Observations of a potential Mars analog at the microscale using rover-inspired methods: A 10-sol observation of Fort Rock tuff ring

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Received 3 June 2008; revised 24 February 2009; accepted 19 March 2009; published 19 June 2009.

[1] The terrestrial geologist's hand lens is a fundamental tool for identifying and correlating rocks and minerals. We used rover-inspired methods of remote hand lens–scale data acquisition to conduct reconnaissance of a well-characterized Martian analog field site. The objective was to determine if the current methodologies associated with the use of remote hand lens–scale imagers maximizes science return. Field geologists provided with hand lens–scale images of targets in geologic context could correctly identify many important characteristics of those targets. However, they could not fully confirm or rule out any formation hypothesis using the data provided solely through rover-driven observational strategies. This was due to (1) a lack of "intermediate-scale," or millimeter- to centimeter-scale images providing important contextual information for the targets studied and (2) the limited number of hand lens–scale images that were taken using rover-driven methodology. We conclude that the benefits of the hand lens as an effective triage tool and discriminator of microtexture are limited using current rover-driven methodology because the hand lens–type imager is not deployed frequently, and resulting data cannot be used to fully support geochemical observations. We recommend pursuing ways to increase the number of images that can reasonably be acquired at the hand lens scale. In order for hand lens–scale imaging to be fully effective, textural characteristics diagnostic of the nature of a geologic site need to be identifiable at a number of different resolutions; rover microscale observational strategies must include more contextual imaging.

Citation: Yingst, R. A., M. E. Schmidt, and R. C. F. Lentz (2009), Observations of a potential Mars analog at the microscale using rover-inspired methods: A 10-sol observation of Fort Rock tuff ring, *J. Geophys. Res.*, *114*, E06004, doi:10.1029/2008JE003223.

1. Introduction

[2] In order to identify and acquire geologic samples that can address specific science questions, potential samples must be efficiently classified in the field prior to further in situ or laboratory investigation. For field geologists, a crucial instrument for this work is the hand lens, which provides microscale textural information about a rock or soil and the characteristics of its components. The size, shape, sorting and texture of individual grains reveal clues as to whether grains were rounded by water or shattered by glacial ice; whether they were pitted and glazed by wind-driven impacts; or whether they underwent very little modification from source to deposition site [e.g., *Wadell*, 1932, 1933; *Zingg*, 1935; *Krumbein*, 1941a, 1941b; *Sneed and Folk*, 1958; *Krumbein and Sloss*, 1963; *Folk*, 1974; *Pettijohn et al.*, 1975; *Barrett*, 1980]. Likewise, the morphology of individual grains (e.g., cleavage or crystal habit) might aid in mineral identification, Chemically precipitated crystals such as gypsum and halite often have a diagnostic shape, which can be retained even in vug form after dissolution [e.g., *Herkenhoff et al.*, 2004; *McLennan et al.*, 2005]. Grain textures in volcaniclastic sediments can reveal important information for distinguishing between primary volcanic processes (including eruptive patterns and transport) and reworking by secondary processes. Sedimentary structures and fabric (e.g., cross bedding, lamination, ripples and mudcracks, biogenic forms) may be revealed at the microscopic scale, even in cases where the initial depositional process is so subtle that macroscale structures are difficult or impossible to discern [e.g., *Pettijohn*, 1949; *Squyres et al.*, 2004; *Stow*, 2005; *Grotzinger et al.*, 2005; *Herkenhoff et al.*, 2006]. The seemingly simple characteristics of grain size and shape therefore provide a rapid, first-order understanding of the local geologic setting and enable practical field exploration priorities to be set. Indeed, this scale is important enough that libraries of terrestrial analogs have been created specifically for comparison purposes [e.g., *Yingst et al.*, 2008]. When the study site is truly remote and when laboratory analysis is not possible, examination at the hand lens scale becomes critical both for extracting maximum information, and for best utilizing finite analytical capabilities.

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0148-0227/09/2008JE003223

[3] Robotic semiautonomous roving vehicles for remote planetary geology studies are designed as human avatars, with instruments meant to mimic or improve upon geologic field or laboratory instruments, including the hand lens. For example, the twin Mars Exploration Rovers (MERs) each include a Microscopic Imager (MI), the first instrument to successfully return hand lens–scale information about Martian surface materials. The MIs have proven capable of resolving some of the fine-scale characteristics of the Martian rocks and soil, as well as the petrologic character of sedimentary and igneous rocks [*Herkenhoff et al.*, 2003, 2004].

[4] However, mimicking the instruments used in terrestrial fieldwork does not assure that their use will yield data of comparable quantity and quality. Terrestrial field geologists are adaptable and can suit their methods to best meet the science goals of the study using the tools at hand. The methods used to characterize the stratigraphy of a sedimentary sequence, for example, are different than those used to map the lateral distribution of a pyroclastic eruption. Field methodologies must be altered on the basis of whether specific tools (e.g., a field spectrometer, a measuring rod, a sledge hammer) are available. In a similar manner, the methodology used in remote, rover-driven field studies is derived from terrestrial field methods (we here define methodology as the manner and sequence in which instruments are used to answer scientific questions). However, this methodology must be adjusted for the unique problems associated with conducting work remotely, and for the abilities of the rovers in their specific environments. Differences between rover-driven and terrestrial hand lens–scale fieldwork affect both the nature of the resulting data set and what can actually be learned from that data set. Inherent constraints include limited traverse distance (per command cycle and in total), long approach times to a geologic feature, low data bandwidth, and a decreased ability to maneuver in and manipulate the local environment [*Squyres et al.*, 2003]. This last particularly hampers hand lens–scale studies, which in terrestrial cases nearly always include significant manipulation of a sample under the lens. These fundamental differences between a terrestrial and rover-driven field experiment mean that a unique methodology is required for rover hand lens–scale studies.

[5] Strategies in developing, testing and utilizing rover-driven field studies have typically involved using a rover mock-up armed with a suite of instruments, with an engineering team in the field and a "blind" team off-site conducting the science. Numerous analog field tests using this model have been conducted, each with different goals, results and recommendations. For example, many field tests were designed primarily to test potential instrumentation and robotics [*Yingst et al.*, 2001; *Stoker et al.*, 2002; *Glass et al.*, 2006; *Lee et al.*, 2007;]. *Taylor et al.* [1995] and *Stoker* [1998] emphasized how the engineering constraints of rover operation in an unknown environment impacted the science team and its requirements. *Cabrol et al.* [2001] conducted rover testing in a Mars-like desert environment, specifically to test whether offsite scientists could determine key attributes of a field site using only images taken under remote conditions by an operating rover. *Stoker et al.* [2001] focused on the interaction between the rover hardware and software, and the scientists and engineers, while *Thomas et al.* [2001] analyzed the effectiveness of an off-site, distributed science team during field tests of a rover in the MER size class. The goal of the rover field test conducted by *Arvidson et al.* [2002] was to rehearse operations for the MER mission, by testing the ability of a MER-like rover to traverse and collect samples. While this test was essentially engineering-driven, *Jolliff et al.* [2002] demonstrated the extent and depth of science produced by the offsite science team using only "orbital" and rover-derived data. The methodology of this test favored detailed investigation of a small number of targets to test the integrated use of the instruments.

[6] Important results from these field tests that have been integrated into MER operational strategies include: the need for mineralogical data to support imaging data; the importance of using a wide range of image resolutions, from orbital to microscale, to document and characterize the local environment; the usefulness of context imaging coupled with spectral data to facilitate target choices (a solution implemented for Pancam to inform targeting of MER's in situ instruments); the need to streamline team communication (specific recommendations are implemented in the way that MER science and engineering teams conduct operations planning); and the high science return gained from the use of color imagers.

[7] The field methodology currently in use for MER was informed by these rover simulations and developed through four field tests conducted prior to landed operations [*Squyres et al.*, 2003]. The results from the first of these tests led to the breakdown of consistent observations into sol types (where a sol is one Martian day). These sol types were defined by their main activities (panorama, drive, approach, spectroscopy and "scratch and sniff," or use of the geochemical and hand lens–scale imaging instruments). The division into tactical (sol-to-sol) and strategic (long term) operations with decision-making "sol trees" developed over all four tests. It was also recognized during these field tests that operations must be adjusted on the basis of when the rover is able to uplink data. If the planning cycle follows a drive, for example, the position of the rover may not be known well enough to perform certain operations, including use of the MI.

