Designing remote operations strategies to optimize science mission goals: Lessons learned from the Moon Mars Analog Mission Activities Mauna Kea 2012 field test

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ABSTRACT

The Moon Mars Analog Mission Activities Mauna Kea 2012 (MMAMA 2012) field campaign aimed to assess how effectively an integrated science and engineering rover team operating on a 24-h planning cycle facilitates high-fidelity science products. The science driver of this field campaign was to determine the origin of a glacially-derived deposit: was the deposit the result of (1) glacial outwash from meltwater; or (2) the result of an ice dam breach at the head of the valley?

Lessons learned from MMAMA 2012 science operations include: (1) current rover science operations scenarios tested in this environment provide adequate data to yield accurate derivative products such as geologic maps; (2) instrumentation should be selected based on both engineering and science goals; and chosen during, rather than after, mission definition; and (3) paralleling the tactical and strategic science processes provides significant efficiencies that impact science return. The MER-model concept of operations utilized, in which rover operators were sufficiently facile with science intent to alter traverse and sampling plans during plan execution, increased science efficiency, gave the Science Backroom time to develop mature hypotheses and science rationales, and partially alleviated the problem of data flow being greater than the processing speed of the scientists.

1. Introduction

In reconnoitering remote regions, geologists utilize robotic landers and vehicles to perform data acquisition and analysis. Operations scenarios are designed, tested and refined for the unique problems associated with conducting geology remotely, for the abilities of the vehicles and landers in their specific environments, and for the science goals of the mission. This allows scientists to use these tools to efficiently maximize science return. For example, Mars Exploration Rovers (MER) science operations strategies were designed

to accommodate the latency in communications between Earth and Mars, a delay that required separating science-driven decisions based on analysis of the surroundings, from the actual execution of remote field activities [1–5]. A science support team (the "science backroom") determined science priorities and observations to be executed by the rover the following Martian day, or "sol"; these observations, along with other necessary activities, were planned and executed by the rover engineers. The science operations strategies for Phoenix were developed from the MER operations blueprint, but were initially planned to meet the dual constraints of a landed (immobile) spacecraft and a known, finite lifetime for mission activities [4]. In addition to the science team that planned each sol's activities (the tactical team), the Phoenix mission was to use a strategic science team to evaluate the returned data and develop a plan for the next sols. The timing of these two processes, tactical and strategic, was to be planned so that the strategic team's input would be the basis for the upcoming sol's plan.

Likewise, the strategies currently in use for the Mars Science Laboratory (MSL) rover mission were created in part by adopting salient parts of the MER and Phoenix lander science operations architectures to meet the unique constraints of MSL. These included the significantly larger data stream acquired by the MSL rover compared to the MER and Phoenix missions, the greater complexity in operations due in part to the number and type of instruments on-board, and the resultant additional tactical (short-term) and strategic (longer-term) planning made necessary by these factors. The MSL model requires a complex interplay of strategic, tactical and supratactical science and engineering processes to manage the demand on resources, each of which must feed into and inform the others. Ultimately, however, the 24-h latency between planning and execution, and the integration and close communication between the backroom scientists and the spacecraft engineers regardless of their role in the tactical or strategic process [6], remain key uniting factors in the science operations of all three missions.

The science-driven operational strategies from these missions have been used to acquire data from which products such as geologic maps, compositional rock classifications, thermal inertia maps, and stratigraphic cross-sections have been produced [7–9]. But the fidelity of these products cannot be fully assessed without comparison to a known standard, which is impossible for a truly remote location such as Mars or the Moon. In lieu of comparing remotely-derived products such as maps to a known standard, products derived from analog activities conducted on Earth can be compared to those derived from standard terrestrial techniques at the same location, to determine the efficacy of those remote methods in acquiring the necessary data to produce high-fidelity products. Mauna Kea, Hawai'i, is a key site to carry out Moon and Mars analog activities [10–13]. For the Moon Mars Analog Mission Activities Mauna Kea 2012 (MMAMA 2012) field test, we compared products and science results derived from field test rover activities at a Mars analog site, with those produced by geologists on the ground using traditional field techniques. Our goal was to assess how effectively the science operations strategy for an integrated team operating on a 24-h planning cycle facilitates data acquisition that yields

accurate, high-fidelity science products. The science objective of this field campaign was to geologically map and determine the origin of a glacially-derived deposit, with two potential hypotheses to be tested: the deposit was the result of (1) glacial outwash from meltwater; or (2) the breach of an ice dam at the head of the valley. This objective provided the parameters by which success was measured (outlined in Section 4).

2. Geologic setting of field site

The field campaign was conducted in a valley on the southeast flank of the Mauna Kea volcano at an elevation of 11,500 ft, in an area known locally and informally as "Apollo Valley;" our study area lies across the access road from the Mauna Kea Ice Age Natural Area Reserve [14] (Fig. 1). Mauna Kea is composed of tholeiitic basalts from an active shield stage, capped by relatively low silicate alkali and transitional hawaiite basalts erupted relatively slowly during a stage of postshield volcanism (e.g., [15,16]). The valley itself has been mapped as an unconsolidated gravel outwash deposit of subrounded to rounded hawaiite and mugearite cobbles and boulders that is part of the Pleistocene-aged Makanaka Glacial Member of the Laupahoehoe Volcanics [16,17], a glaciation episode coinciding with the late Wisconsin glaciation of North America [18,19]. Bounding the valley on the upslope side is till of that same glacial member. This broad ridge of till largely plugs the relatively narrow span between the valley walls here, with the exception of a ravine incised between it and the western wall. At the end of the valley to the southeast, and predating the glacial deposits, are several Pleistocene-aged hawaiite/mugearite cinder cones. An extensive Pleistocene hawaiite/mugearite flow unit forms the bedrock of the valley sides and outcrops from below outwash deposits at the valley's southern end.

