

2012 Moon Mars Analog Mission Activities on Mauna Kea, Hawai'i

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Abstract

Rover-based 2012 Moon and Mars Analog Mission Activities (MMAMA) scientific investigations were completed at Mauna Kea, Hawaii. Scientific investigations, scientific input, and science operations constraints were tested in the context of an existing project and protocols for the field activities designed to help NASA achieve the Vision for Space Exploration. Four separate science investigations were integrated in a Martian analog environment with initial science operations planned based on a model similar to the operations control of the Mars Exploration Rovers (MER). However, evolution of the operations process occurred during the initial planning sessions and as the analog mission progressed. We review here the overall program of the investigation into the origin of the valley including preliminary sensor data results, an applicable methodology for developing an optimum science input based on productive engineering, and science trades and the science operations approach for an investigation into the valley on the upper slopes of Mauna Kea identified as “Apollo Valley”.

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1. Introduction

The 2012 Moon and Mars Analog Mission Activities (MMAMA) scientific investigations were completed on the Mauna Kea volcano in Hawaii. Overall, four investigations were integrated and accomplished as part of the overall MMAMA test with a primary objective of investigating the valley origin using a Martian analog environment. The test provided additional practice in remote robotic science operations, leveraging team member experience on the Mars Exploration Rovers (MER) and Mars Science Laboratory (MSL) missions. The test was conducted on the southeast flank of the Mauna Kea volcano at an elevation

of 11,500 feet in an area known locally as “Apollo Valley”. The robotic science and instrument objectives defined for the field investigation included (1) integrate the instruments onto the rover as part of the analog field test, (2) develop, demonstrate and evaluate operational concepts for remote science investigations, (3) simulate a remote-controlled planetary science mission by minimizing the number of times the rover was physically touched by an operator and (4) determine whether the valley could have been formed by volcanic action or by the release of an ice dam on the upper slopes of the valley by investigating mineralogical sites in the valley. Subsequent discussions also point to the possibility of a valley origin by lava flow over an ice sheet or, more likely, lava flow over permafrost similar to some areas in Athabasca Valles province of Mars (Dundas and Keszthelyi, 2013).

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The four science investigations of the MMAMA field campaign included the “Increasing Robotic Science” (IRS) proposal, the Volatile Analysis by Pyrolysis of Regolith (VAPoR)/Mechanized Sample Handler (MeSH) instruments (a pyrolysis mass spectrometer and sample handler) (ten Kate et al., 2013; Glavin et al., 2012), the Mössbauer/X-ray fluorescence spectrometers (MIMOS II/MIMOS IIA), and an additional investigation designed to field test Science-Driven Rover Operations (SDRO) in an analog environment.

During operation in the field, three of the four robotic science and instrument objectives defined for the field investigation were successfully met including (1) integration of the instruments onto the rover, (2) development, demonstration and evaluation of operational concepts for remote science investigations, and (3) simulate a remote-controlled planetary science mission by severely restricting the rover from being physically touched by an operator. The only exception to this contact restriction rule proved to be the GPR data collection, where the operator had to activate the system that was mounted on the rover for each transect it measured (several times each day). To accomplish the remote hands-free operation, a combination wireless and hardwired on-board instrument suite was developed, similar to a remote planetary rover design. During the field test, control of the remaining instruments was accomplished by four operators remotely controlling specific instruments and the rover using a wireless scheme (Fig. 1). Direct contact by the MIMOS IIA operator was never necessary during the actual test, however. The fourth objective, determination as to whether the valley was formed by volcanic action or by the release of an ice dam on the upper slopes of the valley by investigating mineralogical sites in the valley, could not be definitively addressed with the data gathered.

