Testing the efficiency of rover science protocols for robotic sample selection: A GeoHeuristic Operational Strategies Test

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Testing the efficiency of rover science protocols for robotic sample selection: A GeoHeuristic Operational Strategies Test


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ABSTRACT
The GHOST field tests are designed to isolate and test science-driven rover operations protocols, to determine best practices. During a recent field test at a potential Mars 2020 landing site analog, we tested two Mars Science Laboratory data-acquisition and decision-making methods to assess resulting science return and sample quality: a linear method, where sites of interest are studied in the order encountered, and a “walkabout-first” method, where sites of interest are examined remotely before down-selecting to a subset of sites that are interrogated with more resource-intensive instruments. The walkabout method cost less time and fewer resources, while increasing confidence in interpretations. Contextual data critical to evaluating site geology was acquired earlier than for the linear method, and given a higher priority, which resulted in development of more mature hypotheses earlier in the analysis process. Combined, this saved time and energy in the collection of data with more limited spatial coverage. Based on these results, we suggest that the walkabout method be used where doing so would provide early context and time for the science team to develop hypotheses-critical tests; and that in gathering context, coverage may be more important than higher resolution.

1. Introduction
Two central tensions in any mission are choosing when to use consumable resources (e.g., drill bits, sample canisters, mobility equipment, and other engineering resources with finite lifetimes), and when to invest in utilizing time- or power-intensive activities (e.g., arm deployment, mobility). On a science-driven sample-return or caching mission such as the Mars 2020 rover mission, decisions regarding the consumption of resources will largely be controlled by the number of samples collected and stored; thus, a central point of tension among science team members is likely to revolve around the competing philosophies of immediate, rapid collection, and continued exploration to locate the ideal sample. The way the science team chooses to interrogate a site will be an important component in determining resource requirements and expenditure for a sample return or caching mission.

One end-member decision path is a linear traverse. In this approach, the rover rarely backtracks to re-examine a site; all sites are examined as they are encountered. This approach potentially maximizes the amount of ground reconnnitored, which may improve chances of finding the optimal sampling environment. Examples of this approach include the investigations of Columbia Hills and Home Plate by the Mars Exploration Rover (MER) rover Spirit (e.g. Ref. [1]), Endurance Crater at the
Another end-member, sometimes colloquially referred to as a high-value. This approach mimics that of a deployment of higher-resource instruments on sites determined to be of high-value. This approach mimics that of a field geologist who walks the field site first to gain an understanding of context, and uses that context to prioritize areas for follow-on detailed examination of a subset of those areas. Examples of this mode executed on Mars include the examination of the Whitewater Lake region by Opportunity [5] and of Pahrump Hills by Curiosity [6]. The walkabout approach has the potential benefit of ensuring that contact and sampling resources are used only on the most relevant targets, rather than on general reconnaissance and initial target assessment [7], but it covers less unique ground.

The test reported here is part of the GeoHeuristic Operational Strategies Tests (GHOST) project; it builds on knowledge gained from testing MER-derived semi-autonomous rover science operations strategies in various lunar and martian analog environments [8,9]. For this field test, we explore complex operations scenarios developed for an MSL-class rover (e.g. [6]), and investigate outcomes from these two end-member approaches as they apply to sample selection (for cache or return). Specifically, we used a single field site to compare outcomes of both the linear and walkabout traverse scenarios with respect to resource consumption, and science outcomes.

2. Approach: Roverless roving

Remote rover-based geologic field protocols have commonly been developed [8–13] and tested [13–25] by utilizing a rover mock-up equipped with a suite of instruments analogous to a specific mission scenario. An engineering team in the field runs the rover and payload, while a science team remains off-site, communicating commands to the field and using only incoming data acquired by the rover's payload to advance a pre-determined set of science goals. While this is an appropriate approach by which to test engineering- or operations-driven protocols, there are difficulties when trying to extend it to assessing the efficacy of science-driven decision-making protocols. Difficulties commonly experienced in such tests include faulty instrument performance in an unfamiliar environment, rover hardware failure, and spotty communications. In any case where the non-science portions of the test fail, the test immediately becomes off-nominal with regards to testing science decision-making, and the science team must then determine how to retain as much fidelity to their protocols as possible, make do with non-analog approaches, or interpret results where true baseline information can no longer be acquired.

In order to focus strictly on the science decision-making process, GHOST adopts a “roverless roving” approach [7–9] that more cleanly isolates science protocols from those driven by engineering or operations systems needs. In this approach, a generalized suite of commercial, off-the-shelf instruments provide morphologic, compositional, and geochemical data similar to flight-ready instruments. Humans provide mobility and run the instruments. Although low-fidelity in terms of engineering, this approach is high-fidelity in terms of the data acquired and the resulting science products, permitting a strict focus on decision-making protocols used by the science team. Data that mimics the quality, quantity and cadence of data that might reasonably be expected by a given class of semi-autonomous rover is sufficient to determine whether the protocols used to acquire that data yield optimal results.

3. Field site

In line with the current goals of the NASA Mars Exploration program [26], we chose a Mars analog site with signatures of potential past habitability (e.g., river floodplains with freshwater ponds and lakes) detectable from in situ measurements. Our field site was located on land administered by the Bureau of Land Management (38.851°N, 109.985°W) in the Greater Canyonlands area southeast of the town of Green River, Utah (Fig. 1). Vegetation in the area is sparse reflecting a semi-arid climate. Topography is dominated by irregularly shaped, km-scale mesas that reflect the presence of erosionally resistant cap-rock units that overlie more readily erodible strata. Erosionally resistant cap-rock topping the mesas reflect a regionally shallow dip. Mesa sides are generally steep (~45°) have a maximum relief of 60 m.

The field site was positioned within a region broadly defined by the interaction of four major structural features within the Colorado Plateau physiographic province: (1) the Laramide-age (Paleocene) San Rafael Uplift (also called the San Rafael Swell), (2) the Late Cretaceous Uinta Basin, (3) the Pennsylvanian Uncompaghre Uplift, and (4) the Pennsylvanian Paradox Basin. The sedimentary strata within the field site dip gently northeast towards the Uinta Basin. The Tenmile Graben, located just south of the field site, is a major zone of east-southeast to west-northwest-trending normal faults, with vertical displacements up to 200 m (Fig. 1a and c).

