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The 2016 UK Space Agency Mars Utah Rover Field Investigation (MURFI)

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Abstract

The 2016 Mars Utah Rover Field Investigation (MURFI) was a Mars rover field trial run by the UK Space Agency in association with the Canadian Space Agency's 2015/2016 Mars Sample Return Analogue Deployment mission. MURFI had over 50 participants from 15 different institutions around the UK and abroad. The objectives of MURFI were to develop experience and leadership within the UK in running future rover field trials; to prepare the UK planetary community for involvement in the European Space Agency/Roscosmos ExoMars 2020 rover mission; and to assess how ExoMars operations may differ from previous rover missions. Hence, the wider MURFI trial included a ten-day (or ten-'sol') ExoMars rover-like simulation. This comprised an operations team and control center in the UK, and a rover platform in Utah, equipped with instruments to emulate the ExoMars rovers remote sensing and analytical suite. The operations team operated in 'blind mode', where the only available data came from the rover instruments, and daily tactical planning was performed under strict time constraints to simulate real communications windows. The designated science goal of the MURFI ExoMars rover-like simulation was to locate in-situ bedrock, at a site suitable for sub-surface core-sampling, in order to detect signs of ancient life. Prior to "landing", the only information available to the operations team were Mars-equivalent satellite remote sensing data, which were used for both geologic and hazard (e.g., slopes, loose soil) characterization of the area. During each sol of the mission, the operations team sent driving instructions and imaging/analysis targeting commands, which were then enacted by the field team and rover-controllers in Utah. During the ten-sol mission, the rover drove over 100 m and obtained hundreds of images and supporting observations, allowing the operations team to build up geologic hypotheses

for the local area and select possible drilling locations. On sol 9, the team obtained a subsurface core sample that was then analyzed by the Raman spectrometer. Following the conclusion of the ExoMars-like component of MURFI, the operations and field team came together to evaluate the successes and failures of the mission, and discuss lessons learnt for ExoMars rover and future field trials. Key outcomes relevant to ExoMars rover included a key recognition of the importance of field trials for (i) understanding how to operate the ExoMars rover instruments as a suite, (ii) building an operations planning team that can work well together under strict time-limited pressure, (iii) developing new processes and workflows relevant to the ExoMars rover, (iv) understanding the limits and benefits of satellite mapping and (v) practicing efficient geological interpretation of outcrops and landscapes from rover-based data, by comparing the outcomes of the simulated mission with post-trial, in-situ field observations. In addition, MURFI was perceived by all who participated as a vital learning experience, especially for early and mid-career members of the team, and also demonstrated the UK capability of implementing a large rover field trial. The lessons learnt from MURFI are therefore relevant both to ExoMars rover, and to future rover field trials.

1. Introduction

The Mars Utah Rover Field Investigation "MURFI 2016" was a Mars rover field analogue investigation run by the UK Space Agency (UK SA) in collaboration with the Canadian Space Agency (CSA). MURFI 2016 was facilitated and made possible by the CSA's 2015/2016 Mars Sample Return Analogue Deployment mission (see Osinski et al., "Mars Sample Return Analogue Deployment (MSRAD) Overview", this issue, submitted). MURFI 2016 took place between 22nd October and 13th November 2016 and consisted of a field team including an instrumented rover platform (Figure 1), at a field site near Hanksville (Utah, USA; Figure 2), and an 'operations Team' based in the Mission Control Centre (MOC) at the Harwell Campus near Oxford in the UK. A key aspect of the investigation was a short 10-sol (a sol is a martian day, simulated or otherwise) ExoMars rover-like mission, which aimed to simulate (within time and budget constraints) the rover payload, tactical planning and operations of the ExoMars rover mission, a European Space Agency and Roscosmos rover mission (ESA) to Mars that will launch in 2020.

Figure 1. The MURFI 2016 rover: a 'Q14' platform with PanCam emulator 'AUPE' (Harris et al., 2015) attached. The large "eyes" contain the filter wheels for the PanCam emulator. Field team for scale. Image credit: Mike Curtis-Rouse

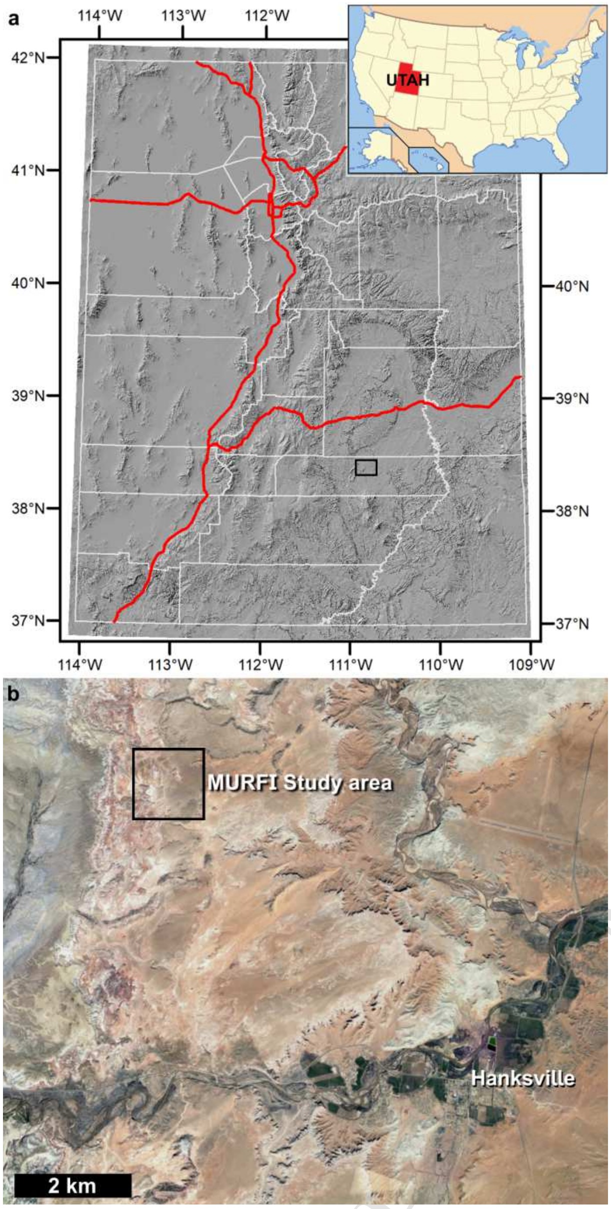

Figure 2. Location of study area. a) Utah state map (above) showing major interstate roads (red) and county boundaries (white) overlain on a 100 m/pixel topographic hillshade map. The black box shows the location of the close-up view in (b). b) Close-up view showing MURFI study area as black box and location of nearest town (Hanksville). Image credit: Utah AGRC/GoogleEarth/Wikipedia.

1.1 MURFI investigation objectives

MURFI 2016 had three primary objectives: (i) to develop the logistical and leadership experience in running field trials within the UK; (ii) to provide members of the Mars science community (especially early career scientists) with rover operations experience, and hence to build expertise that could be used in the 2020 ExoMars rover mission (Vago et al., 2017), or other future rover missions, and (iii) by running an ExoMars rover-like mission simulation to explore how operations for the ExoMars rover (which aims to drill up to 2 m into the subsurface), might differ from past experiences from, for example, the twin Mars Exploration Rovers (MERs; e.g., Crisp et al., 2003) and the Mars Science Laboratory (MSL; e.g., Grotzinger et al., 2012).

Because MURFI 2016 was the first UK SA led Mars rover analogue trial, it was crucial to learn how UK systems and institutions could best implement rover trials in general. This included aspects of planning, logistics, field safety, MOC setup and support, communications, personnel management and science team development. Whilst the starting points for many aspects were based on past experience from previous trials (e.g., Dupuis et al., 2016; Moores et al., 2012; Osinski et al., 2017; Woods and Shaw, 2014) and rover operations experience within the team (mainly on MSL), the focus was on 'learning through experience'.

Although the UK has a well-developed planetary science community, there have been no successful UK-led or ESA-led planetary rover or lander missions. The most recent UK-led mission, Beagle2 (e.g., Pullan et al., 2004) failed to operate, although recent images suggest it at least landed safely on the surface (Bridges et al., 2017a). Hence, there have been few opportunities for UK scientists, especially for early career scientists, to be involved in planetary surface mission operations. To some extent, this also applies to many European planetary scientists. MURFI 2016 was therefore partly designed to provide rover tactical operations experience for members of the UK planetary science community and a learning experience that would be useful in the context of the ExoMars rover, into which the UK has made significant scientific, industrial, and financial investment.

The ExoMars rover is a partnership between the European Space Agency (ESA) and the Russian Roscosmos agency. The mission will launch in 2020 and has the explicit goal of looking for signs of past life (Vago et al., 2017, 2015). It has a mass of 310 kg and is expected to travel several kilometers during its seven-month mission (Vago et al., 2017). The ExoMars rover drill has the capability of sampling from both outcrops and the subsurface, with a maximum reach (i.e. depth) of 2 m. The subsurface sampling capability means that material that has escaped alteration by the martian surface environment (e.g., Kminek and Bada, 2006; Parnell et al., 2007; Summons et al., 2011) can be sampled, providing the best chance to sample well-preserved chemical biosignatures for analysis. The ExoMars rover (Vago et al., 2017) will be different to the preceding MSL and MER rover missions in that it has the capability for the deepest sub-surface sampling of any Mars rover to date. However, a trade-off of this drill capability is the lack of an instrumented robotic arm. This means that any information relevant to understanding the geological context of the landing site must be obtained from stand-off instruments (at least, up to the point at which a drill sample is obtained and ingested into the rover for in-situ analysis). Having the best possible understanding of the geology of the landing site is vital for making the best decisions about where to drill, as drilling is potentially a time consuming and hazardous procedure.

Testing how the ExoMars instruments work together to characterise the landing site at various scales can only be done by field testing of the system as a whole, rather than by utilising instruments individually. Moreover, by using a rover-based instrument suite, an estimate of the number of individual rover-driving commands, or sol-to-sol manoeuvres, necessary to implement different studies could be made. This was the key reason for using an instrumented rover platform, rather than deploying the MURFI instruments independently.

1.2 MURFI investigation overview

To meet the objectives set out above, certain 'philosophical' decisions were made. Firstly, because of the focus on gaining operations experience, it was decided to simulate a rover mission 'as a whole', rather than testing specific instruments or methods. Therefore, the investigation included an 'ExoMars rover-like' sub-mission, with the instruments and rover capabilities chosen based on (i) availability in the limited time frame available for MURFI planning (there was only a few months between the confirmation that the trial would proceed and the date we needed to be in the field), and (ii) being as close as possible to those of the ESA ExoMars 2020 rover (Vago et al., 2017). This 'ExoMars rover-like' mission therefore became the primary focus of the whole MURFI investigation. With reference to the ExoMars rover surface reference mission (Vago et al., 2017) MURFI simulated, at a rather accelerated pace, a possible early ~ 10 sols of the ExoMars rover operations, including setting a strategic target to approach based on observations, characterisation of local outcrops to advance scientific hypotheses, and finally, characterisation and selection of a specific drill site. In addition to the tactical operations associated with these sols of activity, the MURFI team were also tasked with performing a landing site analysis using Mars-equivalent remote sensing data, in order to set out possible strategic targets for the mission prior to 'landing'. The team also performed localisation – a key daily task during MSL and MER operations – of the 'sol 0' location of the rover, based on the first image data returned by the rover and the pre-existing satellite remote sensing data.

Secondly, the ExoMars-like mission part of MURFI 2016 was run as a "blind" mission from the perspective of the MOC science team. The team were not permitted to see any information other than Mars-equivalent remote sensing data, or data returned by the rover itself. For the MOC team, this also meant blocking the social media accounts of the field team members, disallowing access to online remote sensing services, and requesting MOC team members to do no background research into the geology of the field site. Those members of the team with pre-existing knowledge of the site were chosen to form the field team, supporting the operations in Utah.

Thirdly, for the ExoMars-like mission, tactical operations were performed on a daily basis, utilising the seven hour time difference between the UK (UTC) and western USA Utah (UTC-7 hrs) to allow daily uplink cycles to be simulated in a similar way to that of a real rover mission. Each day, the MOC team received data from the rover from the previous sol's activities at around 08:00 UK time. To simulate real tactical operations, they were allowed a limited period to analyze the data returned and to create the plan for that sol's commands, with upload time at 13:00 UK time. This plan was then transmitted to the field site via an ftp (file transfer protocol) link, such that the commands were available for the field team to download and begin to implement as soon as there was enough daylight and sufficiently warm temperatures for activity to commence in the field. This allowed the field team and the MOC team to work asynchronously, making the best use of time while still allowing normal working patterns for both teams. Operations were not shifted each day to simulate the difference between 'Mars-time' and 'Earth-time', as this was felt to be a level of simulation that was not required to meet the MURFI objectives, and would complicate timings in the field.

Finally, the MURFI ExoMars rover-like mission itself was given a science goal for the team to meet within the 10 sol time limit. Mirroring the real ExoMars rover science goal "*to search for signs of past and present life on Mars*" (Vago et al., 2017), the MURFI ExoMars rover-like mission goal, was: *"to locate suitable areas in the field site that have sedimentary geology indicative of an ancient habitable environment, then to drill into the surface to* *acquire a sample from those materials and, finally, to examine this sample with the analytical instruments available onboard the rover.*" Key elements of the mission goal were (i) the necessity to sample 'ancient' environments, which was interpreted by the team to mean sampling in-situ bedrock within the stratigraphy, rather than loose surficial fines of poorly-known provenance; (ii) the requirement to drill, which also meant that the drill site would have to be well characterised prior to drilling; and (iii) the interpretation of 'habitable sedimentary geology' to mean deposits laid down in water in a low-energy environment such as a lake or slow moving water –given the MURFI field site, this meant looking for fine-grained or clay-rich materials within the stratigraphy.

2. Field site and Mission Operations Center (MOC)

2.1 Field site

The Utah field site (Figure 2) was chosen based on the collaboration with the CSA and its Mars-like local geology. It was used by the CSA in 2015 for Mars Rover trials (Dupuis et al., 2016), and in 2016, several teams (see, for example, Hipkin et al., 2017) used the site, each with their own designated working areas. The description that follows provides an overview of the geology of the site, but to maintain the integrity of the trial, this information was not allowed to be seen by the MURFI MOC team prior to the ExoMars rover-like mission.

