3. Workspace Cameras

[23] Two color cameras were located underneath the rover, looking at the ground (Figure 5c). These workspace cameras were used to obtain a close view of rocks and soils but also to record instrument operations and plow activity. They were mounted back behind the fluorescence imager, therefore, they were better suited for observing fluorescence imager deployments or plow trenches rather than for obstacle avoidance like the engineering cameras do on MER [*Maki et al.*, 2003]. This resulted in a pixel size of 1.4 mm at one meter from the camera. One of the difficulties in managing the data sets from these cameras was the heterogeneous lighting below the chassis related to shadows during parts of the day. However, they still proved a useful tool in providing first level information about the success or failure of a plow, and clues about the morphology, structure, and contents of a trench (e.g., physical properties of the soil; colors that could be related to the presence of life).

3.4. Visible/Near Infrared Reflectance (Vis/NIR) Spectrometer

[24] A Vis/NIR spectrometer (350–2500 nm) measured reflectance spectra of rocks and soils (Figure 5a). Many geologic materials have significant absorptions in this

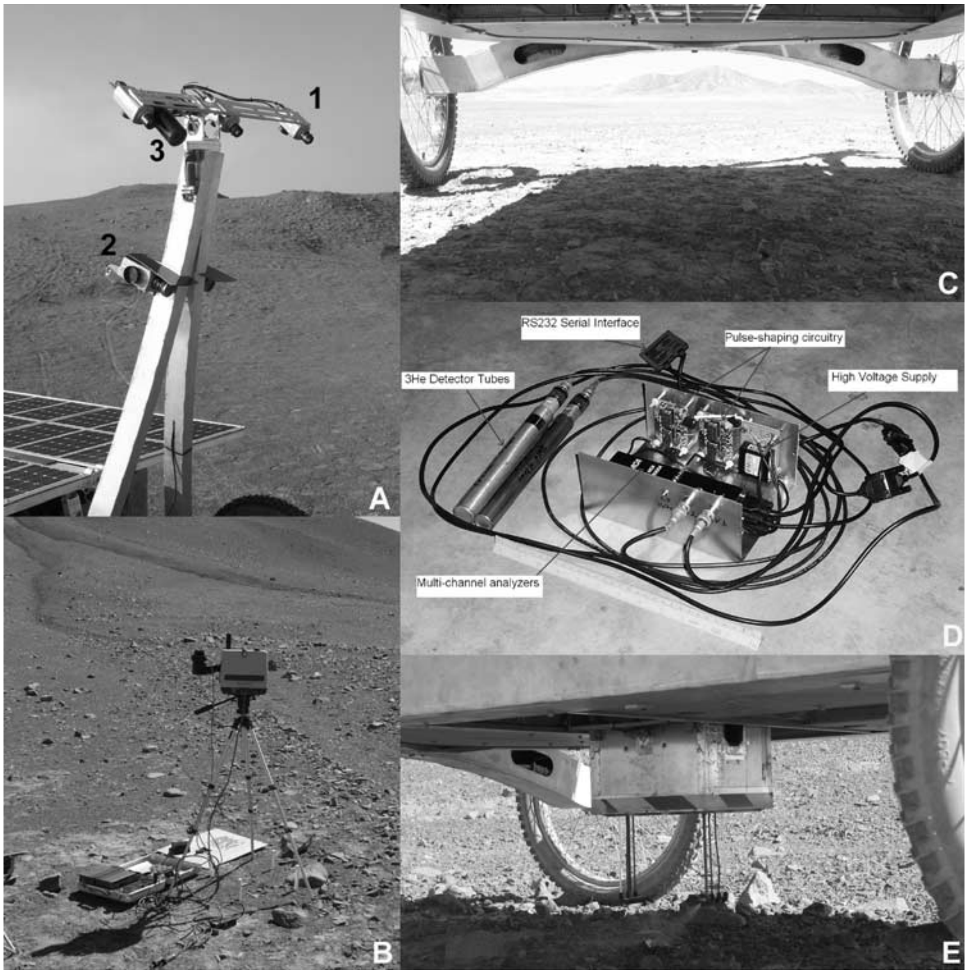


Figure 5. Rover payload: (a) Mast with (1) SPI stereo cameras; (2) Navcams; (3) V/NIR spectrometer. (b) The Designs and Prototypes thermal infrared field spectrometer (Model 101) provided by the University of Hawaii, seen here in operation at Site D. The liquid nitrogen cooled optical head of the instrument is attached to a manual pan/tilt mount on the tripod for pointing at targets. The aluminum briefcase seen at the base of the tripod contains electronics and a laptop computer for controlling the instrument. The wooden board with foil attached is for measurements of downwelling sky radiance, which are used in calibrating the spectra. An electric blackbody (not shown) is mounted on the optical head to provide other calibration measurements. (c) Typical view of the ground under the rover provided by the Workspace cameras. (d) Neutron spectrometer. (e) FI imager and dyes. The photo shows the FI box deployed and water being sprayed on a target. Dyes are contained in the other hoses (3 on each side).

range, including a variety of iron-bearing silicates, carbonates, sulfates, clays, and oxides. This spectral region is particularly useful for identifying secondary alteration minerals and other minerals forming in the presence of liquid water. Many organic molecules have strong absorptions in this region. Chlorophyll has a particularly unique and easy-to-recognize spectral signature. Operation of the Vis/NIR spectrometer was automated as part of the rover's payload. The light-collecting foreoptic of the spectrometer was mounted on the pan/tilt platform, approximately co-located with SPI. The remote science team selected targets for the spectrometer from SPI images when the rover had not moved in the interim. Spectra were also acquired "blind" with azimuth/elevation-based pointing when no current imaging was available for targeting. This latter mode was useful for systematic reconnaissance observations on long traverses.

[25] The field-of-view of the instrument was 1 degree (~1.7 cm at a range of 1m). Spectra of individual spots could be acquired or they could be collected in raster patterns to build a hyperspectral image cube. A single spectrum, along with its associated calibration observations was acquired in under two minutes. Subsequent spectra using the same calibration observations were acquired every few seconds (not counting slew times between positions). Two types of calibrations were necessary for data acquisition. The instrument had the capability of closing its shutter and measuring its own dark current on command. A standard white reference source was mounted on the deck of the rover for taking external reflectance calibrations. Both types of calibrations were acquired at least once per

Table 5. Zoë Camera Specifications

Device	Field-of-View	Dimensions (CCD Pixels)	Angular Resolution	Color Resolution	Model/Manufacturer
Stereo Panoramic Imager (three cameras)	21.1° × 15.9° 16 mm	1280 × 960 ½″ CCD 4.65 mm pixels	0.29 mrad/pixel	16-bit 400–700 nm	Sony DFW-SX900
Fluorescence Imager	10 × 10 cm 17 mm	1392 × 1040 (1024 × 1024) ½″ CCD 4.65 mm pixels	(linear resolution) 223 μm/pixel	12-bit	Roper CoolSNAP
Underbody (two cameras)	81.1°	1024 × 768 1/3″ CCD	1.38 mrad/pixel	8-bit	Point Grey Dragonfly
Navigation	70°	640 × 480 (320 × 240) 1/3″ CCD 7.4 mm pixels	1.90 mrad/pixel	12-bit 400–700 nm	Sony DFW-v500
Sun Orientation	190.0°	1024 × 768 (768 × 768) 1/3″ CCD	4.37 mrad/pixel	8-bit	Point Grey Dragonfly

20 minutes when the instrument was taking spectra of targets. When insolation conditions or instrument temperature were changing rapidly (e.g., scattered clouds or near sunset/sunrise) calibrations had to be acquired more frequently. Calibrations were internalized by the instrument's software so that it could directly output calibrated reflectance spectra. The assumption built into this calibration approach was that the target was illuminated similarly to the white reference source. As a result, the science team had to apply caution when interpreting spectra of targets with significantly different geometries from the horizontal white reference target. Data output from the Vis/NIR spectrometer consisted of binary files containing reflectance data. These files were sent back to the remote science team, who had to decode them and correlate wavelength and reflectance for construction of a spectra (see Piatek et al., submitted manuscript, 2007).

3.5. Thermal Infrared Spectrometer

[26] The Thermal Infrared Spectrometer (TIR) was a direct analog to Mini-TES on MER [*Christensen et al.*, 2003b] and measured emissivity spectra in the 8–12 μm region (thermal infrared) to determine mineralogic compositions of geologic targets (Figure 5b). Most major rock-forming mineral groups, including silicates, carbonates, sulfates, have diagnostic spectral absorptions in this spectral region. The mineral components and abundances in rocks and soils may be determined from their spectra using linear deconvolution techniques along with library spectra of known monomineralic samples measured in the laboratory. The spectrometer was not mounted on the rover due to the logistics of liquid nitrogen cooling, but provided comparable results by deploying the instrument along the rover's path from the same locale as associated observations. The TIR acquired spectra of targets working from SPI images sent back to the field by the remote science team. The spot size measured by the spectrometer was approximately 5 degrees, or 9 cm at a typical range of 1m. Spectra of more distant targets (up to 500 m) were also collected, although they carried a large resolved area and greater atmospheric contributions in some wavelengths. Acquisition of spectra with the TIR implied that calibration measurements of hot and cold blackbody targets, as well as a diffuse reflector target (to characterize downwelling atmospheric radiance) had to be made along with each target spectrum. Data consisted of raw target spectra, raw hot blackbody spectra, raw cold blackbody spectra, and raw diffuse reflector spectra for each target. The remote science team had software that converted these raw data into emissivity spectra (see Piatek et al., submitted manuscript, 2007).

3.6. Neutron Spectrometer

[27] In October 2005, a neutron detector was added to the science instrument payload at Site F (Figure 5d). The purpose of the neutron detector was to detect the abundance of hydrogen (whether it be in moisture, ice, or bound in minerals) in the top 1–2 m of the subsurface. The instrument is similar in concept to the Dynamic Albedo of Neutrons (DAN) experiment that will be carried aboard MSL in 2009 with the difference that, for LITA, an isotopic fast neutron source (^{252}Cf) was used instead of a combination of neutrons naturally generated from the cosmic ray background and a from a pulsed neutron generator. Regardless of their source, high-energy (fast) neutrons are moderated to lower energies when the medium in which they are scattered contains hydrogen because the mass of a hydrogen nucleus is similar to that of a neutron. Thus, the energy spectrum of neutrons leaking from a surface rich in hydrogen is biased toward lower energies compared to that from a hydrogen-poor surface.