The field site includes approximately 1–2 km² exposing the Morrison (Late Jurassic), Cedar Mountain (Early Cretaceous) and Naturita (Late Cretaceous) Formations (Fig. 1b and d). These units are inferred to represent dry conditions during the Triassic and Jurassic, becoming more humid in the Cretaceous, which resulted in intermingled deposits including shallow-marine carbonates, mudrocks, and sandstones; river- and wave-dominated deltaic sandstones, shales, and coal; sandstone ergs; and fluvial sandstones and conglomerates. A number of these units contain micro- and macroscopic biosignatures, including chemical and fossil records [27]. Specifically targeted for the project were the Upper Jurassic Morrison Formation and the Lower Cretaceous Cedar Mountain Formation, as seen in Fig. 1b-d; the most intensive interrogation in this field work was of the Cedar Mountain Formation. The lacustrine deposits in these formations display biosignatures; in this case, microbial carbonate mats. In addition, exhumed curvilinear fluvial channels are common in both the Morrison and Cedar Mountain Formations [28,29], similar to features that have been documented on Mars [30,31]. Finally, if the hypothesis of a martian northern ocean is viable (e.g. [32,33]), this field site is a reasonable analog for martian intermittent sea incursion. A more detailed treatment of the field site at the group/formation level is included in Appendix A. We note again that science team members were not provided with any age or lithological information other than what could be deciphered from processed orbital data.

4. Methodology

As noted in Section 1, the linear method gathers data during a single traverse through the terrain; while the rover may be commanded to backtrack to a previously-interrogated spot, such commands are rare, and the science picture is built up through investigation of virgin terrain. By contrast, the walkabout-first method gathers data acquired through multiple planned passes within an artificially-bounded region of interest defined by the science team. The most frequently used approach by all Mars rovers up to this point has been the linear approach, as exemplified by Curiosity’s traverse through the Kimberley region; Pahrump Hills is the currently the only area that Curiosity has interrogated using the walkabout method. See Appendix B for a summary of MSL’s activities at the Kimberley and Pahrump Hills as examples of how such activities were carried out on Mars.

For these two end-member decision-making paths for interrogating and choosing samples, we set up the test to mimic the driving cadence (Table 1), and the common timing of instrument use and data acquisition, practiced by MSL at the Kimberley (linear) and Pahrump Hills (walkabout-first, hereafter called walkabout) regions.
4.1. Cadence of mobility and data acquisition

The MER tactical process is run on the basis of a generalized sol path [37]: drive to a point of interest; acquire remote data to determine context and choose targets for in-depth interrogation; acquire data using contact instruments if desired (Microscopic Imager, Rock Abrasion Tool and Alpha Proton Xray Spectrometer [APXS]); drive to the next point of interest. At the completion of each of these tasks, the science team assesses the results and decides the next step, which may follow this path or deviate from it. For example, if the data convince the science team that they have sufficient information to test hypotheses, they may choose to drive instead of acquiring contact instrument data. Conversely, if they deem data insufficient, they may choose to acquire additional data at a single target, or choose a new or additional contact science target in the same location.

4.2. Instrumentation

Instruments used for field testing produced data similar in type and resolution to that generated by current or future Mars missions. We chose not to copy a specific payload, but rather chose instruments that fit expected categories of data (e.g., imaging, whole-rock and elemental geochemistry), because we desired the results of this test to be generally applicable to current and future missions. In order to focus on science decisions associated with sample collection and return, our instrument complement also focused on data similar to that expected from the upcoming Mars 2020 mission (Table 1). Specifically, we used a digital SLR camera to cover the range of resolutions produced by Mastcam/Mastcam-Z and MAHLI/WATSON images. The SHERLOC/PIXL instruments were assumed to be germane to the actual sampling process, rather than the process of choosing sampling locations, and were thus not mimicked in this test; this assumption may be altered as the Mars 2020 notional operations planning develops. Upon request of the science team, image and chemical data could be acquired after removal of superficial dust in a fashion mimicking a Dust Removal Tool (e.g., [38]).

Multispectral data was acquired using a TerraSpec HALO field-portable visible near-infrared (VNIR) reflectance spectrometer from ASD Inc. The TerraSpec VNIR is a handheld hyperspectral contact probe that samples the reflected light from a 1 cm-diameter area between 350…

Table 1

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Specifications</th>
<th>Data provided Use</th>
<th>Data type similar to…</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLR digital camera</td>
<td>Focus ~1.5 cm to infinity; FOV 34 × 23 mm@ best resolution</td>
<td>Context imaging at m to cm-scale</td>
<td>Remote Sensing MER Pancam; MSL Mastcam</td>
</tr>
<tr>
<td>TerraSpec VNIR</td>
<td>Hyperspectral data from 350 to 2500 nm, 6 nm/ band spectral resolution</td>
<td>Fine-scale imaging at mm- to μm-scale</td>
<td>Contact Science MER MI; MSL MAHLI</td>
</tr>
<tr>
<td>XRD/XRF Cu-Kα</td>
<td>Mineralogy, derived elemental chemistry</td>
<td>Remote Sensing</td>
<td>MINI-TESS; MSL ChemCam</td>
</tr>
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<td></td>
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<td>MER/MSL APXS; MSL CheMin</td>
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</table>

Fig. 1. Geologic context of study area in east-central Utah. (a) Map of study area including major basins and uplifts. (b) Stratigraphic column of lithologic units within the study region, with the red vertical bar on the right indicating units encountered by the rover team traverses. Thicknesses from Refs. [34,35]. (c) Field site identified by red square. (d) Stratigraphic section exposed at the “Curiosity Mesa” field site showing the top of the Upper Jurassic Morrison Formation (Brushy Basin Member) through the Cretaceous Mancos Shale. View to the east-northeast; photos after [35]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
and 2500 nm with a 6 nm/band spectral resolution. Analogous instruments on Mars include the MER Pancam, MSL Mastcams, MSL ChemCam in passive mode, and the Mars 2020 Mastcam-Z. Unlike the TerraSpec VNIR, the rover-based MER Pancam, MSL Mastcam, and Mars 2020 Mastcam-Z gather spectra across a field of view (1°, 6.8°, and 17° respectively). However, these instruments are also limited in their spectral range (400–1000 nm) and number of bands sampled (11 channels [39–42]). The MSL ChemCam passive mode also samples a narrower spectral range (400–840 nm), but at a similarly high resolution (0.61 nm/band) as the TerraSpec VNIR [43]. Each of the rover-based VNIR spectrometers are optimized for the identification of Fe-bearing minerals such as hematite, but may also suggest the presence of other minerals such as sulfates, phyllosilicates, and primary basaltic minerals such as olivine. The science teams were provided data only in the spectral range sampled by the MER and MSL instruments noted.