Attempts to date the advance and retreat of the Pleistocene glaciers [20–22] have led to various interpretations of the glacially-derived valley deposit. Pigati et al. [21] interpreted the valley deposit as a "boulder fan" and suggested, based on boulder composition, that boulders were excavated from the Younger Makanaka moraine currently plugging the northern valley entrance, and transported a few 100 m downslope. They interpreted the valley deposit as having formed over ~3–4000 years as glacial meltwater cut through and washed out portions of the moraines, redepositing clastic material downstream in channels and fans. However, Anslow et al. [22] calculated a bimodal distribution of ages for boulders in the deposit, and explained this discordance with the dates of Pigati et al. [21] by observing that the fan is composed of unsorted sediment with well-defined edges lying in a V-shaped gully that eroded through the distal moraine to the east of Pu'u Keonehinoe. They interpreted the deposit as having formed by catastrophic drainage of a moraine-dammed lake, a one-time event occurring around 12,000 years ago. Differences in ages of the deposit calculated by the two works would then be attributable to the temporal separation between the glacial retreat and the ice-dam breach. Our focus in this field campaign was to acquire data using a MER-type model of science operations, and to use this data to determine whether the valley deposit formed over time through

Fig. 1. (a) Location of Mauna Kea, on the Big Island of Hawai'i. (b) Mauna Kea, with field location shown in black box. (c) Region of field site with field site boundaries shown in black box. Images downloaded from Google Earth. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

meltwater outwash, or rapidly through breach of a moraine-dammed lake.

3. Field test

3.1. Preparations prior to the field test

Prior to field operations, orbital images of the valley acquired from Google Earth were analyzed, and notional traverses were created, mimicking the process in place to plan traverses for MER and MSL. The orbital dataset served as an analog to the orbital reconnaissance images that would commonly be acquired prior to spacecraft landing, and provided the initial information for the science team to frame the hypotheses to be tested. Orbital images were made available to the science team, but no other in situ measurements at the field site were used for planning notional stops for science observations. However, as for MER and MSL, the Science Backroom was permitted to alter the next day's traverse depending on the current day's data. For the safety of the rover, the Rover Operations Team was permitted to change the traverse based on safety or traversability concerns. Rover traverses as executed are shown in Fig. 2.

Traverses were planned primarily for rover safety and traversability, and secondarily to meet science objectives. Thus, paths were chosen that (1) were estimated to be within the topography and roughness limits of rover traversability; and (2) intersected locations that provided high science return. The Day 1 traverse was designed to primarily gather data on geomorphology and stratigraphy, and included observations taken by the Ground-Penetrating Radar (GPR); the traverse was planned so that depth profiles were acquired across the widest point of the valley deposit, to deconvolve the number and characteristics of

depositional events represented. Day 2, in which the focus was geochemistry, had fewer stops because sampling for the MIMOS IIA (MIniaturized MÖssbauer Spectrometer) instrument required more time than acquiring GPR data. Because the highest priority for the MIMOS IIA team was to characterize the variety of volcanic materials, the stops all occurred at the terminus of the valley deposit, where the unit bounds the local cinder cones. Because Day 3 data was not needed for subsequent planning, observations were designed to address issues raised during the previous two days. Thus, the Day 3 traverse covers the most ground and has the highest number of waypoints.

3.2. Instruments and rover

The MMAMA 2012 test utilized the JUNO II rover, a four-wheeled rover with a U-shaped chassis that allows the rover to accommodate a wide variety of payloads, and a geometric suspension that averages the terrain to provide a reasonably smooth ride while maintaining payload capacity. The JUNO II has an active differential link that allows the rover to pitch fore and aft in response to terrain or payload demands [23]. Mounted on the rover were instruments designed to support rover situational awareness and science, including a panoramic video camera (Lucy), a magnetic susceptibility meter, and a global positioning sensor receiver.