[28] Physically, the neutron detector instrument consisted of two proportional counter tubes filled with pressurized ^{3}He. One of the tubes was covered in a thin jacket of cadmium, which shielded it from counting neutrons with energies below ~0.4eV. The other tube was bare, so the ratio of counts between the two tubes gave a measure of the energy distribution of neutrons incident upon the tubes. Neutron counts were registered as electrical pulses, which were fed to preamplifier/amplifier circuits, and then to multichannel analyzers for summation over a preset integration period. For this preliminary experiment, the neutron instrument was not physically mounted to Zoë but measurements were made in the rover's tracks. This arrangement was transparent to the remote science team since data was returned to the team as if it had been acquired directly from Zoë. In future field trials, we anticipate complete physical integration of the instrument onto the rover. The detailed results of the neutron detector experiment are provided by Piatek et al. (submitted manuscript, 2007). In summary,

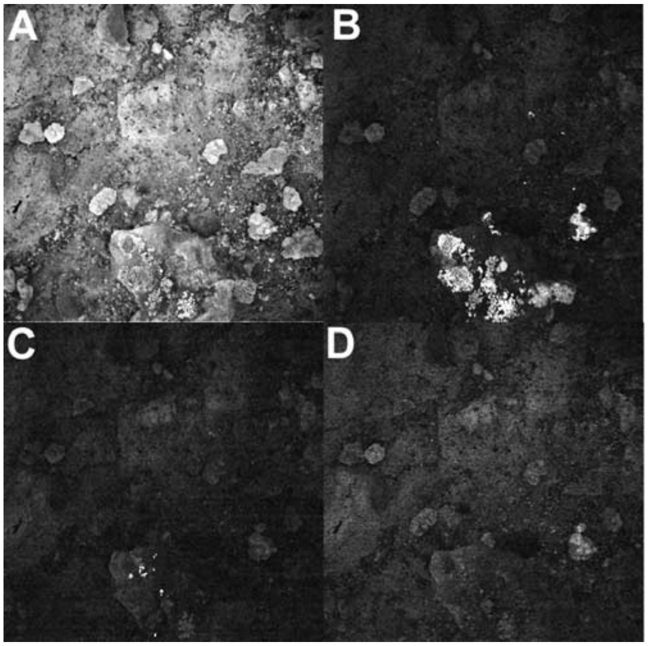


Figure 6. Site B lichen imaged with the FI (transverse resolution is 223 μm). (a) RGB image of the field-of-view. (b) Fluorescence emitted from the chlorophyll of the lichen. (c) Fluorescence from the DNA probe, and (d) Fluorescence from the protein probe. The dyes had difficulty penetrating the lichen, resulting in only small regions where they bound to their target. This resulted in the addition of acetic acid in the spray starting Site C.

neutron counts were taken at locations along the traverse. The hydrogen abundances derived from these measurements were found to correlate well with the vegetation abundances seen in Zoë's camera images. One large-scale dry channel (as observed from an ASTER orbital image) was also correlated with a broad increase in derived hydrogen abundances.

3.7. Fluorescence Imager

[29] The primary goal in the development of the Fluorescence Imager (FI) was to robotically deploy an imager that was capable of detecting fluorescence signals from sparse microorganisms during autonomous rover exploration in daylight under the shade of the rover (Figure 5e). This required band-pass filters and a high-sensitivity camera to prevent fluorescence to be overwhelmed by sunlight. Using 450 nm (blue) or 540 nm (green) excitation and 740 nm (infrared) detection, the natural fluorescence of chlorophyll could be excited and detected. The objectives for the FI were to: identify naturally occurring chromophores, such as chlorophyll of cyanobacteria and lichens; apply fluorescent probes (e.g., chlorophyll check, and biomarkers such as DNA, proteins, lipids, and carbohydrates) to soils and rocks; and obtain quality RGB high-resolution images, including microscopic, of the target's field-of-view.

[30] The FI was composed of a cooled CCD camera. The camera was synchronized with the flash, permitting the detection of fluorescence over diffuse ambient light. The FI was capable of auto-focus and auto-exposure control using customized control algorithms. Color images were created by imaging with 630 nm (red), 535 nm (green), and 470 nm (blue) band-pass filters with full spectrum illumination from the underbody flash lamp. Every RGB image was acquired with flash. Fluorescence images were acquired by flash-no flash subtraction. The instrument was positioned under the belly of the rover and could be moved 25.5 cm along the vertical axis and 67.75 cm along the transverse axis. The size of the camera housing was 21 cm × 24 cm × 45 cm.

[31] The FI was used to identify several possible biosignatures [*Cabrol et al.*, 2005; *Wettergreen et al.*, 2005a, 2005b; *Weinstein et al.*, 2006, also submitted manuscript, 2007; *Warren-Rhodes et al.*, 2005, 2007a, 2007b]. Chlorophyll was checked by the addition of water to the targets through direct spray. Dyes were applied to the surface to detect amino acids, proteins, lipids, and carbohydrates. Their application was manual in 2004 and became automated for the 2005 field investigation. Penetration in lichens was difficult at Site B, the first region explored by Zoë during the first week of the 2004 remote science operations. Acetic acid was used starting Site C in an attempt to break the protective cell walls/glycocalyx surrounding microorganisms and somewhat mitigated the issue (Figure 6). Results from the life detection system are summarized in section 6. Details about the instrument (robotic and operational control), the dyes, the results from the FI investigation and the constraints of dealing with natural mineral fluorescence can be found in Weinstein et al. (submitted manuscript, 2007).

3.8. Environmental Sensors

[32] Acquiring environmental data was a critical step towards understanding the habitability potential of the Atacama and identifying possible areas for oases along a traverse. In 2004, only part of Zoë's payload was integrated and the environmental sensors were not yet on board so they remained fixed at the landing site. In 2005, the remote science could rely on two sources of environmental data: The weather station at the landing site and an onboard data logger that recorded air temperature, air relative humidity, condensing moisture ("leaf sensor"), wind speed, and insolation (Table 6). The data logger sampled at a rate of one measurement per second or per minute. The data were downloaded at the end of each day of operation to a laptop and then sent to the science team as part of the daily download. The measures made during the daily traverses were compared to the data acquired by the weather station at the landing site (temperature, relative humidity, wind, UV).

3.9. Plow: Subsurface Access Mechanism

[33] The primary goal of the plow was to gain access to the subsurface and expose potential habitats protected from surface conditions. In the field, the plow performed the same role as a wheel trenching operation on the MER rovers [*Arvidson et al.*, 2004]. The depth of the trench varied with the terrain, ranging from very shallow on hard surfaces to ~5–7 cm deep on soft terrain. The plow was a 28 cm wide blade with a breakaway mechanism located at the rear of the vehicle, facing rearward, thus plowing occurred when the rover drove backwards (Figure 7). When deployed, the plow was under constant ground pressure from a spring-damper mechanism and could complete a ~1 m long trench in one

Table 6. Zoë Meteorological Sensors

Device	Sensitivity	Model/Manufacturer
Temperature (thermistor)	Sensor accuracy: ±0.7°C @ +25°C (±1.3°F @ +77°F)	Temperature-RH Smart Sensor/Onset Computer Corporation
Humidity	Sensor accuracy: ±3% RH over the range of 0° to +50°C; ±4% in condensing environments	As above
Wind Speed (anemometer)	Estimated at ±0.1m/s	40H anemometer/NRG Systems with S-UCA-M006 counter module/Onset Computer
Insolation (pyronometer)	Sensor accuracy: within 5% error of Epply Precision Spectral Pyranometer	LI-200SA Si pyranometer/LI-COR with UTA amplifier/EME Systems and HOBO S-VIA-CM14 voltage module/Onset Computer
Condensation (leaf wetness)	Estimated at ±10% (uncalibrated)	LWET-V/EME Systems with HOBO S-VIA-CM14 voltage module/Onset Computer

minute with very low power consumption. Trenching was a several step process, which begun by the imaging of the area containing the intended target. The imager was then stowed and the rover drove forward one meter. The plow was deployed to the ground and the rover reversed for one meter. The plow was stowed and the imaging begun over the same spot. Imaging of the targets could be acquired, by the workspace cameras underneath the rover or by the FI. After completion of the trench imaging, the rover could back up an additional 50 cm to allow SPI or spectral imaging.

4. Remote Science Operations

4.1. Overview

[34] The field investigation involved a total of 6 sites between 2003 and 2005. To mitigate any regional familiarity, the sites were labeled “A” through “F”. Site A, May 2003, and Site B (September 2004) were located in the “humid” zone of the Atacama near the Coastal Range (daily range value of RH 20% but overnight to 90%); Site C, (October 2004) was in the arid core of the desert (3–15% RH); Site D (September 2005) was again near the Coastal Range; Sites E and site F (September and October 2005) were deeper inland east of the coastal range with E at low altitude and F, on the western slopes of the Domeyko range at 2,800 m above sea level (see Figure 3). Site A, in Salar Grande, was explored in April 2003 as part of the component testing of the project with no formal remote science operations although the rover was deployed in the field for engineering testing. Sites B-F were investigated both by the remote science team gathered at remote operations facility in Pittsburgh (see section 4.3) and by a ground-truth team located in Chile.

[35] The investigation of one site lasted an average of a week including one sol for simulated landing site analysis and six sols for traverse and exploration. Site E operations were shortened to five days because of chassis and instrument damage sustained by Zoë during transport. As a result, after repair, the remote operations for Site F were lengthened to 12 days.

[36] Before the beginning of the remote operations, the science team had access to visible and multispectral orbital imagery. Data included: Hyperion VNIR hyperspectral 30 m/pixel, 220 bands, Site A only; Ikonos VNIR multispectral 1 m/pixel, 4 bands, Sites B and D; ASTER VNIR multispectral VNIR multispectral 15 m/pixel, 3 bands, Sites B, C, D, E, F; and ASTER TIR multispectral 90 m/pixel, 5 bands, Sites B, C, D, E, F. This data provided resolution and wavelength range equivalent to Mars Global Surveyor, Mars Odyssey, Mars Express, and Mars Reconnaissance Orbiter. A 20 × 10 km landing ellipse was superimposed on the images. The data sets were released online to the science team two days prior to the beginning of the remote operations and team members completed their mapping of the landing area as the operations progressed. This phase of orbital data analysis generated high-level maps, where morphology, mineralogy, and geology were used to identify potential habitat types and traverse directions [*Dohm et al.*, 2005; *Piatek et al.*, 2005, also submitted manuscript, 2007; *Warren-Rhodes et al.*, 2005, 2007a, 2007b; *Weinstein et al.*, 2006, also submitted manuscript, 2007; Hock et al., submitted manuscript, 2007].

4.2. Mission Structure

[37] The LITA field investigations were designed to simulate a planetary mission and included reduced daily bandwidth (150 megabytes), actual command sequencing directly to the rover, and a cycle of one data uplink and downlink per day. The science operational structure was close to that of MER [see *Crisp et al.*, 2003; *Squyres et al.*, 2003] with intrinsic differences related to the search for microbial organisms which required a biology theme group,

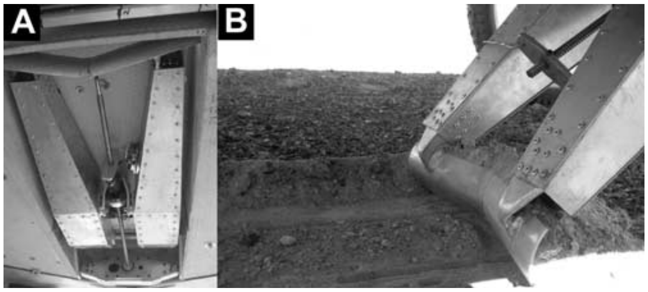


Figure 7. (a) Plow stowed under the belly of the rover. (b) Plow deployed and trenching into soft desert soil. The actual trench is ~7 cm deep.