Mineralogical data was acquired with an Olympus Terra field-portable X-Ray Diffraction (XRD) instrument. The Terra XRD utilizes a Cu-Kα x-ray source, and returns peaks from 5 to 55° 2θ. The Terra is the field-portable analog for MSL’s CheMin instrument, which utilizes a Co-Kα x-ray source and samples from 5 to 50° 2θ [44]. Although the Terra XRD operates with a Cu-Kα x-ray source, which compresses the diffraction pattern and shifts peaks to smaller 2θ values, it has been determined to be a suitable analog for CheMin [45]. There are currently no plans for XRD on Mars 2020.

Instrument specifications and generally comparable Mars-ready instruments are listed in Table 1.

4.3. Acquisition of science observations and interpretations

As with previous tests, personnel in this study were divided into 5 distinct teams. A Site Expert reconnoitered the study site and provided orbital data to the science teams, but did not participate in any data analysis or interpretation, and in the field gave only logistical support—all other team members remained “blind” to the field site until field work commenced. The Site Expert provided the current state of knowledge about the site, against which the results and interpretations of the two Science Teams and the Tiger Team were judged. During fieldwork, the Tiger Team examined the field site in situ, using traditional geologic field methods. The Tiger Team provided the control results, and their analysis provided the baseline against which science teams compared their interpretations. The Rover Crews consisted of two students, the first equipped with a camera, playing the role of rover (one each for the Linear and Walkabout Teams), and a second who supported instrument maintenance and operated the TerraSpec and XRD (since there was only a single TerraSpec and portable XRD, these were handled by one student expert each, who provided data to each team as requested). Finally, the Science Teams consisted of two, two-person teams—one executing a linear approach to field reconnaissance and one executing a walkabout-first approach. The Linear Team examined each site in the order in which it was encountered, while the Walkabout Team did an initial reconnaissance of the site using “remote” instruments, then examined a subset of sites with contact instruments. To ensure that both methods drew on similar expertise, each Science Team had one recognized expert in sedimentology and diagenesis, and one expert in landed rover science operations planning and execution.

The two Science Teams requested observations to be executed by the Rover Crews, based on information acquired from orbital data and from previous “sols”. Science Teams team did not see the field site until after the test was over. Rather, decisional data were acquired by the rover and walked back to a Base Camp, where both rover teams were stationed.

4.4. Estimating sol cost

Available power, time and data volume constrain the number and type of science observations that may fit into any single MSL planning cycle. Similarly, for this test, we limited instrument use per “sol” based on the constraints on timing, data volume, and power typically encountered by MSL during a nominal sol. For this field test, we assumed one martian sol’s worth of rover activities was any set of observations that could be acquired by an MSL-type rover functioning nominally in a single sol. For most sols we assumed approximately one hour of remote data acquisition (e.g., imaging, multispectral image data), followed by either a drive of 50–100 m or a suite of contact observations (e.g., geochemical and mineralogical data, with associated imaging). Because engineering activities (e.g., driving, arm motion) are well understood in terms of time and resource costs, these were bookkept by the Science Teams based on MSL norms (see Appendix B for Tables showing sol costs for two MSL example campaigns). The combined sol cost of science observations plus engineering activities was recorded in terms of martian sols, regardless of the amount of terrestrial time required. This allowed Science Teams to maximize field time by collapsing drive time that would normally require multiple sols to execute on Mars.

5. Field test

5.1. Pre-field observations and planning

In actual mission operations, pre-operational planning begins with orbital data. This data is used by the engineering team to assess site traversability and determine a nominal rover traverse path, while the science team uses the data to construct hypotheses about the site and to determine points of high scientific interest. For this field test, the combined team utilized orbital imaging and spectral data provided by the Site Expert to define hypotheses regarding the origin of site materials and their potential for biosignature preservation, and to preplan nominal locations for in-depth analysis. The Site Expert determined the site prior to fieldwork, and provided the field team with “orbital” data similar to what might be produced for a rover mission. Orthorectified panchromatic 1 m/pixel images of the site were acquired from the Utah Geologic Survey to simulate color images from the High-Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO). To mimic Context Camera (CTX) resolution, visible-wavelength images were provided over broader regions, coarsened to 6 m/pixel and gray-scale. A high-resolution DEM and hillshade were created from HiRISE stereo-pairs (data provided by the Utah Geological Survey). This DEM has a spatial resolution of 5 m/pix and was overlain on a derived hillshade with illumination from the northwest. Landsat 7 Thematic Mapper multispectral data were utilized to simulate Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) spectroscopic data. The Site Expert synthesized these data into a site map with multiple overlays (Fig. 2).

The overarching goal for this test was the identification, characterization, and sampling of biosignatures within an appropriately understood geologic context. The Science Teams used available orbital data to produce a generalized geologic framework for the target site. This site was hypothesized to be composed of bedded sedimentary rocks with one or more generations of fluid-driven diagenesis (Fig. 3). It was noted that some or all of the sedimentary rocks were likely water-deposited, and that many of the minerals identified from orbit were potentially diageneric, but could have formed during either early or late (i.e. burial) diagenesis. The potential for biosignatures and their preservation was determined to hinge upon the ability of the Science team to evaluate the depositional and diagenetic processes from ground-based analysis.

Both science teams reached consensus on the geologic framework of the site. The teams then separated into Linear and Walkabout Teams, and each team identified locations on the orbital images that were likely to offer the best opportunities to determine details of the stratigraphy, sedimentary environments, and diagenesis of the site. This process linked mineral signatures detected from orbit to the observable geologic context, and produced a series of hypotheses regarding biosignatures might be present and accessible. Each Science Team chose potential stations (locations where their “rover” would stop and acquire in-depth data) and
notional traverses based on those stations (Fig. 4). During this stage, the Tiger Team also used the available orbital data to pre-plan in situ field work.