[8] The resulting methodology, utilized successfully for MER, was designed to use the unique strengths of the rover to overcome the limitations inherent in rover-driven science. This methodology has provided the framework for most operational decisions. However, the protocol has been adapted in response to unexpected circumstances subsequent to landing. Also, more efficient ways to utilize the instrument package and the individual instruments have been developed over time. For example, the MI has been utilized for determining the amount of dust contamination more than originally planned and engineering cameras have supported identification of science targets [e.g., *Maki et al.*, 2003]. These were not previously tested strategies in rover analog studies.

2. Approach

[9] The evolution of the current methodology demonstrates the importance of evaluating, and changing where necessary, the methods used in remote rover-driven field-

work, so that they maximize science return. We conducted a field test of hand lens–scale imager (MI) operation and support strategies for a hypothetical 10-sol reconnaissance of a well-understood terrestrial analog site, Fort Rock tuff ring in Oregon. Our goal was to determine if the MER-developed methodology supporting hand lens–scale imaging currently maximizes science return.

[10] This test differs from previous field tests of rover methodologies in several ways. First, we focused solely on hand lens–scale imaging, and the context imaging that supports targeting the hand lens–scale imager. This is because these observations provide the data that fill the gap between outcrop- or meter-scale assessments conducted in previous stationary lander missions and the lab-based analysis methods typically available for terrestrial samples. Second, we conducted this field test without specialized equipment; no rover mock-up was used. Previous studies have focused mainly on testing the equipment synergistically with the field methodology. Examining only the field strategies that scientists have developed around using a hand lens–scale rover instrument, however, requires no specialized equipment. The manner and sequence in which scientists use a hand lens–scale imager may be tested by using commercial instruments that provide similar information as flight ready instruments, and utilizing humans for mobility. This approach is appropriate for this study because our goal is to assess the performance of MER operational strategies, rather than the instruments (including the rover itself), in optimizing science return. Additionally, this approach has the benefit of removing variables such as instrument performance in an unfamiliar environment. Third, we based the number of hand lens–scale and context images acquired on Mars operational experience, something that previous field tests could not do. Thus, the number of images taken in this test is significantly lower than in previous tests. For example, one previous field test acquired 248 images in 10 "sols" of rapid reconnaissance [*Cabrol et al.*, 2001], while in an actual "quick look" situation at the rock "Comanche" on Mars, only 27 images and two MI mosaics were acquired. In our test, we acquired a total of 26 images over 10 "sols" of observation, much closer to the actual number commonly acquired during such activities on Mars (see Table 1).

3. Method

3.1. MER Hand Lens Methodology

[11] For MER, an observing campaign is organized by operational activities conducted over a number of sols. Observing campaigns may be divided into two types: (1) a "traverse mode" typical of operations performed when the rover is traversing and may stop for 3–5 sols to examine targets of opportunity along the way, or has a limited time to gather basic information about a location or feature; and (2) a 25–40 sol (or greater) "survey mode" that has been practiced when conducting a more in-depth examination of a feature of high scientific value. An example of the former mode includes Spirit's traverse up the Columbia Hills [e.g., *Arvidson et al.*, 2006], a period when many sites were left before it was scientifically optimal to do so. Examples of the latter mode include the investigations of "Home Plate" by Spirit prior to and following the second Martian winter [e.g., *Arvidson et al.*, 2008] and the detailed examination of the Burns formation at the Opportunity landing site [*Squyres and Knoll*, 2005; *Grotzinger et al.*, 2005]. We focus on MI observations and support activities in the first type of campaign because this type has been most commonly utilized on Mars.

[12] Traverse mode methodology occurs when the primary objective of the rover is to reach another location. When power and data constraints permit, it consists of a systematic set of observations conducted before and after every drive, to search for features that might be of enough interest to halt forward progress for a 3–5-sol analysis. In the following discussion, "feature of interest" refers to a scientifically interesting object, rock, outcrop, geologic formation or portion thereof, while "target" refers to a subset of that larger feature analyzed in detail. Thus, a feature may be associated with one or more targets.

[13] When a feature of interest is found, observation begins with low-resolution images taken while approaching the feature from afar, followed by medium resolution images at closer approach. Owing to data volume, data rate and power constraints, some, but not all, of these images may be taken using three multispectral filters to mimic color [*Bell et al.*, 2003, 2004a, 2004b]; more rarely, an image using the entire range of multispectral filters is taken, often after other instrument activities have concluded. One or more targets may be selected on the basis of data observed at this resolution; these targets are imaged by the MI at best resolution (~31 μm/pixel, or the ability to effectively resolve objects 100–150 μm in diameter) [*Herkenhoff et al.*, 2003] and analyzed for mineralogy and geochemical composition by other instruments.

3.2. Mimicking MER Hand Lens Methodolgy

[14] For our analog mission, we required an imager capable of mimicking the resolution of both the MI and the imagers used to choose features and targets in support of the MI (primarily Pancam, with context images commonly taken at millimeter- to centimeter-scale resolution) [*Bell et al.*, 2003]. We chose a professional single lens reflex (SLR) digital camera with interchangeable lens capability and megapixel imaging, including a macro lens. The focal range of the camera and the selection of lenses allowed us to image features at all scales used by the MER imagers. In particular, the 100 mm f/2.8 macro lens yielded 24 × 36 mm images at ~10 μm/pixel, mimicking a hand lens–scale instrument such as MI [*Herkenhoff et al.*, 2003] or the Mars Hand Lens Imager (MAHLI) slated to fly on Mars Science Laboratory (color imaging with best focus resolution ~12 μm/pixel) [*Edgett et al.*, 2005]. A working distance from the front of the lens to the target of ~15 cm allowed hand lens–scale or better images to be taken using either ambient light or a light ring attached to the front of the lens barrel.

[15] Two teams conducted the fieldwork: the three-person Primary Team that led the rover-driven fieldwork and a two-person subset of this team (the Terrestrial Team) that examined the site using traditional field methods. Two additional team members (the Rover Mock-up Team) mimicked rover activity by taking all images. Ideally, the Primary Team would have had no physical access to the site until the rover-driven test was complete. The original

Table 1. Observations and Implications at Fort Rock and Gusev Crater Sites

	Rover-Driven Observations	Traditional Observations[a]	Key Features[b]
All sites	Panorama (12 images at 1 m/pixel)	The site was visually examined from a distance	Outturned rims of structure (This set of images was taken once, to inform all subsequent observations)
Site 1	1 approach image at 10 mm/pixel; 1 image at 5 mm/pixel; 5 mosaicked images at 10 μm/pixel; 2 single images at 10 μm/pixel	3 approach images at 10 mm/pixel; 1 image at 5 mm/pixel; 2 images at 0.5 mm/pixel; 1 image each of 3 targets at 61 μm/pixel; 5 mosaicked images at 10 μm/pixel; 3 mosaicked images at 10 μm/pixel; 4 single images of 4 targets at 10 μm/pixel; Several loose samples examined at ~1 mm and 200 μm resolution	Stacks of layers showing alternating levels of resistance to erosion; Poorly-sorted angular clasts in a clast-supported matrix; Abundant small, poorly-sorted angular particles, lithic fragments; Presence of juvenile material; *Palagonitization; Presence of scoria; Alternating coarse- and fine-grained layers of angular clasts within clast-supported matrix*
Site 2	1 approach image at 0.25 mm/pixel; 1 image at 56 μm/pixel; 2 mosaicked images at 10 μm/pixel	1 approach image at 0.25 mm/pixel; 1 image at 56 μm/pixel; 8 mosaicked images at 10 μm/pixel; 2 mosaicked images at 10 μm/pixel; 2 single images of 2 targets at 10 μm/pixel; 1 loose sample examined at ~1 mm and 200 μm resolution	Fine-grained cross-cutting feature; Small, angular, lithic fragments distributed randomly throughout this deposit; *Lithics pervasive throughout the feature; Presence of microcaverns partially filled with zeolites; Palagonitization*
Site 3	1 image at 1.0 mm/pixel	2 images at 1.0 mm/pixel; 2 mosaicked images at 10 μm/pixel; 2 nonmosaicked images at 10 μm/pixel; 6 mosaicked images at 10 μm/pixel	Barely-resolved poorly-sorted clasts protruding from overhanging layer; Poorly-sorted angular clasts randomly distributed throughout a finer-grained matrix
Site 4	n/a	3 approach images at 10 mm/pixel; 1 image at 5 mm/pixel; 1 image at 0.25 mm/pixel	*Country rock block impacted into ductile, plastically deformable layers (bomb sag)*
Site 5	n/a	1 approach image at 10 mm/pixel; 5 images at 1.0 mm/pixel; 5 images at 10 μm/pixel; 4 mosaicked images at 10 μm/pixel; 9 mosaicked images and 1 additional at 10 μm/pixel; 4 mosaicked images at 10 μm/pixel; Several loose samples examined at ~1 mm and 200 μm resolution	*Pillar containing zeolites layered in sequence with zeolite-poor layers; Highly vesiculated, zeolite-rich layers interspersed with more massive layers*
Comanche (Gusev)	1 13-filter approach image at 31 cm/pixel; 3 13-filter images at 2.1 cm/pixel; 2 targets, 2 × 2 × 5 mosaics at 31 μm/pixel best resolution; Images at 31 μm/pixel best resolution; Geochemical information: MTES, APXS and MB observations	n/a	Poorly-sorted grains 0.5-1 mm in diameter; Mix of rounded and angular grains in clast-supported texture; Cementing agent prevalent