Additional instruments were chosen for the rover when plans for the field campaign were already mature. Major criteria in selecting science instruments for the field rover included: 1) applicability to a general scientific investigation of the valley, 2) mobility, 3) availability, 4) remote control capability, and 5) weatherproofing capability [24]. The instrument package was not chosen specifically to meet the science goals of the field campaign, as these were defined after instrument selection. The instruments included the
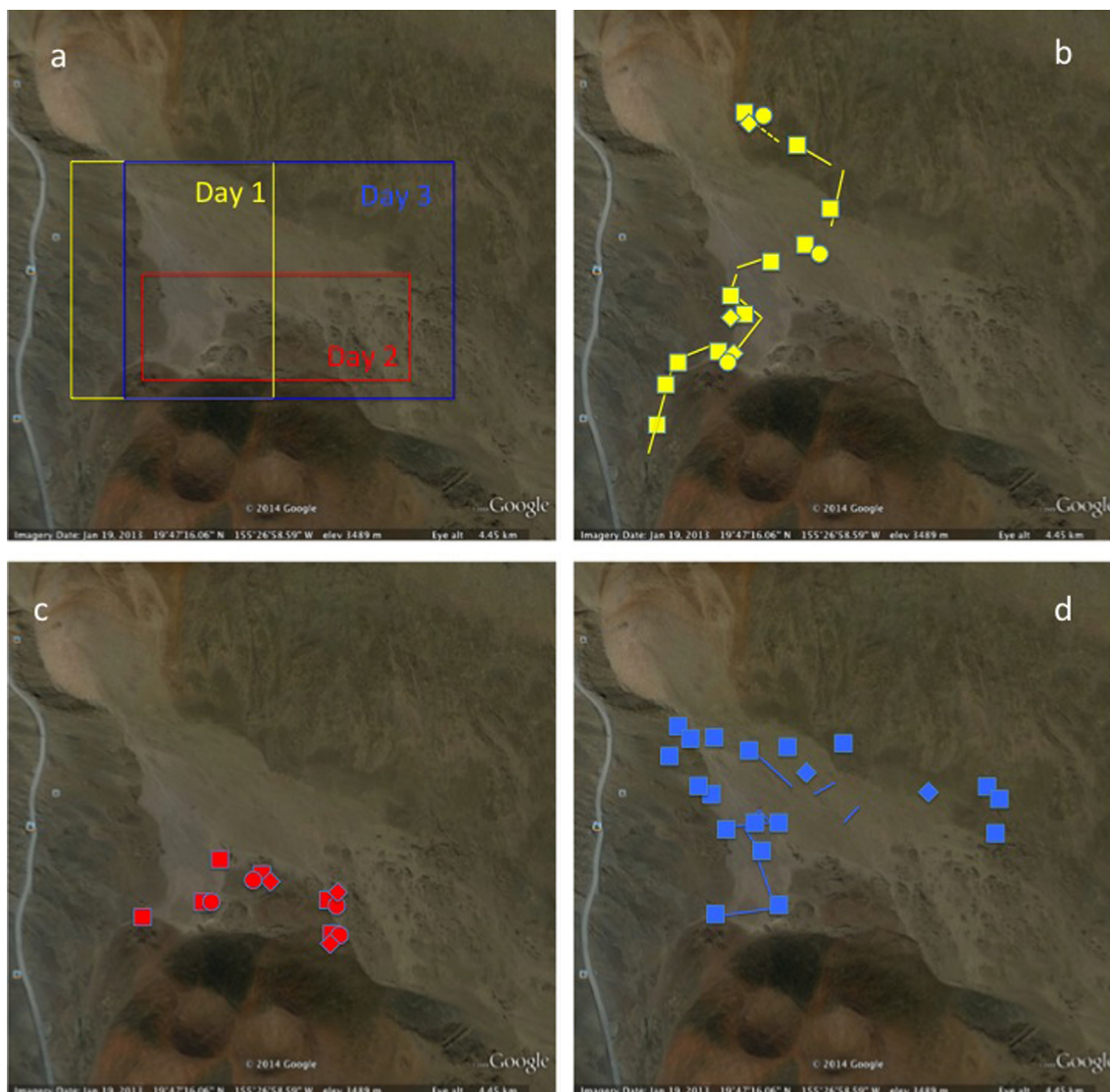
Fig. 2. Three days of rover traverses as executed by the Rover Operations Team. (A) Field area with locations of traverses on Day 1 (yellow), Day 2 (red) and Day 3 (blue). (B) Day 1 traverse. (C) Day 2 traverse. (D) Day 3 traverse. GPR transects are shown as lines; camera panoramas were taken at squares; MIMOS II samples were acquired at circles; VAPoR samples were acquired at diamonds.

Volatile Analysis by Pyrolysis of Regolith (VAPoR/MESH) instrument, a pyrolysis mass spectrometer [25] in an early stage of development supported by a crusher/sieve apparatus [14], a 400 MHz ground penetrating radar (GPR), and a second- generation Mössbauer/X-ray fluorescence (XRF) spectrometer known as MIMOS IIA [26,27].

The Lucy camera was meant to be a primary science instrument as well as an engineering instrument, but unlike the other science instruments, this low-resolution camera was not selected by the peer-review process, but by the engineering team. The choice was made during the period when the field team expected to utilize the communications structures set up for another test (discussed in Section 3.3). We thus originally planned to transmit the data back to the science room real time (hence the reason data volume was a driver for instrument selection). When the MMAMA field test lost most of the expected communications support due to the split in

test areas for the two field campaigns, the field team was required to transfer data at the end of the day rather than real time. This issue is expanded upon in Section 3.3.

3.3. Field test parameters

The field test was originally part of the two-week NASA Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE) field test conducted at nearby Pu'u Hawahine cinder cone (see ten Kate et al. [13] for a description of that site), and was initially designed to be conducted with a rover running real-time or near-real-time operations. A "blind" science backroom was to plan rover operations, analyze data continuously as it was acquired, and feed results into tactical decisions made in real-time. However, because the test was uncoupled from the parent RESOLVE test late in the planning process, this necessitated

changes in the planned science operations structure, to accommodate a less reliable communications architecture. The tactical timeline for this test was readjusted to run on a 24-h cycle: the data was acquired only once per day, rather than continuously. The data acquired during the day was analyzed by the science backroom in the evening, and used by that team to inform and develop the next day's tactical plan of traverse and observations.

The tactical science planning process as run adapted the current MER and MSL science operations concepts to fit the needs of the field campaign. On these two missions, the science and engineering teams plan a full Martian day's worth of activities (about 24 h, or one "sol") based on data downlinked, reduced and refined from the previous sol's plan by scientists serving as payload downlink leads (PDLs). The next sol's plan of activities is created through discussion, debate and consensus, by a rotating team of scientists and engineers called the Science Operations Working Group (SOWG) headed by a scientist in the role of SOWG Chair. Science priorities are determined and science goals are weighed against engineering constraints and needs (for example, data rate, available power, acquisition of data critical for decision-making in future sols). The result is a set of rover and instrument activities that maximizes science return within the parameters of the environment and the limitations of the mission architecture.