The MMAMA team utilized a rover, the JUNO II, provided by the Canadian Space Agency (CSA) (Fig. 2). The use of this new rover posed some risk with respect to the integration of the instrument suite. To reduce the overall rover integration risk and subsequent threat to operation in the field a risk reduction plan was implemented. First, the MMAMA team developed several computer graphic models for the mounting and operation of the instruments in the field, in close cooperation with the rover builders, Ontario Drive and Gear (ODG) of Canada. Second, one of the most complex IRS instruments, the ground penetrating radar (GPR), was brought to the Johnson Space Center (JSC) where several key attachment dimensions were confirmed and the GPR was tested. Third, members of the team flew to the ODG plant with several instruments to perform fit checks and local field tests to test the actual integration and determine any operational constraints. The issues that were identified at the factory and during testing nearby were quickly resolved by the ODG rover team and were key to the success of the field operations. In addition, during the actual field-testing, the special features of the rover design were nearly optimal for the condi-

tions expected at Mauna Kea. Steep slopes, loose tephra, boulder fields, and a’a lava flows were commonly encountered during the valley traverses. The unique flexible plate wheel design developed by ODG, combined with the capability of the rover to tilt the entire vehicle to change the vehicle center-of-gravity, were used several times to get out of difficult surface terrain features. The rover performed very well in terrains far more difficult than those traversed by the rovers currently on the surface of Mars.

2. Field operations

The original goal of the supporting SDRO proposal was to assist in designing and field testing operations strategies and scenarios (when, how often, in what order and in what priority instruments are utilized) that effectively provide geologic context and allow science goals to support mining/prospecting goals. Because of the change from an anthropometric robot on a chassis to a new rover platform, however, the SDRO main goal was refined prior to the field test. The new goal became to test how well the science operations scenario allowed scientists to translate remotely-acquired rover data (e.g., visual and spectroscopic images, geochemical data from specific targets) into analysis tools and products such as geologic and geomorphic maps, and whether these products were sufficient to discriminate between the competing hypotheses of geologic processes presented for the site. To support this new goal, participating instrument scientists and engineers were divided into a rover field team (to support rover operations at the field site, including monitoring rover mobility and data acquisition) and a science backroom to plan the rover activities to be executed each day. The science backroom team was not allowed to physically inspect the site until the test was complete. The teams came together at the end of rover activities for each day, so that all instrument and rover data could be reviewed and changes to the next day’s tactical plan could be made, if necessary. Following this review, backroom scientists met to further discuss the data and debate hypotheses. Any additional refinements to the plan that came from this discussion were fed forward to the rover field team for the next day’s activities. Following the three-day test, the science backroom team was allowed into Apollo Valley to see it in person for the first time. A detailed description and analysis of the operations scenario will be published in a follow-on work.

The mission timeline presented logistical problems when science objectives were put at potential risk by breakdowns in hardware, software or communications. However, because the rover field team and science backroom debriefed together at the end of each day, the rover field team members were well-versed enough in the science objectives that they could carry out the intent of the science backroom without the backroom being in the real-time loop. This allowed the backroom scientists to utilize the tremendous data stream provided by real time or near-real time operations to inform both the short-term (tactical)