[a]Because of its nature, the discrete observations of traditional fieldwork are too complex and numerous to be easily quantified. The observations shown in this column represent the minimal images taken to represent the most salient observations taken by the field team using traditional methods.

[b]Key features in italics were observed only using traditional field methods (the difference between rover inspired and traditional field methods is outlined in Figure 1).

plan consisted of Primary Team members remaining in the field vehicle with windows covered, within a few meters of the field locality, while data were relayed to and from the rover team by passing them a thumb drive through the vehicle window. Data would have been immediately downloaded onto a laptop and reviewed, so decisions could be made for next observations. This scenario turned out to be impractical, given the distance of the vehicle from the field site and the nature of the site as a state park. Instead, the Rover Mock-up Team first acquired an image from a distance based on the choice of the Primary Team. The Primary Team then chose sites, features and targets to examine from that distant position. The Teams did not approach the site or visually examine nearby areas until a choice had been made. While not ideal, this method preserved the unknown nature of each site, feature and target during the crucial decision-making process. Thus, the images chosen by the Primary Team and taken by the Rover Mock-up Team were the primary data set used to choose targets for in-depth examination (geochemical and microscopic analysis), as is the case for MER.

[16] The Primary Team assumed 10 sols of an interrupted traverse were available to examine the location. Within this time frame, they chose three targets of interest for detailed analysis, requiring about 3 sols each to conduct all observations (drive time was ignored). Images mimicking those produced by Pancam and MI were taken by the Rover Mock-up Team in a sequence and frequency similar to what would occur during traverse mode, as detailed in section 5. As each image became available, team members viewed it and then discussed options, following the flowchart in Figure 1a. Once consensus among team members was reached, the Primary and Rover Mock-up Teams moved to the chosen site, feature or target and the Rover Mock-up Team acquired the images requested by the Primary Team. The process was repeated until all three sites were analyzed in this manner.

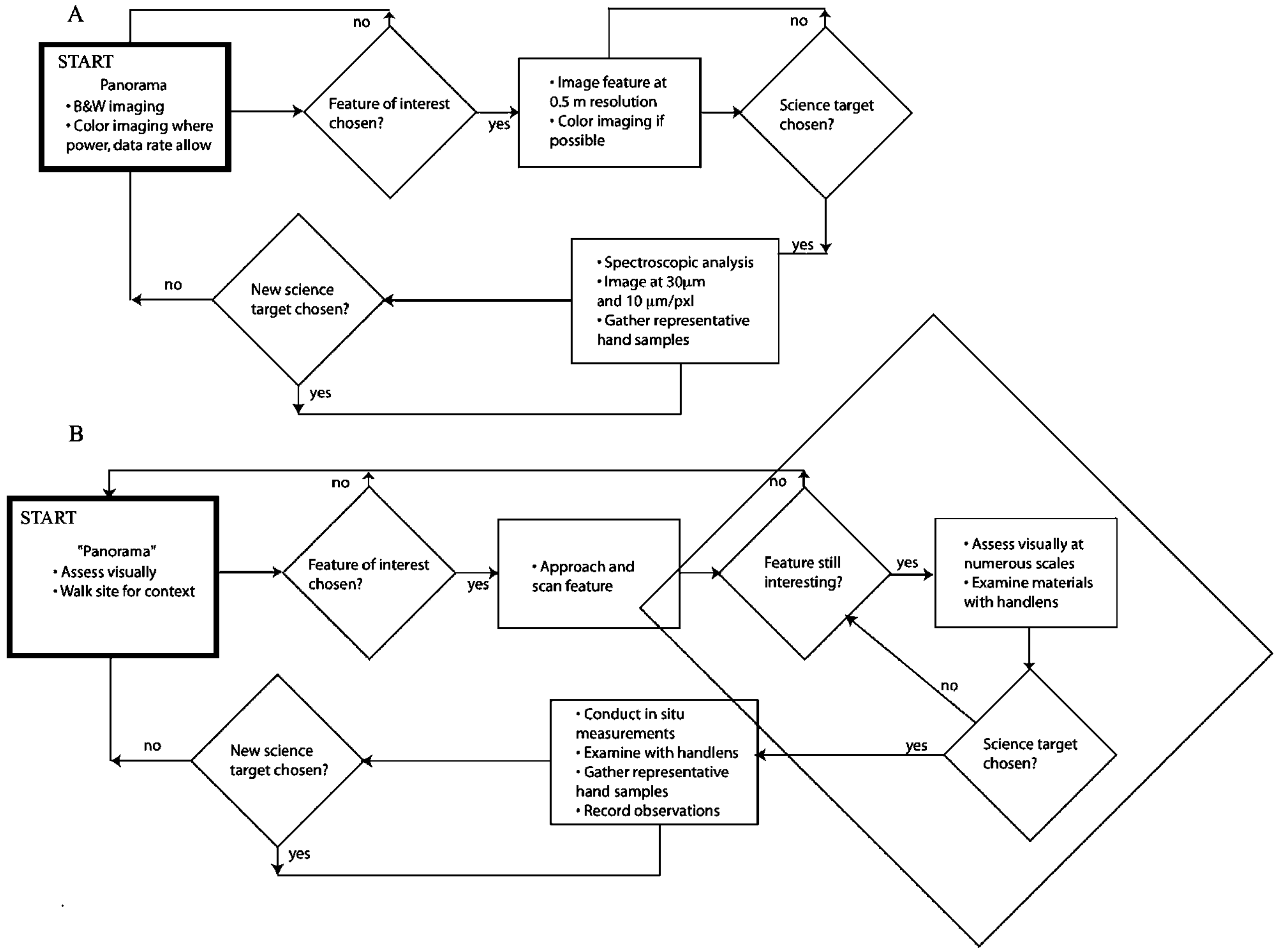

Figure 1. Decision-making flowchart for (a) rover-driven (adapted from *Squyres et al.* [2003]) and (b) traditional terrestrial fieldwork. Observations are noted in rectangles and decision points are shown in diamonds. The term "site" refers to the location as a whole; "feature" refers to an outcrop, rock, or other discrete geologic object or formation; "target" refers to a subset of the feature of interest, or approximately hand sample scale for Figure 1b. Differences between the two methods include availability of the hand lens at multiple decision points and the activities enclosed in the large box, which may be repeated as often as desired.

[17] Following data collection using rover-driven methods, the Terrestrial Team analyzed the site using the traditional terrestrial field methods upon which rover operations were originally based. This allowed us to make a direct comparison between what human field geologists were able to learn and what the rover-inspired methods revealed. The Terrestrial Team was equipped with rock hammers, two hand lenses, a brunton compass and a tape measure; no binoculars or other visual aids were used. Team members examined all three sites chosen by the Primary Team but were also permitted to choose additional sites of interest on the basis of their assessment of the geology of the location. A summary of observations taken at all sites, compared to a site in Gusev Crater for which a comparable number and type of observations were taken, is shown in Table 1, and a flowchart outlining the steps taken for each type of methodology is shown in Figure 1.