The crucial roles of the MER/MSL model that informed our science operations scenario were that of the PDLs, SOWG, and SOWG Chair. The Instrument Leads, who were responsible for both their instrument and their instrument's science investigation, served as PDLs and were part of the Field Team. These team members (all with geology backgrounds) were an important component in reducing the data into manageable bits for the Science Backroom to ingest rapidly enough to make daily tactical decisions [28,29], as well as ensuring that science intent was transmitted accurately to the engineers in the field. All participants with geological and similar backgrounds comprised the Science Backroom (mimicking the SOWG), while the Science Lead of the field test served in the role of the SOWG Chair. These roles are noted in Table 1; the roles of the Field Operations, Science and Integration Lead (FOSIL) and the Field Team have no close analog in MER/MSL experience and will be discussed in more detail in Section 3.4

3.4. Field test activities

A full day of operations began with the Field and Rover Operations Teams executing the day's planned field activities. Near the end of field operations for the day, while the rover was powered down by the Rover Operations Team, the Field Team returned to team lodgings and assisted the Instrument Leads in reducing and refining the instrument data acquired that day. Each Instrument Lead produced a report for their instrument, noting the data planned compared to the data acquired, any problems with the instrument or the data processing, and a high-level summary of important science results, especially those potentially decisional for sampling, traverse or observation planning. The rover operators also reported on the health of the rover, and whether there were any constraints or limitations placed on science planning from an engineering perspective. Armed with this understanding of the parameters and constraints, science discussion followed among the Science Backroom, focusing on the science goals and testable hypotheses laid out before the field test. The Instrument Leads assessed collected samples, and the Science Backroom determined the next day's instrument activities and observations, including any additional sample acquisition. This plan was relayed to the Field Team for the next day's activities. The daily timeline is shown in Table 2.

This field test was originally planned for two weeks, but was shortened to only three days of rover operations when it was uncoupled from the RESOLVE activities. To accommodate this collapsed timeline, and given the lack of reliable communications between the tactical Science Backroom and the Field Team, a change in the MER/MSL model was adopted. It was decided not to stop the rover's activities in the field when challenging terrain forced a change in the traverse or science plan, as would occur in a remote situation. Instead, the Science Backroom created both the next day's traverse plan based on the current day's data, and a number of alternate traverses and sampling targets, to be implemented in the event of unforeseen problems with the hardware or terrain. These alternate traverses were designed based on a well-articulated science intent and resulting set of priorities that were communicated to the Field Team. Thus, in cases where the original traverse would mean downtime for the rover, the

Table 1
List of field test roles and responsibilities.

Operations role	Key responsibilities	MER/MSL-like role
Instrument Lead	Refine the day's data from each instrument and distill important results to the Science Backroom.	PDL
Field Operations, Science, and Integration Lead (FOSIL)	Facilitate integration of rover operations and science instrument operations	No equivalent
Field Team (comprised of Instrument Leads and the FOSIL)	Monitor the plan as it executes; ensure science intent is followed as far as possible in light of engineering challenges; adjust plan to mitigate problems and take advantage of opportunistic discoveries in near real-time.	No equivalent
Rover Operations Team	Execute the plan; operate the rover	Engineering team
Science Backroom (includes Field Team members)	Determine science activities (traverse, observations, sampling) based on science data acquired during the day.	Science Operations Working Group (SOWG)
Science Lead	Lead the Tactical Science Backroom; feed science intent for next day's activities to the Field Team; ensure science activities map back to science and sampling goals and testable hypotheses.	SOWG Chair

Table 2
Timeline for science backroom operations.

Time	Activity	Responsible party
8 a.m.–5 p.m.	Data acquisition, rover activities	Field Team (Rover Team and Instrument Leads)
2 p.m.–6 p.m.	Data reduction/refinement and preparation of reports	Instrument Leads
6 p.m.–7 p.m.	Break/Food	All
7 p.m.–8:30 p.m.	Data reports, review of traverse, summary of engineering constraints for next day's plan	Instrument Leads, Rover Lead
8:30 p.m.–10:30 p.m.	Science discussion; create plan for following day	Science Backroom led by Science Lead
10:30 p.m.–11 p.m.	Upload plan; brief Field Team on science intent.	Science Backroom led by Science Lead

Field Team (Instrument Leads and FOSIL) made science-informed decisions to alter the plan that were true to the intent of the original plan decided on during the last cycle (i. e. the night before). The Field Team was also empowered to maximize rover data acquisition time by choosing alternate sampling targets based on the science intent. For example, if the highest priority target was not reachable with the rover, the Field Team could choose to sample a different target that was not called out by the Science Backroom, but served the original science intent, and which would have been seen in images with resolutions more typical of current and previous Mars missions (sub-mm at 1.5 m distances). Thus, intervention by the Field Team was limited only to situations where following the traverse planned by the Science Backroom would result in a dangerous or untenable situation for the rover or other hardware. They intervened not to make science decisions, but to make required engineering decisions that followed the intent of the Science Backroom. The empowerment of the Field Team to make such decisions allowed us to return to a modified near real-time operational mode. A simplified graphic of information flow for MER and this test is shown in Fig. 3.

4. Assessing outcomes

This test was designed to measure the success of science outcomes, and because science outcomes are discovery-driven, there is no hard and fast rule for judging success. Instead, to qualitatively determine the efficacy of the tested operational strategy, we have utilized a rating system, such that if the metric was fully achieved, the metric receives a "yes" and if it is not fully achieved, the rating given is "no". In one case there is insufficient data to come to a conclusion. A more detailed explanation of the reasoning for each rating is also given. This information is summarized in Table 3.

5. Discussion

Significant findings based on science operations conducted for this field test involve (1) science data product generation and interpretation; (2) instrumentation; and (3) science decision-making on the tactical timeline.