5.2. Data acquisition and analysis in the field

All team members were co-located during the field test, in order to facilitate communication between Science Teams and Rover Crews. Protocols were put in place to avoid potential cross-talk between teams. A base camp was set up from which the Linear and Walkabout Science Teams planned and submitted observation requests to the Rover Crews. Laptops were used to observe data from rover observations (i.e., images; geochemical observations were relayed verbally) and to place ground-based observations into the context provided from orbital images. All targets provided to the Rover Crews for observations had to be visible in previously acquired images to be eligible for analysis in upcoming planning cycles. Walkie-talkies were used for communication between science teams and rovers for both safety of the team members, and when necessary to repeat commands to the rovers. Once the Rover Crews left the base camp, no changes to commands could be made.

Both Science Teams began the field test by following their preplanned traverses; data acquired at each traverse stop were used to determine potential changes to either the original traverse or potential sample localities. Both teams were required to use only data in-hand for the decision-making process, and for choosing and prioritizing samples. Each team was limited to acquiring four samples during the field test. Features targeted for contact science observations or sampling were named for easy referral by the team.

Imaging was acquired, minimally, before and after every drive sol,
with a single drive sol defined as traversing at least 50–100 m, or to the farthest point visible on previously acquired images. Drive-related images covered at least 120° of azimuth in the rover’s drive direction, plus any additional imaging requested by the team. Standard imaging was taken at a designated 0° elevation (i.e. at eye level, perpendicular to a vertical Rover Crew member) to mimic standard Mastcam imaging. Additional images could be requested from the Science Team to cover higher or lower-elevation views. Each team also used imaging data to choose areas for data collection and analysis by the TerraSpec and XRD instruments. This analysis occurred in the field, mimicking ChemCam and APXS observations, and compositional and geochemical information thus informed subsequent science decisions. After each drive, the Rover Crews returned to Base Camp to download data and receive further observation requests. Data were assessed as they were downloaded and based on these data, decisions were made as to instrument usage and targeting, and whether the rover should collect more data, continue to the next station, or divert from the original planned path.

The number of estimated sols used by each team is summarized in Table 2 and fully described in Table C.1 of the supplemental material; sol cost is estimated based on the number of sols each set of observations would commonly require if run on Mars by MSL.

5.3. Science team field activities

Both the Science Teams and the Tiger Team focused the majority of their efforts and time on the key facies present in Curiosity Mesa (an informal name for the central mesa in the study site; Fig. 4), because of the inferred higher likelihood of finding biosignature samples. These facies are covered by Stations 1–6, described below.

5.3.1. Linear Team results

The Linear Team’s initial planned traverse included seven stations around Curiosity Mesa; based on in-situ data the team added five additional stations at which imaging and geochemical data were acquired, and/or at which the rover was told to stop and acquire mid-drive imaging for better situational awareness (Fig. 4; Appendix C). The final traverse included 11 stations: Station 1 (unit A in Figs. 3 and 4), Stations 2 and 3.1, as well as 7, 9 and 10 (unit B-C in Figs. 3 and 4, a continuum that was unclear in the orbital images) Stations 4.1 and 4.2 (interpreted to be float from higher up in unit B-C), and Station 11 (unit E in Figs. 3 and 4).

Stations 1 and 2 were quickly assessed as representing primarily detritus from higher, consolidated layers, with low biosignature potential. The porosity of these layers was seen as having poor biosignature preservation potential, and whereas Mn-rich desert varnish can be associated with Mn-reducing bacteria, no observations specifically indicated biotic activity. Thus, the team chose not to use the contact science instruments at these stations.

At one of the added stations (2.1 in Fig. 4), several boulders were imaged that the team hypothesized originated from layers of dark and light-toned material upslope. The team chose to add an additional stop (Station 2.2) and interrogate these boulders as proxies for the upslope layers, as the likelihood of being able to climb the mesa was low and the ability to sample higher layers would then rest in these boulders. The darker boulder was ferric with a varnish coating, showing little biosignature preservation potential. The lighter boulder, while more promising in terms of biosignature presence, showed a minor calcite signature under a rapidly-weathering phyllosilicate exterior. Both boulders’ texture, macromorphology and color all indicated origin from the higher dark and light layers respectively, allowing the team to identify and trace these layers throughout the site. The team considered examining a third boulder at this station, but decided that Station 3, with a spectral calcite signal evident from orbit, likely consisted of additional similar blocks, that could be physically more stable, and potentially more targetable for contact science.

The boulders at Station 3 were confirmed to be much higher in calcite, with uniform 20–30 cm vertical jointing characterized by orange staining and greater erosion. These joints were also seen in the light layer from which the team inferred the boulders originated. Discussion prior to Station 3 noted the vertical columns in the upper layer are superficially similar to columnar stromatolites. This was contra-indicated by observations of boulders that suggested joints accentuated by weathering rinds (e.g., onion-skin weathering). The boulders were deemed to have medium probability of biosignatures, primarily based on high calcite content; consequently, one of these boulders (Fig. 5) was sampled.

The unusual morphology and orbital geochemistry of a light-toned layer at Station 4 led the team to infer that this unusual facies was potentially the source of a dolomite signature evident from orbit (dolomites are Mg-rich calcium carbonates). However, multispectral data on five different targets, and geochemical analysis on one target found no dolomite, and the dolomite spectral signature could never be identified on the ground. The carbonate content of the outcrop drove the team to acquire a sample nonetheless, as carbonate was seen to have high biosignature relevance.

The team moved on to Station 7 (Stations 5, 6 and 5.1 were only visited by the Tiger Team and Walkabout Team respectively), but while examining mid-drive images acquired during the traverse to that Station, they decided instead to backtrack and add an additional Station (4.1 in Fig. 4). In the mid-drive images (an example of which is shown in Fig. 6a), the team saw a lobed slump deposit that appeared to comprise carbonate-rich, angular, blocky clasts and smaller chert nodules entrained in a yellowish-tan, lumpy matrix. Some larger blocky clasts contained a mixed lithology of gray and dark brown, with a patchy or
laminated texture. Overall unit morphology suggested brecciation, but composition of a neighboring “CRISM” pixel was smectite/sericite (clay and/or hydrothermal alteration mineral). Though this unit lay behind the rover when the images were examined, it was decided to turn around and reassess the site for the following reasons: (1) its clasts were not repre-
sented in any other population seen up to that point; and (2) clasts contained the first meso-scale structures seen at the site, structures that appeared to be embedded in another, fine-grained matrix that was highly localized as opposed to being an inherent part of the stratigraphy. Laminated to patchy texture within some of the clasts were seen as similar to what microbial laminae might produce, suggesting to the team that the clasts represented a microbe-rich layer. Images of the target at 10 μm/pixel (Fig. 6b and c), as well as compositional data, confirmed it as a fossilized microbial mat, and so it was chosen to be sampled. An additional station (4.2) was added to identify and sample the upslope source of these clasts.