[18] Team members did not take geochemical measurements of field samples. Though we recognize that geochemical analysis is a crucial component of the MER mission, and will likely play a part in any remote field situation, we considered this an acceptable trade-off for the simplicity and cost efficiency of not being burdened with complex, expensive instrumentation in the field. Instead, we assumed the tephra composition at Fort Rock to be palagonitized basaltic andesite on the basis of previous work [*Heiken*, 1971; *Heiken et al.*, 1981]. We note that microtextures guide the choice of samples for mineralogic and geochemical analysis in a terrestrial setting; this has not been the case in remote rover operations. We explore this important issue in more detail later.

4. Site Selection and Geologic Setting

[19] MER science operations are primarily driven by the scientific rationale of discovery or a hypothesis to be tested. Our objective in this field experiment was to use rover-driven field strategies as developed and adapted for MER hand lens–scale analysis, to test various hypotheses for the origin of a terrestrial structure that may be analogous to one

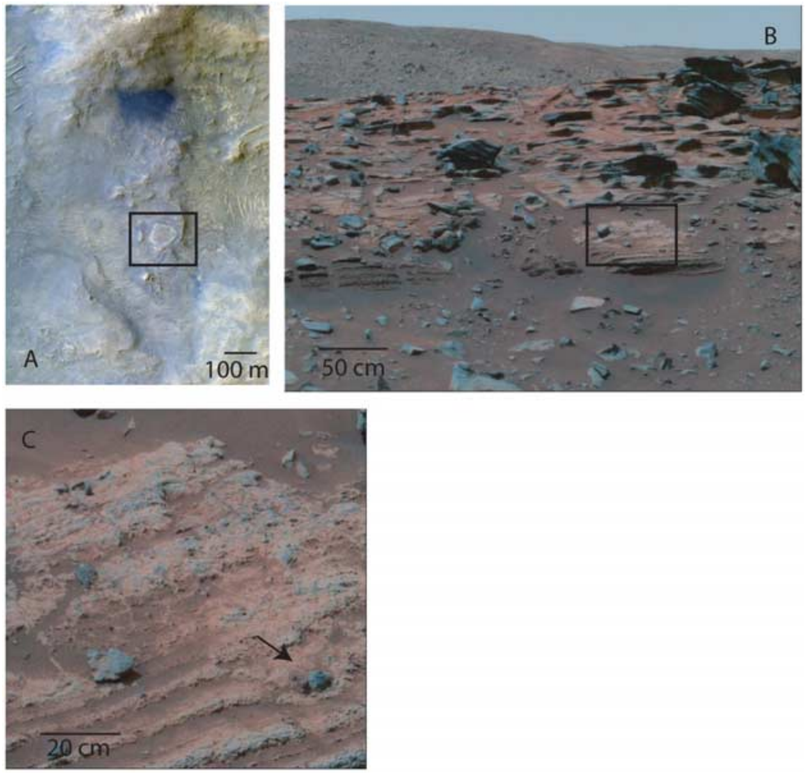

Figure 2. (a) High Resolution Imaging Science Experiment image PSP-001513-1655 of the "Home Plate" structure and its environs. The area enclosed by the box shows (b) Pancam 13 filter image taken on sol 746 of the feature "Barnhill" in context. The box encloses (c) Pancam 13 filter image of "Barnhill" taken on sol 754 showing alternating coarse- and fine-grained layers. A bomb sag is indicated by the arrow.

seen by MER on Mars. We first chose a site on Mars to serve as the Martian standard for comparison with our terrestrial analog. We selected the "Home Plate" structure in Gusev Crater because it is a relatively small, discrete feature that in early reconnaissance had two competing hypotheses for formation: a pyroclastic surge deposit [e.g., *Ennis et al.*, 2007; *Squyres et al.*, 2007] or an impact structure [*Knauth et al.*, 2007].

[20] At 80 m across and <1 to 2 m tall, "Home Plate" is the largest exposure of layered outcrop examined by the Spirit rover in its first 4 years of operation. Spirit first approached "Home Plate" at its northwest corner, where it examined the 2 m tall "Barnhill" section (Figure 2). Two stratigraphic units at "Home Plate" were identified: the lower, laminated, coarse-grained "Barnhill" unit and the upper, cross-bedded, finer-grained "Rogan" unit [*Squyres et al.*, 2007; *Lewis et al.*, 2008]. Steep topography and severe time constraints caused by the impending Martian winter limited Spirit's examination of the "Barnhill" section to three features: a portion of the lower "Barnhill" section, a float block that apparently fell from the above "Rogan" unit, and the upper surface of "Home Plate."

[21] Most notable in the lower "Barnhill" unit is a conspicuous bomb sag (Figure 2) that formed when a 3-cm diameter ballistic impacted deformable (likely wet) sediment. The bomb sag, together with spherical millimeter-scale clasts that may be accretionary lapilli, alternating coarse to fine-grained clastic sequences, and high- to low-angle cross beds, have been used as evidence that "Home Plate" is a base surge deposit that formed during a hydrovolcanic eruption [*Squyres et al.*, 2007; *Schmidt et al.*, 2008]. However, *Knauth et al.* [2007] noted that the coarse-grained layers at the base of "Home Plate" and the low-angle cross bedding, in general, are widespread in known impact surge deposits.

[22] The composition of "Home Plate" is basaltic and similar to nearby scoriaceous blocks, but with elevated volatile elements, including Cl, Br, Zn, and Ge, suggestive of a pyroclastic or hydrovolcanic origin [*Squyres et al.*, 2007; *Schmidt et al.*, 2008]. Geochemical data do not explicitly indicate an impact origin.

[23] Our chosen terrestrial field site, similar in some characteristics to "Home Plate," is Fort Rock tuff ring (a ring of tephra formed during a volcanic eruption that is a result of interaction between abundant water and magma). Fort Rock is a 1.4 km-diameter structure in the Christmas Lake Basin southeast of Bend, Oregon. Although the current environment of Fort Rock is arid, sage bush country, a large lake filled the basin from the Late Pliocene to Pleistocene during the Pleistocene. Fort Rock is one of 40 maars, tuff rings, and tuff cones that formed by phreatomagmatic eruptions when abundant water was present. Subsequent wave action breached the Fort Rock tuff ring and eroded all but the most lithified (palagonitized) tephra layers. Orange-brown lapilli tuff in graded beds 1 cm to 1 m thick make up the steep walls of Fort Rock [*Heiken*, 1971]. We chose to test the same two working hypotheses

Figure 3. Panorama of Fort Rock made of 12 images mosaicked together. Study sites are numbered.

for Fort Rock: the product of a hydrovolcanic eruption or impact.

5. Data Collection

[24] In discussing data collection, it is first important to emphasize the inherent differences between traditional field geology and remote geology performed by a robotic surrogate. Figure 1 highlights some of these key differences. For example, for a single sample or portion of outcrop, it may require several days of rover maneuvering, instrument deployment and data gathering to attain the same information as that which may be gathered during a 5-min reconnaissance done by a human geologist. Even basic reconnaissance observations such as visually examining (imaging) a hand-sized sample are limited by data rate, data volume, power and time available for communication with Earth. Additionally, the field geologist chooses field locations and features to investigate based partly on the quality of outcrop exposures. In remote investigations to unexplored planetary surfaces, missions often must target landing sites where there are fewer outcrops, for landing safety reasons; rock outcrops are thus not always available nearby for analysis. These differences are part of the price of exploring remotely and must be kept in mind when comparing the science return of remote versus traditional terrestrial field geology.

[25] As summarized in Table 1, the Primary Team chose to take a panoramic 145° color mosaic of 12 images of the entire ring from a distance of ~2 km, as shown in Figure 3. "Approach" images at 1–10 mm/pixel resolution were taken in color and gray scale to document and choose features for closer study based on the scientific hypotheses we compared for the site. These features were imaged further at resolutions of 0.25–1 mm/pixel, and then targets within these features were imaged at 10 μm/pixel in color. On the basis of the number of images commonly taken in rover traverse mode, the Primary Team was allowed ~10 images per feature, including context images, single hand lens–scale images and hand lens–scale image mosaics. We note that the MI commonly takes many more images than this of a single target to comprise a mosaic. However, many of these images are taken to ensure that most of the target is imaged in focus. We required fewer images to create an in-focus mosaic, because focus was confirmed after each image was acquired.