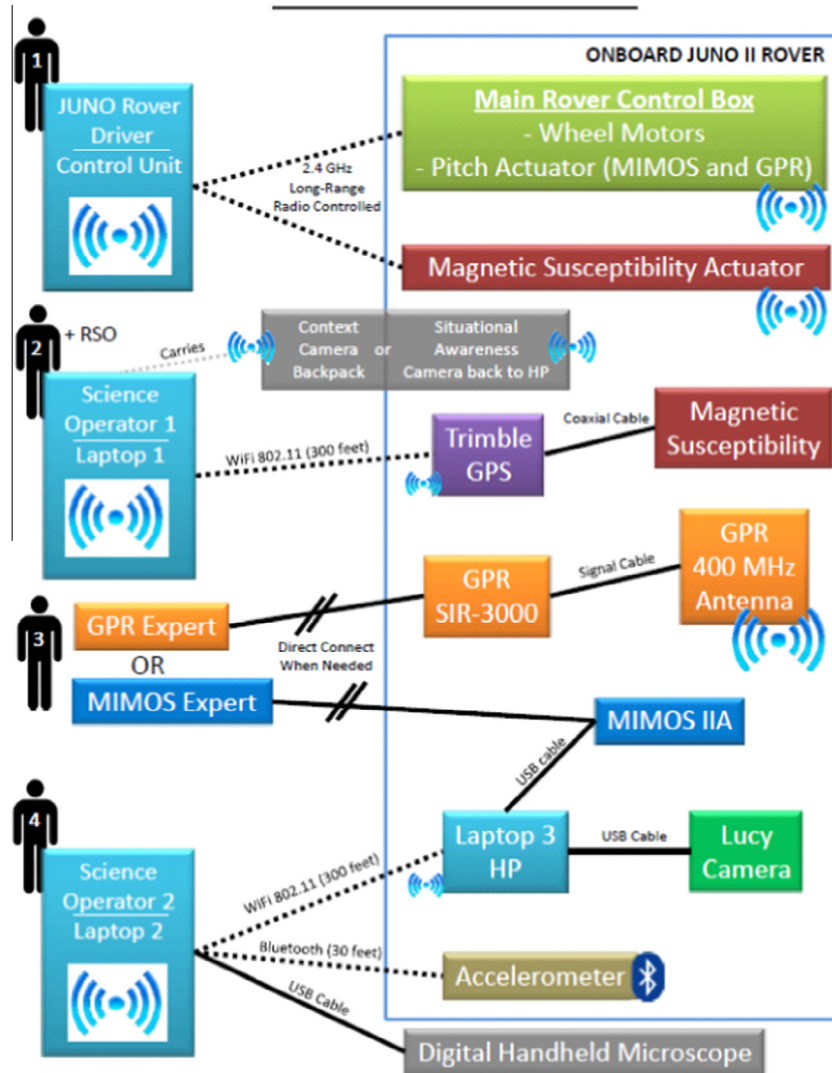


Fig. 1. Rover control schematic.

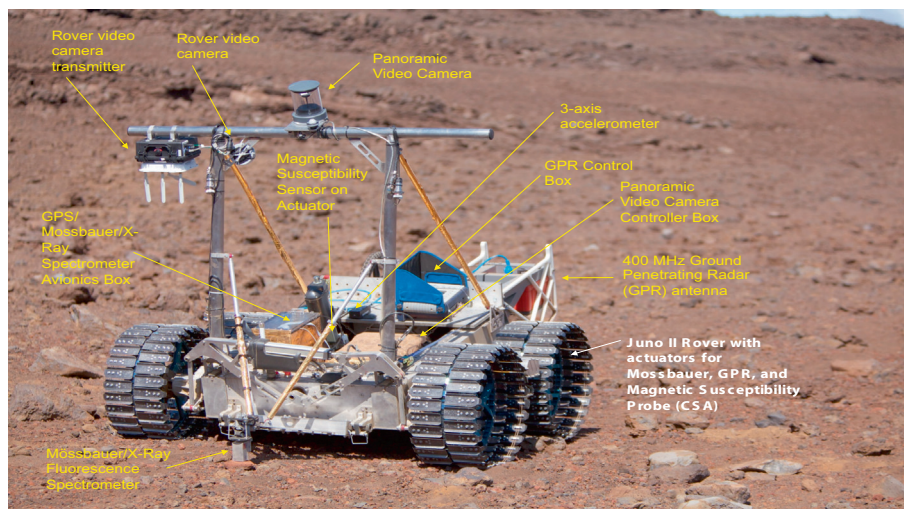


Fig. 2. OGD rover with MMAMA instruments.

and long-term (strategic) goals of the mission. Thus, the operations scenario used here may be useful in informing discussions of how to improve science-driven operations efficiency for future rover missions, as it allowed for maximum rover usage and data acquisition time, given human limitations in ingesting science data real-time. The decisions of the rover field team 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. 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.