5.3.2. Walkabout Team results
Nine stations were examined in the first loop around Curiosity Mesa. Similarly to the Linear Team’s traverse, the actual stations and the order in which they were visited changed slightly from the planned traverse due to the realities of accessibility and terrain occlusions between stations. Three loops were envisioned for the walkabout: the first to survey the stratigraphy and mineralogy of the field site and develop a working stratigraphic column, the second to collect detailed mineralogical and textural data from high priority sites identified in the first loop, and the third to acquire samples from the sites deemed to have the highest habitability and preservation potential. The final traverse included: Stations 1 and 2 (units A and B-C in Figs. 3 and 4), Stations 3, 4, and 5 (units B-C and D in Figs. 3 and 4), Station 6 (unit E in Figs. 3 and 4), and Stations 7–9 (highly dissected terrain, Fig. 3).

Remote data gathered from Stations 1 and 2 (including an isolated sandstone unit at Station 1) were used to build geologic context from the bulk of the field area, including an early assessment of the two units in the cliffs visible from those stations: a lower, primarily pink-toned slope-forming unit, and an overlying, tan-to-white cliff-forming unit. A thin white horizon present within the slope-forming unit at Station 2 was book kept as a lithology of interest for its habitability and preservation potential, because the color and mineralogy of the layer (fine-grained, pale green, with a montmorillonite and potentially Mg-illite mineralogy) suggested the material might represent a reduced horizon in a shale unit (Fig. 7), possibly representing floodplain or tidal flat deposits, representing a shallow to intermittently exposed setting with redox gradients. Unfortunately, there was insufficient outcrop to search for physical evidence supporting this hypothesis, such as mudcracks, burrows or root traces. It was a priority to investigate the stratigraphic relationship between the sandstone and red/pale green layers.

Station 3 possessed a boulder hypothesized to represent the overlying cliff-forming unit (Fig. 4, unit D), whose massive areas cut with perpendicular joints were interspersed with fragmented sections that suggested a poorly-sorted conglomerate. However, the untargeted analysis of one of the boulders revealed it to have a pale orange color, sugary
Fig. 5. Image suite acquired for the Linear Team target boulder from Station 3. (a) Approach image, location of (b) denoted by red square; (b) M100-type mosaic, location of (c) denoted by red square; (c) MAHLI-type image of the outcrop in (b). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 6. Target of high biosignature potential at Station 4.1. (a) Image acquired mid-drive of a rock slump of unusual morphology and composition. Red box denotes the area targeted in (b). The target clast in this image is ~40 cm across. (b) M100-type mosaic of rock similar to that in (a), where wavy lamination was identified. Red box denotes the area targeted in (c). (c) MAHLI-type image of the rock in (b), showing wavy laminae 0.5–2 mm thick. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
texture, and hydrated silica mineralogy. The team therefore acquired data at the cliff base, which revealed a pale tan lithology with embedded clasts (gray and orange) up to granule-size, and a smooth gray surface coating over the pale tan bulk rock. Both surfaces exhibited a calcite signature, which was contrary to the team’s assumption that the rocks represented a non-marine setting. The team noted that the source of the boulders at Station 3 was yet to be discovered. At this point, the team members hypothesized that the calcite in these and other samples might represent surface weathering.

Station 4 was chosen to gain a view of the western side of the mesa, and thus plot a path to the next station, but also to gain another perspective of unit D. Drive direction imaging revealed a decimeter-thick, dark brown bed (unit E in Fig. 4) above unit D that was traceable for tens of meters around the alcove west of Curiosity Mesa; these were clearly fluvial in nature. This was consistent with the Team’s hypothesis of a river/floodplain system and, in hindsight, caused the Team to miss the microbial carbonates, since all the strong units above seemed to weather similarly, and were thus assumed to be sandstone. At Station 4, the team gathered mineralogy and texture observations of unit D to follow up on the calcite discovery at Station 3. However, the selected targets at Station 4, gray bulk rock and orange-toned surface material yielded a mixed signature of hydrated silica, calcite, and clay (most likely illite), different from the calcite at Station 3.

The team stopped at Station 6 to gather mineralogy and texture data from unit E (Fig. 8). Millimeter-scale imaging of the upper portion of this layer revealed a wavy pattern across its surface and a granular texture (Fig. 8b). The wavy pattern in the upper layer was hypothesized as possible trough cross-beds and the lack of such a pattern in the lower layer suggested there were two different depositional histories for the upper and lower portions of the layer (Fig. 8c). Both upper and lower portions of the layer exhibited the same mineralogy: amorphous silica, calcite, and some montmorillonite. The wavy pattern observed by the team was not as well preserved or exposed as that observed by the other teams (Fig. 8b vs. Fig. 6b and c). This and the non-distinct mineralogy of the layer contributed to the team passing on it as a sampling target.

The team acquired large-scale mosaics, targeted close approach images and mineralogy data at Stations 7 and 8, but only large-scale mosaics from Stations 9 and 11. Both coarse-grained, well-sorted sandstone at Station 7 and a powdery white layer smoothly pasted over underlying clasts at Station 8 yielded similar mineralogy: silica, calcite and montmorillonite. The team noted this mineralogy was also detected at Stations 4 and 6 despite very different lithologies at each of these stations, and that the mineralogy was not particularly indicative of habitability or preservation potential. Imaging at Station 9 revealed interbedded fluvial sandstone (cross-beds, large grains) and conglomerate, neither of which had high habitability or preservation potential. Imaging at Station 11 demonstrated that the east side of Curiosity Mesa retained the same stratigraphy as the south and west sides, but the E-W-trending cliff extending away from the mesa consisted of dark-toned sandstone. While a striking difference, the team thought the sandstone resembled those observed elsewhere in the field area and did not warrant further investigation. Observations at Station 11 marked the end of loop 1.
The team then assessed all data in hand to determine stops on loop 2. Further inspection of imaging acquired at Station 4 revealed a lens at the base of Unit D containing massive, red- and green-toned materials (Fig. 9a). Unit D above the lens assumed its blocky, more massive form. The team hypothesized that this blockier form of the unit might be the same calcite-dominated lithology measured at Station 3, providing a potential material for sampling. Its juxtaposition with the lens, whose red and green colors suggested redox gradients consistent with habitable environments and whose smooth texture suggested a material with high preservation potential (such as a clay-bearing or chert phase), led the team to select this site as the first stop of loop 2.