[26] The Primary Team assessed the approach images for clues indicating potential locations of finer-scale diagnostic features. Three features of interest were selected for detailed analysis, including a ~2 m wide, very fine-grained feature crosscutting tens of m of layers, a set of graded clast-rich layers, and a zone of palagonitized clasts. These targets were imaged in color at millimeter- to centimeter-scale and at ~10 μm/pixel. Rocks and soils were assessed for grain texture and morphology, the presence of evaporite or sedimentary textures and fabric elements, and any other identifying lithologic, textural or structural characteristics diagnostic of hydrovolcanic or impact origin. All three sites were then examined by the Terrestrial Team using traditional field methods (e.g., walking reconnaissance, hand lens observation and analysis, sample collection using a cleaning material such as water or air and a rock hammer). The Terrestrial Team identified two additional features not detected in approach images and examined these during this traditional field assessment as well.

[27] We emphasize that during the rover-driven fieldwork, the Primary Team made all decisions regarding selection of sites for detailed analysis and data collection and drew all conclusions from these data on the nature of the Fort Rock region, based solely on the images taken. Examples of images produced through rover-driven methodology are shown in Figures 4a–4c, Figures 5a–5b and Figure 6a. Data (visual and otherwise) gathered during the traditional field assessment of Fort Rock were used only after rover-driven fieldwork was completed, as a baseline for comparison; these are shown in Figure 4d–4e, Figure 5c, and Figure 6b. The two additional sites identified using traditional field methods are shown in Figures 7 and 8.

6. Observations

6.1. Rover Method Observations

[28] Site 1 is a 30 cm^2 portion of a layered sequence within the interior of the ring structure, chosen for analysis because of the evidence of layers imaged at the outcrop scale (Figure 4a). Macroscale features seen in context images that were consistent with hydrovolcanism included the outturned rim of the structure as a whole (imaged in the panorama), and stacks of layers showing alternating levels of resistance to erosion at lower resolution and poorly sorted angular clasts in a clast-supported matrix at higher resolution [e.g., *Schminke*, 1998]. The hand lens–scale images of site 1 revealed an abundance of small, poorly sorted angular particles, potentially formed through either catastrophic disruption through impact or intense fragmentation of magma (Figure 4b). Lithic fragments (<10 μm to >cm across) were plentiful, consistent with fragmentation of the country rock along the conduit walls (possibly caused by magma-water interaction; impact would be less likely to cause such fragmentation along conduit walls). Evidence of palagonitization (consistent with, though not diagnostic of, hydrovolcanic activity) was pervasive, seen as rims sur-

rounding lithic fragments (Figure 4c). Juvenile basalt fragments and scoria were also evident.

[29] Site 2 is a relatively narrow, very fine grained deposit crosscutting a number of horizontal layers (Figure 5; crosscutting relationships were detected in the panorama). The identification of fine-grained ash with lithics intermixed was not diagnostic of a base surge deposit, though the Primary Team chose this feature for closer analysis because it appeared so different from its surroundings in the context images. Such factors often drive location and feature selections in a planetary setting, because unusual features have often been found to provide completely unexpected insights. Hand lens–scale images revealed small, angular lithic fragments mixed randomly throughout this deposit (Figure 5b), consistent with violent disruption of the country rock. Both impact and hydrovolcanic processes could potentially produce such fragments. The feature may be a clastic dike. Clastic dikes form either by passive deposition of clastic material into preexisting fissures or by fracturing and injection of clastic material. The causes of fracturing can include seismic shaking, passive overpressure, impact [e.g., *Kriens et al.*, 1999; *Masaitis*, 2005] and fracture due to the interaction of lava and water [e.g., *Schminke*, 1998]. Because of their similar final geometry, the origin of clastic dikes is commonly ambiguous, so this feature would not be considered diagnostic of either proposed hypothesis of formation.

[30] Site 3 is an ovoid hollow approximately 2 m across (Figure 6). This site was selected for imaging because poorly sorted clasts were seen protruding from the overhanging layer, revealed by the sun angle in outcrop-scale images. Higher-resolution images showed angular clasts averaging 1–10 cm in diameter, poorly sorted and randomly distributed throughout the finer-grained matrix. Impact and hydrovolcanic processes might both potentially result in such a mix of grains.

6.2. Terrestrial Field Method Observations

[31] The Terrestrial Team acquired several images representing their visual assessment of site 1, as well as their hand lens–scale examination of an additional three targets (portions of site 1, and sites 4 and 5, shown in Figure 3) and several samples procured from the outcrop using a rock hammer. Using these data, team members were able to confirm the results of the rover-driven assessment, as well as identify several additional diagnostic features, including, most notably, alternating graded layers of angular clasts within clast-supported matrices, as shown in Figure 4d. This architecture is a strong indicator of cyclic, explosive pulses associated with tuff ring formation, rather than the single pulse expected from an impact.

[32] Examination of site 2 confirmed the characteristics of the features identified by rover-driven methods. Terrestrial Team members noted that lithic fragments were more pervasive throughout the feature than in the original assessment, however, and the nature of the country rock repre-

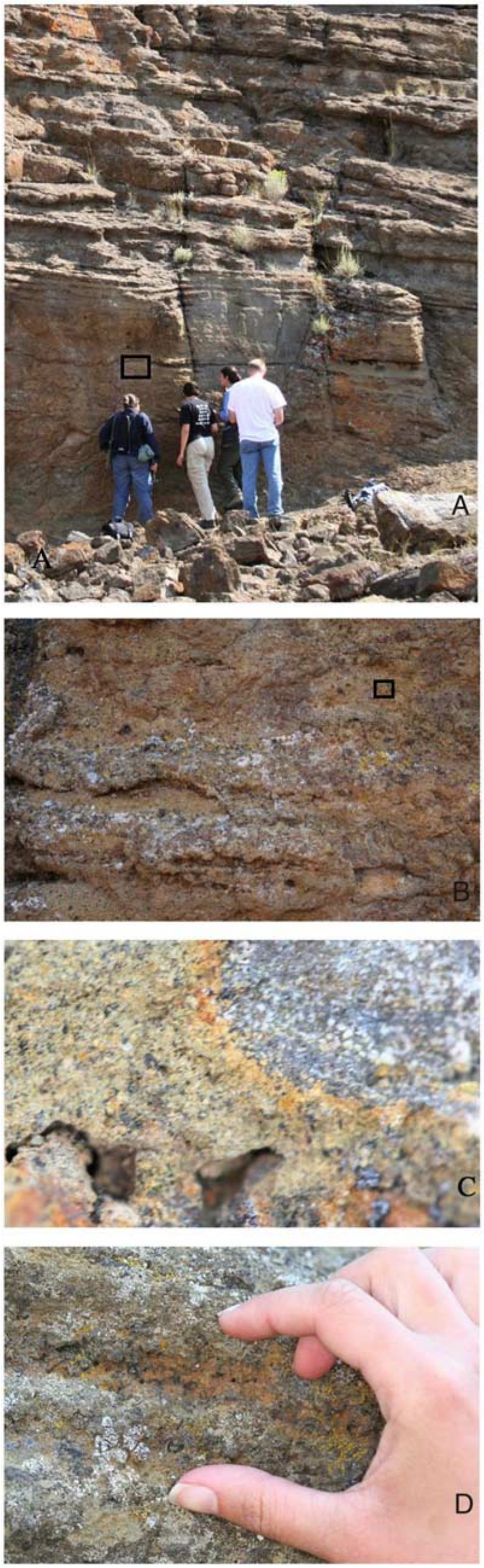

Figure 4. Site 1. Particle texture and grain-to-grain contact in alternating layers. Boxes in each image indicate the area imaged at the next higher resolution: (a) approach image taken at 10 mm/pixel with people for scale; (b) 0.5 mm/pixel; (c) 10 μm/pixel, where best focus is in the center of the image. Also shown is (d) one graded bed (between thumb and forefinger). Note the angular lithics interspersed throughout the layers.