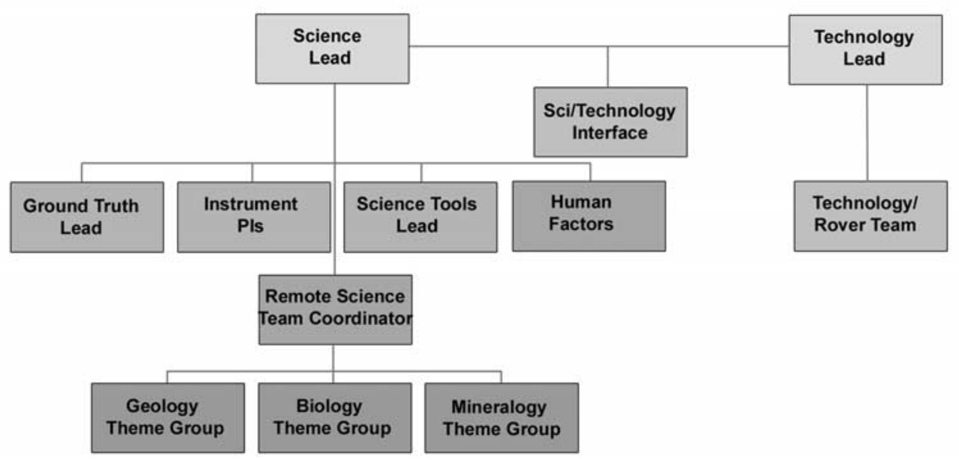


Figure 8. Organization chart of the LITA Science Team.

and to Zoë's unique autonomy capabilities enabling traverses of several kilometers per day. These autonomous traverses were completed using autonomous beyond-the-horizon navigation and no Global Positioning System (GPS) [*Wettergreen et al.*, 2005a, 2005b]. This rover field experiment was also the first to search for life, which led to iterative refinement of the method of exploration in 2003. This resulted in modifications during subsequent field seasons as the remote science team became increasingly comfortable using the full range of Zoë's capabilities. In 2004 and 2005, the remote science team had developed and consistently applied a set of innovative and robust exploration methods and templates adapted to the mission's goals (section 5) [*Cabrol et al.*, 2005; *Wettergreen et al.*, 2005a; Hock et al., submitted manuscript, 2007]. Each template was consistent for its assigned task and did not change. One example of a template would be that devised by the LITA team for science-on-the-fly (D. Thompson et al., Life in the Atacma: Science autonomy and increased data quality, submitted to *Journal of Geophysical Research*, 2007) (see also section 5 for complete description). Other templates were developed for different tasks.

[38] During operations, the remote science team schedule was dictated by the time zone difference between Chile and Pittsburgh (from 0 to +3 hours). The team assembled midday at the Remote Experience Lab in Pittsburgh for several hours to analyze data from the previous day. Science groups met midafternoon to discuss previous days' results, preliminary interpretations of latest downlink and their possible impact on mission goals for the following days, both at a tactical and strategic level. Downlink occurred at ~7:00 pm. The team had to triangulate and localize the rover's position, review new data, identify targets of interest and build a plan by ~1:00 am. Overall, daily remote operations represented a 12 hour-day on average in 2005, whereas 17 hours were sometimes necessary during the 2004 investigation. Improvement in automated triangulation and planning tools, the team's accumulated time in tool training, including a series of Operation Readiness Tests (ORTs) prior to the field investigations, and actual 6 field missions are directly related to this increase in mission productivity. The planning time alone went from 5–7 hours in 2004 to an average of 1 hour in 2005.

[39] The remote operations were supported by distinct groups that make the LITA Project Team (see Figure 8). The remote science team itself was composed of 18 members whose expertise covered planetary geology, geophysics, mineralogy, astrobiology, ecology, microbiology, and biosensing. The team members had no prior knowledge of the location of the LITA investigation sites and remained "blind" until after the presentation of their results during each year's final workshop held at NASA Ames Research Center in 2004 and Antofagasta (Chile) in 2006 [*Cabrol et al.*, 2005; *Wettergreen et al.*, 2005a, 2005b; *Dohm et al.*, 2005; *Piatek et al.*, 2005; *Warren-Rhodes et al.*, 2005; *Weinstein et al.*, 2006]. The last workshop was completed by a field trip to all the sites investigated by Zoë (2003–2005) for final ground-truthing.

[40] The LITA team was organized so as to establish a channeled decision-making path. The remote science team was organized in three theme groups: Geology, Mineralogy, and Biology. Biology was also overlooking atmospheric events (e.g., fog, cloud cover, wind) with the environmental data. The remote science team coordinator (RSTC) role was to facilitate the team's decisions, lead scheduled meetings, ensure that the team's actions would meet both tactical and strategic mission goals, and verify that uplink priorities were clearly identified prior to early morning uplinks. The RSTC was also the team member performing the command sequencing into Eventscope, which then uploaded directly to the rover in the field.

4.3. Mission Planning

[41] Three main elements contributed to remote operations: The setup of the remote operation center itself, the uplink interface through which commands were sent to the rover, and the downlink interface through which data from the rover were viewed. Both uplink and downlink interfaces were performed through Eventscope. EventScope is a 3D software, immersive virtual environment, for exploring mission data and remote experience files. For the LITA project, EventScope capabilities that were originally designed for education were extended to assist the remote science team planning activities. The remote operation center setup included workstations, projectors, and screens (Figure 9). A ceiling grid and curtained off areas served to

Figure 9. Remote operation center in Pittsburgh. Computers projected data directly on the wall screens to facilitate the team's discussions during data analysis, meetings, and daily traverse planning. The desktops were also used for download of rover data at the end of the day and upload of the daily traverse plans. Laptops were used by science team members to complete personal data analysis and reports.

accommodate monitoring equipment used by human factor specialists analyzing the system performance [*Thomas et al.*, 2007]. The technical support team had workstations on-site so that software updates and other technical issues could be resolved efficiently.

[42] To plan a day's traverse, the science team used the specialized version of the EventScope visualization software to view, navigate, and annotate 30-m resolution/pixel digital elevation models (DEMs) and high-resolution orbital data of the desert (15 m/pixel or 1 m/pixel). Virtual pins were placed in the terrain (Figure 10) indicating waypoints and detailed sampling areas. They assigned task actions to each pin, specifying appropriate parameters for each action through graphical user interface. When all commands were entered, EventScope generated a plan including unique identifiers (request IDs) for each data request. The plan was then reviewed and directly uploaded to the rover in the Atacama.

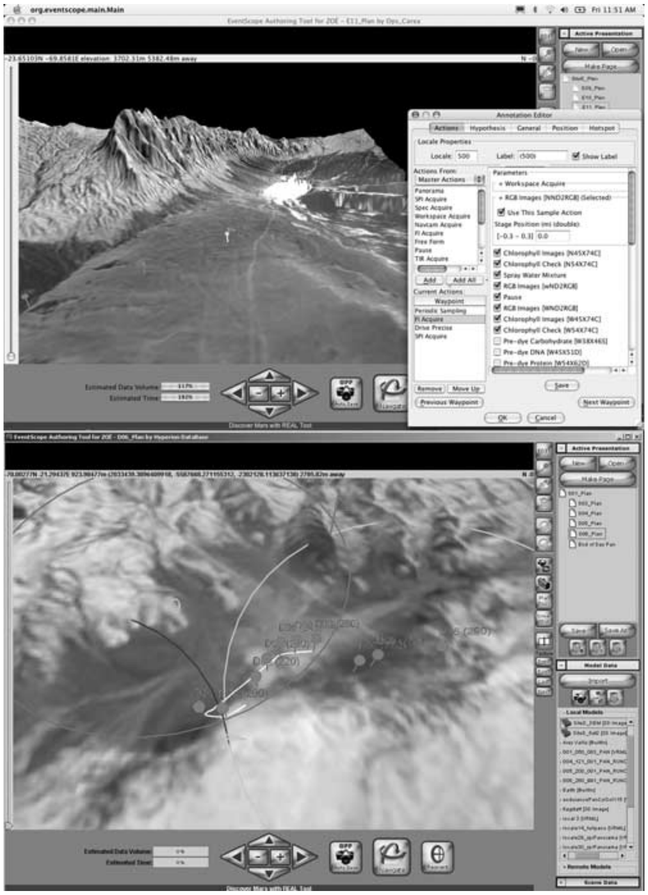
[43] At the end of each sol, data was downlinked and correlated with the respective request IDs. Using telemetry from the rover, the path of the sol's traverse was imported into EventScope and displayed on the DEM to illustrate the rover's traverse. In addition, panoramas were imported into EventScope in 3D for automated triangulation. All science data were made available through the science website so that the science team could download it and continue working with it on their own computers. Generated files were then shared through a file upload system on the science website. Science data visualization in EventScope was also created for education and public outreach at this point. For details on Eventscope, planning and mapping tools, see Hock et al. (submitted manuscript, 2007).

5. Exploration Strategies

5.1. Advantages and Challenges of Long-Range Mobility for Science

[44] Daily temperature swings, enhanced UV radiation and soil oxidation make oases in the Atacama extremely localized. They become increasingly rare in the arid core of the desert with local exceptions [e.g., *Bada et al.*, 2003; *Navarro-González et al.*, 2003; *Quinn et al.*, 2005; *Warren-Rhodes et al.*, 2006; *Wierzchos et al.*, 2006]. These oases are often reduced to subsurface soil niches, selected rocks, cracks in rocks, or specifically oriented slopes. Finding and identifying them, and establishing their distribution demanded more than choosing the right landing site and investigating its immediate surroundings. It required exploration of vast expanses of desert.