5.1. Data product generation and interpretation

The Science Backroom generated a geologic map based on the compilation of all available rover data (Fig. 4), and they utilized this map to assess hypotheses of deposit origin.
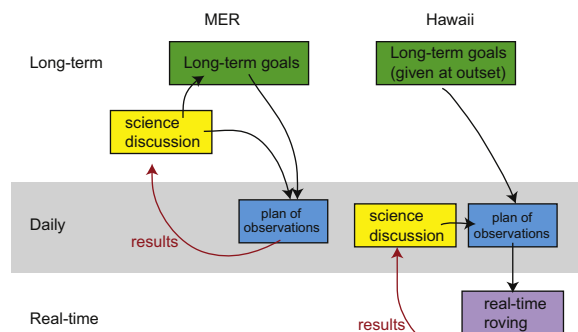
Fig. 3. Simplified information flow diagram comparing this MMAMA field test on the right to MER operations on the left.

The resulting map provides greater detail than previously available geologic maps of the area [16] and was sufficient to drive progress towards a discrimination of competing hypotheses, though the rover's instrument package did not provide data that would allow full confidence in results. The Science Backroom divided the valley deposit into an extensive outwash plain with headwaters emanating from the west portion of the valley, and an eastern flood deposit resulting from the breach of an ice dam, extending partway into the valley. The boundaries and interpretation of the nature of the flood deposit were based primarily on the location of poorly-sorted finer-grained material, and the presence of large cobbles and boulders ponded behind kipukas, suggesting a flow velocity greater than would normally be expected for a common glacial outwash channel carrying only sand and gravel. This hypothesis is also consistent with the deposit age estimates of both Anslow et al. [22] and Pigati et al. [21]. The Science Backroom also noted that the western deposit might be younger based on superposition relationships, although this relationship was not unambiguous based on rover imaging data alone.

GPR subsurface data revealed several potential reflecting surfaces, one at ~ 1 m depth, and less coherent ones down to ~ 3 m depth (although some may be multiple reflections of the surface). The ~ 1 m reflector displays troughs and dipping reflectors in GPR transects taken perpendicularly across the western part of the valley, but only horizontal to sub-horizontal reflectors in transects taken running longitudinally down the valley (Fig. 5). These reflectors are flat and smooth at the scale of 30–40 cm (approximate radar wavelength in the gravel), indicating that the surface they represent must be also, with any roughness or

Table 3
Assessment of science outcomes for remotely acquired data only.

Metric	Rating	Comments
Was the data acquired using the planned operational strategy sufficient to inform tactical science decisions?	Yes	Reasonableness and efficacy of science decisions made by Science Backroom were confirmed by follow-on in-situ assessment of site by geologists.
Was the data acquired using the planned operational strategy sufficient to assess presented hypotheses?	Yes	Method provided sufficient flexibility to acquire the necessary data had the instrumentation been available to provide it.
Was the data acquired using the planned operational strategy appropriate to inform tactical science decisions?	No	GPR characterization of subsurface layers was key, but resolution of Lucy camera was not optimal and not of sufficient quality to address science objectives; grain-scale resolution required but unavailable.
Was the data acquired using the planned operational strategy appropriate to assess presented hypotheses?	Insufficient data	Data types acquired (e.g. image mosaics in conjunction with sample measurements) were likely appropriate but the actual data acquired was not. Cannot determine usefulness of compositional data without high-resolution context imaging.
Was the data acquired using the planned operational strategy ultimately sufficient and appropriate to discriminate between presented hypotheses?	No	Science Backroom favored the hypothesis confirmed by follow-on in-situ geologists, but could not commit strongly to it based on evidence available through rover activities only.

included materials being smaller than this diameter. One interpretation of these signals is that there are multiple overlapping or adjacent elongate tongues of material with a downslope flow direction under the western valley deposit; the separate tongues are seen in cross-section by the GPR when it executes a transect perpendicular to the valley. Another potential interpretation is that the reflectors represent smooth or gently undulating lava flows (or flat pavement-like surfaces composed of decimeter-scale fragments of lava as observed on adjacent terrains) that predate glacial activity. The troughs and dipping reflectors would then represent boulders greater than ~1 m diameter that are part of, or rafted on, that flow. However, based on transects taken next to outcrops of lava bedrock, solid lava has a different characteristic signal and dives to depths > 3 m. In the first scenario, the valley fill deposits would be significantly thicker than in the second, in which case they may only be ~1 m deep in places. The nature of the layers could be better constrained over the entire area with a test pit, though this was beyond the scope of the field campaign work. In any case, there was a notable absence of hyperbolic-like point reflectors, suggesting that the occurrence of boulders > 30 cm, which are common at the surface of the eastern unit, is rare within the deposit of the western unit. If the multiple-tongues interpretation of the data is correct, it would suggest that the western valley had a minimum of two depositional events, though the timing of those depositional events cannot be determined from the GPR data. The dataset provided by the rover's other instruments was not such that the team could further explore the veracity of this interpretation.

In short, this field test demonstrated operational success by showing that the current MER-type operations scenario provides sufficient and appropriate remotely-acquired data to be able to address certain types of science questions and produce reasonable geologic maps. The map in Fig. 4 shows one of the scientific outcomes of these operations. However, even though operationally the necessary data could have been acquired to provide further detail on the origin of the glacially-derived deposit, with respect to the two hypotheses to be tested, the dataset provided by the instrument package was not of a nature that allowed the team to definitively confirm either one of these hypotheses. The tension point was the instrument package used, rather than the operations strategies.

5.2. Instrumentation

Instrumentation drives the type and quality of science-related data that can be acquired. Instruments are ideally chosen to perform the tasks needed to meet both engineering and science goals; however, for this field campaign the instrument package was chosen prior to science goal definition. In practice, the remote instruments (the GPR and Lucy camera) were utilized as tactical instruments, informing the science decisions made for the next day's planning, while the sampling instruments could only inform strategic decisions. Thus, we focus assessment on the choice of remote instruments, which was consequential to tactical science decisions.