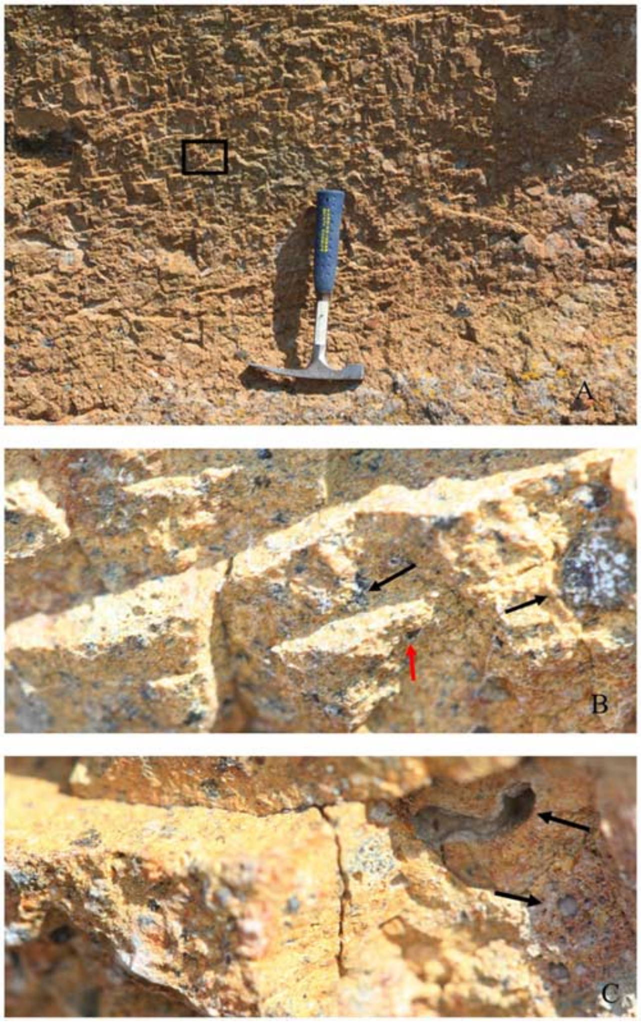

Figure 5. Site 2. Fine-grained crosscutting feature. Boxes in each image indicate the area imaged at the next higher resolution: (a) approach image taken at 0.25 mm/pixel with rock hammer for scale; and (b) 10 μm/pixel, showing small, angular, poorly sorted lithic fragments of various sizes (black arrows). Note the zeolite partly filling a void in this image (red arrow) that cannot be fully resolved but was positively identified during traditional assessment. (c) Larger zeolites also identified at that time at 10 μm/pixel (black arrows).

sented by these fragments could be better determined. Additionally, team members discovered and identified zeolites within microcaverns with a hand lens (Figure 5c). Zeolites are hydrated aluminosilicate, low-grade metamorphic minerals that form under a number of conditions involving chemical reaction with water. In this case, one interpretation would be formation in voids when volcanic rock or ash reacted with alkaline groundwater (syneruption or posteruption). However, zeolites may also form by precipitation or by alteration from percolating groundwater. Formation is more favored if fluids are warm and hydrothermal systems can be sustained by a large impact event. At site 3, traditional field techniques confirmed the presence and nature of larger angular particles as lithics. Additionally, Terrestrial Team members found significantly more micro-scale evidence of palagonitization, a strong indicator of water interaction (Figure 6b).

[33] Site 4 contained a bomb sag, itself highly diagnostic of volcaniclastic deposition in wet finer-grained layers (Figure 7). This bomb sag was easily visible in the Terrestrial Team's visual reconnaissance of the ring, but as it was not identified initially in approach images taken by the Primary Team, it was not included as one of the three rover-explored features. This is also true of site 5 (Figure 8), a pillar that contained a preponderance of zeolites, layered in sequence with zeolite-poor layers. These two sites, taken together, would have strongly supported the hydrovolcanic hypothesis over the impact hypothesis.

7. Discussion

7.1. Rover-Driven Methodology: What Worked

[34] Several features of the methodology were important in revealing clues to the nature of Fort Rock. First, the imaging sequence commonly employed (successively higher resolutions of the same feature or target) successfully mimics the manner in which human geologists use their eyes and a camera or hand lens. The efficacy of this methodology has been repeatedly demonstrated in remote rover analog situations [*Stoker*, 1998; *Arvidson et al.*, 2002; *Cabrol et al.*, 2001; *Jolliff et al.*, 2002]. In short, given hand lens–scale images of targets, in context, team members found it a relatively straightforward task to identify characteristics likely indicative of hydrovolcanism.

[35] Another powerful benefit of rover-driven methodology is the science team itself: numerous, interdisciplinary, highly motivated, trained for a specific task, and available whenever science decisions must be made. As stated earlier, the Primary Team mimicked current MER operational strategies by discussing the choice of targets and the rationale for each measurement conducted at each feature or target until consensus was reached among competing ideas and hypotheses. The knowledge of many geologists, all working on the same problem simultaneously, is a strength of rover-driven field work that terrestrial field studies can rarely match [*Squyres et al.*, 2003].

7.2. Rover-Driven Methodology: What Did Not Work

[36] Although the Primary Team identified important clues to Fort Rock's origin using rover-driven hand lens–scale methodology, many diagnostic features were missed. Though rover-driven field methods produced data that were consistent with the correct hypothesis of origin for Fort Rock, this hypothesis could be fully confirmed only by the Terrestrial Team using traditional field methods. Importantly, we note that this result was not because of a limitation inherent in using a remote semiautonomous rover for fieldwork. Every field study has inherent limitations that must be overcome or mitigated, while still remaining within the framework of the science questions to be answered. This is done by defining and using the appropriate methodology. We thus conclude that the current rover-driven field methodology does not compensate for the limitations of the experiment sufficiently in two areas. First, it does not permit a large number of targeting and context images to be acquired that would mimic the ability of the human eye to rapidly, efficiently and comprehensively survey surround-

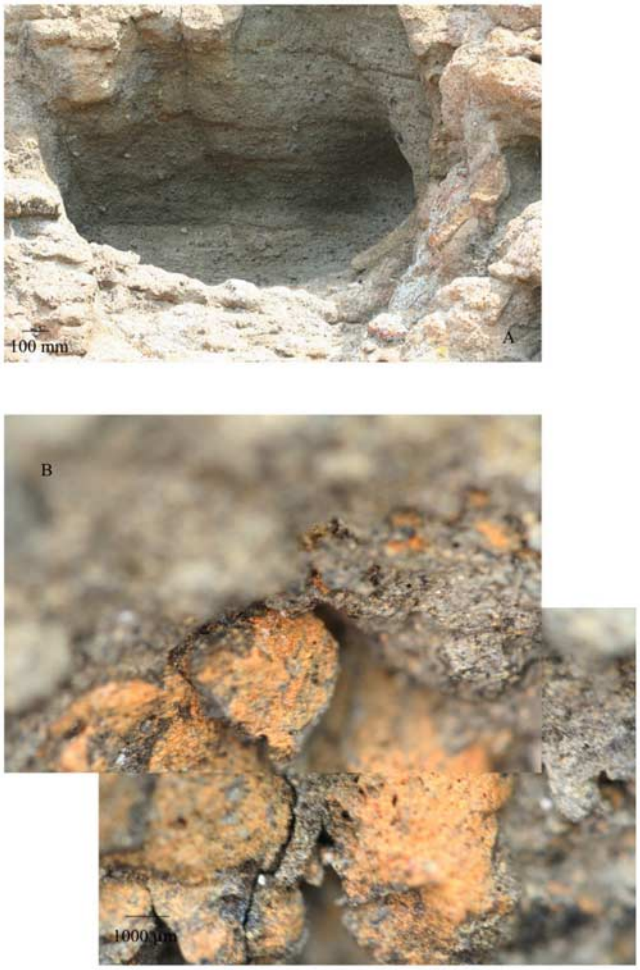

Figure 6. Site 3. Poor sorting and palagonitization of angular clasts: (a) approach image taken at 1.0 mm/pixel; (b) image at 10 μm/pixel taken during traditional field assessment.

ings at a very wide range of resolutions. Second, it does not currently allow for the extensive microscale imaging that would mimic the geologist's frequent use of a hand lens for systematic textural assessment and sample triage. These two points are detailed below.

[37] 1. For sites 1 and 2, the image suite taken was inadequate for determining the nature of the feature as a tuff ring. Specifically, it was only after the rover methodology had been tested that the Terrestrial Team identified the coarse- to fine-grained alternating nature of the clastic layers, a sequence diagnostic of cyclic volcanic pulses. The bomb sag was also discovered only using traditional methodology (e.g., walking the outcrop).