[45] When the characteristics of scattered and rare oases are unknown at the beginning of an investigation, and knowledge based at first on orbital data only, increasing the sampling diversity augments the potential of a find. A rover has greater statistical likelihood to randomly detect habitats and life along a long traverse by covering a large diversity of favorable environmental units than by systematically applying its entire payload capabilities to a limited set of samples in the reduced area of the landing site that may or not have conditions favorable to life. Moreover, because the LITA investigation involved the characterization of spatial changes, long-range mobility imposes itself as an essential requirement. It also became a primary science tool in reaching those locales where mission success had the highest theoretical chance of being achieved using a follow-the-water strategy. The guiding principle is that the odds of finding life and habitats in areas of predicted low microbial abundance will increase as the surface mission evolves and a more comprehensive understanding of the environment is acquired by the science team. To gain this first-level understanding of the environment and its biological potential, and visualize the range of possible habitats and oases, it is, however, critical to allow long-range reconnaissance the same way ecologists and biologists explore first the environment they will investigate to define where those oases have the best chance to be discovered. This first step is critical in helping build a mental model of the area to be explored. Allowing such capabilities for a rover also requires the development of a rover's ability to



Locale: 500 Label: (500) ☑ Show Label

☑ Use This Sample Action

Stage Position (m) (double): [-0.3 – 0.3] 0.0

☑ Chlorophyll Images [N45X74C]
☑ Chlorophyll Check [N54X74C]
☑ Spray Water Mixture
☑ RGB Images [wND2RGB]
☑ Pause
☑ RGB Images [WND2RGB]
☑ Chlorophyll Images [W45X74C]
☑ Chlorophyll Check [W54X74C]
☐ Pre-dye Carbohydrate [W38X46S]
☐ Pre-dye DNA [W45X51D]
☐ Pre-dye Protein [W54X62D]

Figure 10. Science tools displayed with Eventscope. (top) DEM of site E with pins showing locales where Zoë will stop on her traverse. Tasks are assigned to each pin. They are entered in the pop-up window (shown to the right superimposed to the screen) where clickable commands are listed for each instrument and each type of science activity. The window display includes: A clickable top bar to call for other windows (e.g., actions, hypothesis); locale properties where the label of each new locale is entered; clickable master actions to select the type of action to be performed by the rover (e.g., panorama); parameters necessary to complete the action (e.g., angles of the cameras). A menu allows the user to select the characteristics of the action (e.g., drive precise). The final plan includes all commands for all locales and is consolidated by Eventscope into one document and uploaded directly to the rover after a last review. (bottom) Autonomous triangulation in Eventscope. Science team members enter flags into the DEM on Eventscope after matching landmarks on a panorama with landmarks in the DEM. Eventscope generates a series of best-fit circles. The location of the rover is where the greater number of circles intersect. These features helped the science team to localize the rover rapidly with precision (generally between 15 and 30 min).

return to interesting sites if necessary, and to allow the in-depth investigation of the most promising targets, the same way scientists finally focus on the object of their investigation after their reconnaissance. Another method is to allow the rover to detect promising targets on its own while it traverses. The rover should be able to make decisions about their validity and priority in the greater scheme of the mission and finally, it should be capable of taking action accordingly. While the science team has only partial contact with the explored area through the selected data that the rover returns at the end of each day, the rover on the other hand is in constant contact with its environment. Provided the proper scanning mode is used, the rover (or for that matter any other type of autonomous exploration technology) is the best positioned to make a discovery. It also saves time by skipping the ‘‘return to target’’ step. This was proven true during LITA in the Atacama but it will be equally relevant for Mars. The challenge for rovers is always the science/mobility trade-off, which is already experienced to some extent by the MER rovers, for instance when Spirit had to run against the winter clock to reach the Columbia Hills (winter #1) or to the McCool Hill (winter #2) while still trying not to miss any critical scientific evidence on its way to her winter safe heaven.

[46] The LITA team was confronted very early in the project to the potential downfalls of trying to apply both detailed science and long-range mobility during daily traverses before understanding what exploration strategy would provide the best productivity from both. This strategy had to provide the right mixture of science and mobility, and in 2005, the decision was left to the only team member who could make a timely and educated decision case by case for each locales, and for each different traverses: Zoë herself (see section 5.2.4, Science-on-the-Fly).

[47] When a rover traverses several kilometers daily beyond the horizon, it cannot be known in advance which specific rock or outcrop will be in front of the cameras or in the working space at the end of the day. Knowledge is limited to the starting point of the rover at the beginning of the sol and to an area in an orbital image where the rover will end the day. This area is known within an error margin of a few percent, uncertainty related to terrain conditions and rover slippage (1–5% of distance depending on terrain type) [*Wettergreen et al.*, 2005a, 2005b] and to the potential for the rover to fault out. In that too, navigation beyond-the-horizon required a new approach to exploration. For MER, whether close or relatively distant, science targets are always selected within the field-of-view of the imagers. During LITA, the strategy was different to take full advantage of Zoë’s unprecedented mobility while searching for scattered and rare life. The remote science team had knowledge of what was in the actual field-of-view of the rover only during ‘‘landing day’’ or when the evening download occurred and data from the last position of the rover had been reviewed. These were the only times when the team could actually select visible targets for early morning operations. Otherwise, the team designated locales along the daily traverse where the rover could stop and perform analysis. The selection of these locales was based on orbital high-resolution and multispectral evidence of habitability potential. However, what was to be found on the ground at those locales sometimes several hundreds of meters apart was a priori unknown. As the mission progressed, more data from the ground were acquired and, although specific targets remained unknown except at the two ends of a daily traverse, the type of terrain to be encountered and its habitat and life potential could be

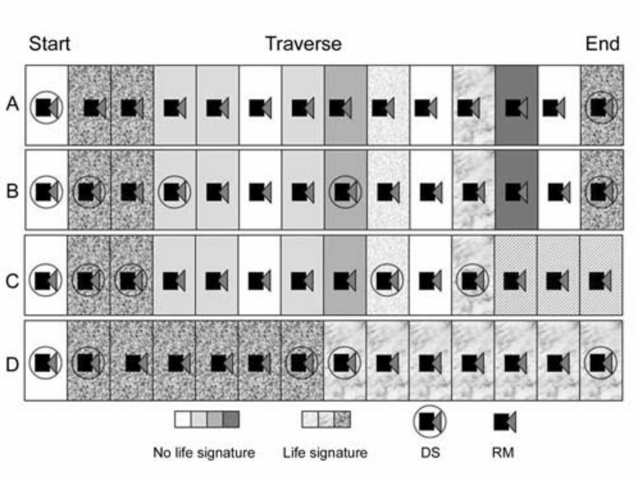


Figure 11. Exploration strategies tested during LITA. DS, detailed sampling; RM, regional mapping or HASTA. Each row represents the same traverse (A, B, C) investigated with different exploration strategies. Note that the distance covered by each column may vary from A to D (see text). Row D represents two segments of a traverse exploring two different environmental units. The columns show environmental units containing life or not (as indicated by the respective patterns). (a) HASTA (regional mapping). Fast survey of a diversity of units, some with evidence of life, others not. HASTA does not allow one to identify the presence of life (unless macroscopic) but to assess its potential by characterizing the environment. (b) Detailed sampling. Locales where to stop for detailed sampling are chosen by the science team from both orbital images and experience gained in prior days of investigation. This experience helps recognize units potentially bearing favorable targets but might lead to favor those compared to potentially new and not yet encountered oases. On this example, a few life-bearing units are missed. (c) SOTF: With the exception of the first and last locales on the traverse, the choice of what locales to select for a detailed sampling is left to the rover. The rover initiates a detailed sampling when obtaining a positive response to its biosignature trigger regardless of the type of unit. While the bias toward known habitats is removed by this systematic approach, SOTF introduced a bias toward targets responding to the rover's biomarker. For instance, in some cases, nonchlorophyll-based life was not detected by the rover. This bias could be resolved in the future by modifying the type, or number, of triggers for a mission depending on its objective. (d) SPSU: Detailed investigation of the evolution of habitat conditions and life across two units, including the transition between one unit and the other.

inferred from experience. Therefore, for similar terrains, the chances of finding life, when present and/or detectable by Zoë's payload, statistically increased as the mission progressed. Trends of life detection obtained by the remote team also mimicked better that of the ground-truth team in 2005 than in previous years (see section 6 and trends in Figure 15).

[48] In summary, to achieve mission success and optimize the science productivity using Zoë's unique mobility capabilities, the remote science team had to solve two main issues: (a) to cover long distances to increase the chances of encountering rare microbial oases and (b) to perform sufficient stops along the traverses using enough of the science payload elements to identify and characterize microbial habitats without impeding overall progress. Solving those two issues resulted in the development of specific science exploration strategies and templates, which culminated in 2005 by the first field testing of Science-on-the-Fly (SOTF). At this stage, the selection of locales of interest became for the first time the shared responsibility of the rover itself and that of the science team.

5.2. Science Exploration Templates

5.2.1. HASTA (Regional Mapping)

[49] Habitat Standard Transect Action, or HASTA, allowed a fast regional mapping and made full use of Zoë's mobility (Figure 11a). It was designed to plan long daily traverses to optimize the sampling of environmental diversity, provide context information regarding the geology and potential habitats encountered over long distances across units of interest, and build mental models of the environment and its potential for habitats. At the same time, it enabled a homogeneous mapping of large traversed areas. HASTA included regularly spaced navcam images, single compressed resolution grayscale SPI frames, partial pans in the cardinal directions (facilitating localization of locales on the traverse a posteriori). Meteorological data were recorded as the rover went during the day. Vis/NIR spectra could be acquired upon request. Overall, the collection of HASTA data at each waypoint could take less than 10 minutes, was low-cost on the bandwidth, and provided a wealth of critical environmental data. These data products allowed the remote operations team to visualize geologic contacts, geomorphic evidence for water, and identify potential habitats for life. Before the implementation of SOTF, those points could be targets of interest where the rover could return afterward for detailed investigation. In 2005, with SOTF, such sites became locales where Zoë would trigger detailed sampling on her own.

[50] Waypoints were always separated by the same distance to allow homogeneous mapping within units of interest. However, this distance was not necessarily always identical from one segment to the next or from one daily traverse to the next in order to accommodate variations in geology and transitions between units. For instance, the distance between waypoints could be augmented when the geological unit was homogeneous over an extended surface area with no major environmental change (e.g., slope, orientation). It could be decreased when transitions were rapid within a geological unit (for instance, an alluvial fan with rapidly changing topography and sedimentological gradients). However, distances were always kept as multiples of each other to allow sub-sampling of results and homogeneous mapping. For such fast transitions, another exploration template was designed to better accommodate the reality of the terrain (see SPSU, section 5.2.3). HASTA provided a fast and very efficient way to characterize the environment. However, it did not provide information about life itself (or only in a few cases, when macroscale oases

existed). In order to document life and its diversity, the remote science team designed another template that allowed a detailed sampling of targets.