The GPR provided data that was especially useful in deconvolving site history. Specifically, because the GPR was able to resolve layers at depth, the presence, thickness and topography of subsurface units could be estimated. These data were key factors in building reasonable interpretations of the site's geologic history. In addition, the video capability of the Lucy camera allowed the Science Backroom in some instances to capture the exact location where the rover crossed unit boundaries, as the camera was able to image coarse changes in morphology (e.g., Fig. 6).

However, the Lucy camera did not have the resolution, focusing, mosaicking and other capabilities needed to address the stated science goals of this test. Specifically, the morphology and distribution of clasts less than ~20–30 cm diameter (cobbles and boulders) could not be resolved. Within this size range is recorded the abrupt change in rounding of the abundant cobbles and boulders from the eastern to the western sections of the upper valley, a relationship easily visible in the still images taken by the Field Team's hand-held cameras, and diagnostic of a difference in transport mechanisms responsible for these two units. Additionally, the camera meant to resolve grain-scale morphology and relationships (i.e. a handlens-type imager similar to the MER Microscopic
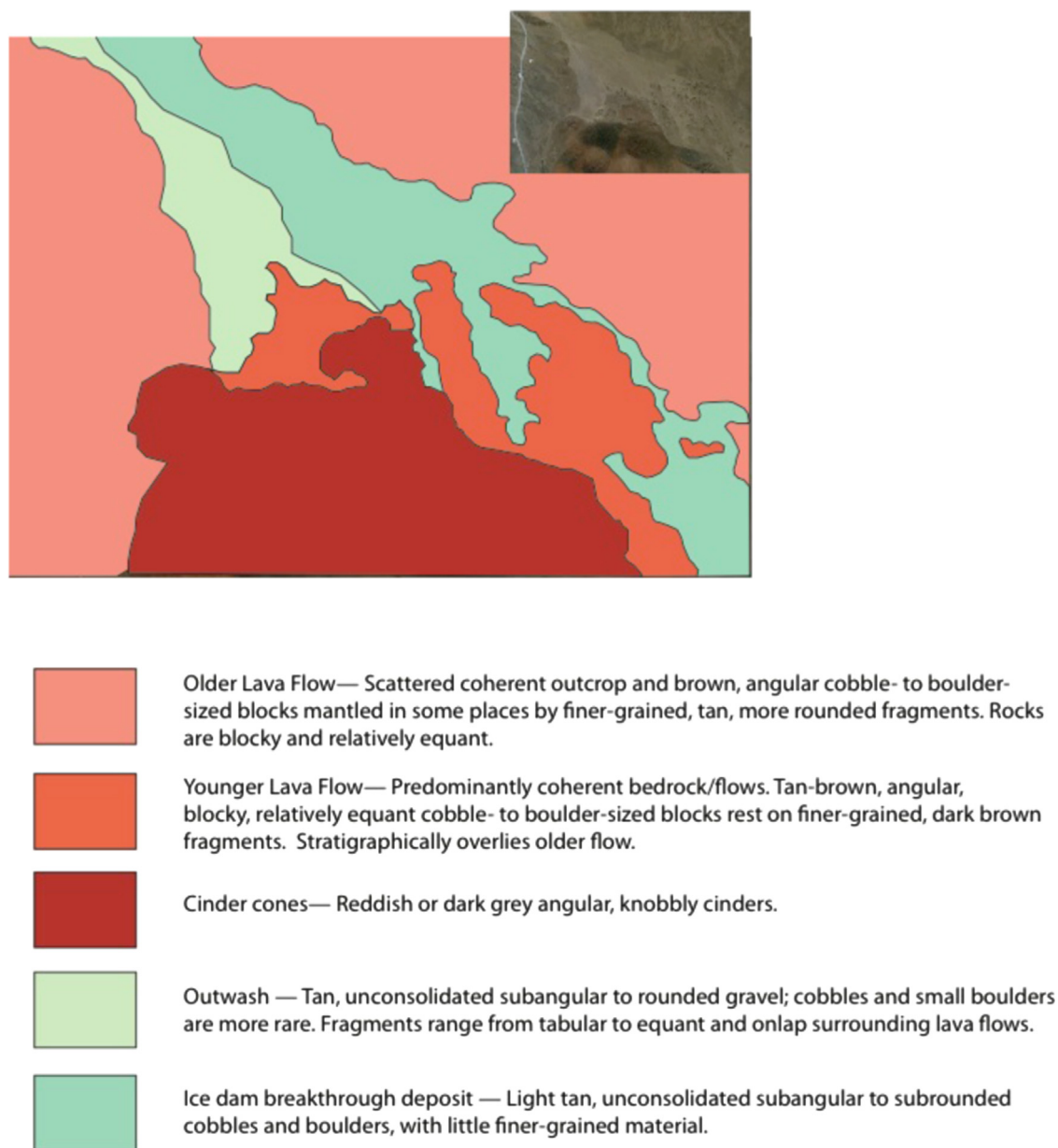
Fig. 4. Geologic map of the field site with description of material units. Satellite image of map area shown in inset is the area in the blue box in Fig. 1.

Imager or MSL Mars Hand Lens Imager) never worked properly in the field, and thus lithologic data was never available to the Science Backroom. The result was that geologic unit boundaries that might have been identified by mapping the presence and abundance of fine-grained (0.1–1 mm diameter) material were invisible to the rover.

5.3. Science decision-making on the tactical timeline

The change in the field campaign timeline necessitated significant alterations in the length and execution of the tactical process. The operations scenario finally settled upon was one in which some real-time decisions were made on the ground by the Field Team, informed by the science intent stated during planning. Without this change, reconnaissance of the site within the time limit of the field campaign would have been impossible. Additionally, this model increased efficiency significantly, by eliminating rover downtime due to engineering or communications issues. Based on the current MER and MSL science operations activities, this model saved a minimum of 1–3 sols worth of science activities every time a problem of this type occurred in the field.