The field site is in the Canyonlands section of the Colorado plateau, a geologically stable terrain that represents a crustal block of relatively undeformed rock covering an area of 337,000 km^2. The plateau is bounded by the Basin and Range province to the west and the Uintas Mountains and Rocky Mountains to the northeast and east. To the south west, the plateau is bounded by the Mogollon highlands. The stratigraphy of central Utah is dominated by Mesozoic rocks (with large inliers of Permian-age strata), which represent a predominantly continental succession, with several significant marine incursions (Stokes, 1986). The area local to Hanksville consists of Jurassic- to Cretaceous-age strata, with dips < 10°, recording continental conditions during the Jurassic. The field study site is within the Late-Jurassic (Kimmeridgian) Morrison Formation. This Formation is divided into three Members: The Tidwell Member, which represents lakes and mudflats; The Saltwash Member, which represents coarse alluvial sediments (average 63% net sand), and the Brushy Basin Member, which represents finer-grained (average 10% net sand) alluvial deposits (Heller et al., 2015). The study site was located solely within, but near the base of, the Brushy Basin Member, which locally has an exposed thickness of ~100 m.

Outwardly, the Brushy Basin Member is predominantly slope-forming, characterised by weathered interlayered and interfingering white and red-brown soil profiles which form rilled slopes which weather and erode to angles up to ~30 degrees. In flat-lying areas, these weathered soil profiles are overlain by superficial pebble-lags of more resistant material, such as jasper and quartz derived from the Morrison and other local formations. The soil profiles reflect the underlying sediments. The red-brown units comprise very fine-sands, and silt-grade sediments that are well cemented, and commonly contain climbing-ripple strata and horizontal laminations. The white units are medium-grained sandstones which are well sorted and poorly cemented.

In the study area, slope-forming sections of outcrop can be capped by cliff-forming units between 2-5 m thick. These units are characterized by cross-bedded sandstones and angular matrix-supported conglomerates, within channelized fluvial architectural components. When viewed in planform, these cliff-forming cap rocks have high aspectratios (widths of 20-50 m, and lengths of hundreds of metres to kilometres) and are curvilinear. These features have been described as inverted channels and are documented throughout the Morrison Formation (Clarke and Stoker, 2011; Williams et al., 2009, 2007).

Light-colored, very poorly sorted, structureless layers of bentonitic volcanic ash, 5 – 20 cm thick can be found at various levels in the silty flood plain deposits and are interpreted as airfall deposits due to the lack of laminations within the layers. They have U-Pb zircon ages of 149 Ma (Kowalis et al., 1998; Kowallis et al., 2007). The presence of clays is evidenced by the shrink-swell weathering of the mud- to silt-grade material, as well as the presence of well-developed desiccation cracks in the present-day ground surface. These clays might have been sourced from the volcanic ash layers (Heller et al., 2015). The Morrison Formation contains abundant macroscale ‘biosignatures’ in the form of fossils and ichnofossils. Overall, the palaeoenvironment of the Brushy Basin Member is characterised as the distal part of a distributive alluvial fan system that drained toward the north-east from the system’s fan apex on the Mogollon Highlands (Owen et al., 2015).

Figure 3. Characteristic sedimentary facies encountered during field reconnaissance of the MURFI study area. a) Numerous small outcrops of silty to very fine sand (red/purple in color) were common, particularly in areas of reddish soil. b) Fine- to medium-grained quartz-rich sandstone found cropping out from lighter colored soil. Both the red silt-to-very fine sand and white fine-medium sands were highly fractured and showed onion skin weathering or cracked textures. The white sands were often trough cross laminated, and found in isolated, elongated exposures which could be interpreted as barforms, fining to the northwest. c) Cross-bedded pebbly conglomerate from the upper platform of 'Big Mesa' – an inverted fluvial channel section in the MURFI study area. d) Texture of the pebbly conglomerate in c) showing the very poor sorting and polymictic composition, with sub-rounded to

sub-angular clasts within a quartz-rich matrix. The smallest black and white divisions of the scale bar are 1 cm in each photograph. Image credit: Robert Barnes and Steven Banham.

2.2 Field logistics

The MURFI base camp was intentionally co-located close to the area of science operations for several reasons: (i) to reduce transit time between accommodation and working areas, (ii) to ensure that equipment deployed was secured at all hours of the day, and (iii) to facilitate collaboration with the other agencies who were working nearby. The basecamp was divided into three areas; sleeping, food preparation and storage, and operations (Figure 4).

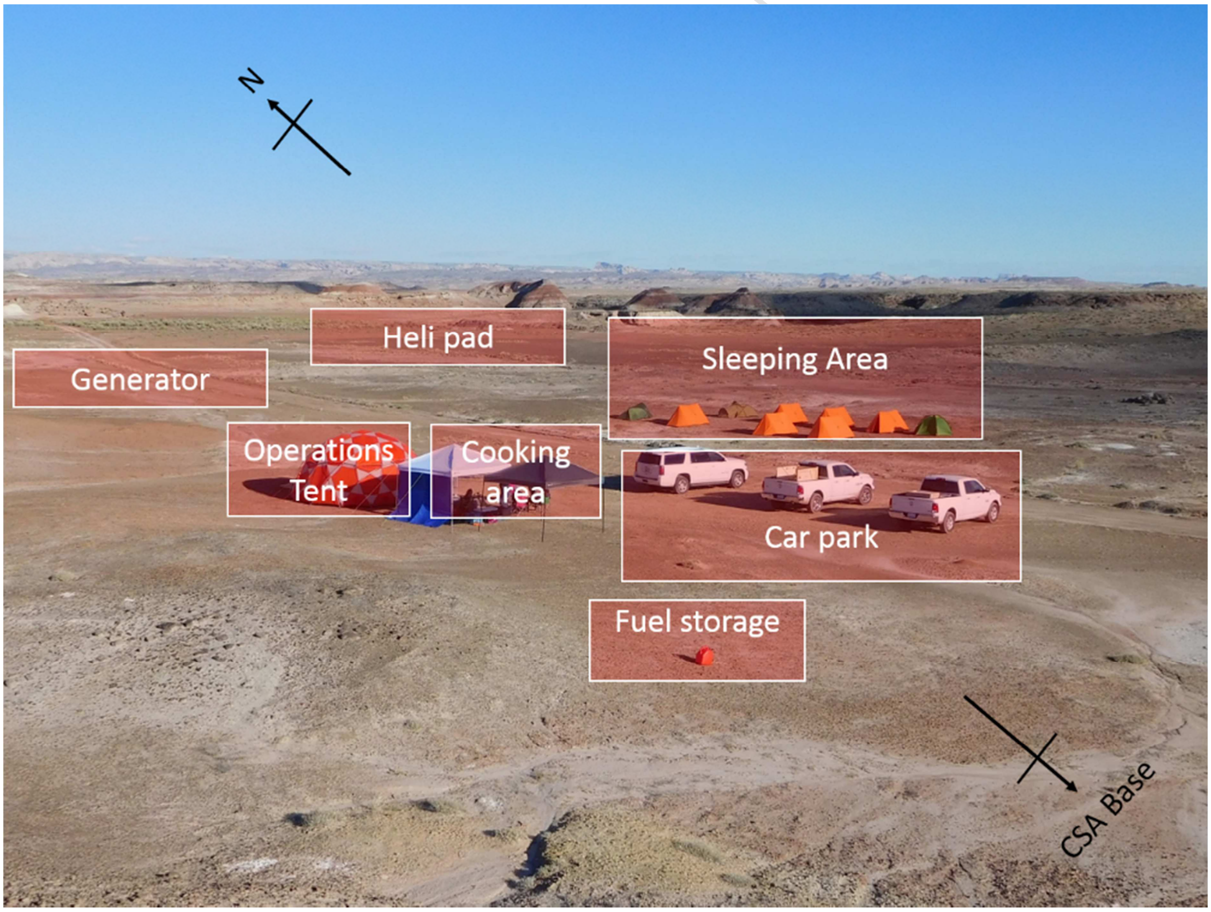

Figure 4. MURFI basecamp showing key locations. Image credit: Mike Curtis-Rouse

The base camp was designed to accommodate a maximum of 16 people, this being based not on the number of sleeping tents deployable (essentially unlimited) but on the capability of the local infrastructure to support such numbers. The base camp command tent provided a variety of different functions: (i) science operations including command and control of the platform, (ii) operational planning for the mission and as a meeting space, (iii) social and eating space for the team, (iv) storage of equipment, including the rover platform and instruments, and (v) acting as an emergency shelter in the event of extreme weather.

Local electrical power was provided by a single phase gasoline generator which was situated 100 m from the basecamp. This was used to provide lighting, charge batteries and laptops, and heat water as needed. Charging of the platform batteries was performed at the closest motel (~ 30 min drive), where two rooms were rented to provide this function, and additionally to give people the opportunity to shower and wash on a rotating basis. The motel rooms were also used to provide secure storage of complimentary equipment that was not kept at the field site, and again offer alternative shelter in extreme weather.

Communications at the field site were split into three types: local cell phones, where signal permitted, satellite phones which were hired in Salt Lake City to provide emergency communications at all times, and finally a share of the CSA satellite uplink for data transfer to and from the UK.

A variety of equipment was procured and disseminated to personnel on arrival in Utah; this included basic sleeping equipment (e.g. cold weather sleeping bags, inflatable mats and pillows), and additionally emergency equipment including first aid kits, whistles, compasses and head-torches. This kit ensured that all personnel had the basic necessities to survive should conditions change.

Prior to the mission commencing, a comprehensive risk assessment was conducted to cover all eventualities, this included an evaluation of the potential medical situations which could arise, emergency, as well as routine. The general strategy in the event of a critical medical situation, was to evacuate the respective personnel to a primary medical facility e.g. Price General Hospital by ground vehicle. This thus influenced the type of vehicle selected and numbers available to the mission; all were four wheel drive and by necessity off-road capable. There would always be one more vehicle than was needed and the spare vehicle would always be fueled and located at the base camp. In the event of a critical medical situation at night or during adverse weather e.g. monsoon, then a designated heli pad was marked out adjacent to the base camp and illumination systems available close by to assist landing. The base camp GPS coordinates were logged with the local Bureau of Land Management, the local state police and the venom safety unit (in the event that evacuation of personnel due to snake bite was needed).

2.3 The Rover Mission Operations Centre (MOC)

The MOC was located at the Satellite Applications Catapult's operations center at Harwell, United Kingdom. The MOC contained eight computer workstations, each with space for two workers, configured in a two-tiered 'control room' style, as well as several breakout rooms. The main focus of the MOC was a large multi-panel video wall, comprising 18 large HD monitors (Figure 5). Multiple outputs from the MOC workstations could be presented at various sizes on the video wall, allowing easy comparison of the different datasets. In addition, the very high specification PC used to drive the video wall could be used directly to allow the display of datasets (e.g. remote sensing products) across the whole screen in very high definition.

All workstations were linked using a local area network, with shared network folders used as document stores, data stores and file-sharing working space. Also, an external ftp site, visible both from the MOC and by the field team, was used to receive incoming data from the field, and to communicate with the field team. This ftp site was also used to back-up all data produced by the MOC team each night after operations.

Figure 5. MOC setup. a) The large video wall. The desktop view of one workstation could be stretched over the whole wall, as here, or several workstation desktops could be split across the screen 'on the fly'. b) The tiered workstations for the SWT stations. Image credit: Andrew Griffiths.

3. Field equipment

3.1 Rover platform

The rover platform comprised a 'Q14' robot from Advanced Robotics Concepts (ARC; Figure 1). The platform, together with in-field engineering support was provided by the Oxford Robotics Institute. With active 4-wheel steering and drive, and a passive dynamic suspension system, the rover provides a reasonable payload capacity and good mobility over a range of terrains within a relatively low mass package, thus simplifying deployment of the rover to the field location. The rover mass without payload is approximately 30kg and it can carry up to 40kg of payload. The MURFI rover was not intended to match the ExoMars rover's capabilities, being smaller and four – rather than six – wheeled, but instead to provide a suitable mobility platform to carry out the trial.

The primary navigation sensor comprised a 'Point Grey Bumblebee XB3' stereo camera mounted mid-way up the central rover mast. The platform was also fitted with a Lord Microstrain 3-DM-GX4-45 inertial sensor, which was primarily utilized for automatic logging and reporting of the platform orientation during imaging sessions. The 4-wheel steering capability enabled MOC team path planning to be simplified to construction of the paths as a series of linear drives linked by point turns. 4-wheel steering also means that wheel-slip is much reduced compared with simpler differential steering platforms, reducing the impact of the rover on the terrain and minimizing track deposition.

3.2 Rover Instrumentation

The Pasteur payload (Vago et al., 2017)of the ExoMars Rover consists of 11 panoramic, contact, and analytical instruments. Of this suite, four were emulated for MURFI and were either integrated onto the rover platform, or available as standalone instruments that could be operated in the same way, as perceived by the MOC team, as if integrated into the rover. The instruments emulated were the stereo-panoramic/high resolution camera imaging suite 'PanCam' (Coates et al., 2017), the infrared spectroscopy instrument, 'ISEM' (Infrared Spectrometer for ExoMars; Korablev et al., 2017), the close-up imaging camera, 'CLUPI' (CLose UP Imager; Josset et al., 2017) and the Raman spectroscopy system (Rull et al., 2017) that is part of the ExoMars rover's Analytical Laboratory Drawer. In addition, the MURFI investigation could simulate ExoMars's drill capabilities.

For PanCam emulation, the Aberystwyth University PanCam Emulator (AUPE; Harris et al., 2015) was used, mast-mounted on a pan-tilt unit on the rover mast. AUPE allows stereo capture across a suite of multispectral filters (Cousins et al., 2012) and high resolution imaging of distant features using the High Resolution Camera (HRC; for MURFI this was a single panchromatic sensor; but for ExoMars this will be a color Bayer sensor). AUPE is an assembly of off-the-shelf, commercial scientific cameras, matching closely the specifications of PanCam, and consists of the Wide Angle Cameras (WACs) and the HRC. The WACs provided the primary means for obtaining color panoramas, and provided stereo-pair images for 3D reconstruction and visualization of the rover environment via the PRoViDe pipeline and PRo3D software (Barnes et al., 2017). For multispectral imaging, a MacBeth ColorChecker was included in scenes for calibrating images to reflectance units at the MOC. The narrow-angle optics of the HRC are coaligned with the right WAC, such that high resolution images may be obtained in subframes, via control of the pan-tilt unit. In addition to PanCam, the ExoMars rover includes panchromatic navigation cameras to collect black and white images and image mosaics. This capability was simulated on MURFI using the

AUPE WACs, operating using a panchromatic filter. This allowed the MOC team to request images at a lower data cost than the RGB triplet images of AUPE.