The JUNO II rover traversed and explored a valley region largely composed of outwash material and the surrounding terrain such as cinder cones (Fig. 3). In accomplishing the field test, the CSA JUNO II rover performed extremely well traversing ~5 km each day over extremely rough terrain (Fig. 4). The flexible instrument integration design and all-terrain capabilities of the rover were integral to the rapid integration and successful instrument deployment during the test. The instruments themselves were selected based on several considerations. The major criteria included: (1) applicability to the scientific investigation of the valley, (2) mobility, (3) availability, (4) remote control capability, and (5) weatherproofing capability. The instruments included the VaPOR/MeSH instrument, a ground-penetrating radar, a second-generation Mössbauer/X-ray Fluorescence (XRF) spectrometer (MIMOS IIA), a panoramic video camera, a magnetic susceptibility meter, and a global positioning sensor (GPS) receiver. While the instruments used in the test were not optimum for data gathering to address the various hypotheses for the origin of the valley, they did provide important data which allowed key inferences.

3. Science instruments used

One of the key instruments in the investigation was the ground penetrating radar (GPR), which was used to



Fig. 3. Apollo Valley looking upslope to Mauna Kea peak.

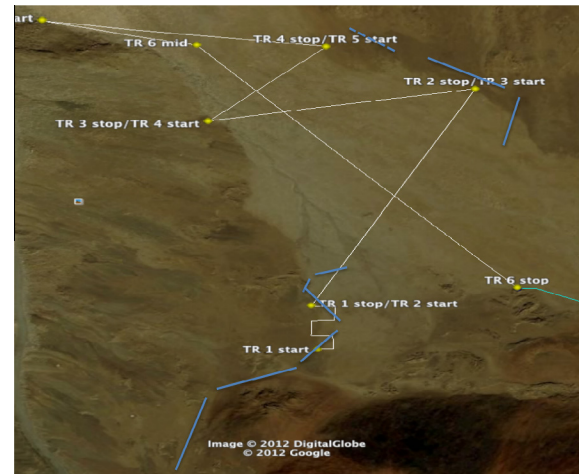


Fig. 4. Pre-mission traverse plan – Day 1.

investigate the subsurface features of Apollo Valley. The 2012 MMAMA team conducted the first known GPR science investigation of Apollo Valley, collecting approximately 4 km of data lines. The GPR used during this field test was a commercially available Geophysical Survey Systems, Inc. monostatic radar unit. Both a 400 MHz and a 200 MHz antenna were deployed in Apollo Valley during this test, however only the 400 MHz unit was attached to the rover on a trailing near-constant-height radar-transparent composite support structure. The 400 MHz antenna has a mass of 5 kg and measures $30 \times 30 \times 17$ cm with a signal penetration up to a maximum of 4 m in depth (the radiated peak power of the antenna is 1.7 W). The 200 MHz antenna has a mass of 20.5 kg and measures $60 \times 60 \times 30$ cm with a signal penetration up to 9 m in depth (the radiated peak power is 3 W.) During this investigation the 200 MHz radar was manually dragged over particular areas of interest requiring either verification of the 400 MHz radar results or requiring deeper penetration than the 400 MHz could provide (Grant et al., 2003, 2004). The different data collected allowed for a direct comparison and evaluation of the reflections of objects, layers and different materials. The GPR team was able to generally determine lava flows under the valley fill material with resolution providing detailed interpretation of subsurface features such as sands, gravels, cinders that sometimes interfingered or stopped against adjacent material (Fig. 5). This suggested multiple episodes of various material movements (whether by wind, water, or mass wasting) and different source directions.

Another instrument carried on a fixed boom system at the front of the rover was the Mössbauer/X-ray Fluorescence (XRF) spectrometer is a MIMOS IIA (Miniaturized Mössbauer Spectrometer) with combined backscatter Mössbauer and XRF capability (Blumers et al., 2010; Klingelhöfer et al., 2011). It should be noted that the MIMOS team was also there on a separate MMAMA investigation with a portable battery/solar power MIMOS II unit. Similar MIMOS II instruments on board the Mars Exploration Rovers (MER) have collected valuable



Fig. 5. Actual GPR traverses – Day 2.

scientific data of the Martian surface for more than seven years (Klingelhöfer et al., 2003, 2004). For the Apollo Valley test however, the robotic-based MIMOS IIA unit was mounted on a forward boom system and was the key scientific instrument for investigating the heavier element samples. The innovative backscatter design allows for the MIMOS IIA instrument to be placed in contact with a rock or soil sample via tilting of the robotic platform, providing *in situ* analysis with no sample preparation. The advanced MIMOS IIA prototype uses new detector technologies and electronic components to significantly increase the sensitivity and performance of the instrument and thus reduces the integration times for instrument sampling to 30 to 90 min per sample.