5.2.2. Detailed Sampling

[51] Detailed Sampling allowed the investigation of science targets by both in situ and remote payload elements (Figure 11b) and is equivalent in its goal to what is performed currently by MER. It includes: High-resolution imagery, Vis/NIR and TIR spectra, and complete FI deployment. In 2005, neutron spectrometer data were also acquired on one transect at Site F (Piatek et al., submitted manuscript, 2007). While SPI, Vis/NIR, and TIR data were cheap and fast in terms of bandwidth and acquisition time, a full FI deployment was not. The FI operation was divided into 5 minutes for control on a dry target with acquisition of a RGB image. Water was then sprayed on the target. After 2 minutes, another FI RGB image was taken of the wet target for a chlorophyll check. Dyes were then applied (carbohydrates, lipids, proteins, and DNA) and the result of their application checked with FI images. The dye process required 20 minutes. Since this instrument was central to the identification of biosignatures, limiting its usage because of its constraints on Zoë's potential mobility range was defying the purpose of the mission's first priority goal. On the other hand, deploying the instruments and always performing the full set of FI operations for each locale would have drastically limited Zoë's ability to explore more environmental units, hence decreasing her probability of finding microbial habitats and illustrating efficiently their spatial distribution. This, too, would have defied the purpose of LITA's objectives. In 2004, the search of the optimum trade-off between science and traverse time led the science team to develop hybrid versions of HASTA and Detailed Sampling before SOTF optimized the trade-off and transformed mobility into a powerful science tool in 2005.

5.2.3. Trade-Off Strategies (SPSU and Random)

[52] The Standard Periodic Sampling Unit (SPSU) was designed to be a 180 m transect exploring a unit of interest and its spatial changes within a daily traverse (Figure 11d). Detailed sampling was performed at each end of the traverse. In between end points, the rover stopped at 5 waypoints spaced about 30 m (the resolution of the digital elevation model) where quick surveys and a short FI sequence acquiring only visible and chlorophyll channels were performed (<10 minutes per waypoint). The daily traverse could be planned as a simple succession of SPSUs. The average distance of the transect itself was chosen to provide a representative unit by which the types of environments and potential habitats in the landing site regions could be compared systematically. If the SPSU did not include follow-up, the bandwidth consumption was 2,590 Kb per SPSU. With FI follow-up, the operation took a little over 23 minutes and 5,920 Kb.

[53] The remote science team also made use of random exploration strategies, especially in early field investigations (Sites B-C) which were hybrids of HASTA, SPSU, and Detailed Sampling. This mode had its merits in that it allowed some flexibility in complex terrains and transitions where established templates presented more probability of missing important observational clues by passing by them. The constraint of such a strategy was the difficulty to sometimes reconcile the data with the larger perspective of a homogeneous mapping along the transect.

5.2.4. Science-on-the-Fly

[54] To detect life on the fly, the rover had to analyze its observations. The software that enabled SOTF consisted of two principal parts: The Science Observer and the Science Planner. The Science Observer interpreted image and instrument data to find possible targets of scientific value. The Science Planner, took these interpretations and planned experiments that would be of maximum scientific value [*Wettergreen et al.*, 2005a, 2005b; *Smith et al.*, 2005]. In effect, it decided when the observation was significant enough to warrant additional measurements. The trigger used for the LITA operations was a cholorophyll-check. The rover stopped at waypoints planned by the remote science team and, as part of a quick survey, acquired a RGB image of a potential target in the FI work volume. Then, the targeted area was sprayed with water. After two minutes, a FI image was acquired to check for chlorophyll response. If the response was negative, the rover moved on; if the response was positive, the rover triggered the entire suite of FI operations (carbohydrate, protein, lipid and DNA dyes).

[55] FI images could be difficult to analyze because of potentially low signal-to-noise ratio and in the interpretation of the image, both high-intensity pixels (typical of a positive response) and local patterns and contrast with background had to be considered. Baysian Network classifier algorithms were applied to the FI images. Prior to 2005, the rover was trained to recognize examples of biosignatures using hundreds of positive and negative responses and the network assigned a single probability that the image contained a biosignature based on the analysis of all subregions of that image [see also *Wettergreen et al.*, 2005a, 2005b; *Smith et al.*, 2005]. This algorithm was implemented onboard Zoë in 2005 as part of the science observer and was used for the investigation of Sites D, E, and F.

[56] With SOTF, the responsibility of optimizing the science/mobility trade-off was therefore shared for the first time by both the remote science team and the rover. The science team made the decision of selecting a daily traverse path on orbital images that covered environments of interest. On that path, they selected locales of interest (from orbital clues) where to stop. The team could choose one or several exploration templates for the traverse documentation depending on the type of terrain. Detailed Sampling was performed at each end of the traverse. During the traverse, Zoë executed the plan and SOTF gave her a "trigger" (chlorophyll) that allowed her to make decisions on her own to, whether or not, perform a full FI investigation on a sample. In summary, this software used sampling preferences to decide whether it was worthwhile to delay the rover's traverse in order to perform follow-up observations. If not, the rover moved on along the planned traverse (Figure 11c).

[57] A full sample took about 35 minutes to complete. Every time the rover did not stop unnecessarily for a detailed sampling was 25 minutes (35 – 10 minutes of quick survey) saved on mission time and resources that could be used to reach higher priority sites. Every time Zoë triggered a full FI operation on a waypoint, there was a high

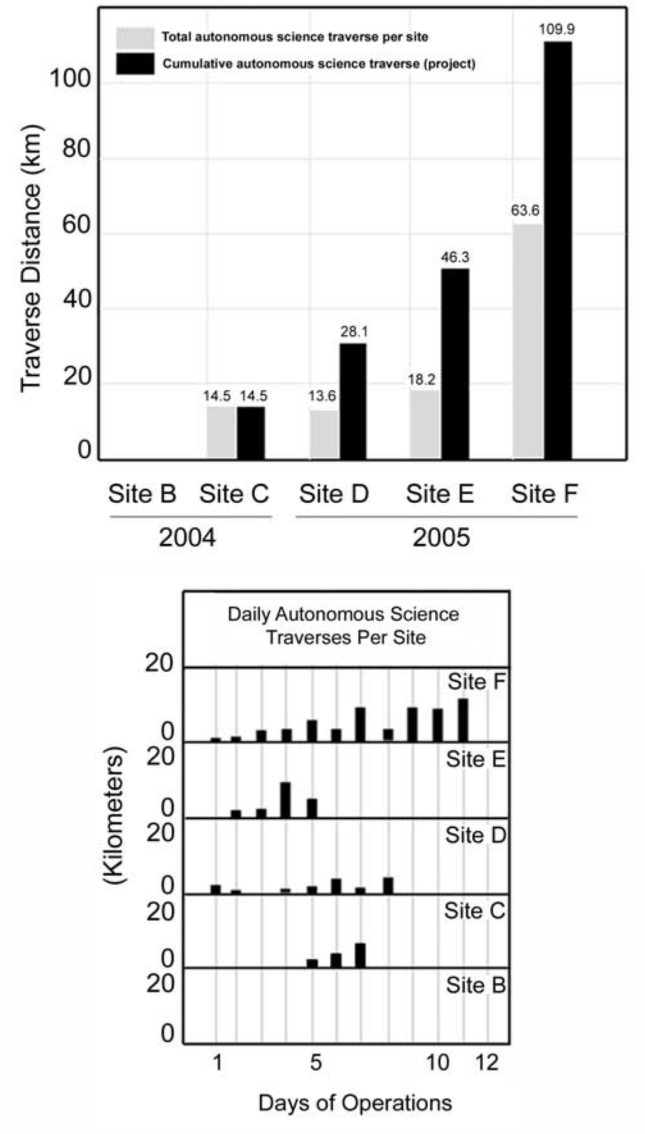


Figure 12. Autonomous science traverse. (top) Total autonomous science traverse per site and cumulative distance covered autonomously by the rover during the project. (bottom) Detailed daily autonomous science traverses per site. Note: Strict rules were applied in considering a traverse autonomous. As soon as human intervention was necessary, the traverse was not considered as autonomous regardless of how much distance the rover had performed on its own prior to that interruption or how short the interruption was. At Site B, ~6 km of science traverse were completed; however, because of fine-tuning of the rover in this first integrated test, which required repeated human intervention, none were considered autonomous.

potential for a positive that the remote science team could not have known existed since it did not have the data yet.

6. Synthesis of Results

[58] The gradients of life and habitats in the Atacama Desert established during the LITA project are representative of the types of life and habitats that were detectable by the rover and of the traverse choices made by the science team. By no means do they reflect an "absolute reality", which is always elusive when it comes to quantifying microbial abundance and diversity. Rather, they are a window into the biological diversity of the Atacama. Therefore, our conclusions are limited to the scope of LITA, the same way future astrobiology missions will only be able to conclude about their ability to find what they came for and not everything that might be observed. LITA was a first step. One of its merits was to, in many instances, help identify and formulate new questions of significance for the search for life in extreme environments or beyond planet Earth. The response to those questions will require more iterations here on Earth.

[59] The questions raised and documented by LITA are at two levels, that of the project discussed in this section, and that of planetary exploration discussed in the conclusion. Those questions can be summarized as follows: What is the vision of life and habitats as seen through a rover's payload along transects in the Atacama Desert, and how did the results of remote operations compare to ground-truth? What lessons learned from LITA can be applied to planetary exploration? Will rovers be useful platforms in the search for life on Mars?

6.1. Technical Advances

6.1.1. Autonomy and Navigation

[60] Over the entire project, Zoë traveled over 275 km, 110 km during the 6 weeks of science operations, 165 km during engineering demonstration in the desert. Over the three years of the project, daily traverses beyond 4 kilometers (>10 km for the longest) were also completed regularly but some of these traverses included several command cycles because of interruptions (e.g., rover faulting out, mechanical or software adjustments). During science operations, the rover's longest single-day distance total was just over 13 km. During engineering tests, this single-day distance total was 17 km. Zoë's longest autonomous traverse in one day and one command cycle (without human intervention) during science operations was 4,987 m. Along this traverse, the rover regularly executed science templates and did not simply drive. During the engineering test, the longest autonomous traverse in one day and one command cycle was 6,274 m. The rover repeatedly (74 times) covered 1 km or more in one command cycle demonstrating a robust result. Figure 12 summarizes the distribution of autonomous science traverses for 2004–2005 (Sites B-F).

6.1.2. Impact of Autonomous Science

[61] For the first time, SOTF gave significant decision-making to a rover. In 2005, Zoë made decisions on her own about what targets were worth fully documenting or ignoring within the scope of the mission. The efficiency of this strategy is quantified by the number of samples it returned to the science team compared to previous exploration modes. Comparable sites on the Coastal Range were investigated without SOTF (Site B in 2004) and with SOTF (Site D in 2005). Over a period of 7 days (~3,360 minutes of mission time, or MT), 26 samples were documented at Site B and 92 at Site D. Out of the 92 samples, 47 were found to be negative by the rover. It could either have meant that no life was present or that life was present but could not

be detected by the capabilities of the rover (out of mission scope). To reach a "negative" conclusion with SOTF took less than 10 minutes for the rover. Over the entire week, this translated into 470 min (14% MT). If Zoë had been on previous exploration strategy modes (such as that of Site B which required that each sample was fully investigated) the same analysis would have taken 48% MT. This freed MT translated into more samples being investigated at Site D and more time to fully detail 45 positive samples compared to the 24 at Site B. The freed MT also translated into more distance being covered by Zoë (~6 km at Site B and 14.1 km at Site D).