The Field Team essentially ran in real-time, a scenario that has not been attempted on Mars, as the travel time for communications imposes a latency of at least 40 min at the most favorable orbital positions. This is comparable to the Apollo and Lunakhod architectures, and to some prior lunar-model field tests (e.g., [30] and ⟨http://astrogeology.usgs.
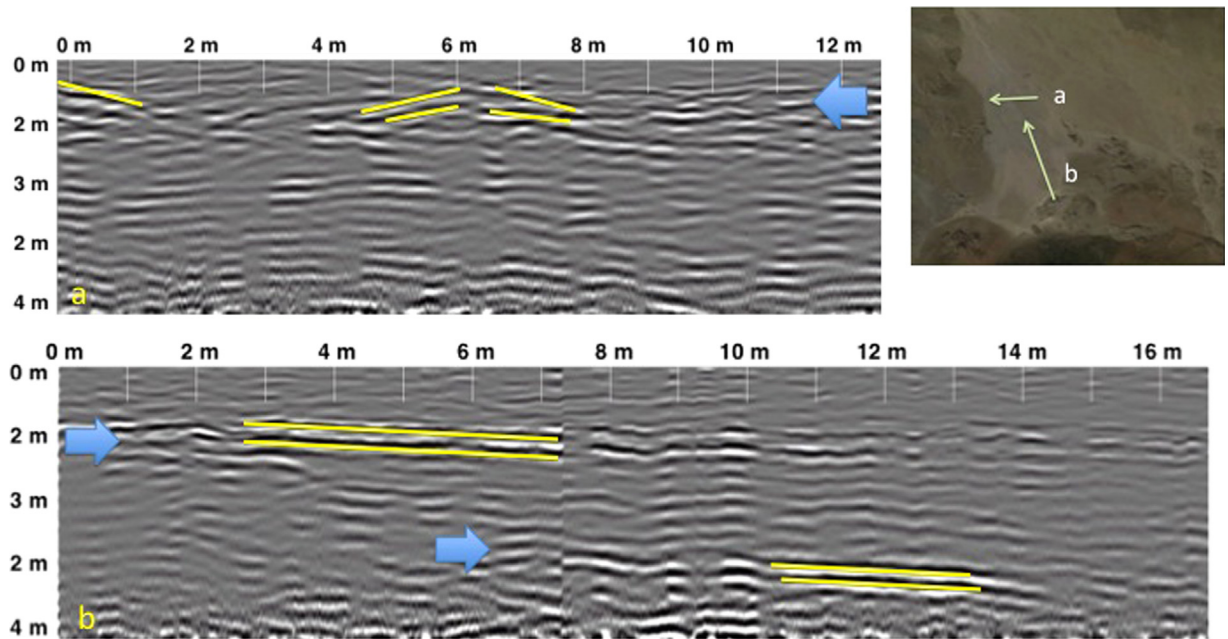
Fig. 5. GPR data acquired on Day 3. (a) Transect acquired perpendicular to downvalley direction. Note reflector at ∼1 m depth (blue arrow); reflecting surfaces are traced in yellow. (b) Transect acquired parallel to downvalley direction. Note straight reflectors at ∼1 m and ∼3 m depth (blue arrows); reflectors are traced in yellow. (Inset) Location of transects (a) and (b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
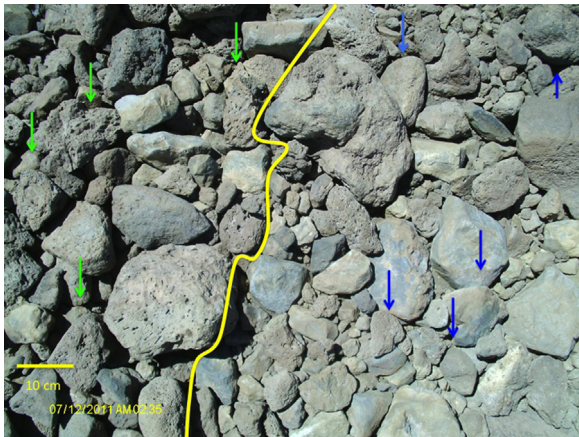
Fig. 6. Hand-held camera image of boundary between Older Flow unit (left of yellow line) and Outwash unit (right of yellow line). Fragments of the underlying lava flow are angular to very angular, with higher vesicularity (examples indicated by green arrows), while fluvially-altered clasts transported in glacial meltwater channels are more rounded and the population has fewer vesiculated fragments (blue arrows). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

gov/About/AstroHistory/astronauts.html⟩). However, the broader concept of operations, in which rover operators were sufficiently facile with science intent to alter traverse and sampling plans during plan execution, took advantage of the concept of dividing the tactical and strategic science teams, as modeled by Phoenix and MSL operations [4,6]. This increased the efficiency by which science was conducted. Such a model also applied the lessons learned during previous analog tests [29,31], by giving the Science Backroom time to develop mature hypotheses and science

rationales, and choose optimal sampling sites and traverses to address them, while a well-informed tactical team conducted the actual data acquisition. Additionally, our concept partially alleviated the problem of data flow being greater than the processing speed of the scientists [29], by requiring the Field Team to give daily reports directly to the Science Backroom, while memories were fresh. Science Backroom team members could ask questions, get clarification, and then move on to the decision-making process when they felt that they understood the data and the engineering situation in full. In this way, we expanded on the MER model of PDLs providing reports of the previous sol's data at the SOWG meeting (we must also note that the amount of data acquired was significantly greater for tests where humans were used to acquire the data rather than a rover [28]; thus the problem of data ingestion was necessarily more severe in such tests than here).