Similar to the MIMOS II instrument, it measured quantitative Fe-mineralogical composition for one soil sample and eight rocks tested in Apollo Valley (Fig. 6). In addition, both MIMOS II and MIMOS IIA instruments measured 3 common samples for comparison of Mössbauer performance. The MIMOS IIA sample characterization identified several Fe-bearing phases including olivine, pyroxene, ilmenite, magnetite, hematite, basaltic glass, and nanophase ferric oxide (npOx) (Graff et al., 2012).

The panoramic video camera provided a scrollable video showing the area around the entire rover. The camera system is a Lucy-S, a professional-level panoramic capture system for collecting seamless 360° video. The camera head was mounted on the JUNO II cross bar and is approximately 13 cm in diameter, 20 cm tall, and has an approximate mass of 2.5 kg. The video camera head is controlled by a small computer placed inside a weatherproof container mounted on the bed of the JUNO II rover. The video that is recorded is also stored on this computer until manually uploaded to the Internet at the completion of the day's testing. The panoramic video camera acquired numerous video pans for site characterization and planning. The integration of video into the strategic process for rover operations was unique to this test and requires

further evaluation. An example of the video taken during the test can be seen at <http://www.kogeto.com/dotspots/NM5M1Y5OSDH>. The data from the panoramic video verified the usefulness of video for situational awareness and geologic context, and identified a need for improved resolution for science-driven imaging. In this particular investigation, high resolution (2 cm/pixel) was available only for nearby objects; resolution degraded rapidly for objects at a distance. This degradation was extremely noticeable and significantly impaired the team's ability to resolve key distant details or features, a critical lack for strategic planning purposes. The implication is that the parameters of the imaging system of any rover that has a science-driven set of objectives must be determined as part of the design and implementation process, with science in the loop. Basic issues such as resolution, color/multispectral and video capabilities all directly affect what science results are possible, and thus, whether science objectives can be met.

Another instrument used in the 2012 MMAMA testing was the VAPoR/MeSH instrument. The VAPoR/MeSH instrument is a pyrolysis mass spectrometer supported by a crusher/sieve apparatus. During operation, a sample is placed in MeSH, which crushes and sieves the sample to 150 microns. The crushed sample is subsequently transferred to a sample holder and placed inside the VAPoR oven on a rotating tray. The rotating tray is then placed under the mass spectrometer and the sample is raised to come in contact with a small pressure dome. This small dome creates a vacuum tight seal and the system is pumped down to vacuum, typically to the 10^{-7} torr region. The sample is then heated to 1000 °C at a rate of 20 °C/minute and the gases that evolve from the sample are then analyzed by the mass spectrometer (ten Kate et al., 2010; Glavin et al., 2012). The instrument can help indicate the presence of clay minerals or carbonates, but can also help identify which mineral is present based on the evolution temperature of H₂O and CO₂. Furthermore, VAPoR can show the presence of organic compounds that are not detectable by most contact instruments.

Fig. 7 shows data from the sample collected at location VAPoR3-20120716. This figure is used to illustrate the capabilities of the VAPoR/MeSH instrument. VAPoR measures a range of evolving gases, which include inorganic species, such as CO₂, H₂O, SO₂, and CO/N₂. Currently, VAPoR is not matured enough to be able to distinguish between CO and N₂ therefore they are plotted together and contributions of either gas are derived from presence of CO₂ and its spectral features and the additional spectral lines of N₂. Water evolves at different temperatures, depending on its phase. Adsorbed atmospheric water evolves between 100 and 200 °C, while structural water, present in hydrated minerals like clays, evolves at temperatures >300 °C, where different H₂O evolution temperatures are characteristic for specific clay minerals. CO₂ can evolve from different sources, for example as trapped gases in inclusion, but also from carbonates that break down due to heating. Fig. 6, left plot, shows the evolution temperatures of the four species mentioned before. The H₂O shown