The Infrared Spectrometer for ExoMars (Korablev et al., 2017) was emulated with an ASD Inc. FieldSpec3, with 1° field of view fore-optics, mounted on the AUPE optical bench. This allowed near-infrared reflectance spectra to be obtained for mineral identification. Whilst ISEM covers the infrared spectrum at 1.1 - 3.3 μm, with 3.3-28 nm resolution, the FieldSpec3 infrared portable spectroradiometer spans visible and a smaller portion of infrared, at 0.35 - 2.5 μm, with 10 nm resolution above 1 μm. During MURFI, we did not seek to match the wavelength range of ISEM exactly – we did not truncate the spectrum below 1.1 μm prior to transmission to the MOC, for example – but this could be put in place for future trials. A Spectralon target was used for in situ calibration, such that measurements were recorded in units of surface reflectance, rather than radiometrically.

For CLUPI emulation, a Sigma SD15 DSLR camera with a macro lens was used to provide high-resolution color images comparable to the CLUPI instrument. The Sigma SD15 uses the same 2652x1768 pixel Foveon X3 z-stacking color detector as the CLUPI flight instrument, with a matching 11.9°x8.0° FoV macro lens. The drill body, to which CLUPI will be attached on the ExoMars rover, was not included in the MURFI payload, so the CLUPI emulator was attached to an articulated Photo Variable Friction Arm so that it could either be clamped to the front of the rover platform, or used as a standalone instrument. In either case, the operation of the arm was restricted to match the viewing geometries available to CLUPI, such that orientation of the camera was primarily controlled by the movement of the rover.

To simulate the ExoMars rover's ability to drill to depths of up to 2 m and obtain a core sample, the field team were equipped with a hand-held core drill and hand tools to extract an ExoMars-like core from a depth specified by the MOC team. This allowed sub-surface samples to be extracted and then analyzed by instruments representing those in the Analytical Laboratory Drawer of the ExoMars rover (Vago et al., 2017).

Of the analytical instruments in the ExoMars rover Pasteur suite, only the Raman Laser Spectrometer (“RLS”; Rull et al., 2017) was emulated in MURFI. Two Raman instruments were used: a portable ‘Deltanu Rockhound’ spectrometer and a benchtop Raman Laser Spectrometer prototype, developed by the University of Leicester in preparation for the ExoMars rover mission. Raman spectroscopy is a molecular identification technique based on the vibrational modes of molecules. It is a fast, non-destructive analytical tool that is capable of acquiring chemical and molecular structure information from unprepared samples (Smith and Dent, 2013). The Deltanu Rockhound spectrometer was used to simulate the functionality of miniaturised Raman instruments, such as RLS on the ExoMars rover. The Rockhound instrument uses a 785nm laser to produce a laser spot of 50 µm, equivalent to the spot size of RLS (Rull et al., 2017). The prototype system uses a 100 mW laser at a wavelength of 532 nm (the same as that on RLS) and produces a laser spot size of 50-150 µm. The system spectrograph and CCD detector generate a spectral range of 200-4000 cm^{-1} at a resolution of 3 cm^{-1}, comparable to that of the ExoMars rover RLS instrument, which will operate with spectral range of 100-4000 cm^{-1} and a resolution of 6-8 cm^{-1} (Díaz et al., 2011). The Raman spectra acquired allowed for precise mineral identification of samples retrieved by the core-drill, and the capability to find signatures of organic molecules.

The primary ExoMars ‘geology instruments’ lacking from the MURFI payload included the ground penetrating radar (WISDOM; Ciarletti et al., 2017) and the fuller suite of instruments within the drill package and in the Analytical Laboratory Drawer. We hope to include emulators for these instruments in the future – especially WISDOM, which provides sub-surface information – but to meet the overall goals of MURFI 2016 within the limited time available for planning, only the stand-off instruments that allow characterization of the geological setting and determination of drill location, and the Raman spectrometer, were used in this trial.

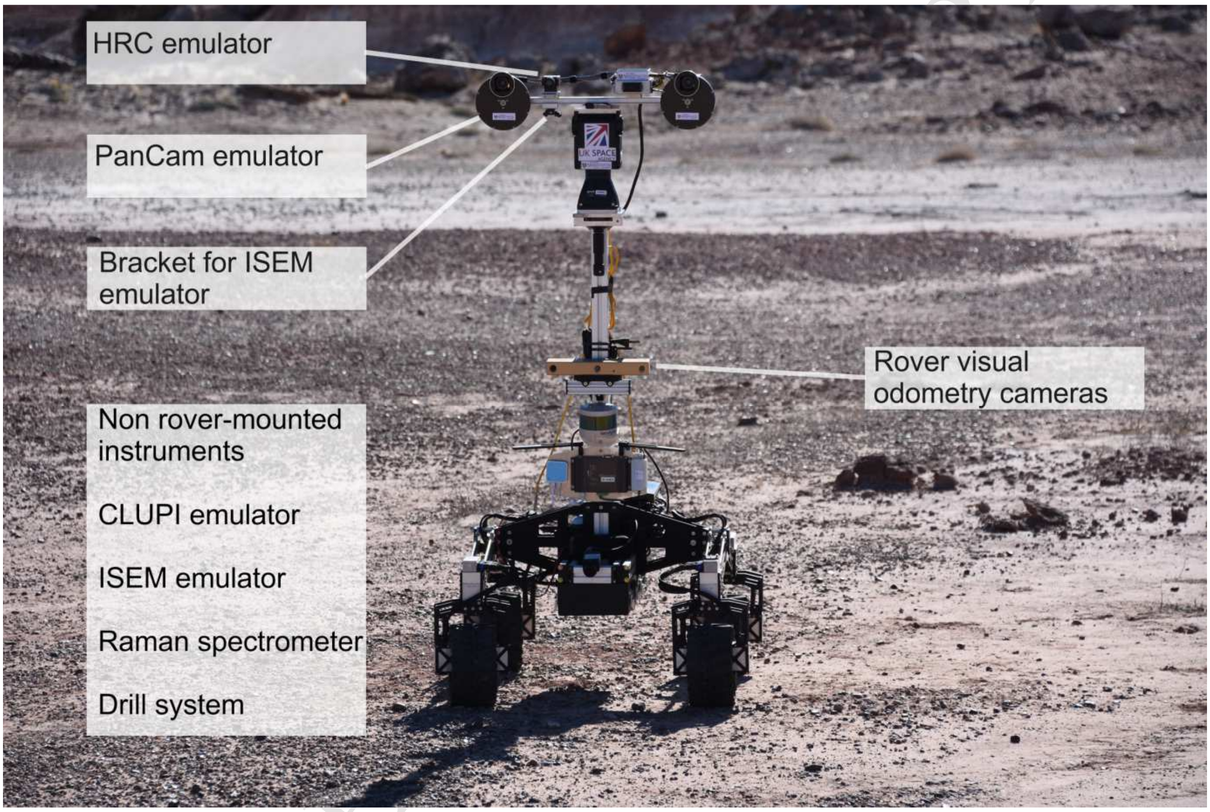

Figure 6. The MURFI rover platform showing the rover instruments. The main imaging instruments were rover-mounted, but the spectrometers were mainly used demounted from the rover for the convenience of the field team. The ISEM emulator could be used mounted or demounted. See Figure 1 for scale. Image credit: Mike Curtis-Rouse

4. ExoMars rover-like mission operations

The MURFI 2016 campaign was carried out over a 3 week period (Figure 7). In the field, the first week (week 0) of the mission was dedicated to field camp setup and testing of instruments and the platform. In week 0 at the MOC, 'landing site' mapping and hazard evaluation from remote sensing data was conducted. Weeks 1 and 2 consisted of the 'ExoMars rover-like' portion of the mission itself. The first two days of week 1 were used for tactical operations rehearsals, which then continued into the 10 Sol mission. During week 3, the field team disassembled the camp and began homeward travel, while two members of the MOC team joined the CSA team (Osinski et al., 2017) to observe their operations.

<table>
<tr><td colspan="8">October 2016</td><td colspan="11">November 2016</td></tr>
<tr><td>Mon 24</td><td>Tue 25</td><td>Wed 26</td><td>Thu 27</td><td>Fri 28</td><td>Sat 29</td><td>Sun 30</td><td>Mon 31</td><td>Tue 1</td><td>Wed 2</td><td>Thu 3</td><td>Fri 4</td><td>Sat 5</td><td>Sun 6</td><td>Mon 7</td><td>Tue 8</td><td>Wed 9</td><td>Thu 10</td><td>Fri 11</td></tr>
<tr><td colspan="7">Week 0</td><td colspan="7">Week 1</td><td colspan="5">Week 2</td></tr>
<tr><td colspan="2" rowspan="2">MOC SETUP</td><td colspan="5" rowspan="2">Landing site assessment from orbital data:
1. geological mapping
2. hazard mapping
3. science target identification</td><td colspan="2"></td><td>Sol0</td><td>Sol1</td><td>Sol2</td><td>Sol3</td><td>Sol4</td><td>Sol5</td><td>Sol6</td><td>Sol7</td><td>Sol8</td><td>Sol9</td></tr>
<tr><td colspan="3">EM-like mission operations rehearsals</td><td colspan="9"><---------------ExoMars-like mission---------------></td></tr>
<tr><td colspan="7"></td><td colspan="3"></td><td colspan="5">Characterise local geology</td><td colspan="2">Study drill site area</td><td colspan="2">Drill + analyse core</td></tr>
</table>

Fig. 7. MOC mission timeline overview.

4.1 Roles in MOC and in field

The structure of the MOC staff was determined in in consultation with advisers who had experience of the NASA MSL mission and previous CSA trials (Dupuis et al., 2016; Osinski et al., 2017). However, out of necessity, the operations structure was also shaped by availability of personnel. The roles of the MOC team and field team are summarized in tables 1 and 2 respectively. The MOC personnel swapped in an out of the team based on availability, with the total number of team members in the MOC usually being between 8 and 12 people.

The field team consisted of up to eight people during the investigation, including field geologists, rover and instrument specialists, and logistic and leadership personnel.

Mission scientist (MS)	The MS was a fixed position held by one person throughout the investigation. The MS was “in simulation” (although sometimes “out of simulation” discussions with the MM were necessary) and was responsible for the set up and commissioning of the MOC, the overall scientific direction of the mission, including long-term planning and strategy, and for MOC leadership.
Mission manager (MM)	The MM was a fixed, technical position, held by one of two people across the trial. The MM was the only MOC member who was “out of simulation”. MM was responsible for logistics, safety, and leadership in the MOC, for direct communication with the field team, and for setting daily mission constraints (such as data volume allowed). The MM also ensured each daily plan was uploaded to the field team FTP site.
Science working team chair (SWTC)	The SWTC held responsibility for making sure that the tactical plan was delivered each day. SWTC was appointed from early and mid-career scientists on the team to give experience of leadership roles. Hence, the SWTC position was held by five different people across the 10 day ExoMars rover-like mission.
Traversability,	The TML team (usually one or two people) was responsible for all

Mapping and Localisation (TML)	remote sensing and drive-planning tasks, as well as daily localization of the rover. TML was responsible for keeping GIS maps of the rover up to date and advising on safety of planned drives.
Instrument scientists	Instrument scientists formed the largest part of the team (usually 2-4 people per day) and were responsible for daily image processing, analysis and reporting to the larger science team. The AUPE scientists were busy daily, but some other instruments were not used each day. A consequence of this was that demands on the team were not equally divided between instrument teams.
Planner	The planner documented the daily tactical planning and targets chosen for analysis during planning, and ensured that mission constraints (e.g. data volume) were not breached. In addition, the planner was responsible for creating the final version of the tactical plan and handing it over to the MM by the daily deadline
Rapporteur	The rapporteur recorded daily minutes in the MOC, including notes on discussions and decision making processes. These minutes were used to assist the planner during the often hectic tactical meetings, as well as being useful after the investigation to evaluate decisions and assess how well the team worked together.
Advisors and observers	Two senior scientists with tactical mission planning experience from the MSL mission were present during part of the ExoMars rover-like mission to provide advice and instruction. An observer from the European Space Agency was also present for several days.

Science Working Team (SWT)	Due to the limited number of people who could be involved in the wider investigation, the SWT comprised the entire membership of the MOC, aside from "out of simulation" visitors and the MM. Every team member was welcome to contribute to the discussions, as chaired by the daily SWTC.

Table 1. MOC team responsibilities.

Mission Commander	The mission commander was responsible for all logistical, leadership, safety, and operation aspects in the field, as well as for communication with the MM at the MOC.
Geology lead	The geology lead was responsible for documenting the local geology prior to the ExoMars rover-like mission, and, most importantly, for deciding where to place the rover to provide a starting point that would allow the MOC team a reasonable chance of meeting the mission goal.
Field team	The field team was primarily responsible for collecting data from the field instruments based on the daily plan communicated from the MOC. Additional tasks, such as collecting samples and testing other instruments were performed once the daily plan for the ExoMars rover-like mission was executed.
Platform lead	The platform lead was responsible for ensuring that the rover platform operated safely. This role was vital to ensure that the MOC team did not inadvertently command the rover to do something that could cause it damage.
Platform team	The platform team (2-4 people) were responsible for deploying, controlling and maintaining the rover platform.

Table 2. Field team responsibilities.

4.2 Mission schedule

4.2.1. MOC team schedule

The field team positioned the rover at the 'landing point' on Sol 0, in a location they decided would maximize the possibilities for the mission, and from that point onwards a new tactical plan was generated each sol by the SWT (the sol N plan). The daily planning deadline was 13:00 UK time, meaning that the time zone difference between the UK and Utah allowed the field team to receive the command plans early in the morning and execute it, and then to return data to the UK before the start of the next sol's tactical planning schedule. The first five sols of the mission consisted of using the rover instruments to characterize the local geology and drives towards outcrops. The next three sols were devoted to characterizing a possible drill target, with the command to drill being given on sol 8. Post-drilling observations and CLUPI/Raman analyses of the drill sample were returned on sol 9 for later analysis. This is probably a much more rapid drilling time than is likely for a deep drill on ExoMars, but simulating a slower drill process was not deemed useful for the MURFI mission. No planning was done on sol 9 and it was used to discuss the final data sets returned and for a MOC-team debrief.