Upon return to Station 4, reexamination of the massive unit D material indicated crystalline texture, with a white matrix and gray mottled surface, and yielded a calcite spectrum like that obtained from the contact science target at Station 3 (Fig. 9b). The lens materials exhibited a grainy texture yet weathered from the outcrop in thin, layered spalls (Figure Walkabout 3c). The lens materials also contained mm-scale, red-orange clasts with greasy luster like those seen at other stations. The mineralogy of the lens materials was dominated by montmorillonite with amorphous silica also present; the red target had a more Fe-rich chemistry than green target. The target was hypothesized to be a limestone, though the depositional environment remained unclear. Both the massive unit D target and the green (and presumably more reduced) lens target became high priorities for sampling.

Another high priority for loop 2 was to gain a clearer picture of the relationship between the rubbly and massive portions of unit D, and to further study unit D up close. Review of mosaics from loop 1 identified a particularly good exposure of unit D within an alcove cut into Curiosity Mesa west of Station 5 (Fig. 10a). The team returned there and planned a drive into the alcove for further unit D imaging. Mid-drive imaging to this spot identified two large boulders within the alcove presumably derived from unit D in the alcove (Fig. 10b; Station 5.1) that were later approached for contact science. Close approach imaging of a less weathered face of one boulder revealed a sugary, granular texture and gray-white color, and mineralogy measurements confirmed it as predominantly calcite (Fig. 10c). Contact science at Station 5.1 marked the end of loop 2.

At the end of loop 2, the team elected to sample the calcite-bearing boulder at Station 5.1, return to Station 4, and sample the massive unit D calcite target and the green, clay-bearing lens target. Finally, the team returned to Station 2 to collect a sample of the green, clay-bearing horizon (Fig. 7c). The samples offered two clay-bearing and two calcite-bearing materials from different parts of the stratigraphic section, a variety the team felt increased the chances of identifying evidence of habitability.

5.3.3. Tiger Team baseline results

The Tiger Team’s exploration of the field site mirrored the general route taken by both rover teams, but included multiple deviations to explore other outcrop exposures or strata off this route, with the objective of deriving an overview knowledge of the geologic history. The team created a geomorphic map, stratigraphic column, and unit descriptions of their results. The Tiger Team was able to perform reconnaissance observations on the entire geologic section in one day, and returned the second day to key locales to further investigate working hypotheses.

At Station 1, float rocks were prevalent. The Tiger Team climbed onto
the ridge and explored in-place outcrop to examine trough cross-stratification, to confirm paleoflow direction to the northeast. A brief examination of the clay and sandstone beds at Station 2 (unit B-C in Figs. 3 and 4) was supported by XRD data that confirmed the inferred clay mineralogy. The Tiger Team elected to continue moving after concluding that there were limited observations that could further the investigation of the biosignature-bearing potential of this facies.

From Station 2, the Tiger Team proceeded upslope to the base of the cliff (Station 3.2; unit D in Figs. 3 and 4). An in-situ hydrochloric acid (HCl) test was performed to substantiate carbonate composition, confirmed by XRD analysis. Multiple collected samples had calcite and silica signatures, regardless of color variation. The massive, knobby carbonate facies generated a number of formation hypotheses (e.g., groundwater tufa, hydrothermal deposit, lacustrine carbonate). This facies was also observed in a large boulder in the lowlands (Station 4; also the Linear Team’s target Nataschka).

The Tiger Team then assessed the upper cliff-forming units. These were noted as being composed of three facies, including a thick knobby carbonate (observed in situ at Station 3.2) and a couplet capping rock (observed at Station 7). The first rock exposure identified above the talus (Station 6) was a crystalline carbonate facies that formed the lowermost component of the cliff-forming unit in conjunction with the overlying laminated carbonate facies. The gray, crystalline facies had no discernible microstructures or noteworthy textural attributes, but did effervesc with a HCl test. Subsequent XRD analysis confirmed calcium carbonate composition, but did not identify any other minerals, although the team speculated that thin, branching veins within these rocks were likely silica.

Exposures of a laminated carbonate were first encountered as float during the Tiger Team’s traverse up the ravine towards Station 6 (Fig. 11), and were subsequently correlated to a 0.5 m thick ledge unit at Station 6. Once the source layer was identified, the Tiger Team explored laterally ~200 m along the exposure, and selected multiple locations to obtain fresh surfaces to examine the sedimentary texture (breaking off rocks with a hammer). While wavy laminations were evident in the cliff face, the team discussed the challenges in identifying this texture in remotely sensed data due to the mm-scale of the features, secondary mineral replacement that obscures the texture in places (Fig. 11), and the apparent presence of desert varnish. They hypothesized that the most critical data for identifying features of this type from a rover platform would likely be acquired from a MAHLI-like instrument or from core sample. This subtle sedimentary texture is a difficult one to identify in typical drive-by rover imaging, as confirmed by the results of both rover teams. The Tiger Team performed VNIR to determine dolomite composition, and noted the wavy laminations were diagnostic of microbial mats. They elected not to sample this lithology for XRD analysis, as this was considered unnecessary for identification.

6. Assessment of methods

The ultimate goal of testing various science operational strategies is to derive the highest quality science out of field work on another planet. However, quantifying “science return” is not straightforward, because science itself is a process, and the most common science-related goals (e.g., characterize the geology of a site) tend not to have defined end points. Instead, we must design a process that allows for characterization of the expected or hypothesized, and discovery of the unexpected. We thus assess our overarching hypothesis in terms of what would constitute best practices in a given situation.

Our original hypothesis was that employing the walkabout-first strategy would require more time, but save mission resources and improve science return. Thus, we must address in our assessment the following: (1) science quality, or how well the approach provided the appropriate data to address the given hypotheses; (2) sample quality, or how well the samples addressed the goal of identifying and characterizing biosignatures; and (3) expenditure of time required by each method for comparable science results to be achieved. The first and second points require comparing science conclusions, interpretations, and chosen samples derived from each method, with those produced by the baseline results produced by the Tiger Team. The third requires quantitatively estimating the sols that would be expended by each approach had it been executed in a martian setting.