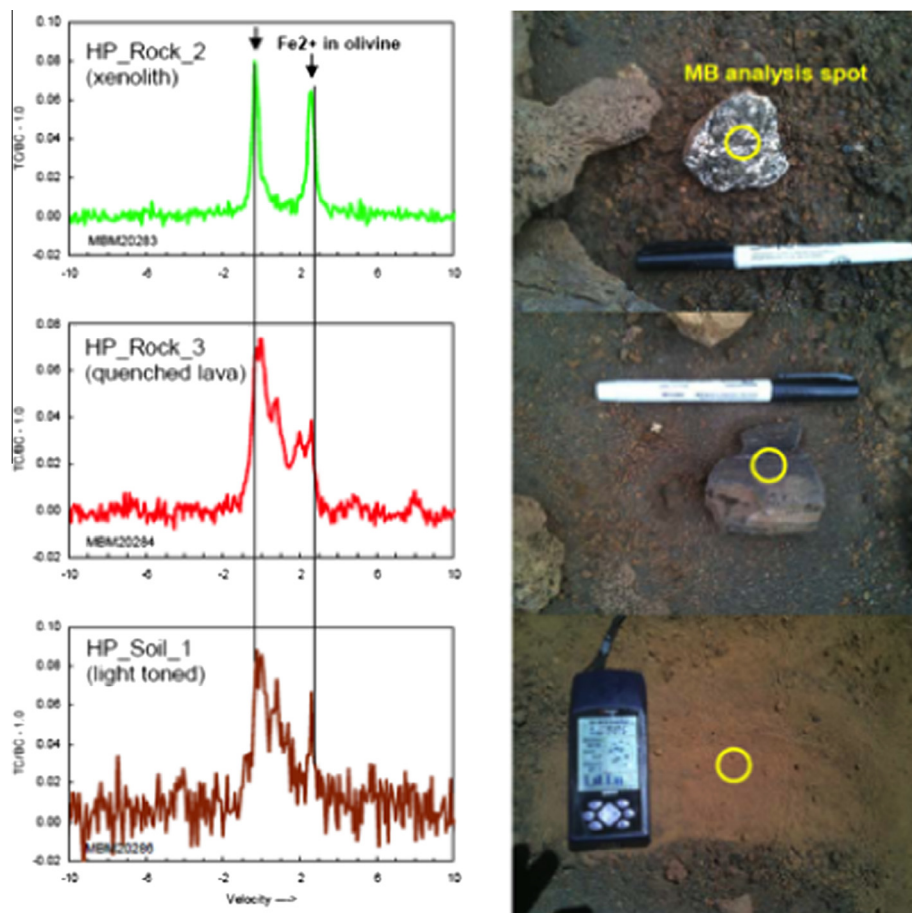


Fig. 6. Representative MIMOS IIA data.