The MOC SWT followed the same fixed schedule each day (Table 3). The day began with the Mission Scientist designating roles within the team, a report from the Mission Manager, including 'flagging' problems or issues on the rover or for the field team, and confirmation of the rover data that had been downlinked from the field. After a period of data processing, tactical planning discussion began, and the sol N plan proposed, discussed, and finalized. After the planner submitted the Sol N plan to the Mission Manager the commands were 'uplinked' to the field team. After a lunch break, the SWT returned and begun more wide-ranging, free-form science discussions based on the data obtained in the mission so far. Later in the afternoon another formal planning session, led by the Mission Scientist, began. During this session, the current longer term plan was discussed and modified, as well as an outline sol N+1 plan created for use as the basis for the following day's sol N planning. Daily activity at the MOC was completed by the MS and MM creating an archive backup copy of all the documentation and data generated during the day. After dinner, the MS produced a summary of activities and targets from the day for distribution to all team members, and various team members updated blog posts and social media accounts.

During the daily planning cycle, several formal documents were produced and archived to keep a record of the operations. These are numbered in Table 3 and included: *(1) Sol N Rover Status Report*: localization results and GIS shapefiles provided by the TML team, and data downlink lists from the MM.

(2) *Interpreted Data Reports:* results from the previous sol's activities, such as annotated 'screen grabs' of images. Presented by the instrument scientists to further science and planning discussions.

(3) Sol N Target Overview Document: produced during the planning meeting by Planner and SWTC to demonstrate locations of targeted observations planned for the day. This included screenshots images showing the expected field of view of desired observations and target names. These helped the field team to obtain the correct data in case of confusion over the plan.

(4) *Sol N Plan Summary:* produced by SWTC to include all aspects of the sol N plan as agreed by the SWT.

(5) Sol N Plan for Uplink: Sol N plan, including all drive commands and targeting locations, to be uplinked to the field team, produced in a specific format by Mission Manager, assisted by the Planner, and checked against daily constraints.

(6) Sol N+1 Plan: outline-level document, prepared by Planner, describing the proposed plan for sol N+1 activities.

(7) Strategic Plan: a 'living document', updated daily by the Mission Scientist, that summarized sol-by-sol activity to date, proposed activity within the next 3 sols, and milestones and stage-gates necessary to meet the overall mission goals.

(8) Rapporteurs Minutes: describes the day's discussions for later use.

Other documents and presentations focussing on the scientific interpretations were created and presented to the team by members of the SWT as and when necessary.

Time (local)	**Item**	**Responsibility**
07.45	Catch-up meeting for MM and MS –discuss designation of roles for the day.	Mission Scientist and Mission Manager.
08.00-8.15	Kick-off team meeting "outside sim" – designation of roles for the day, essential info from Mission Manager (e.g., fire alarm tests, IT issues etc, early closure of facilities, absences of team members).	All MOC team.
08.15-08.45	Sol N tactical planning meeting preparation and data processing time (1).	Instrument scientists, TML team, Mission Manager
08.45-11.30	Sol N tactical planning discussions (2).	SWTC to chair. All SWT input into discussion.

11.30-11.45	Documentation prep time.	
11.45-12.30	Sol N tactical planning final meeting (3).	SWTC and Planner to lead. TML produces drive plan. All SWT to input into discussion.
12.30-13.00	Sol N Mission plan checking and agreement (4).	SWTC to chair, Planner, Mission Scientist, Mission manager.
Deadline: 13.00	Mission plan for sol N sent to Utah field team (4). *Set to arrive no later than 6am Utah local time so dependent on time-difference.*	Mission Manager.
13.00-14.00	Lunch.	
14.00-15.00	Science team discussion, analysis, hypothesis generation.	SWT, Mission scientist to chair.
15.00-~15.30	Sol N+1 planning discussion meeting (5).	SWTC
~15.30-16.30	Strategic planning meeting and Sol N+1 plan finalization (6). Strategic plan updated (7). Daily documents archived, including rapporteurs minutes (8).	Mission Scientist, SWTC, Planner.
evening	Handover activities for incoming team members.	Mission Scientist, incoming/outgoing team members.

Table 3. Daily schedule during the ExoMars rover-like mission. Numbers in parentheses refer to formal documents produced during the day, as described in the text.

4.2.2 Field team schedule

The field team arrived in Utah on 24th October, and the basecamp was fully operational by the 28th October. The field team spent several days ensuring the rover and instrumentation were fully functional, as well as performing geological reconnaissance of the operations area, and deciding where to position the rover to maximise the return from the exercise. The field team began regular daily operations (Table 4) on sol 1 of the ExoMars rover-like mission, as the first daily tactical plan was uploaded to the field team from the ROC.

Time (local)	**Item**
07:00	Incoming data received from UK. Data were collected in Hanksville or via the CSA downlink, depending on bandwidth and location of personnel.
08:00	Mission Commander coordinates with MM at the MOC to ensure that information was correct and the day's activities achievable (considering local conditions).
09:00	Daily briefing and planning chaired by Mission Commander.
10:00-16:00	Daily mission activities performed following tactical plan.
16:00	Data collated and prepared for upload to UK.
17:00	Data package sent back to UK / instrument and platform maintenance.
18:00	Review of the day's activities at base camp.

Table 4. Field team daily schedule

4.3 Data processing and/or software

The majority of the data returned to the MOC by the field team was images. These included daily NavCam (panchromatic WAC images taken using the visible light filter) panoramas, and targeted observations using the WAC RGB and multi-spectral filters, the CLUPI emulator, or the HRC. Various commercial and open-source software packages were used to display and mosaic image data, or visualise stereo images in 3D, including ESRI 'ArcGIS', 'Hugin' (derived from "Panorama Tools"; Dersch, 2007), and AgiSoft 'Photoscan'. Also, stereo panoramas acquired through the left and right WACs were uploaded to an ftp processing pipeline set up by Joanneum Research, and automatically converted into 3D digital outcrop models using the PRoViP tool. The resultant 3D Ordered Point Clouds (OPCs; Traxler et al., 2018) were visualized in PRo3D; a software tool developed specifically for quantitative geological analysis of OPCs created from stereo rover-derived images(Barnes et al., 2018). PRo3D enabled immersive, real-time visualization of the 3D rendered image data for scientific purposes (e.g., Balme et al., 2017; Barnes et al., 2018), allowing for free roaming of a virtual representation of the rover's environment. Measurement tools built-in to the software allowed for the true scale and distances of objects to be measured, up to a distance of about 20 m from the Rover, beyond which the errors become higher. This will be similar for the real ExoMars Rover This was important for planning drives, identifying targets and for avoiding obstacles. It should be noted that these 3D rendering and analysis techniques are still in the early stages of testing, and validation of the processing techniques and PRo3D are ongoing, so MURFI was also a useful trial for this system.

The multispectral WAC data were processed using ENVI software and the ISEM emulator reflectance spectra were processed and analyzed using 'The Spectral Geologist' software. Satellite remote sensing data were used to generate a variety of mapping products (see section 5.1) both before and during the ExoMars rover-like mission. ESRI ArcGIS software was used extensively for processing, display and digitising of these data.

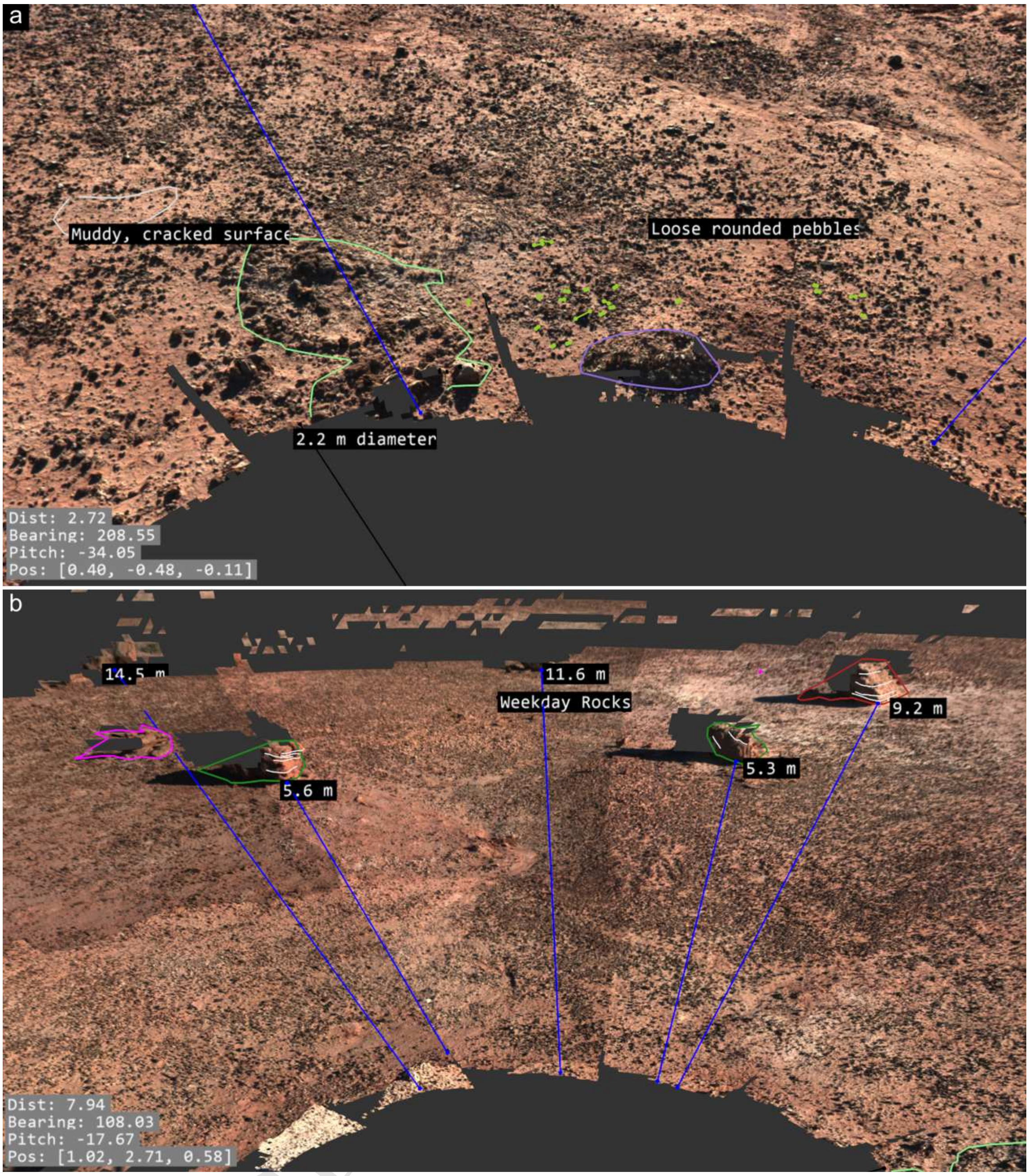

Figure 8. PRo3D example outputs. a) Near-field view showing annotations made onto the PRo3D scene. b) Distance measurements, useful for drive planning, made using PRo3D – in this case, to the 'weekday rocks' using sol 1 data.

5. ExoMars rover-like mission summary

5.1 Preliminary Landing Site Assessment

In line with the objective to simulate an ExoMars rover-like mission, a subset of the SWT conducted a preliminary assessment of the 'landing site' area in week 0. The aim of the preliminary landing site assessment was to understand the local geology of the area in order to build working hypotheses for the palaeoenvironments represented by the bedrock geology at this site. An assessment of the nature and distribution of hazards, in line with scientific and engineering criteria of the ExoMars rover mission, was also made, as well as identification of possible science targets for the rover. Crucially, this task was conducted within the simulation, and so the mapping team were allowed no prior knowledge of either the chosen site area, or the start point for the rover mission.

To conduct this preliminary landing site assessment we produced a variety of Mars-equivalent data sets from the available terrestrial data sets (Table 5). No additional knowledge (e.g. higher resolution aerial photographs, more extensive areas of color or spectral data) of the mission landing site was allowed or considered, to make the process similar to the ongoing assessment of the ExoMars landing sites (Bridges et al., 2017b). These data sets were used to (1) create a reconnaissance photo geological map, (2) assess slope and other traversability hazards and (3) build working hypotheses for the origin of the geological units and therefore to identify science targets for the rover based on these hypotheses.

The preliminary analysis was performed by five team members who had Mars remote sensing experience. All targets, units, contacts etc. were digitized using ArcGIS software, and outputs produced for the wider team to analyse. The various maps produced were displayed and referred to often during the ExoMars-like mission trial.

Mars dataset emulated (spectral range and pixel size)	Earth data used (spectral range and pixel size)	Processing	'Mars like data' (spectral range and pixel size)
HiRISE[1] (RED, RGB; 0.25 m)	World View 2[2] (0.39 m RGB)	Export Red channel Clip central RGB strip	0.39 m RED 0.39 m RGB
HiRISE Digital Terrain Model (DTM)[3] (~1 m)	NAIP*[4] 5 m DTM [3]	none	5 m DTM
CTX[5] (Panchromatic; 6 m)	NAIP*[6] 1 m RGB	Merge RGB (grey scale function) to grey scale, resample to 6 m/pixel	6 m Panchromatic
CTX DTM (~20 m)	NAIP 5 m DTM [3]	Resample to 20 m	20 m DTM
HRSC[7] (12.5 m Panchromatic, 50 m RGB)	LANDSAT 8[8] bands 4; Red 3; Green, 2; Blue, (30 m/pixel) and 8; Panchromatic (15 m/pixel)	Composite RGB bands, Resample to 50 m/pixel, rescale pixels from 16 bit to 8 bit, pansharpen 8 bit RGB with 8bit panchromatic data	15 m RGB
THEMIS[9] IR daytime surface temperature (12.17 µm – 12.98	LANDSAT 8 band 11 (11.5 µm – 12.51 µm, 30 m/pixel)	Band 11, resample to 100 m/pixel, rescale pixels from 16 bit to 8 bit	100 m (11.5 µm-12.5 µm)

μm; 100 m)			
CRISM[10] (400 nm – 4000 nm wavelength range; 16m)	HYPERION[11] (250 nm – 2500 nm; 30 m/pixel)	Resample pixels to 32 m	½ spectral range & spatial resolution

Table 5: Mars like data sets made from available terrestrial counterparts*NAIP = National Agriculture Imagery Program. [1]High Resolution Imaging Science Experiments (McEwen et al., 2007), [2]DigitalGlobe (https://www.satimagingcorp.com/satellite-sensors/worldview-2/), [3]Kirk et al. (2008), [4]NAIP DTM (https://gis.utah.gov/data/elevation-terrain-data/#AutoCorrelatedDEM), [5]ConText Imager (Malin et al., 2007) [6]NAIP RGB (https://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/), [7] High Resolution Stereo Camera (Neukum and Jaumann, 2004) [8]US Geological Survey (https://landsat.usgs.gov/landsat-8), [9] THermal EMission Imaging Spectrometer (Christensen et al., 2004), [10] Compact Remote Imaging Spectrometer for Mars (Murchie and the CRISM Science Team, 2007), [11]US Geological Survey (https://eo1.usgs.gov/sensors/hyperion)

5.1.1 Physiography of the Landing Site

The study area mapped using the Mars-like data is shown in (Figure 9). Elevation in the study area ranges between ~ 1,430 and 1,350 m. There is a 40-50 m high scarp at the western edge of the study area, but the majority of the study area is a gently undulating plain. Across the plain, there are a series of semi-continuous mesas and ridges which are up to ~ 15 m high. Local drainage is defined by ephemeral stream and alluvial deposits, which drain towards the east, and has exposed much of the underlying stratigraphy.