To determine the quality of the science and the samples produced by each approach, we used a rating system such that if the metric was fully achieved, the metric received a “yes” and if it was not fully achieved, the rating given was “no”; if a metric was partly achieved, the metric received a “partly.” The results (summarized in Table 3) show that when compared to the baseline observations and interpretations of the Tiger Team, the amount and extent of contextual information provided by the linear and walkabout-first approaches were similar (as measured by the ability of the teams to assess geologic history and environment). Neither the Walkabout nor the Linear Team was able to characterize site history as fully as the Tiger Team, and both indicated their dismay in the sheer volume of data that was missed despite their efforts (results consistent with previous GHOST tests [7,9]). However, both teams acquired data that enabled them to interpret the broad sequence of geologic events and unit emplacement in the region. They were also able to use both orbital and in-situ data as it was collected, to determine promising sites for biosignature preservation. In addressing the science goals, both teams noted that they chose to spend the most resources on acquiring broad imaging coverage at coarser resolution, rather than on fewer, more targeted high-resolution images. Additionally, as the layers tended to indicate geochemical homogeneity at the granularity of instrument resolution, both teams acquired multispectral data at less frequency than they may have chosen to do at a different site.
With respect to sample choice, because the Linear and Walkabout Teams had sufficient data to pinpoint layers and units with biosignature preservation potential, both teams were able to choose samples that appropriately addressed the goal of the field work. Additionally, while the amount and extent of contextual information provided by each method was similar, since that contextual information was acquired earlier in the process for the walkabout-first approach, team members had sufficient time to discuss results and come to robust conclusions, leading to greater confidence in sample selection. By contrast, the Linear Team took more time at each site, and was under significant pressure to decide immediately whether or not to sample, leading to less optimal samples being acquired in lieu of additional information. The team executing the linear method would have ejected two samples they acquired (the targets Buckley and Snowflake) in favor of others, had they had that option. However, both teams struggled to identify the highest value fossilized microbial mat layer, and a sample was acquired only by the Linear Team. The Linear Team saw no evidence of the nature of this layer until they had an opportunity to review mid-drive images from a previous sol’s drive, and then it was the experience of one team member interpreting a single image that drove the decision to turn around and go back to interrogate the clasts further. Additionally, whereas both teams ultimately imaged the layer as outcrop, the Walkabout Team imaged a portion of the layer with poorer textural evidence of microbial mats and therefore did not identify its full biologic nature. Both teams agreed that with days to examine the imagery acquired in loop 1, rather than the few hours available during the field test, coupled with a broader array of scientific expertise on the team, the Walkabout Team would have likely identified the importance of the appropriate layer.

As noted above, both methods allowed similar characterization and interpretation of the general geologic history of the site. However, the walkabout-first method yielded a savings in sols, taking 54 sols to execute compared to the 80 sols required by the linear approach (Table 2), even when the additional traverse over the same terrain was taken into account. Again, this was likely the result of contextual information being available to the Walkabout Team earlier in the process, combined with the realization that there would be another opportunity to see each site during a subsequent loop, so that there was less pressure to gather additional resource-intensive data, or to come to a sampling decision before the team felt comfortable doing so. Consequently, once the rover began the second loop, there were almost no time-intensive science decisions to be made, and data acquisition proceeded very rapidly.

7. Lessons learned and recommendations

7.1. Lessons learned

The findings from this field test are consistent with the initial conclusions from previous work testing the walkabout-first method in more narrow circumstances [7] — specifically, that given a limited area of exploration (~1 km²), the walkabout-first method provides high-quality data sufficient to address the hypotheses that were tested. The fact that the method does so at the cost of fewer sols than exploring the same region in a linear fashion was an unexpected result, likely revealed because both methods were run simultaneously, allowing direct comparison. Two unique and interwoven aspects of the walkabout-first method were isolated as the most important contributors to these conclusions: (1) the walkabout-first method provides geologic context early; and (2) the walkabout-first method gives the science team more time and space to digest data.

For any rover-based mission, our understanding of geologic context is derived both from the choice of data acquired, and from human expertise and time spent in discussion and analysis. Geologic context is also the rate-determining step that drives confidence in science decision-making. In this field test, both teams spent the majority of their resources on acquiring data that would allow them as rapidly as possible to determine the general geology of the site, so that any subsequent resource-intensive decisions would be made with a robust understanding of geologic implications. However, the Walkabout Team was able to examine nearly every station before the Linear Team, and was able to craft a more comprehensive picture of the region prior to making those resource-intensive decisions. Thus, their final product (the sample suite) better fit mission objectives, and the team was more confident in their interpretations of that suite. Additionally, the time required to produce that final product was ~33% less than that required for the linear method. In comparison, the linear method yielded some non-optimal samples, and required at least one major backtrack to identify the unit that best met mission goals. In short, broad contextual data, provided early in the process, yielded the best results in the most efficient manner.

It is important to clarify that both the walkabout-first and linear methods were demonstrated to be sufficient for providing basic geologic context. However, building a deeper picture of context (especially important in an environment where biosignatures are subtle, or are