[62] In summary, current planetary exploration sends a rover from point A to point B focusing on the analysis of A and B. SOTF also allows the analysis of both A and B but additionally documents the changes between A and B. It allowed the science team to develop a higher resolution (30 m compared to previous years 200–500 m), more rigorous, and more homogeneous mapping of life and habitats over greater distances than previous exploration strategies. More environmental units were visited. Both positives and negatives were mapped and Zoë collected sufficient data to enable a characterization of those "non-habitat" (no detectable life, past or present) during the quick surveys. However, time and in-depth analysis were focused on the first priority of the mission: Finding life and characterizing its habitats through a climatic gradient. The use of SOTF brought in focus the relatively subtle changes within a unit and throughout units, and showed the characteristic patchiness of life within local oases that was not captured in previous years because of the spatial spread of each detailed sampling.

[63] SOTF was not flawless. In some cases, the trigger did not work when life was shown to be present by ground-truth. Overall, the rover was correct 75% of the time by not triggering a full sample. The remaining 25% of the cases are related to three types of situations: (a) The presence of nonchlorophyll-based life that the rover could not detect using chlorophyll as a trigger. This suggests the possible replacement of the single-trigger scenario used by LITA by a suite of quick triggers involving more biomarkers. Here, the rover could only detect what it was taught to identify, emphasizing the weight carried by the decision of choosing a specific payload for a mission. On Earth as on Mars, we will find only what we came to search for, not necessarily what is there; (b) the presence of chorophyll-based life but no adequate reaction to the water spray; (c) the last case was related to wrong decisions by the rover that could have been due to a diversity of factors (e.g., imaging conditions, lighting, contrast). Those cases point toward areas where SOTF and its use could be perfected in future field campaigns (detection limits, detection methods, selection of biomarkers). Ultimately, and ideally, SOTF should become flexible enough to allow the choice of specific triggers that can be adapted to a specific mission's objectives.

6.2. Detectable Habitats and Life

[64] The Atacama Desert is the most arid in a corridor bound to the West by the reaches of coastal fog and to the East by aquifers supplied by storms in the Andes. Crossing the Atacama, the resulting West/East transect between the Pacific Ocean and the Andes can be then profiled as a Wet/Dry/Wet gradient with hundreds of square kilometers of scattered microbial habitats and the occasional oasis of bushes, plants, and trees in the arid core of the desert (e.g., Site F).

6.2.1. Mineralogical Signatures of Habitats

[65] Orbital multispectral image analysis proved invaluable both for identifying potential areas of interest prior to remote operations and for targeting specific locales during operations [*Piatek et al.*, 2005]. More compositional diversity than predicted from orbit was observed on the ground, which has implications for landing site selections for future Mars missions. Rover spectroscopic results were consistent with orbital results and ground truth, suggesting that most sites had an igneous origin, but are now dominated by alteration materials (i.e. clays) with minor concentrations of evaporites (sulfates), quartz, and iron oxides. The optimal targeting strategies for identifying compositional variation were rock and soil targets identified in images by the remote science team. Spectra targeted "blind" (without aid of images) tended to be spectrally bland. This is likely the result of a large field of view (due to low tilt angles necessary to avoid targeting the rover) that is dominated by soils rather than rock targets. For this reason, blind targeting was avoided in later field seasons.

6.2.2. Habitats and Life

[66] Prelanding assessments of geological orbital data, particularly when coupled with a 'follow-the-water' strategy, accurately identified many promising macroscale habitats within regions and locales, and predicted geological diversity at the microscale ($10\ \mathrm{cm}^{-2}$) by broad type and composition, as obtained from microscopic imaging. That orbital data can help accurately identify consistent geological and mineralogical units from macroscale to microscale, along with transitions between such units, is of fundamental importance for astrobiological exploration in the search for promising habitats at multiple spatial scales. However, as described for Site B [*Warren-Rhodes et al.*, 2007a], orbital data attained only mixed success in terms of predicting the relative promise of different macroscale environments for containing life. This mixed success was evidenced by (a) positive results for the detection of significant lichen populations at Site B locale 19—a region predicted to have high potential for life from chlorophyll signatures in the VNIR satellite imagery; but (b) negative results with regards to the lack of prediction from orbital data of habitats colonized by lichens at locales 1 and 2 at Site B. Correlating and confirming which types of habitat units have a higher probability of containing life both from orbit and on the ground remains at this stage a significant challenge for remote astrobiology missions.

[67] Although scattered, habitats often had common mineralogical, morphological, geological, and topographical characteristics. For instance, at the microscale, heave-type substrates were shown to have significantly higher microbial abundance than pebble-type habitats. In some instances, they were correlated to the types of microbial organisms identified (e.g., gravel bar habitats and moss or heaved gypsum and lichen) and the presence (or lack thereof) of measurable evidence for life. Overall, desert pavement was the dominant habitats at all sites (Figure 13). Heaved gypsum crust was prevalent as well in both Coastal Range sites (B and D). At mesoscale to microscale (m to μm)

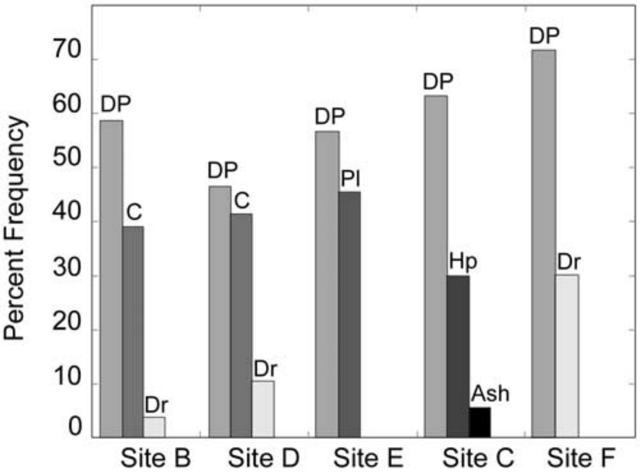


Figure 13. Diversity and frequency of habitats per site. DP, desert pavement; C, crust, often observed as heaved gypsum crust; Dr, drainage; Pl, Playa; Ash, ash deposit or combination of ash and other materials; Hp, hypersaline environment, typically halite deposits.

heterogeneity was significantly greater and niche microbial populations, such as lichens, moss, and endolithic microbiota, were observed (Figure 14).

[68] Similar to the findings for chlorophyll-based microbial communities, rover FI data also showed strong variations in the percent positive ratings for nonphotosynthetic populations (i.e., the DNA-Protein-Lipid-Carbohydrate biosignature rating). At Site D, for example, trends in the relative microbial abundance between locales mirrored those obtained in the laboratory culture of species of heterotrophic bacteria in soil samples from the investigated locales (Figure 15). Results indicate abundance ranging from 10 to 1,000 colony-forming units/gram-soils (CFU) determined as Most Probable Number (MPN) enumerations on 1/10 strength PCA medium [*Navarro-González et al.*, 2003]. The geometric mean for samples from 12 locales at Site D was 15 CFU/g-soil, lower than Site B also in the Coastal Range (32 CFU/g-soil). Site B provided also the highest and lowest abundance of all field campaigns within a few meters with 10,000 CFU/g-soil at locale 5 and 1 CFU per gram-soil at locale 6, clearly illustrating both the patchiness of the desert and the often very localized extent of favorable conditions for life. At Site D, the highest bacterial numbers were observed at locale 210 (1,000 CFU/g-soil) and locale 110 (100 CFU/g-soil), site predicted to have high-potential for life. These results also underscore the effectiveness of pretraverse selection of regions of interest from orbital multispectral imagery and follow-the-water exploration strategies.

[69] This becomes particularly important in light of across-site comparisons that revealed that nonalluvial fan habitats (i.e., playas, hypersaline environment, heaved crust) had significantly lower microbial abundance (as surveyed by the rover) than alluvial fan habitats, with the exception of those in exceptionally wet environment (drainage areas in the oasis at Site F). This finding occurred not only for orbital-scale habitat classifications but also for ground-based classifications based on SPI and FI data (e.g., crust heaves versus pebbles at Site D), with desert pavement habitats (SPI) and pebble habitats (FI) generally exhibiting the lowest abundance. Surprisingly, however, real-time analysis of habitats at SPI scale (1–200 m^2 field of view) was less predictive than anticipated when compared with orbital and FI analyses. Details about analytical methodology and biological results can be found in *Warren-Rhodes et al.* [2007a, 2007b] and Hock et al. (submitted manuscript, 2007).

[70] Climate data, particularly solar insolation and air relative humidity, enhanced the team's ability to understand particular habitats potential for life and interpret fluorescence image sets. For example, the presence of lichens, which can utilize atmospheric water vapor, were found only in sites where the rover RH sensors and insolation data indicated the influence of nightly fog at the Costal Range sites (B, D). Clear fluorescence evidence of chlorophyll and traces of protein and nucleic acid were also observed on those lichen structures. In contrast, no lichens were detected at sites within the desert interior. In such cases as Sites C and E, no evidence of life was found in the RGB or chlorophyll fluorescence in many samples. However, most of these samples ($\geq$75%) showed positive signals after DNA and protein dyes. The location of the fluorescence was occasionally associated with cracks and light-colored veins.

[71] Overall, LITA biological and habitat data demonstrate that the gradient of life mapped across the five Atacama sites surveyed by Zoë reflects the wet/dry/wet climate gradient from the Coastal Range to the Atacama Desert: Wet sites had comparatively higher diversity and abundance compared to dry sites, with the former mainly due to the loss of shrubs, moss, and lichens at the driest sites. LITA mapping results also reveal the nonrandom nature of life within the world's driest desert. Microbial abundance and spatial distribution at every scale examined, from the orbital to the microscale was patchy, with this variation explained, at least in part, by heterogeneities at these same scales in geological, environmental, and other factors (e.g., terrain).