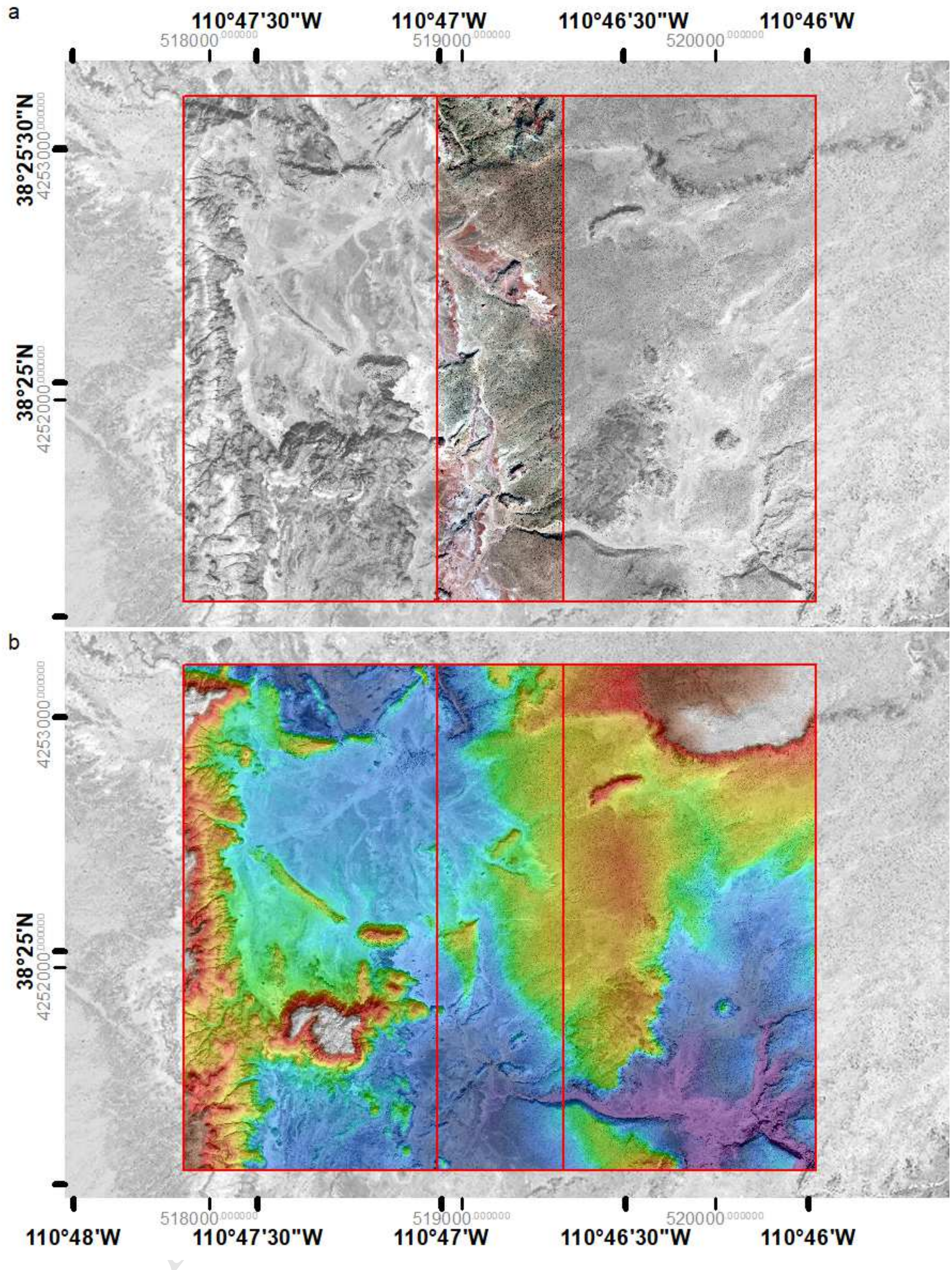

Figure 9. The MURFI field site area mapped using Mars-like remote sensing data (cf. black box showing study area in figure 2b). An area ~ 2 by 3 km was mapped. a) A simulated HiRISE image (Worldview 2), including the central color strip and the lateral greyscale areas. b) 5 m resolution DTM showing topography. Note that this DTM actually has lower resolution than the best Mars DTM data

(5 m/pixel vs 1 m/pixel). Graticule and grid show WGS (World Geodetic System) 1984 latitude and longitude and UTM (Universal Transverse Mercator) zone 12N projection scale information. Image credits: see Table 5.

5.1.2 Photogeological mapping.

The photogeological map (Figure 10) covered an area of 2 x 1.75 km and was digitized at 1: 1,000 scale over three days in the style of the USGS astrogeology program (Tanaka et al., 2011). The mapping used a HiRISE-equivalent base layer, with color data available only in the central portion. CTX, HRSC, and THEMIS equivalents (Table 5) were used for regional context. Hyperion data were only available later in the mission: CRISM-like summary products were generated but did not provide significant additional information that altered the mapping.

At the time of mapping, the SWT did not know where in the mapped region the rover would 'land', hence it was important to build up a consistent geological interpretation for the region. This 'rapid mapping' approach has relevance to the ExoMars rover mission as quickly building up a good understanding of the local geology will be important for guiding the initial drive direction of the rover following disembarkation from the landing platform.

The MURFI mapping produced a proposed stratigraphy (Figure 11) divided into 10 units organized into four formations: (i) and (ii) the Upper and Lower Layered Formations, (iii) the Resistant Formation, and (iv) the Dark Formation. Henceforth, we only describe the units and relationships that were close to the actual landing point and relevant to the MURFI ExoMars rover-like mission, rather than trying to provide complete detail of the wider map.

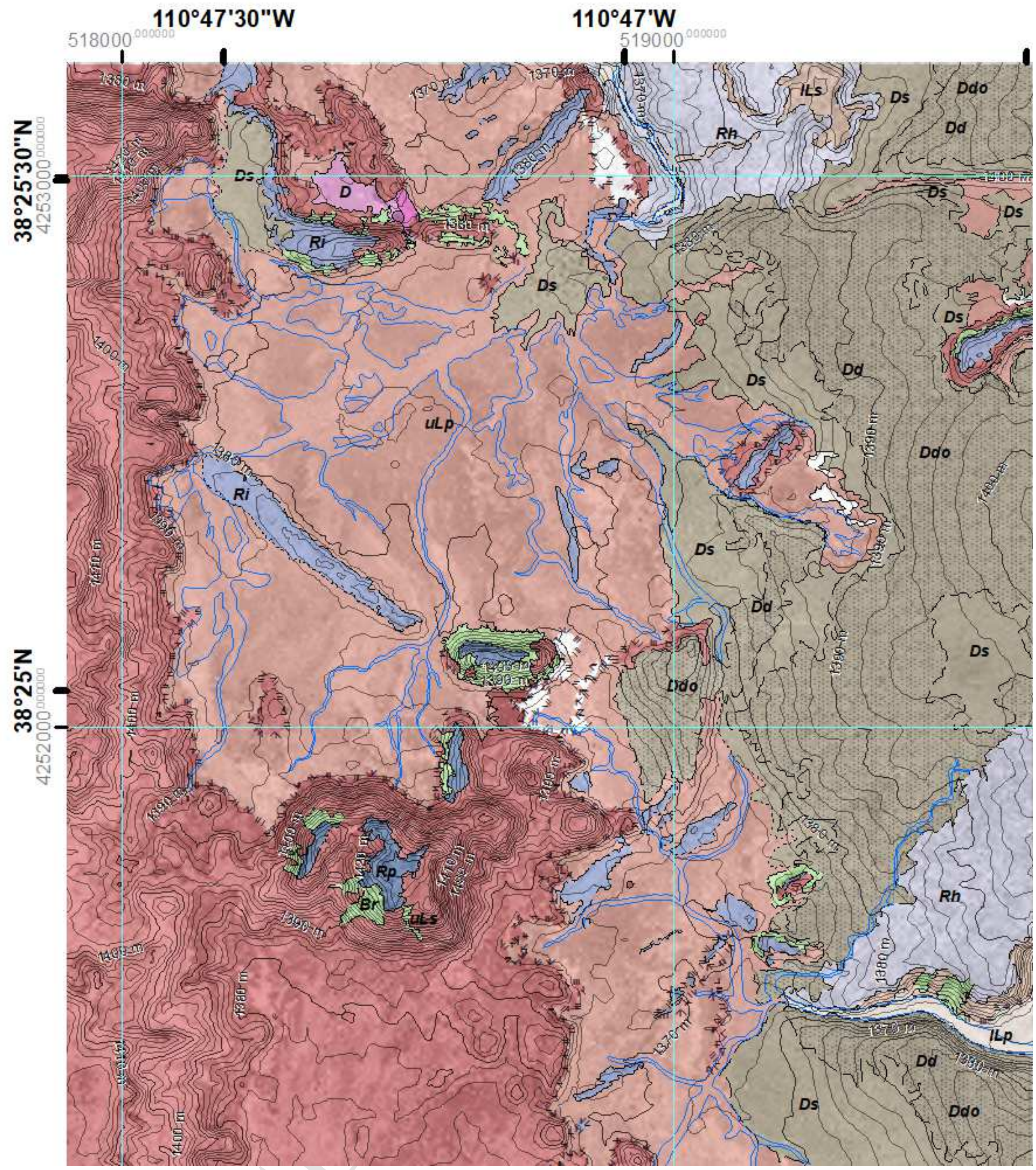

Figure 10: Subset of the photogeological map of the landing site region. Reds = Layered (scarp and plains-forming) Formations, Blues = Resistant Formation, Browns = Dark Formation, Green = out-of-situ rubbly boulder and debris, White = Anomalously Bright Unit (a distinctive unit in the Layered Formations). Blue lines = modern alluvial deposits and green lines = targets. Additionally Pinks indicate anthropogenic features, such as a dam structure in the north of the region. Graticule and grid show WGS1984 and UTM zone 12N; pale blue gridlines are 1 km apart.

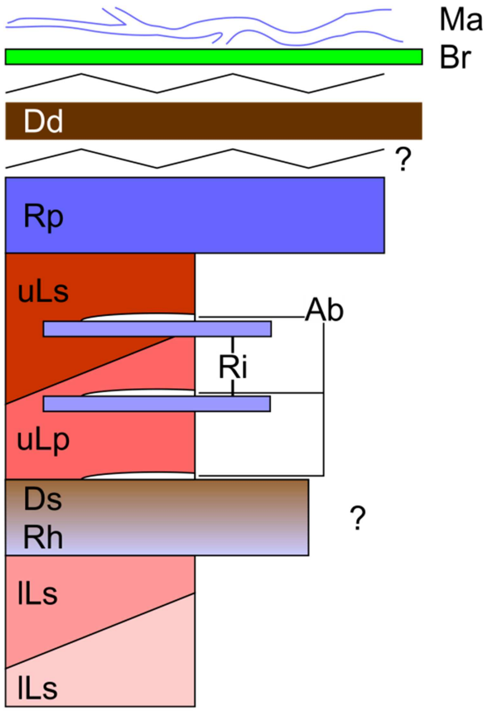

Figure 11. Proposed stratigraphy based on remote sensing mapping. Zigzag lines indicate unconformities or poorly constrained contacts. Ma = Modern alluvial material. Br = Blocky rubble unit; Dd = Dark dappled unit (part of the Dark Formation), Rp = Resistant Plateau Unit (part of the Resistant Formation), uLs and uLp are upper Layered Formation Units (Scarp and Plains-forming respectively), Ab = Anomalously Bright Unit (part of Layered Formation), Ri = Resistant Interbedded Unit, Ds and Dh are part of the Dark Formation (Smooth and Hummocky respectively), lLs and lLp are Lower Layered Formation Units (Scarp and Plains-forming respectively).

The Resistant Formation consists of three units characterised by a tendency to crop out as ridges or flat caps on top of mesas and plateaus. Sub-curvilinear ridges of resistant material from this formation are set within the stratigraphy and form the 'Resistant Interbedded Unit' (Ri). Examples of this unit were found on top of mesas and hills close to the MURFI rover landing point. Based on the mapping and the geomorphology observed in the highest resolution images, we interpreted them to be resistant materials composed of the upper parts of inverted fluvial channels. Hence, our hypothesis was that they were fluvial sandstones or similarly coarse-grained sedimentary materials.

The upper and lower Layered Formations are each formed of horizontal to gently dipping layers with varying albedo and meter- to decameter-scale repeating layering that is continuous across much of the study area. These units were interpreted to be sedimentary material, with the variations in color reflecting paleoenvironmental conditions (proposed to be related to types of iron-minerals present). Also located within the Layered Formation are the 'Anomalously Bright Units' (Ab), which appear similar to the other layered unit, only brighter and with a spatially restricted outcrop pattern (contrary to the rest of the Layered Formation in which layers strike across the whole mapping area). Our interpretation for these materials was that they were part of the same fluvial assemblage as the inverted channels, as they were often found directly beneath the Resistant Interbedded Unit, within curvilinear ridges. We concluded that these represented quiescent fluvial sub-environments such as flood plains or channel overspill deposits, and hence would have finer grains sizes and possibly more clay rich assemblages.

The overall conclusion of the mapping was the following working hypothesis: that parts of the study area comprised a fluvial assemblage, including both channel fill (now seen in inverted relief on top of mesas and hills) and quiescent fluvial deposits such as flood plains facies (now seen as spatially continuous layered scarp, or undulating plains).