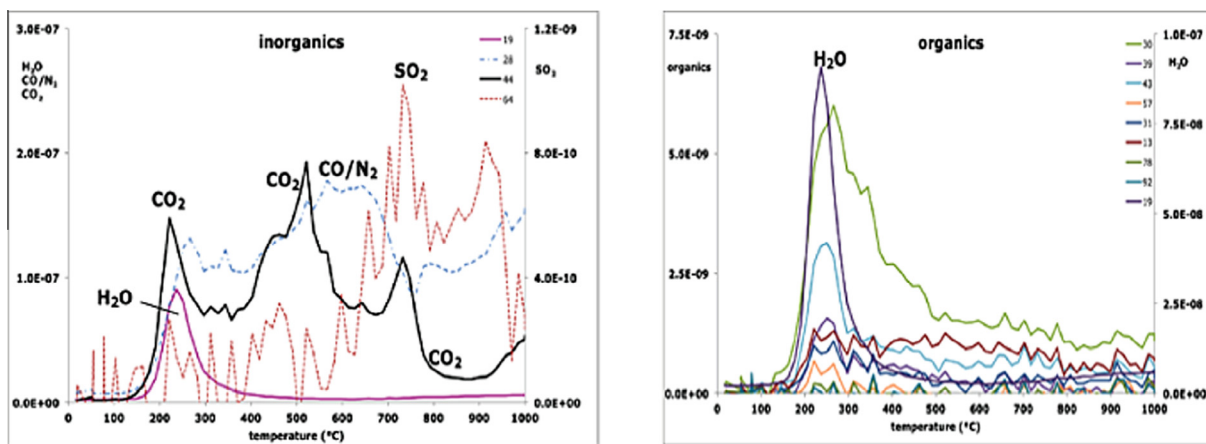


Fig. 7. Representative VAPoR/MeSH data.

is most likely adsorbed atmospheric water. The lack of any higher H₂O peaks points towards the lack of any water bearing minerals, such as clays. CO₂ shows three clear peaks, one at 200 °C co-evolving with H₂O, one around 520 °C, and one around 750 °C. The latter two are indicative of the presence of carbonates, probably magnesite and calcite, although additional contextual information is needed to confirm this hypothesis. The first peak will be

discussed below. SO₂ evolves at two high temperature ranges. The presence of SO₂ in this environment is not surprising as this is a volcano, however, due to lack of contextual data it is at this stage not possible to attribute these peaks to certain minerals or the presence of adsorbed gaseous SO₂. The CO/N₂ plot shows a similar pattern as does the CO₂ plot, apart from a wider band between 500 and 650 °C.

Fig. 7, right pane, shows the organic fragments evolving from the same sample. These organic fragments did all evolve at the same time as the water, around 200 °C. This leads to the assumption that the organics and the water are somehow related. This relation may include the presence of CO₂ at the same temperature. Several hypotheses can be posed here. One hypothesis is the presence of organics from exhaust-gases adsorbed from the passing traffic on the access road to the top of the volcano. The mobilization of the atmospheric water at 200 °C may have helped mobilizing these compounds, driving them off at the same time. The CO₂ could be an additional reaction product of hydrocarbons and water being heated at the same time. Another hypothesis is the presence of small microbial communities that are decomposed at 200 °C. This hypothesis does address the presence of the organic fragments, the CO₂, and H₂O. It could even be an explanation of the CO/N₂ band between 500 and 650 °C, which could have been caused by further decomposition of the microbial remains, releasing N₂. This hypothesis is not further verifiable, because no instrument to test of biological activity was part of the instrument package and there is a lack of temperature related evolved gas analysis data of microbes, in contrast to high temperature pyrolysis data.

4. Lessons learned

Several key lessons learned in this field simulation are applicable to future planetary surface explorations. These include:

A rigorous test is needed of the science 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.

The GPR proved to be a key instrument in the field test and its use should be expanded in future tests. Initial pre-mission discussions with individuals familiar with the Apollo Valley indicated the radar wave penetration may be limited to only 10–15 cm due to the ground water content so there was limited planning for the instrument. Actual test results showed radar penetration to 4 m and occasionally as deep as 6 m thus providing key information of the valley underground structure.

The rover platform tilt capability was adequate for this field simulation, however, this limits MIMOS IIA target selection to essentially horizontal rock and soil surfaces. Additional movement capability is necessary to allow placement and contact with more vertical surfaces as well.

The parameters of an imaging system of any science-objective rover must be determined as an early part of the design and implementation process, with science in the loop. Basic issues such as resolution, color/multispectral and video capabilities all directly affect what science results are possible, and thus, whether even minimum science objectives can be met with the proposed system. Interactive and often evaluations for the specific mission and

equipment need to be done to determine the optimum performance versus cost results for the system. Finally, as seen during the field test and as demonstrated on the Curiosity rover on Mars, additional camera and/or sensor views are necessary for obstacle avoidance, site/sample selection and situational awareness of remote operations.