[38] The limitations of discrete imaging over a wandering, trained pair of eyes are difficult to quantify, but in this field test, it was clear that the small number of acquired intermediate-scale (millimeter to centimeter scale) images was the primary reason for our inability to select ideal targets for analysis by hand lens–scale images. If we assume that each 0.5 m^2 area examined in detail in traditional mode represents a single intermediate-scale image, we estimate that for a 5 m^2 site, a minimum of 20–30 images at intermediate scale would be needed to locate the high science sites that would best inform microscale analysis. We derived this estimate by taking the average number of discrete 0.5 m^2 portions or samples of each outcrop examined in traditional mode, and comparing this to the average size of each site studied in this manner.

[39] 2. The Terrestrial Team used their hand lenses frequently at every site and on multiple targets. This was done to detect textural connections between various portions of outcrop, to identify minerals within samples, to construct an overall picture of the microscale textural characteristics of each site, and finally to interpret how Fort Rock formed. Team members identified, examined using a hand lens, and discarded dozens of samples at some sites before selecting the most representative, diagnostic samples to be included in the baseline study. Samples retained included the strongest examples of clast-supported coarse- to fine-graded layering. By contrast, the rover-driven microscale images revealed less diagnostic examples of clast-supported matrices and palagonitization, and did not reveal the coarse-to-fine alternating beds at all. The underlying cause of this was the small number of hand lens–scale images taken based on current rover-driven strategies. We can place this in quantitative terms by assuming that each 2 cm^2 area examined by a hand lens in traditional mode represents a single hand lens–scale image. The Terrestrial Team made approximately 15 hand lens observations per 5 m^2 feature area, meaning that another 45 images or mosaics at MI-type scale (10–30 μm/pixel) at each site, selected on the basis of intermediate-scale context imaging, would have provided comparable information for determining the microscale characteristics of this structure.

[40] These two results are complementary, but not mutually dependent upon each other; increasing the microscale information alone would have provided important information to interpret the origin of Fort Rock. This is so because systematic stratigraphic observations of a feature return the deepest science by sampling the largest sequences of time and thus the longest periods of geologic history. To demonstrate this, we show the science return from site 1 using rover-driven methodologies, alongside that using traditional

Figure 7. Site 4. Bomb sag, 40 cm long axis, imaged at 0.25 mm/pixel. Black arrow indicates a sagged bedding plane.

Figure 8. Site 5. Zeolites imaged at (a) 0.25 mm/pixel, with the zeolite band indicated, and (b) 10 μm/pixel. Pen indicates the location of Figure 8b, an area ~1 cm across.

methods (Figure 9). Figure 9b is an MI or MAHLI-like resolution (~10μm/pixel) color image, which represents the microscale data set acquired by MER in one observational sequence. From this image we can identify the clast-supported nature of the material and the sorting and angularity of the individual grains; some alteration products are also evident, but it is not clear from this image whether these materials were a result of a ''wet'' eruption or subsequent weathering. Figures 9c–9g show five images at approximately hand lens–scale resolution (100 μm/pixel). This represents a portion of the microscale data set retrieved for site 1 through traditional field observations. The nature of the outcrop is revealed much more clearly by the traditional hand lens observations, even though the resolution is coarser. Visible along with the clast-supported texture (Figure 9c) are entrained angular lithics (Figure 9d); fine-grained ash with angular lithics intermixed (Figure 9f); clasts coated with zeolites (Figure 9e); and alteration products formed by the eruption (Figure 9g). Note that Figures 9b and 9c are identical but for resolution; coarser resolution in this case does not preclude the original interpretation of this image, but the addition of the other images provides a much richer picture of site 1, greatly facilitating the correct interpretation of its origin.

8. Lessons Learned

[41] Four years of remote rover operations on Mars with the Mars Exploration Rovers represents a significant increase in experience with robotic reconnaissance missions. This gives us an unprecedented opportunity to reassess and refine the methods employed to explore other planets remotely, to improve science return. Lessons learned from this study suggest potential improvements to current MER rover methodology in traverse mode, and future rover-driven studies.

8.1. Recommendations for Hand Lens–Scale Imaging

[42] The geologist's hand lens is the ideal instrument for sample triage. The hand lens works particularly well for quick assessment and narrowing of samples for more detailed analysis. Additionally, hand lens–scale observations of the texture of rocks and outcrops often reveal similarities that allow geologists to connect distant formations with one another. Indeed, previous field test results using MER-like configurations indicated that hand lens–scale imagers were highly underutilized instruments, and these studies recommended that such imagers be utilized every time a rover stops [*Jolliff et al.*, 2002; *Cabrol et al.*, 2001]. These are primary reasons that such instruments have been or will be included on mobile robotic geologists (e.g., MSL) [*Edgett et al.*, 2005]. However, the benefit of convenient, rapidfire high-resolution assessment and the ability to connect distant outcrops texturally, are essentially lost using the current methodology because the hand lens–type imager is not easily deployed or used frequently. In the MER configuration, for example, the MI must share power, data volume, data rate and time resources with the geochemical analysis instruments that it was meant to inform. Additionally, any deployment of the MI also requires taking assessment images by the hazard avoidance cameras (Hazcams), adding additional time to the observational process. The MI thus plays a part in detailed sample work (with the accompanying large expenditure of time, data volume and power) rather than assisting in the triage of samples. This facet of the current methodology will worsen for MSL, as even more instruments will be mounted on the robotic arm. An additional issue is the fact that MI images are often sent back to Earth after geochemical measurements have been commanded or taken by the Alpha Proton X-ray Spectrometer (APXS), because the APXS costs less data volume compared to a standard set of MI images. Remote analysis thus often reverses the order in which terrestrial field measurements are taken and so APXS geochemical data do not have the support of microtextural information sufficient to inform targeting decisions. Pancam resolution, while very high, is insufficient to reveal many submillimeter-scale textural differences that may indicate if taking geochemical data is warranted.

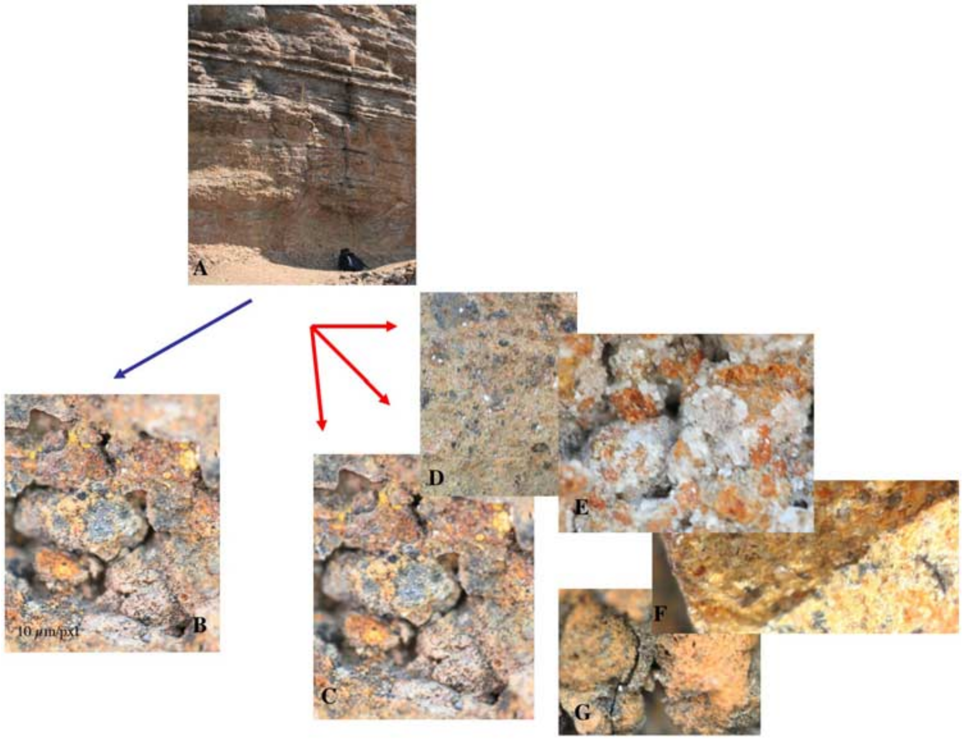

Figure 9. (a) A portion of site 1 (backpack for scale). Important microscale characteristics in understanding the nature of this rock package include clast-supported textures, alternating coarse and fine-grained layers, and the presence of altered minerals. (b) Single color image at MI-like resolution showing clast-supported material and angularity of individual grains at a single point in the stratigraphic package. (c–g) Multiple images representing handlens observations taken during traditional field assessment, all at 0.1 mm/pixel resolution. Note that Figures 9b and 9c are identical but for resolution. Along with the clast-supported texture (Figure 9c) are entrained angular lithics (Figure 9d), angular clasts coated with zeolites (Figure 9e), fine-grained ash with lithics entrained (Figure 9f), and alteration products formed by the eruption (Figure 9g).