5.1.3 Hazards.

As part of the preliminary landing site assessment, rover traversability hazards were evaluated. This exercise is directly relevant to the ExoMars rover mission; very similar analyses were performed at the landing ellipse scale for ExoMars landing site selection, and detailed traversability maps will be needed as soon as the landing position of the ExoMars rover is determined to allow for drive planning.

The resulting hazard maps (Figure 12a) were used to place constraints on the routes the rover could traverse and which targets were accessible. Four types of hazard were identified and mapped:

(i) Slopes: areas of steeper ground where it was either not possible to drive the rover or where it was more likely to encounter impassable breaks in slope. As the 5 m resolution of the Digital terrain Model (DTM; Figure 9b) is poorer than the HiRISE DTMs available for Mars, it was difficult to assess true slope at the shorter baselines that could most seriously affect rover movement. Instead, we mapped out slopes across the study using the 5 m/pixel DTM to produce a color-coded slope map to inform traversability. Across the study area the majority of slopes are < 10°. Locally steeper slopes around scarps, mesas, ridges may impede access to outcrops of high scientific interest.

(ii) Loose material: numerous areas of loose material are found in the area, including modern ephemeral fluvial channels deposits and talus slope material. We conservatively decided that the low-relief modern channels visible in mapping were a loose sediment hazard, as well as having possibly 10-50 cm steps at the dry channel margins, so all these regions were ruled as being hazardous.

(iii) Blocky debris: we included blocks shed from the Resistant Formation materials as a mapped unit. However, more examples of these exist in the area of the layered plains. Where these can be identified from orbit they can be avoided, but boulders below the resolution of satellite imagery will also be a possible hazard and can only be identified from the rover.

(iv) Bushes/Boulders: The unit Dd appears to have dark patches which may be boulders, as judged by shadows and bright regions on their sunward side. However. many more had diffuse margins, a possibly organized spatial distribution, and occur at low elevation near areas of modern fluvial channels. This suggests they may be small bushes. Both terrain types pose a hazard to the rover so were classed as hazardous.

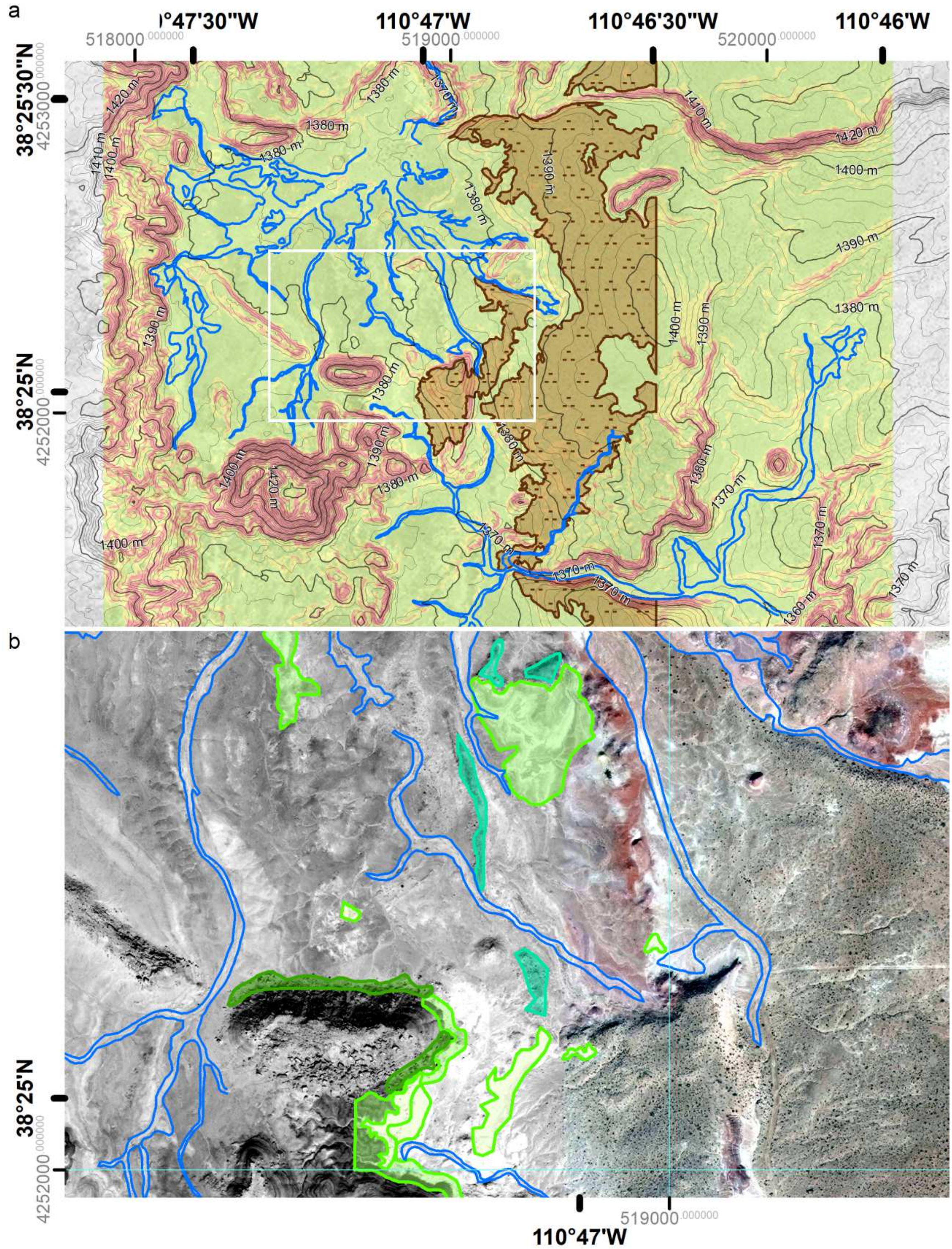

Figure 12 – Hazard and science target mapping. a) Hazards within the wider mapping region. Modern Alluvial hazards are outlined in blue. In the background, slopes < 5˚ are colored green, slope 5˚ -10˚ are yellow, slopes of 10-15˚ are orange, and slopes >15˚are red. The brown area is the 'Dark Dappled Unit', Ddu – interpreted to be densely covered with boulders and vegetation. White box

shows position of Figure 12b. b) Possible science targets in the central portion of the remote sensing map region. Dark greens show Resistant Formation outcrops or float rocks that could be rover accessible, mid-green are other possible bedrock outcrops, and bright green show the edges of the Layered Plains Unit or the Anomalously Bright Unit (Abu). The blue lines show modern alluvial hazards. Backgrounds image is a HiRISE-like image (Worldview 2). Graticule and grid show WGS1984 and UTM zone 12N. Image credits: see Table 5.

5.1.4 Science targets.

As a result of the reconnaissance mapping, four types of science target were identified and their locations recorded on the map (Figure 12b). Based on discussions in the SWT, these target categories represented our evaluation of what would be the highest priority science targets when the mission began.

(1) Resistant outcrops: identified to test the working hypothesis that the Resistant Interbedded Unit was channel-fill exposed in inverted relief. This could be partially tested by remote observation if all examples proved inaccessible.

(2) Resistant float rocks: these targets provided opportunities to investigate the sedimentology of outcrops that were otherwise inaccessible. Close-up analysis of these could be used to investigate the sedimentology of the resistant outcrops from which they have fallen.

(3) Scarp-forming Layered Units: as possible ancient flood plains deposits, a key priority was to assess their grain size via close-up analysis of bedrock examples of this material. Furthermore, these strata might have a geochemistry that varies between darker (reddish color, possibly Fe^{3+}-rich) and brighter (whitish or pale grey, possibly Fe^{3+}-poor). This might reflect changes in environment, depositional style, or later alteration. Hence another goal

was to determine if this variation is associated with deposition or post-depositional diagenesis.

(4) Anomalously bright regions associated with resistant materials, but within the Layered Formation: these outcrops might represent diverse paleo-environments, or extrema in the diversity of the interpreted geochemical variation expressed in the Layered Formations.

(5) Bedrock in the Layered Formation: if our working hypothesis was supported by rover observations, then finding competent, in-situ examples of these types of terrain would provide the ideal target for a drill sample.

5.2 Traversability, Mapping and Localization (TML)

Driving instructions for the rover were generated as 'waypoint files' describing rover-relative positions for the rover to travel to, and the final azimuth for the rover. Drives were planned daily by the MOC SWT, with the waypoint files then being created by the TML team and uploaded as part of the daily tactical plan. To keep planning simple, drives were planned as a series of linear paths linked by point turns. At each waypoint, the location and direction of the rover was specified in the waypoint files, to put it in the best position for imaging or other tasks.

While driving, the rover operated autonomously. To ensure the rover actually drove the planned track, the rover utilised its XB3 stereo cameras linked to the Oxford Visual Odometry application (Churchill, 2012) which generates frame-by-frame estimates of the rover's motion. This is the same visual odometry algorithm as will be used on the ExoMars mission (Shaw et al., 2013; Woods et al., 2014)

In any rover mission it is imperative to know where the rover is, both relative to science targets and potential hazards, but also to its previous position to determine how successful the last commanded drive has been. This was especially important on the first sol of the mission. To localize the rover, we used distal and proximal trigonometry based on objects seen on the horizon or in the near field, and that could be located in remote sensing images. Where possible, proximal localization and planning within the meter-scale workspace was done using the PRo3D tool described above. The 3D scenes were created from AUPE panchromatic mosaics acting in 'NavCam' mode. The PRo3D scene close to the rover was used to characterize the workspace surface topography and hence fine tune the rover position for drill core acquisition.

For targeting of the instruments on certain locations, a naming convention was adopted, analogous to the conventions used on MSL and other missions. Features large enough to be identified from orbital remote sensing analysis were given non-genetic names (e.g. "Big Mesa"). Features and targets identified from rover data were named after UK towns/villages with a population of fewer than 10,000 residents (e.g. 'Wimblington') using a name-randomiser tool and database. The TML team had ownership of this tool and were responsible for generating target names. Figure 13 shows the localisation and driving results of the MURFI ExoMars rover-like mission, and examples of targets determined during planning.

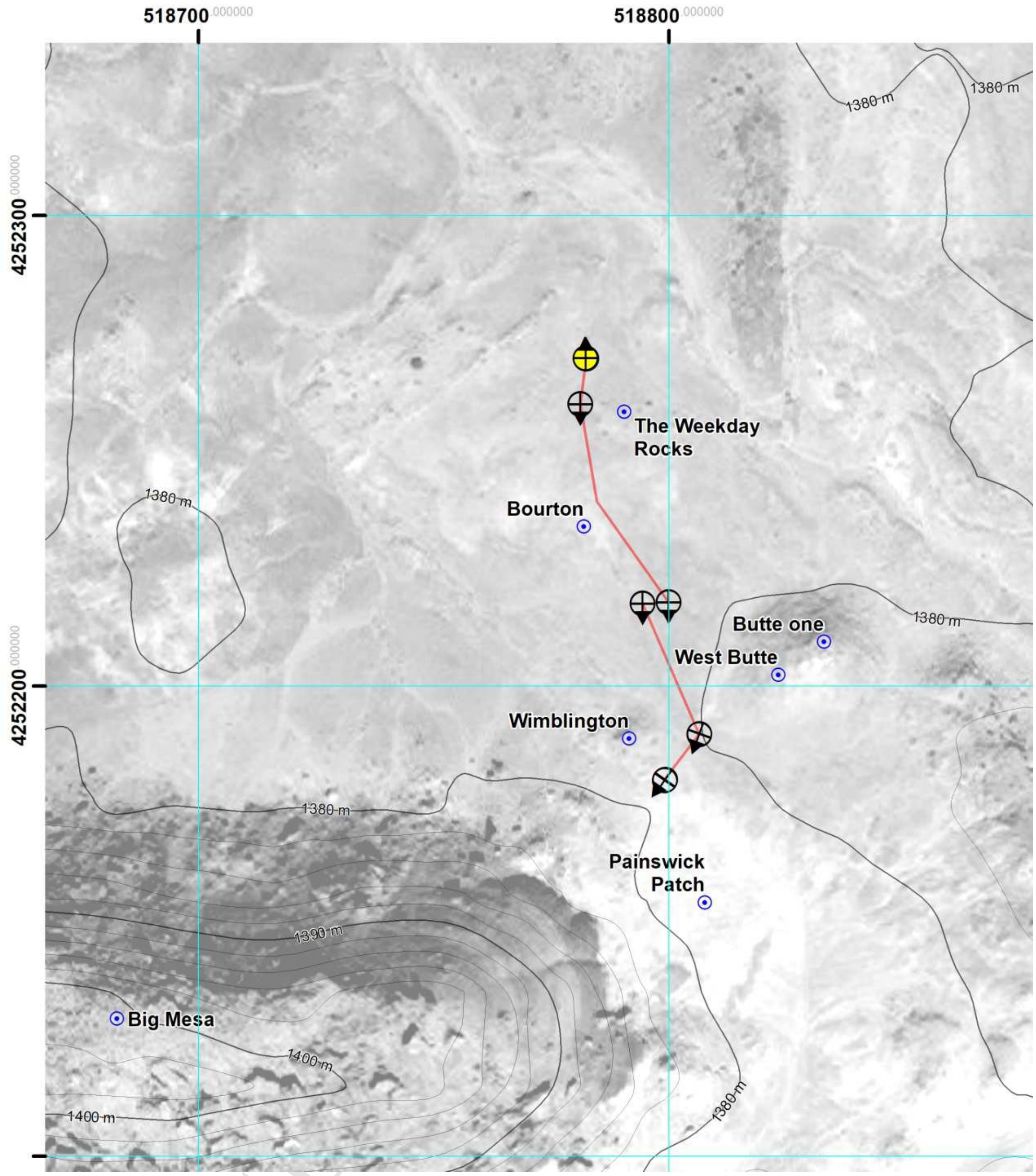

Figure 13. Localisation and drive calculations for the MURFI ExoMars rover-like mission, including some of the key targets and their locations. Note the Sol 5 localisation recalculation that resulted in the rover positioning being moved ~ 5 m to the west. Graticule and grid show UTM zone 12N so blue lines are 100 m apart. Dark lines are 2 m contours based on the 5 m DTM. Image credits: see Table 5.

5.3 Daily mission operations log

The following describes the sol-to-sol activities of the MURFI ExoMars rover-like mission. In general, each sol's tactical plan involved a science block (targeted observations using one or all of the standoff instruments), then a drive block. A NavCam emulator panorama acquisition was included as a standard post-drive imaging command. The post-drive panoramas were either 180° or 360° depending on data volume available and/or planning needs, and allowed choice of the next sol's targets from the panorama.