6.2.3. Mapping the Distribution of Life

[72] The need to systematically map environmental factors that influence potential habitability and the results of biological investigation led the LITA team to consider a scoring system for locales that would serve to integrate data from multiple sources and streamline analysis. The development of this system, including methods and data analysis, is detailed in Hock et al. (submitted manuscript, 2007). The LITA scoring system was developed and tested using the 2005 data sets of Sites D, E, F. Scoring categories included environmental variables such as the presence of traces of the action of water visible from orbit (e.g., morphology, geology, mineralogy, meteorology, slope orientation), or visible from the rover (response to biological triggers - chlorophyll, DNA, proteins, lipids, carbohydrate). Final scores resulted in various levels of confidence about the presence of life that were translated into color coding on maps (Figure 16). The variability in biology as a function of environment ratio was also documented. Variability in data availability by locale presented difficulties for in-depth statistical analysis. However, preliminary results indicate that of individual environment factors, observations of bound interlayer water

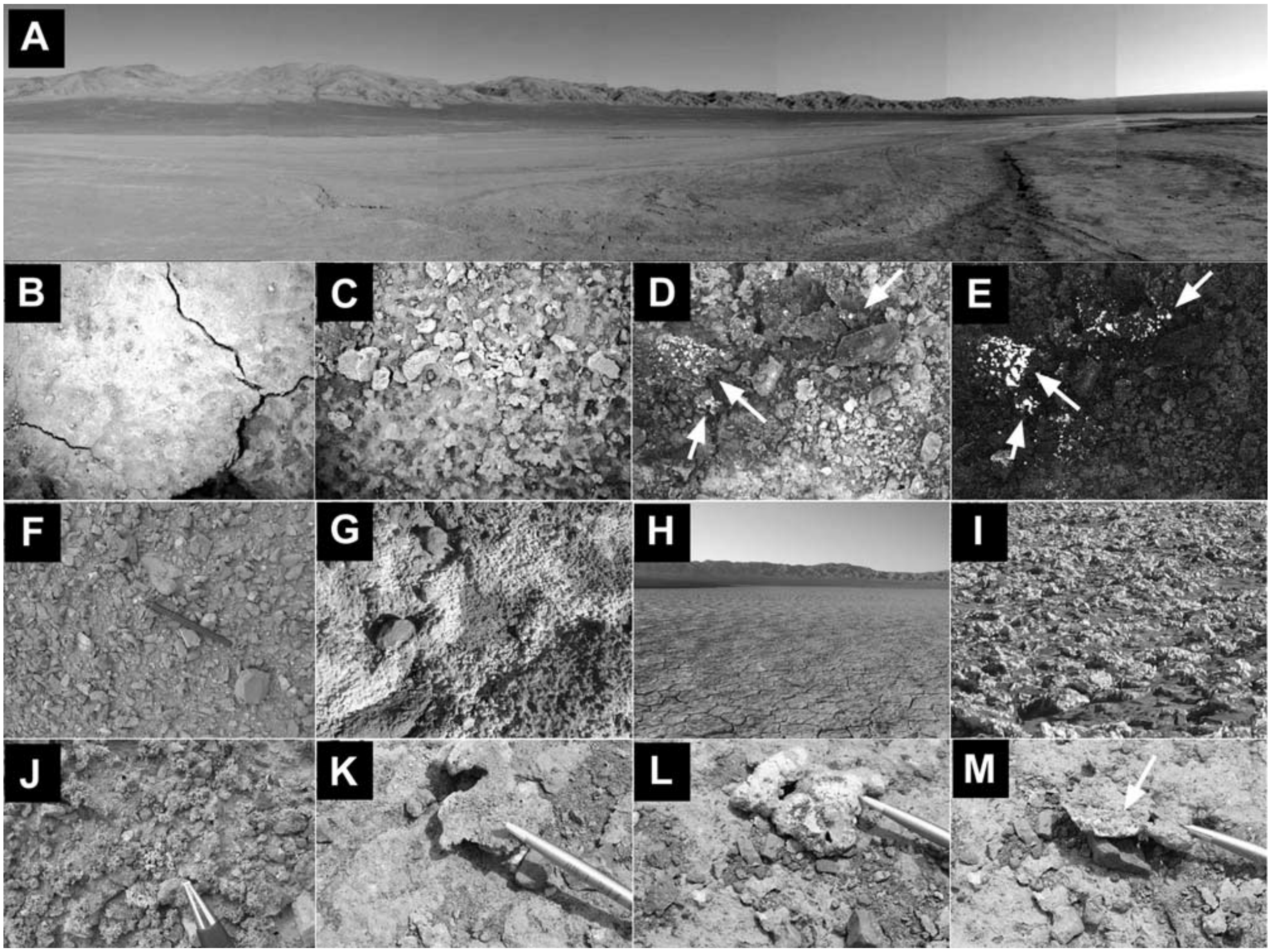


Figure 14. Diversity of terrains and habitats. (a) Panorama of Site E, locale 217, acquired by Zoë in October 2005. It shows mountainous terrain, mudflats, and alluvial fans in the background. (b) Site E12, locale 640, a RGB FI image (223 μm transverse resolution) detailing cracks and microcavities in the mudflat. (c) Site E12, locale 650, RGB FI image showing the diversity of micromorphologies associated with the mudflat. (d and e) Site D03, locale 060. RGB FI image following water spray on a gravelly surface. Arrows indicate microscopic lichens, which triggered a response in the chlorophyll channel characterized by bright patches and dots visible in field-of-view of the FI image E (arrows). (f–m) (ground-truth photographs): (f) Desert pavement. (g) Salty, heaved, material. (h) Mudflat (Salar de Navidad). (i) Hypersaline environment. Halite deposit at Salar Grande near Site A. (j) Moss and lichen colonizing soil and pebbles near Site B. (k) Lichen colonizing isolated halite block covered by desert dust at Site A. (l and m) ''Troglodyte lichen'' observed inside heaved gypsum crust. Few, dried, isolated lichens are attached to the surface of the heaved crust. The gypsum crust surface has holes that can be few millimeters to centimeters in size letting sunlight penetrate inside the microcave. When turned over, blooming lichens are observed attached to the inner wall of the microcave.

(field, rover spectrometer), evaporite mineralogy (orbital, ASTER spectrometer), and insolation (field, rover pyranometer and visible-band cameras) correlated most strongly with biology ratio, respectively. Of individual biology factors, DNA fluorescence exhibited the only significant positive correlation with environment ratio. Future analysis includes the assessment of the feasibility of predicting the location of habitable environments and potential refuges for life in the desert.

6.3. Ground-Truth

[73] Ground-truth samples were collected in two stages. First, during each field investigation, a ground-truth team followed the rover traverse about a day behind and collected rocks and soils for laboratory analysis. The samples to be collected were designated on digitally annotated SPI and FI images transmitted to the field by the remote science team. After field collection, there was no communication about potential visual observations between the ground-truth and remote science teams to preserve an unbiased experiment. The samples were transported to the laboratory after the field campaigns. After analysis, the conclusions from the laboratory and that of the science team were compared. Because of the number of locales documented by Zoë over the three years and limited resources, not all targets were sampled this way. However, comprehensive transects were

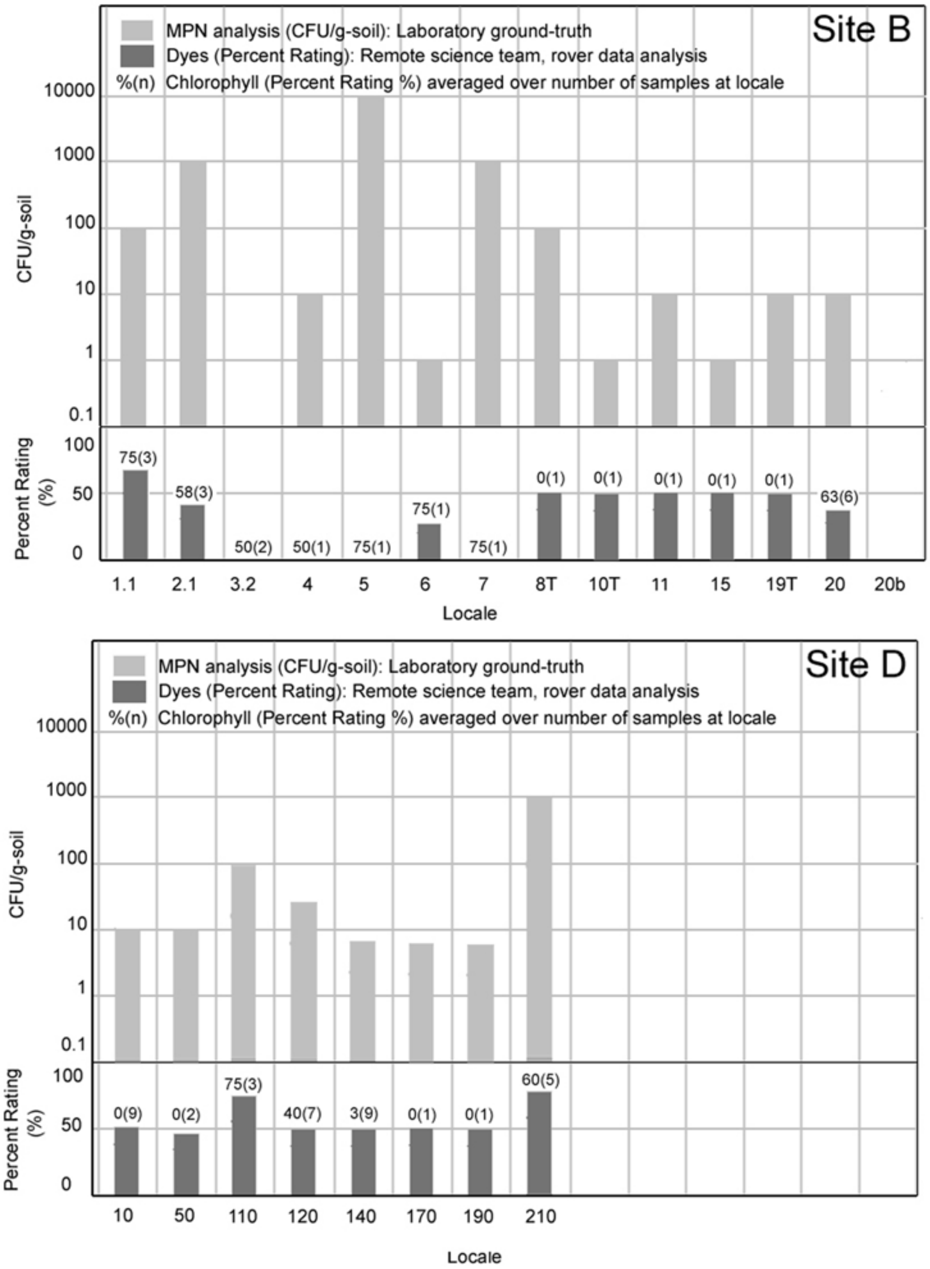


Figure 15. Life abundance as estimated by MPN analysis on ground-truth samples and by rating of the presence of life by the remote science team from rover data (chlorophyll + visible channel and dyes) for the same samples. MPN results are given in CFU/g-soil. The percent (%) rating for chlorophyll + visible channel is shown as the number on top of the dye histogram: 0% is no signal on either 2 channels and 100% corresponds to a strong signal in both channels (suggesting the presence of photosynthetic organisms). The number of samples per locale used to average the rating is shown under brackets. Percent (%) rating for DNA + Protein + Lipid + Carbohydrate (DPLC): 0% is no signal in any channel; 100% is a strong signal in all 4 channels. Results are averaged over the number of samples per locale. The parallel between the distribution obtained from laboratory analysis and the distribution obtained from rover data at Site D compared to Site B shows that the exploration strategy used at that site was better mimicking results from human field work. In general, for these locales where ground-truth is available, life was identified in the rover data by the remote science team where it was identified by the ground-truth team. Overall, when the remote science team scored a locale high (strong signal), the scoring was correlated with a high-abundance of life in the CFU analysis.