[43] An ideal remote hand lens, then, must be utilized differently than in the current methodology if it is to function in the manner hand lenses are used on Earth. The instruments themselves produce highly useful data but the current method of using hand lens–scale imagers, driven in part by present and planned rover configurations, is insufficient for the tasks they were meant to mimic. Our results suggest that for future missions, increasing the number of images that can reasonably be taken at this scale, and/or decreasing the power and data volume required for those images, would yield a better science return than focusing on improving resolution. This is especially true since even higher-resolution images than those currently available for Mars (as we have utilized here) often cannot provide the same quality or quantity of information as a human eye looking through a hand lens [*Schieber*, 2007]. This implication will play an especially critical part in developing sample return missions, as context and microscale imaging will be crucial in selecting potential return samples. One option for future missions would be to design a mast-mounted hand lens imager. Such an imager would not require deployment on an instrument arm, thus using fewer rover resources and requiring fewer command cycles to use effectively. Another option would be to pursue ways to decrease the number of images that must be acquired to ensure an entire target is in focus. The MI is a fixed-focus imager, meaning that the imager must be physically moved through several positions to acquire an image set in which most of the target is in focus [*Herkenhoff et al.*, 2003]. The addition of zoom capability, or of software that would provide a single best focus image (as proposed for MAHLI) [*Edgett et al.*, 2005; *Minitti et al.*, 2007] would mean fewer downlinked images per target, and thus, decreased data volume.

[44] How can these recommendations be adapted to current MER operations? Given the rover configuration and its inherent limitations, we outline the following options:

[45] 1. We can acquire significantly more hand lens–scale images, allowing both a fuller characterization of each location at this scale and rapid assessment of rover-accessible targets. For example, we may place the MI and acquire images after each drive (as recommended by *Cabrol et al.* [2001] and *Jolliff et al.* [2002]), or at every point millimeter- to centimeter-scale images are acquired. Such a methodology would require a significant increase in the use of other rover resources, especially the Instrument Deployment Device (IDD). More command cycles would also be required to position the MI instrument safely, assuming the

"autoplace" option developed for the MI is not utilized each time, and the large increase in data volume that these images represent would lead to significantly less data volume available per command cycle for engineering and other science requirements. This is impractical in light of the overall science goals of the mission.

[46] 2. We can alter the current methodology to acquire a few more MI images than we currently do in traverse mode. One option would be to plan systematic observations based on the drive activities, rather than utilizing the MI only on targets of opportunity observed in or near the work volume during a traverse. For example, the MI could acquire images once every n drives (where $n > 1$) or every 50–100 m of traverse distance. This methodology would provide a systematic assessment of microscale texture along each rover traverse, though it would not allow rapid sample analysis. Accomplishing that would require a related option, systematically increasing the number of targets imaged to some minimum number per feature examined. Either or both of these options would also require an increase in the use of rover resources, number of command cycles, and data volume devoted to MI images, though to a lesser extent than using the MI at the end of every sol.

[47] 3. We can choose to accept the current traverse mode methodology with a clearer understanding that it does not mimic hand lens usage and will thus not yield the in-depth textural information that systematic terrestrial hand lens usage would provide.

8.2. Recommendations for Context Imaging for Hand Lens–Scale Analysis

[48] In a remote field setting, intermediate-scale images (those at millimeter-centimeter resolution) serve as the bridge between orbital, descent and panoramic-type image mosaics, and very high-resolution images that mimic a hand lens view. This and previous studies have demonstrated the importance of intermediate-scale images in best revealing the characteristics required to choose targets of high science value for detailed analysis [e.g., *Stoker*, 1998; *Arvidson et al.*, 2002; *Jolliff et al.*, 2002]. But while a field geologist has essentially an unlimited resource for locating and identifying key features, this is not the case when conducting fieldwork using a rover. In this study, we have shown that because the current methodology for traverse mode lacks a large number of intermediate-scale images, a number of promising targets for hand lens–scale analysis are missed. Thus, textural characteristics diagnostic of the nature of a geologic site need to be identifiable at a number of different resolutions; rover microscale observational strategies must include more contextual imaging.

[49] The MER rovers acquire intermediate-scale images much more frequently in survey mode, where the goal is systematic reconnaissance of a particular feature, than they do in traverse mode, where the primary goal is travel to another location. For example, reconnaissance of the "El Dorado" ripple field at the Spirit landing site entailed ten separate imaging sequences to support geomorphologic analysis, spectroscopy, drive support and context imaging for five MI targets and other instruments (not including the images taken for photometry). Combined, these totaled over 70 Pancam and navigational camera images [*Sullivan et al.*, 2008]. By contrast, during Spirit's initial traverse around "Home Plate" on its way to the stopover location for its second Martian winter, only nine intermediate-scale images were taken of individual targets in the 27 sols between sol 746 and sol 773. One option is to add more survey-type activities into the current traverse mode by acquiring images to systematically search for potential targets for hand lens–scale imaging. This might be done by altering the current MER methodology to include more frequent use of the navigational cameras (Navcams), especially after drives. Though not primarily designed for this purpose, the navigation and hazard avoidance cameras (Hazcams) produce high-quality images that in many cases have been used to identify high-interest science targets. This particular application of the engineering cameras has evolved and increased over the course of the mission, because Pancam images, especially ones that utilize a large number of filters, are expensive in terms of power, data volume and data rate. Currently, minimum engineering operations require that Hazcam images be acquired after each rover move, but Navcam images have a wider field of view and higher resolution, and are often acquired at the end of drives. Acquiring additional systematic Navcam images for the express purpose of searching for targets of interest is one possible observation that could be added to rover operations strategies. More images, however, would mean more data volume and power would be used after each drive, a scenario that would press against current rover engineering constraints. Additionally, systematic Navcam observations during traverse mode would likely slow down forward progress at times when forward progress is often mission critical.

[50] For future missions, a dedicated, rapid, low-power targeting imager with broad options for decreasing image data volume would be one solution. Alternately, recognizing that navigational instruments have been successfully used for targeting could inform future instrument and rover chassis design. Higher-resolution front hazard avoidance cameras might be designed for easier target identification, for example, or future rover missions might consider using a configuration similar to that of the MER rovers and explicitly designing field methods around the use of navigational instruments as lower-power options for targeting. Another possibility that is the subject of ongoing work is autonomous feature recognition [*Gulick et al.*, 2001; *Stoker et al.*, 2001]. Such onboard capabilities would identify desired characteristics of rocks or soil for possible hand lens–scale analysis, without the need for human intervention and decision making. Data volume would not be affected, as fewer decisional images would be downloaded, though such activities might be power-intensive. However, our results indicate that autonomous feature recognition may not be as scientifically optimal as scenarios in which humans and semiautonomous rovers work synergistically.

[51] In spite of the data, power, and time limitations imposed on MER Microscopic Imager usage, the methodology of approach and imaging at successively higher resolutions, especially at the hand lens–scale has worked remarkably well. The desire for more imaging is mainly science-based, but also partly a derivative of our human desire for exploration and aesthetics. Rovers will be used

heavily in planetary exploration, including ongoing MER operations and upcoming MSL. The imaging methodology that is now used is a reasonable starting point for future studies on Mars and elsewhere.

[52] **Acknowledgments.** We gratefully acknowledge the insightful comments of several members of the Mars Exploration Rover Athena Science Team and the careful reviews of Ken Herkenhoff, Barbara Cohen, and an anonymous reviewer. Undergraduate field assistants Ruben Behnke and Matthew Christman provided much needed technical support. This research was supported by the Mars Fundamental Research Program grant NNG05GL66G and Mars Exploration Rover Program JPL contract 1278721 to R.A.Y.

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