Sol 1. (3rd November 2016) – first drive.

The rover was placed at its landing site by the field team. The only data available to the SWT was a full-color, stereo, 360° WAC panorama (Figure 14). The TML team produced an accurate localization result using triangulation based on features identified in the panorama and the satellite remote sensing images. This located the rover within the study area, at a point ~ 70 m north of a large mesa (named "Big Mesa" by the team) and facing north. A small collection of ~ meter-sized boulders (named 'the Weekday Rocks' – Monday through Friday, by the team) was seen to the southeast. Targets chosen during Sol 1 tactical planning included: (i) 'Byfield': HRC imaging of pebble-rich ground near the rover (hypothesized sheet wash deposits), (ii) 'Fiskerton': HRC, WAC multispectral and ISEM emulator targeting of pebble-free soils near the rover, aiming to determine composition and texture, (iii) 'Ochiltree': HRC observations of mud cracks near the rover, (iv) HRC mosaic of the eastern part of the distant 'Big Mesa' to look for possible sedimentary structures, (v) 'Thursday': HRC of one of the weekday rocks to look for possible layering, and (vi) 'West Butte': HRC single images of a smaller butte in the middle distance and a boulder near the rover.

The overall strategic plan for the mission was discussed in the SWT, with the conclusion that heading south towards the largest vertical exposure gave the best chance for understanding the local geological setting. Hence, the Sol 1 drive plan included turning the rover 180° and then heading south 10m to bring the rover alongside the boulders. The

SWT were cautious about hitting the boulders in case the rover turn manoeuvre (or initial localisation) was inaccurate, so only a short drive, finishing before the boulders, was planned.

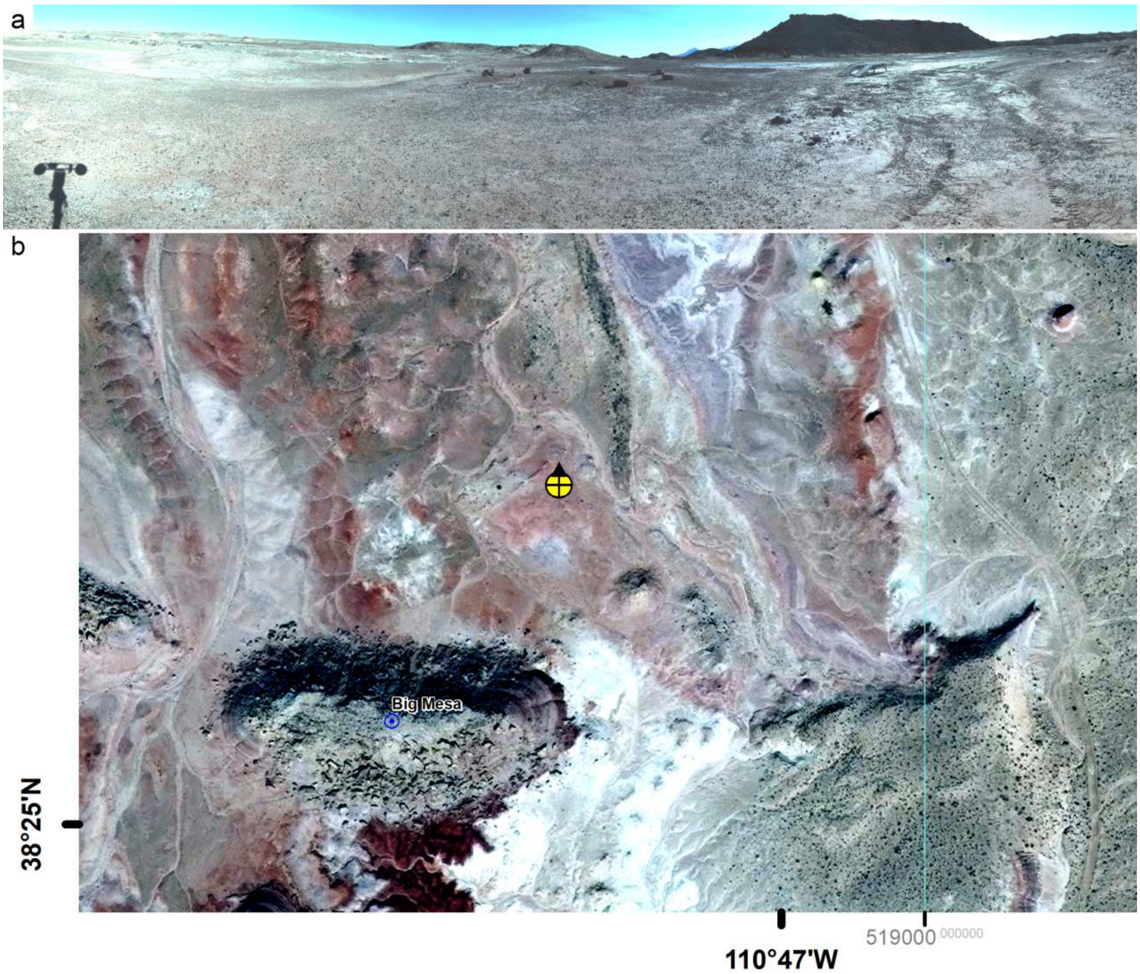

Fig 14. a) AUPE full color, stereo panorama data returned after sol 0. b) Position of rover at start of Sol 1, as determined by the TML team. Image credits: see Table 5.

Sol 2. (4th November 2016) – moving towards science targets

Data returned on Sol 2 showed that the rover had successfully avoided the Weekday Rocks and moved ~ 10 m south towards the Big Mesa. The SWT wished to characterise 'Bourton, a small patch of high albedo material immediately south of the rover, for which two working hypotheses existed: (i) an inlier of high albedo bedrock, and (ii) an area of higher albedo surficial material. The team did not want to 'waste' a sol examining this area further if it was surficial material, but if it were bedrock this could provide a promising target for drilling. It was also suggested that this material could be a possible rover traversability hazard if it were loose sand. The outcome of discussion in the SWT was that a two-part drive, first to the edge of Bourton, then skirting to the east and then southeast of it, was appropriate. An untargeted right-looking imaging sequence of the centre of Bourton using WAC, HRC and ISEM emulator acquisition was planned to occur before the second drive. If Bourton was found to be bedrock, the rover could then retrace its drive back to this area on future sols. Additional pre-drive targets included several HRC mosaics of the buttes and mesa in the area to search for sedimentary structures, and an HRC/ISEM emulator study of a bright patch of soil and a small rock (possibly bedrock) near the rover.

Sol 3. (5th November 2016)

No operations (scheduled rest day). We note that the provision of rest days will be very unlikely in the early part of the ExoMars rover mission.

Sol 4. (6th November 2016) – targeted instrument analyses

Due to scheduled changeovers in the field Platform Team, no driving was possible on sol 4. The returned HRC and WAC data showed strong evidence for the Big Mesa being composed of sedimentary material, based on observations of albedo, texture and layering at smaller scale than visible in the remote sensing data. HRC images showed inclined strata, interpreted as being cross-bedding in the Resistant Formation materials, both in situ and in debris at the base of the slopes. The data also showed further patches of high albedo material to the east and north of the Big Mesa. The SWT proposed these to be bedrock examples of the Anomalously Bright Unit of the Layered Formation, and so might be possible future targets for drilling. The data obtained on sol 2 revealed that Bourton was composed of surficial material so sol 4/5 drives were planned towards the south to bring the rover into an area with more outcrop and drill targets. The targeting strategy was to build up more information about the geology by observing outcrops in the local area. Sol 4 targets included (i) HRC mosaic of 'Painswick Patch' the bright terrain west of Big Mesa, (ii) Wimblington, an area of jumbled debris north of Big Mesa, and (iii) 'Weeting' and 'Swanland' patches of brighter terrain on the rover's southward drive path.

Sol 5. (7th November 2016) – long drive towards region of interest

The plan for sol 5 included further HRC and WAC imaging of the Painswick Patch area and two HRC and ISEM emulator analyses of possible bedrock outcrops nearby ('Cransford' and 'Dunoon'). The previous sol's imaging allowed a long drive to be planned as the absence of drive obstacles was quite clear. Hence, a 30 m drive south to the edge of Painwick Patch was planned.

Sol 5 contained a few examples of logistical and communication problems. First, the planned drive for sol 5 brought the rover to the edge of the MURFI 'working space', agreed between the UK SA and CSA field teams. The working spaces were relatively close together for communications and logistics reasons. Unbeknownst to the MOC team, the CSA rover was working just a few tens of meters further south and there were worries that the presence of two field teams working so close to one another would compromise both investigations. The field team did not know that this was likely to be the last long drive performed by the MOC team, as the strategic plan for sols 6-9 included detailed studies of the locations near the rover to prepare for drilling, rather than further long drives. The problem was resolved after field and MOC team communicated directly via satellite phone, reassuring the field team that the MURFI rover would not be progressing much further south into the CSA workspace. This incident demonstrates the need for well-defined working spaces and reinforces the necessity of readily available communications between MOC and field.

A second issue that arose on this sol was that the TML team became concerned that a localisation error could have propagated throughout the entire mission, potentially putting the rover 10-20 m from where the SWT thought it was. However, re-localising revealed that the rover was within 5 meters of the previous estimate. Nevertheless, this recalculation put increased pressure on the tactical planning time window.

Sol 6. (8th November 2016) – characterizing possible drill site

Sol 6 saw a change in the pace of the mission: the team transitioned from “observing and driving” to “characterising and deciding about drill sites”. The SWT were aware that sol 6 would be the last driving sol, if drill workspace characterisation was to be performed on sol 7, and the command to drill being given on sol 8. This meant that tactical planning on this day would finalise which of the several possible drill sites were chosen.

At the start of the sol, the rover was positioned close to the Cransford outcrop, which appeared to be composed of finely layered sedimentary material with recessive interbeds. Other possible targets included ‘Outwood’, an area that appeared to be a small patch of Layered Formation material, and ‘Skinningrove’, a target in the Painswick Patch bright terrain. After much debate, the SWT decided that Skinningrove would be the drill location, so a 12 m drive to the southeast was planned. Prior to the drive, both Cransford and Outwood were targeted with ISEM emulator and HRC, to better constrain their lithologies and potential for future drilling, and an HRC mosaic was taken of the Skinningrove area.

Sol 7. (9th November 2016) – positioning for drilling

Following the sol 6 drive, the rover was correctly positioned at the Skinningrove target in an area of loose sediment with a light cover of small (cm-scale) pebbles and cobbles. The aim of the sol 7 plan was to characterize the location in detail, prior to making a decision exactly where to drill. It became clear during tactical planning that being able to position the rover on a precise spot would be difficult, but was required – we did not want to choose a drill location with a large cobble or surface fracture that could damage the drill. Although the rover has good visual odometry capabilities, this technique is less accurate if turning, so the SWT felt that specifying a drill position based on mast instrument data, and then asking the rover to drive more than a few tens of centimeters to reach it, was too inaccurate. Given that the drill is attached to the rover body (at least, it will be for ExoMars rover and so this was assumed for the purposes of the trial), rather than being on a robotic arm, the contact point of the drill with the ground cannot be imaged directly with ExoMars' mast instruments. This means that, without moving the rover, the specific drill location can only be imaged with CLUPI, which is mounted on the drill casing (Josset et al., 2012) or using HRC via the 'Rover Inspection Mirror' (Coates et al., 2017).

The SWT devised a CLUPI-based tactical plan that enabled a reasonably large area of ground near the rover to be imaged, but which retained the ability for the rover to return to the chosen location precisely. The plan involved moving the rover backwards ten times in 10 cm steps, acquiring a vertically-targeted CLUPI emulator image at each step. The aim was to create a long swathe-like mosaic of CLUPI images that would allow the surface to be analyzed, and so that any location chosen in that swathe could be returned to simply by driving the rover forward with no turns (the most accurate driving mode) a certain distance. In addition to this CLUPI emulator mosaic, several ISEM emulator measurements of the surface near the rover were planned in order to analyze the mineralogy of the surface materials. The final targeting request was for an early morning full color WAC mosaic of the Big Mesa to image it in optimal lighting conditions.

Sol 8. (10th November 2016) – drilling and observation of drill tailings

Sol 8 was the last sol of daily tactical planning. The CLUPI emulator mosaic returned following sol 7 activities revealed that a small miscalculation was made in the drive distances, such that each drive step was a few cm longer than the field of view of the CLUPI emulator images. Hence, the image mosaic was more of a 'ladder' than a swathe. Nevertheless, the 'CLUPI ladder' was still fit for purpose, and allowed a drill location (target name: 'Poddington') to be identified that was clear of large clasts and on a straight forward path for the rover. The tactical plan for sol 8 was complex: the first science block involved pre-drive imaging with HRC and ISEM emulator of Poddington and acquisition of an early morning WAC color image of Big Mesa, as a final 'press-release' style image. Next, a short forward drive of 20 cm was commanded, followed by CLUPI emulator imaging of the Poddington drill site. The next set of commands was the drill and sample sequence, and then CLUPI emulator imaging of the drill tailings. This was followed by a second reverse-direction drive of 20 cm, and then by a second science block including ISEM emulator, HRC and multispectral WAC imaging of the drill tailings to provide information about the composition and texture of the subsurface material. Finally, the drill core was imaged using CLUPI and analyzed with the Raman spectrometer.