Not applicable to future planetary surface exploration, but key to future tests on Mauna Kea are cultural constraints. These were not discussed earlier, however, these constraints initially presented several potential significant impacts on proposed operations in Apollo Valley. The people of Hawai'i are understandably very protective of their historic cultural activities on Mauna Kea. Early understanding of these unique constraints involving restricted paths and potential historic points of interest significantly modified the initial traverse plans. In addition, on more than one occasion, a local geologist and a local anthropologist also accompanied the rover team in the field. Future investigations must ensure they are aware of these constraints and can accommodate the additional personnel in the field.

5. Summary

This multi-instrument investigation allowed scientists to utilize the tremendous data stream provided by real time or near-real time operations to inform both the short-term (tactical) and long-term (strategic) goals of a semiautonomous rover mission. Specifically, the operational strategy as employed (rather than as originally proposed) may be an ideal paradigm for future rover missions, as it allowed for maximum rover usage and data acquisition time, while avoiding overwhelming either the science team or the scientists on the ground. 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. 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.

The initial investigation in Apollo Valley was targeted to address the origin of the valley (using the available science instruments) with two potential hypotheses to be tested: the deposits were the result of (1) an ancient lava flow from above; or (2) the release of an ice dam at the head of the valley. Subsequent discussion also highlighted two additional possible origins: lava flow over ice or lava flow over ice-rich permafrost. GPR, VAPoR/MeSH and MIMOS IIA data were re-reviewed to examine these additional origin possibilities. Review of the GPR, VAPoR/MeSH and MIMOS IIA data showed no results indicative of lava flow over ice or permafrost. In addition, photographic review of the valley area traversed did not show any immediate

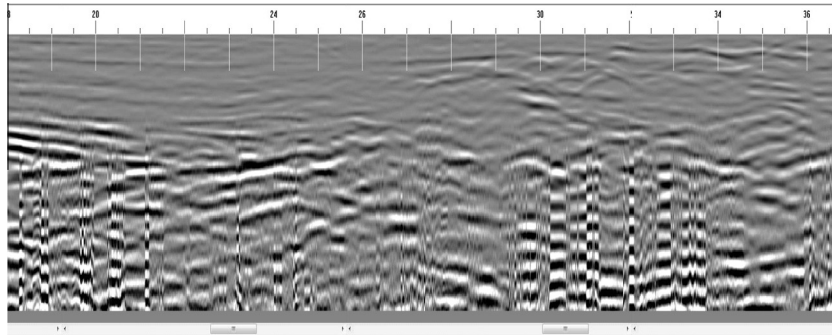


Fig. 8. Representative GPR data.

indications of phreatomagmatic eruptions (Starostin et al., 2005; Lescinsky and Fink, 1996), dikes or sills, nor signs of rootless pyroclastic deposits and cones (pseudocrater) features (Smellie and Chapman, 2003). Geomorphology was most consistent with the ice dam hypothesis. However, GPR data showed indications the valley has a complex geologic history with intermingled multiple layers of cinders, sands and gravels suggesting many episodes of material movement from different directions (Fig. 8).

Future investigations to resolve the valley origin could include a more detailed review of the valley terrain for dikes and sills and an examination for the start of fretted terrain, with a deeper and more extensive GPR examination looking for evidence of a more widespread lineated valley fill. Additionally, investigating for potential depositional features laid down by any potential ice flow in the area circled in Fig. 8 would be appropriate. Modeling of a thick lava flow over a thin layer of loose tephra with 25% ice content may also provide additional indications of the origin.

Due to the combination of weather conditions and recent eruptions (<5000 years ago) there remains a possibility that Apollo Valley on Mauna Kea represents a terrestrial analog of a Martian lava flow over ice or permafrost, currently covered by reworked ice- or water-transported materials. Additional investigations of the types listed above would provide the necessary data to identify the specific origin.

6. Conclusions

The robot-based science investigation provided a representative analog robotic science mission to the NASA Science Mission Directorate. Specifically, the test was successful with a small team performing significant science while having only a minimal number of personnel in the field. This analog field test showed that the geochemical and geophysical results pointed to the probability that valley was of a burst ice-dam origin, however, further investigation is needed to eliminate the other origin theories of lava flow over ice or lava flow over permafrost.

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