<table>
<thead>
<tr>
<th>Science Metric</th>
<th>Linear Team</th>
<th>Walkabout Team</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within the uncertainty of orbital data resolution, did the teams identify as</td>
<td>Yes</td>
<td>Yes</td>
<td>There was a nearly one-to-one correlation between the traverse and stations chosen from orbital data by the Linear Team and Walkabout Team, and those examined by the Tiger Team. Some stations were added as refinements to reach specific points as seen from orbit.</td>
</tr>
<tr>
<td>initial stations the most relevant locations for meeting the science goal</td>
<td></td>
<td></td>
<td>The teams were able to identify major geologic units and the environments in which they were emplaced, including diageneisis. They were also able to test their original hypothesis of geologic site history. However, the approach was not sufficient to allow the Linear or Walkabout Teams to identify smaller units such as lenses, localized channel fills and thinner beds. Some details of diageneisis were not deconvolved.</td>
</tr>
<tr>
<td>and addressing the science hypotheses?</td>
<td></td>
<td></td>
<td>Both teams were able to interpret their acquired data sufficiently to identify the predominant units with high biosignature preservation potential.</td>
</tr>
<tr>
<td>Did the team characterize the overall geologic environment of the geologic</td>
<td>Partly</td>
<td>Partly</td>
<td>The Linear Team struggled to find, and then accurately interpret, the unit with the most prevalent biosignature (the microbial mat-bearing layer).</td>
</tr>
<tr>
<td>units?</td>
<td></td>
<td></td>
<td>The Walkabout Team did not successfully interpret structures related to the microbial mat-bearing layer where they observed them (a mistake not likely to be made by a larger team with broader experience) and thus did not sample the layer.</td>
</tr>
<tr>
<td>Did the team identify units of high biosignature preservation potential at the</td>
<td>Yes</td>
<td>Yes</td>
<td>The Walkabout-first approach allowed that team the contextual data and the analysis time to efficiently test and eliminate hypotheses prior to committing sampling resources. By comparison, the Linear Team acquired two non-optimal samples.</td>
</tr>
<tr>
<td>site?</td>
<td></td>
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<tr>
<td>Did the team identify and sample biosignatures at the site?</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Would the team have chosen to abandon one or more samples it had previously</td>
<td>Yes</td>
<td>No</td>
<td></td>
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<tr>
<td>collected?</td>
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heterogeneously distributed) requires much more comprehensive data coverage. When walking the site after the field test had concluded, both teams commented about the significant amount of data missed. For example, the site appeared relatively homogeneous to both teams early on, such that they acquired geochemical data less frequently on the compressed tactical timeline; however, heterogeneities at the scale of meters to 10s of meters were important clues to a more detailed understanding of site history, and these were missed by the teams. This implies that any method or observational sequence that can increase situational awareness at the granularity of site heterogeneity (and within the resource budget of the mission) would increase the chances of reaching mission goals in such an environment.

This test reinforces conclusions from other field analog tests (e.g., [7–9]) that there is no substitute for providing time and space for science to occur. Having adequate time to assess incoming data lessens the effects of fatigue, allows time for alternate hypotheses to coalesce, be debated and tested, and thus allows deeper science to be done. In the case of this test, we saw that the Linear Team required more time to assess the data from each site, because of the pressure placed upon it to decide immediately whether the site was appropriate for contact science or sampling. By comparison, because the Walkabout Team knew they would have an opportunity to see each site again if they desired, they spent less time poring over data from each station and making tactical decisions in real time. Instead, as the rover went from station to station the team members focused on building an overall picture of the site, a framework into which new observations could be compared and fit. This more comprehensive understanding allowed the team to make more informed choices regarding sampling; it also lessened stress and thus worked against long-term fatigue.

7.2. Recommendations

Results from this field test indicate that the walkabout-first method may be the more efficient method of exploration for a geographically bounded site, because such a method provides additional time and space in which to do active science analysis, and yields more contextual data sooner in the process. Based on these results, we make the following recommendations that may provide the conditions for which the walkabout-first approach could be efficiently used:

(1) Where practical, invest the resources in time, technology, and personnel to formally organize rover operations around specific “campaigns” in which the walkabout-first method is employed. A campaign would be defined as a strategically planned, in-depth interrogation of a bounded region of interest. Organizing around campaigns allows the science team to be engaged early in the reconnaissance process, and to bound areas such that they are more efficiently explored using the walkabout-first method. While it is unknown whether this approach would save absolute personnel time over the mission, our results demonstrate that it saves tactical sols by costing less rover time, while greatly increasing the validity of, and confidence in, the science conclusions. This recommendation may be especially valid for Mars 2020, because it may obviate, or at least mitigate, concerns regarding collection of non-optimal samples early in the mission that cannot be ejected later for more optimal ones.

(2) For missions where campaign planning is not feasible, or for which the environment is not well-suited for such planning, consider using the walkabout-first approach to explore regions small enough to be reconnoitered in a limited number of sols. Again, this would provide geologic context early in the reconnaissance process. While it is not clear what the ideal number of sols would be, we note that in our test, the first loop of the rover was executed in 18 sols.

(3) Invest in technology and continue practices that support strategic planning (e.g., providing high-resolution orbital images and geochemical data prior to rover arrival at a site, developing tools to quickly create science products for analysis). Strategic planning, such as that required to execute a walkabout-first approach, invests science team members early in the planning process.

(4) Both teams quickly focused on acquiring broad imaging coverage rather than spending time and resources on fewer, more targeted high-resolution images. This indicates that greater data coverage at coarser resolution may in some cases be a better expenditure to obtain context information than less data coverage at higher resolution (spatial, spectral, or otherwise). Thus, when a choice must be made between observations and tools that provide greater data coverage, or those that cover fewer spots at a much higher resolution, contextual understanding tends to be most supported by choosing the former. As coarser-resolution instruments also tend to utilize fewer spacecraft resources and take less time to acquire data than comparable instruments that yield higher-resolution products, such a strategy may yield more time for data analysis prior to tactical choices needing to be made. A corollary is that more frequent systematic observations (e.g., clast surveys, mid-drive imaging with multispectral filters, blind ChemCam shots), especially where the heterogeneity of the region is unknown, or is known to be significant, may be helpful in better understanding context for a relatively small outlay of resources, and might also increase the chances that small units or features may be found.

(5) In choosing rover landing sites, where scientifically valid and reasonable, the community might consider returning to a previously reconnoitered site. For such sites, much of the context is already understood, and thus mission resources can be focused on more targeted analysis.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.actaastro.2018.02.029.

References

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Thomas Chidey is a Senior Scientist for the Utah Geological Survey. He earned BS and MS degrees in geology from Brigham Young University. Mr. Chidey’s expertise includes leading field trips, teaching rock core workshops, and promoting geology to the public. He has wide interests in geology and has authored numerous publications on Utah petroleum geology, facies studies, outcrop analogs for oil and gas reservoirs, microbial carbonates, carbon capture and sequestration, hydrogeology, and the general geology of the state.

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Ruby Schaufer recently completed her bachelor of arts in geology at Gustavus Adolphus College and is currently pursuing a Masters degree in Physical Oceanography at Texas A&M University. Her research currently centers on ocean currents and their influence on polar regions, with the ultimate goal of creating models that will help the scientific community and the general public better understand the ocean’s role in the rapidly changing Arctic and Antarctic environments.

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