The Field Team's ability to intervene when necessary was a change made to our operations out of immediate necessity. As such, we were unable to set the quantitative constraints around this parameter that would allow us to document rigorously individual interventions by the Field Team in the tactical process. However, we note that on Mars, often sols must be spent to reassess terrain or targets based on safety, reachability or traversability concerns, and in such cases the tactical Science Backroom's expertise is only needed to confirm that the science intent is being carried forward. Such changes in the plan, then, are not a result of the science process failing. For this test, in almost all cases where the Field Team changed the traverse, it was for traversability or safety reasons. Changes more salient to this analysis occurred on Day 2, where the original sampling-heavy traverse was changed because the sample targets were not reachable;

instead, secondary sample targets called out by the Science Backroom were acquired. In one case where even that was not possible, the Field Team chose a tertiary target that matched the unit the Science Backroom was attempting to sample. In this case as well, the Science Backroom intent was carried out rather than over-ruled.

6. Lessons learned

Lessons learned from this field campaign emphasize the following common themes: (1) current rover science operations scenarios tested in this environment provide adequate data to yield accurate derivative products such as geologic maps; (2) instrumentation should be selected based on both engineering and science goals; and (3) paralleling the tactical and strategic science processes provides significant efficiencies that impact science return. We expand upon each of these themes below.

(1) Although the instrumentation was not optimized for the science goals and the science operations scenario was compromised early in the planning stage, the Science Backroom ran smoothly, acquired some robust data, and was able to produce a geologic map that informed the given hypotheses positively. The key factor of the MER/MSL-based science operations scenario that alleviated the crush of data flow to the Science Backroom was the set of reports given by all Instrument Leads, thereby efficiently summarizing for the scientists the necessary and important facts for them to make tactical decisions. We believe this system worked significantly better in this test than prior tests (e.g., Desert RATS [28,29]), because our data volume was much less than a human-driven mission would produce. Thus, for rover-only missions (i. e. those without in situ humans), the test demonstrated that the science operations approach tested here is such that the resulting data products are high-fidelity. However, the level of certainty regarding conclusions made solely based on rover-acquired data was not high, and we believe that to a large extent this was due to the instrumentation, specifically the lack of high-resolution imagery and the VAPoR/MESH instrument being in a too early phase of development (as noted in Section 3.2).

(2) The very low resolution of the Lucy camera, chosen when the communications structure allowed real-time communication but low data volume, greatly hampered the ability of the Science Backroom to produce a reasonable geomorphologic analysis within the mission timeline. It is, in fact, uncertain whether the data sets acquired will ever be sufficient for this purpose. As noted in Section 5.2, Lucy did not have high enough resolution (by a factor of 10) to provide any but the most basic clast morphology, a crucial data point in discriminating between transport processes. Lucy's resolution was difficult to assess in a quantitative sense regardless, because the only data available to the Science Backroom was in moving 360° panoramas that immediately went out of focus once the camera completed the pan. Stills could only be acquired by pausing the pan mid-process and capturing a screen shot. Best qualitative estimates of

resolution were 10 cm for an object of contrasting albedo to be detected and its gross shape resolved (elongate vs. equant) if it was within 1.5 m of the rover. Effective resolution was closer to 20–30 cm since most features were of similar albedo. Resolution decreased rapidly with distance and distance from the rover could not be measured tactically, only guessed by the Field Team.

Attaining and retaining situational awareness, and providing scientific context, each require different imaging capabilities. This need is one reason why the MER and MSL rovers were equipped with hazard avoidance and navigational cameras for engineering needs, and a panoramic imaging system with a suite of spectroscopic filters chosen for geologic and atmospheric assessment. The science goals of this field campaign would have required the integration of a higher-resolution imager into the rover system than was used for situational awareness. Future simulations must give more thought to including on the payload an imager or set of imagers that are designed to fully document the local morphology of the site and the samples acquired. In a more general sense, however, to ensure that chosen instruments meet the needs of science and engineering combined, both groups should be fully integrated in all planning stages to ensure optimal science output.

(3) The change in the operations structure to one in which rover operators were sufficiently facile with science intent to alter traverse and sampling plans during plan execution allowed for maximum rover usage and data acquisition time, while avoiding overwhelming either the Science Backroom or the Field Team. When engineering issues of safety, reachability or traversability occur on Mars, additional sols are added to the long-term operations plan to provide the engineers time to follow the intent of the Science Backroom by finding another path, or a reachable target roughly equivalent to an unreachable one. In the case of this fieldwork, we stipulated to the lost sols, estimated how many sols might have needed to be added to recover, and continued the operations sequence; the result was not a change in the way science decisions were made, but in the speed with which they were carried out on the ground. Based on the reports of the Field Team for each day, the Field Team intervened in the tactical plan for engineering issues a number of times. We estimate that the activities in this field test, if executed on Mars, would have added approximately 2–10 sols to the campaign length, depending on the nature of the terrain. This estimate includes planning cycles for engineers to acquire additional imaging, assess alternate paths for safety and traversability, and approach and attempt the alternate path. However, because these were engineering problems (even on Day 2, when the greatest number of plan changes were made), the number of sols that would need to be added to the planning cycle for the Science Backroom to reassess was zero.

This model of a Science Backroom and a Field Team has potential implications for the use of humans-in-the-loop in a variety of rover mission scenarios. However, this test was an ad-hoc solution to an immediate problem, not a high-fidelity test. The decisions of the "on-the-ground" scientists were informed

by their in situ knowledge of the field site, for example; in a real remote rover mission, these scientists would be limited in their decisions by the data acquired by the rover. Thus, it is not clear how much benefit humans-in-the-loop would be if those humans were not actually standing in the field. A rigorous test is needed of this promising operations scenario, to ensure that other variables can be eliminated or lessened, and the potential benefits in lessening rover downtime and increasing the ability of scientists to ingest and use data as it is acquired, can be assessed.

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