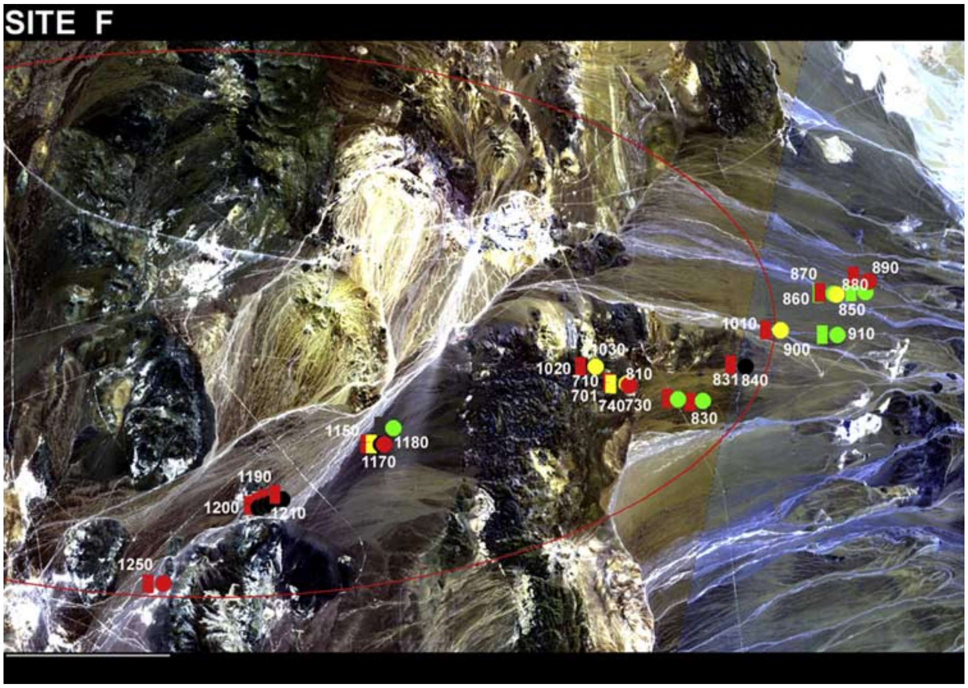


Figure 16. Mapping life along the rover's traverse. The red ellipse shows part of the landing ellipse. The scale bar indicates 5 km. Circles represent bacteria and rectangles are phototrophs. Color code: green, positive; yellow, ambiguous; red, negative; black, undetermined from data set. This map shows the main locales. Details about habitats and life along traverses, determination of their presence, and life mapping methodology are given in *Warren-Rhodes et al.* [2007a, 2007b], Weinstein et al. (submitted manuscript, 2007), and Hock et al. (submitted manuscript, 2007).

documented and provided results as those shown in Figure 15. The second stage of ground-truth allowed a more homogeneous vision of the distribution of life. After the end of the last field investigation, the remote science team went to the Atacama and walked the 2003–2005 traverses. The locales where the rover had stopped had been marked as well as the area sampled. The science team could then assess in situ the presence of obvious signs of life (or lack thereof) and in some instances, more sample collection was performed.

[74] Site C was chosen for an analysis of the microbial diversity because it was one of the most arid sites. A representative of each colony type obtained in MPN enumerations was typed by the nucleotide sequence of its small subunit ribosomal RNA gene. In all, 33 isolates were typed from the 12 Site C locales. Twenty-four of these were members of the Actinobacteria phylum, of which 15 were in the Arthrobacter genus and 5 in the closely related Kocuria genus. Except for two Bacillus species, all remaining strains were representatives of separate genera. Five strains were members of the Proteobacteria phylum, three were Firmicutes, and one was a Bacteroidetes. These results are consistent with the known characteristics of the Arthrobacter as being able to withstand low nutrient levels and desiccation. The above data is a minimal estimate of species diversity since it is derived from strains that were cultured as aerobic heterotrophs.

[75] It may be surprising that aerobic heterotrophs were found at all locales visited. Soil assays for organic compounds that might serve as carbon and energy sources for growth of such bacteria were not carried out during these studies. Photoautotrophs were detected at only a few sites by the imaging system on the rover and thus may not be playing the role of primary producers at a significant scale.

7. Discussion

[76] Zoë is a field-tested prototype; a first configuration of a rover designed for surveying life over large areas. Many aspects of the LITA project could find direct application for the search for life on Mars including the exploration strategies and mapping methods, as well as many of the developing technologies for long-range roving and automated science and navigation. But some of the methods applied in the Atacama on Earth could not be performed on the surface of Mars. Specifically spraying liquid water and dyes on targets is problematic because of planetary protection issues [e.g., *Rummel and Race*, 2002; *Race*, 2004; *Lin*, 2006; *National Research Council*, 2006] and because the liquids would sublimate too quickly in the low pressure atmosphere. Still the process of fluorescence detection of biogenic material demonstrated by the FI could be performed in a sealed container onboard a rover with the added complexity of collecting and transporting a small sample into the instrument. This approach is proposed for a variety of rover instruments and several viable mechanisms exist to accomplish it.

[77] The regional exploration of Mars and the characterization of its habitability (past and present) are driven almost entirely by orbital missions as surface missions, even those that rove, have acquired narrowly focused observations in limited areas. Orbital data gives access to

the macroscale clues about the evolution of Mars habitability. They do not allow access to the microscale, which is generally considered to be critical to search for habitats and identification of life. The only two sites where the microscale has been investigated are Gusev Crater and Meridiani Planum [*Herkenhoff et al.*, 2004a, 2004b] and at those locations, spatial coverage is lacking due to limitations on rover mobility. If exploration remains heavily supported by orbital missions, then we need a method that would bridge orbital data and the detection of potential microhabitats. LITA demonstrated that the evaluation for the presence of microhabitats from orbital data is possible to some extent. However, orbital data attains only mixed success in predicting the relative potential of different macroscale environments for containing life. For LITA as for Mars, the key is in the amount and homogeneity of data supporting the analysis to build predictive models. This can be achieved by increasing the number of landed missions and/or increasing the distance covered by mobile vehicles during individual missions, thereby increasing the diversity of terrains and environments investigated.

[78] The comprehensive search for extant ecosystems would likely involve great complexity. In only one extreme scenario, it may be that life has evolved to the point where it is now completely disconnected from the evolution of surface conditions and thrives at depth. In this instance, orbital data of surficial units and models derived from them would be poorly relevant for the understanding of where to search for microbial organisms. If life is subterranean on Mars, what would matter would be to understand what the subsurface conditions are, and how to access them. Radars, such as MARSIS (Mars Advanced Radar for Subsurface Ionosphere Sounding onboard Mars Express) and SHARAD (SHAllow RADar onboard Mars Reconnaissance Orbiter) will accumulate data that allow documenting the existence of favorable conditions for life, such as subsurface water and ice resources, faults and fracture networks, possibly perched aquifers and caves [e.g., *Boston et al.*, 2001].

[79] Once the characteristics of the subsurface are better known, deep drills would be needed to explore and characterize the Martian subsurface. Using a deep drill as a reconnaissance method to investigate the potential of a promising subsurface habitat with no prior indication of positive life identification would have low likelihood of success if life is not abundant in the subsoil. So far, unfortunately, orbiters have not been successful at detecting unambiguous biosignatures that could allow pin-pointing an individual high-probability site.

[80] On the other hand, orbiters have been highly productive in showing the many sites and extended regions where subsurface material is exposed to the surface. These sites include recent gully, mudflow, debris-covered glacier and stripped valley deposits [*Malin and Edgett*, 2000; *Kargel*, 2001; *Mellon and Phillips*, 2001; *Cabrol and Grin*, 2004; *Gillespie et al.*, 2005; *Head et al.*, 2005; *Forget et al.*, 2006]. These sites have at least three essential qualities for the search for life on Mars, which make them high-priority landing sites for future missions (Mars Science Laboratory, MSL, First Landing Site Workshop, Pasadena, 2006): they are associated with the recent activity of water; they are ubiquitous from orbit; and the mechanisms that formed them may have recently exposed deep subsurface material. *Wynn-Williams et al.* [2001] suggested that this type of mechanism could recently have brought biomolecules from subsurface ecosystems to the surface. Examining the surface, or shallow subsurface, seems more likely to help localize habitats than taking a stab with a deep drill.

[81] A long-range rover landing in a region where any of these landforms abound could investigate many of their deposits in the lifetime of one mission. It would achieve a thorough reconnaissance of multiple environments potentially hosting evidence of a subsurface biosphere recently exposed at the surface through regional and possibly microclimatic transects. A mission concept following this scenario would transform the search for life on Mars into a surface search for scattered potential host environments, a scenario very much like the one LITA has developed and applied. Because those deposits are mostly co-located with the region of origin, the resulting survey data (whether positive or negative), and their correlation with orbital data would provide the statistical base for the first predictive model and mapping of the distribution of Martian habitats. Such a tool is not yet available and is essential in the search for life on Mars.

8. Conclusion

[82] The Life in the Atacama project was motivated by our desire to understand the regional nature of life which survives under terrestrially extreme conditions in the Atacama Desert. Our approach was to perform ecological transects in regions from the relatively wet coastal range to the arid core of the desert. These transects have produced first biogeologic maps of these areas of the desert.

[83] We recognized that evidence of life would be unambiguous only when confirmed by multiple lines of evidence. Thus we sought to create and utilize instruments that would detect life visually and chemically and would collocate their observations on a single habitat. The reasoning being that if within an environmentally and geologically plausible microhabitat we could see biologic structure and had fluorescence indicating multiple organic compounds, then all of these lines of evidence would be sufficient evidence of life. Our comparison to ground truth measurements show that this is indeed a strong method of detecting life.

[84] Our exploration strategy was not to focus intensely on limited samples but because our hypothesis was that life was sparely distributed, we instead sampled broadly to increase the opportunity to observe a viable habitat. This strategy also proved productive in locating evidence of life, sometimes after many kilometers of travel and many negative observations. We have computed the statistics on the productivity of this approach and believe that survey is suitable as a first step and when environments demand broad sampling.

[85] The LITA project identified and confirmed microbial habitats by detecting fluorescence signals from chlorophyll and dye probes in daylight. Using a remotely guided rover we characterized of geology and environmental conditions. We developed mapping techniques including homogeneous biological scoring and predictive models of habitat location. To accomplish this, we developed of exploration strategies adapted to an autonomous rover capable of multikilometer

daily travel. Lastly, we performed the first demonstration of autonomous detection of life by the rover, with the rover interpreting its observations on-the-fly and deciding which targets to pursue with further analysis.

[86] We conclude that there is more field testing required and ethnographic analysis needed to understand the ability of science teams to detect and characterize microbial life signatures remotely using a rover but LITA has made some valuable first steps in terms of creating new technologies and applying new methods.

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