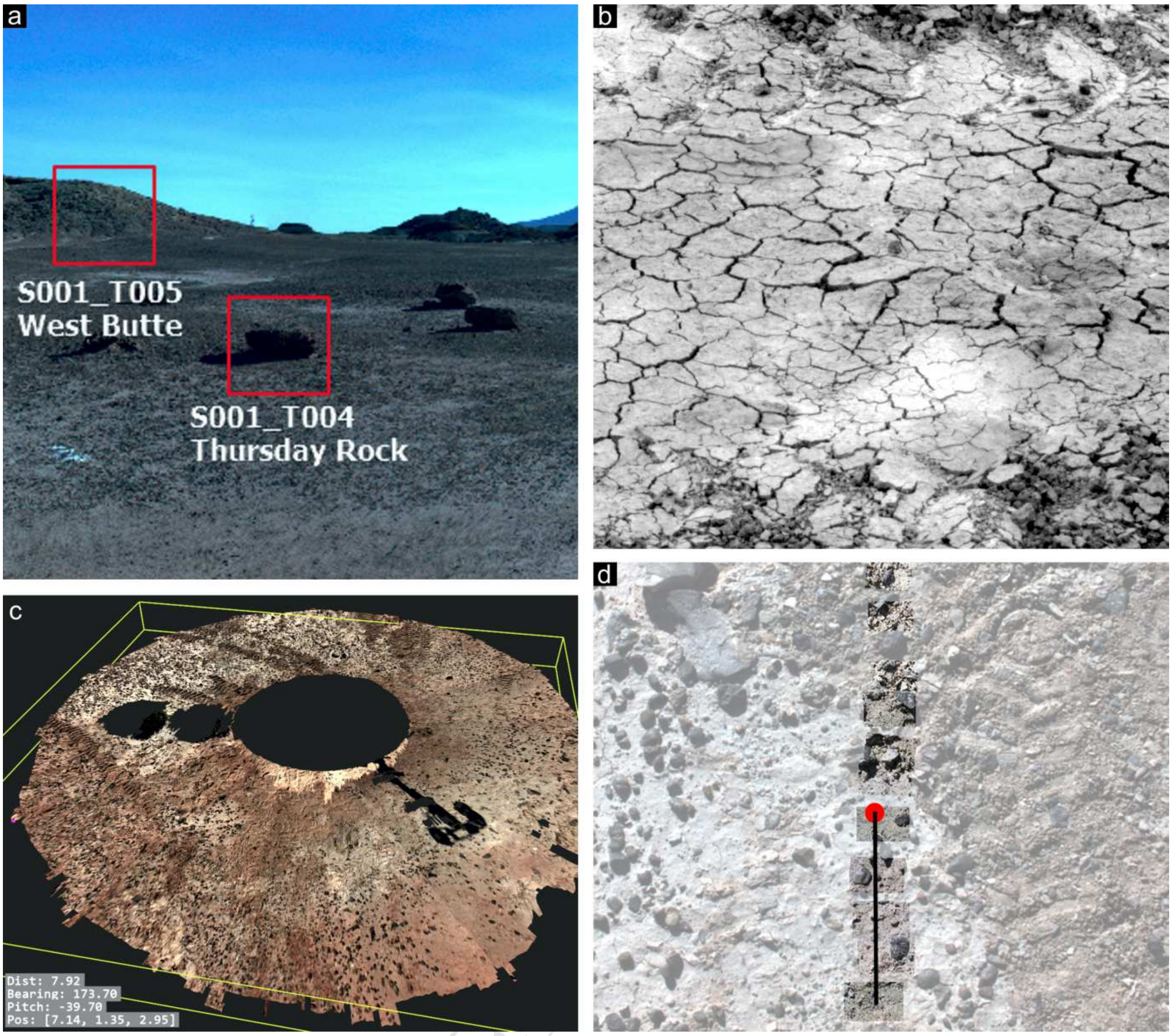

Figure 15. Target examples. a) Sol 1 targeting example showing HRC field of views and target names and codes superposed on a portion of the sol 0 color panorama. b) The sol 2 HRC 'drive-by' image of the Bourton area – this image showed that Bourton was surficial materials and not bedrock. c) PRo3D scene of the local workspace near the rover as the SWT prepared to select the final drill site. PRo3D allowed size and distance to be measured accurately. The two dark circles to the left of the image were vegetation. d) Images from the 'CLUPI Ladder' superposed on a plan view, re-projected WAC color image. The red circles shows the chosen drill target location and the black line the drive distance required to reach that point.

Sol 9. (11th November 2016) – post drill analysis

On sol 9, the data from sol 8 were returned and analyzed by the SWT. The returned core samples were rather friable, and broke into several sub-rounded pieces during extraction. Nevertheless, Raman analysis was still possible, and analysis of the drill-hole debris cone was also performed.

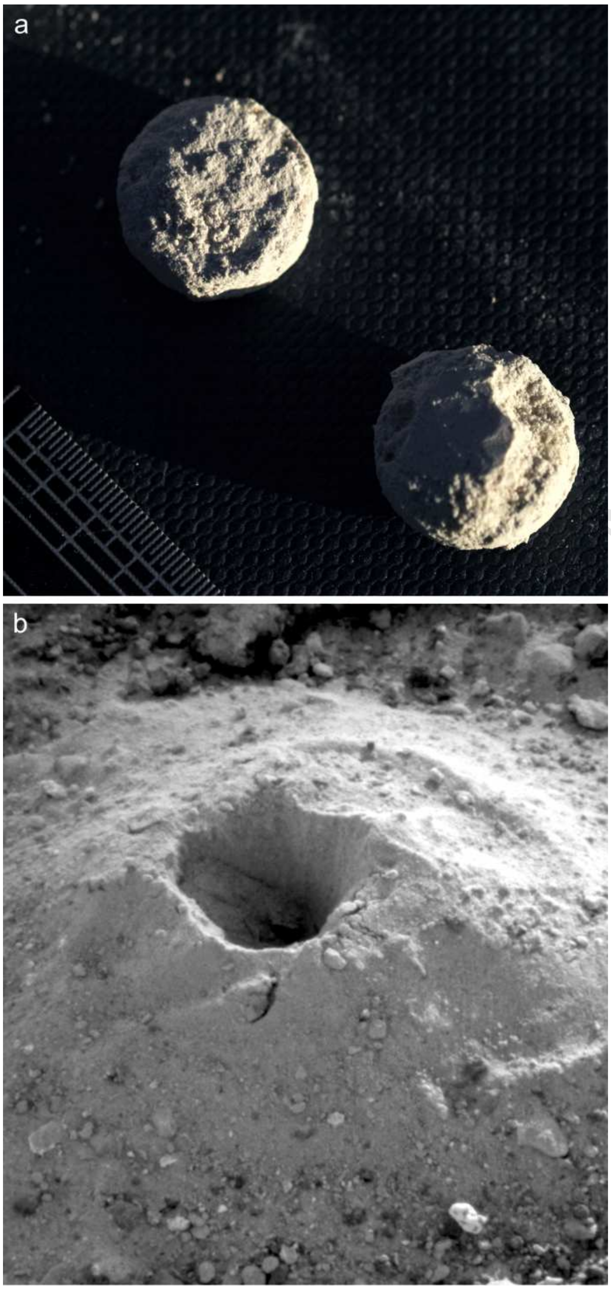

Figure 16. Results of drilling. a) Small parts of drill core obtained. Scale bar lower left is in mm. The CLUPI emulator image of the drill core pieces showed that they contained many fine sand-sized

grains, and were not mudstone as had been predicted. b) The 'drill tailings' that resulted from the drilling. This debris pile was actually constructed by the field team to mimic a real drill-core debris cone as the majority of the depth of the excavation was made using a spade, not a deep drill-corer for reasons of field efficiency. Only the final few centimeters of the excavation was done with a corer. The debris material was obtained from the bottom of the excavation to provide a realistic material sample.

6. Rover science results

During the 9 sols of the ExoMars rover-like mission, the MURFI platform traversed ~100 m and made multiple observations and measurements that were discussed and analyzed by the SWT. These discussions built upon the current working hypotheses from the pre-mission satellite mapping. The MOC team quickly realized that the majority of the bedrock and float rocks were easily identifiable as sedimentary rocks. In order to remain true to the simulation, the MOC team had to overcome certain challenges, such as how to estimate grain sizes and bedding thicknesses, key factors in determining geological provenance. For example, the size of float rocks were estimated from CLUPI emulator images which also included the rover wheel (of known width), and the heights of larger outcrops were correlated to the topographic measurements recorded from satellite data.

6.1 Key mission observations from stand-off instruments

6.1.1. Imaging instruments

The following observations and interpretations were made by the MOC SWT:

(1) The loose float rocks (e.g. Figure 17a) that occur on the plains are compositionally immature and poorly-sorted rounded pebble fragments up to 2-3 cm in diameter (fine to coarse gravels), with occasional larger clasts (rarely larger than cobble size). They are likely water-lain sediments from laterally unconfined modern flood event(s), although it could not be determined whether they were from proximal or distant sources. The grain size of the local soils also could not be determined, but the presence of surface mud cracks indicates that soils were at least partially composed of mud-grade material. It was also unclear whether the local soils had largely been transported (e.g., through flood events) or were the altered surfaces of bedrock, although the SWT generally favored the first interpretation based on the observations of extensive modern drainage morphologies in the area.

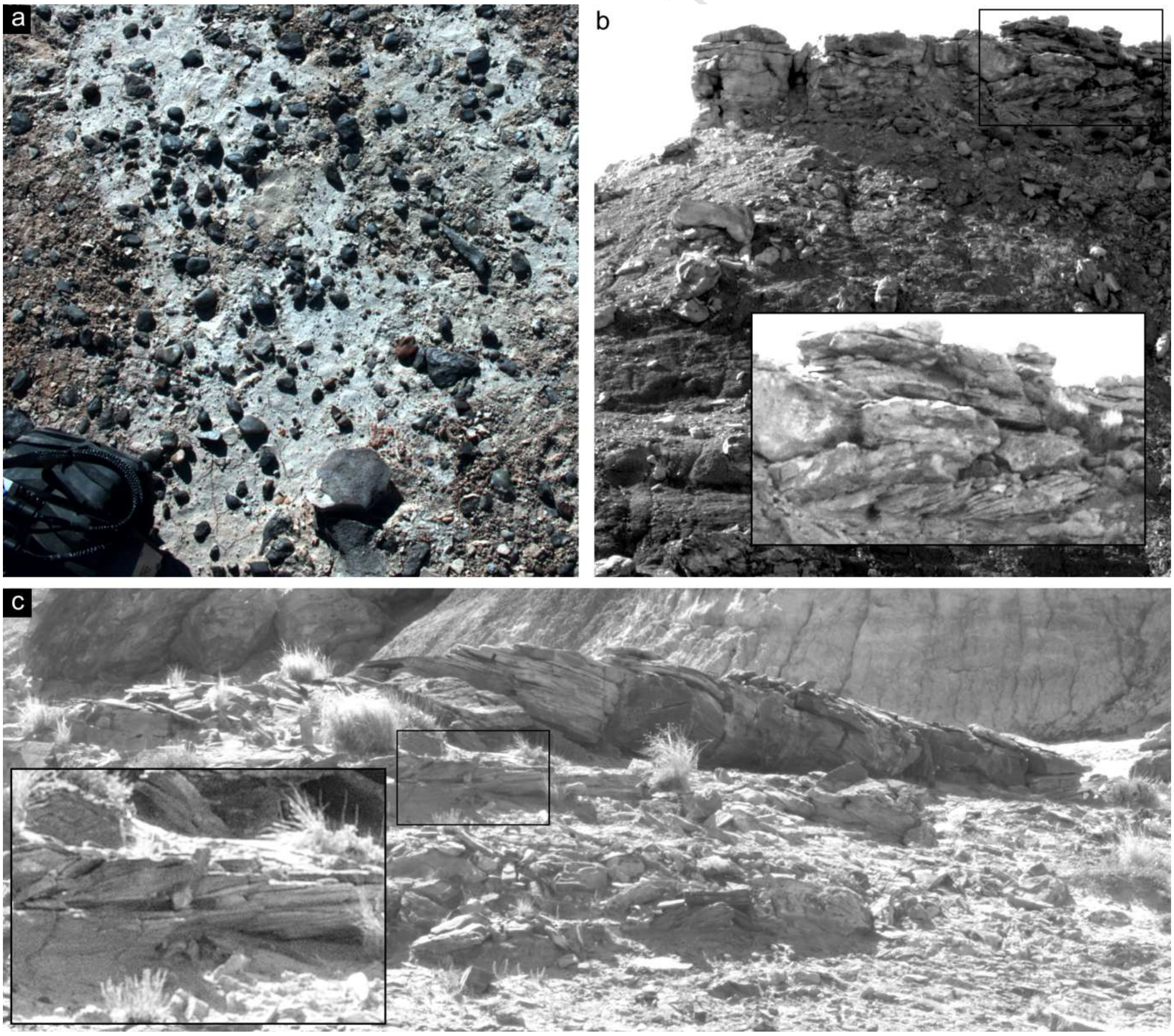

Figure 17. Example science observations and interpretations. a) AUPE image of float rocks and surface texture. Note rover wheel for scale. b) HRC image of resistant material on top of Big Mesa. Layering can be seen, as well as probable crossbedding (inset). This material was therefore interpreted to be a sandstone. c) HRC image mosaic showing more possible cross-bedding (inset) in the 'Wimblington' target area. The SWT were not convinced this outcrop was in-situ, however.

(2) A resistant and blocky material occurs on top of ridges and buttes within the study area (Figurer 17b), and the same materials are seen as piles of rubble at the base of scarps (e.g., locations designated as Big Mesa, Wimblington, and Cransford) as seen in Figure 17c. The location of this material correlates with the Resistant Formation observed in the pre-mission satellite mapping. The Resistant Formation generally sits on top of a more erodible layered material (correlating to the Layered Formation observed in the pre-mission satellite remote sensing mapping), which it has possibly protected from erosion. Within the Resistant Formation, both cross-stratified and planar bedding are visible, which are probably up to tens of cm thick (Figure 17b). Although the cross-bedding generally appears tabular, the possibility of it being trough cross-bedding could not be ruled out with the available data. The presence of cross-stratification indicates that much of the Resistant Formation is sandstone, and therefore of probable fluvial or aeolian origin. Whether the sandstone was fluvial or aeolian could not be determined without further grain size analysis, and no diagnostic pebble-grade or larger materials were observed. Fluvial sandstones would be consistent with the conclusions from satellite mapping, and support the idea that the sinuous ridge landforms were inverted fluvial channels. Wavey, non-parallel bedding of lamination-scale was also observed at Cransford, as well as recessive interbeds (Figure 18a-c). The recessive interbeds here and elsewhere could be eroded mudstones/siltstones or

finer-grained sandstones, suggesting that the Resistant Formation may have been deposited in a variety of different sedimentary environments.

(3) Within the Layered Formation that is exposed at the edges of Big Mesa and the more distant ridges (Figure 18d), layering is visible at the scale of the outcrops (meter-scale), but finer scale bedding or laminations are not observable. Color variations (Figure 18e) between white and dark – sometimes reddish – layers within the Layered Formation suggest geochemical (e.g., Fe^{3+} content) or lithological variations between the layers, possibly due to different depositional environments. However, AUPE multispectral data (Figure 19) revealed spectral consistency across the face of Big Mesa, despite the apparent color differences. The dominant spectral feature observed was the Fe^{3+} crystal field absorption band superimposed on a steep ferric absorption slope between 350 and 1000 nm. These features are present in all layers in Big Mesa.

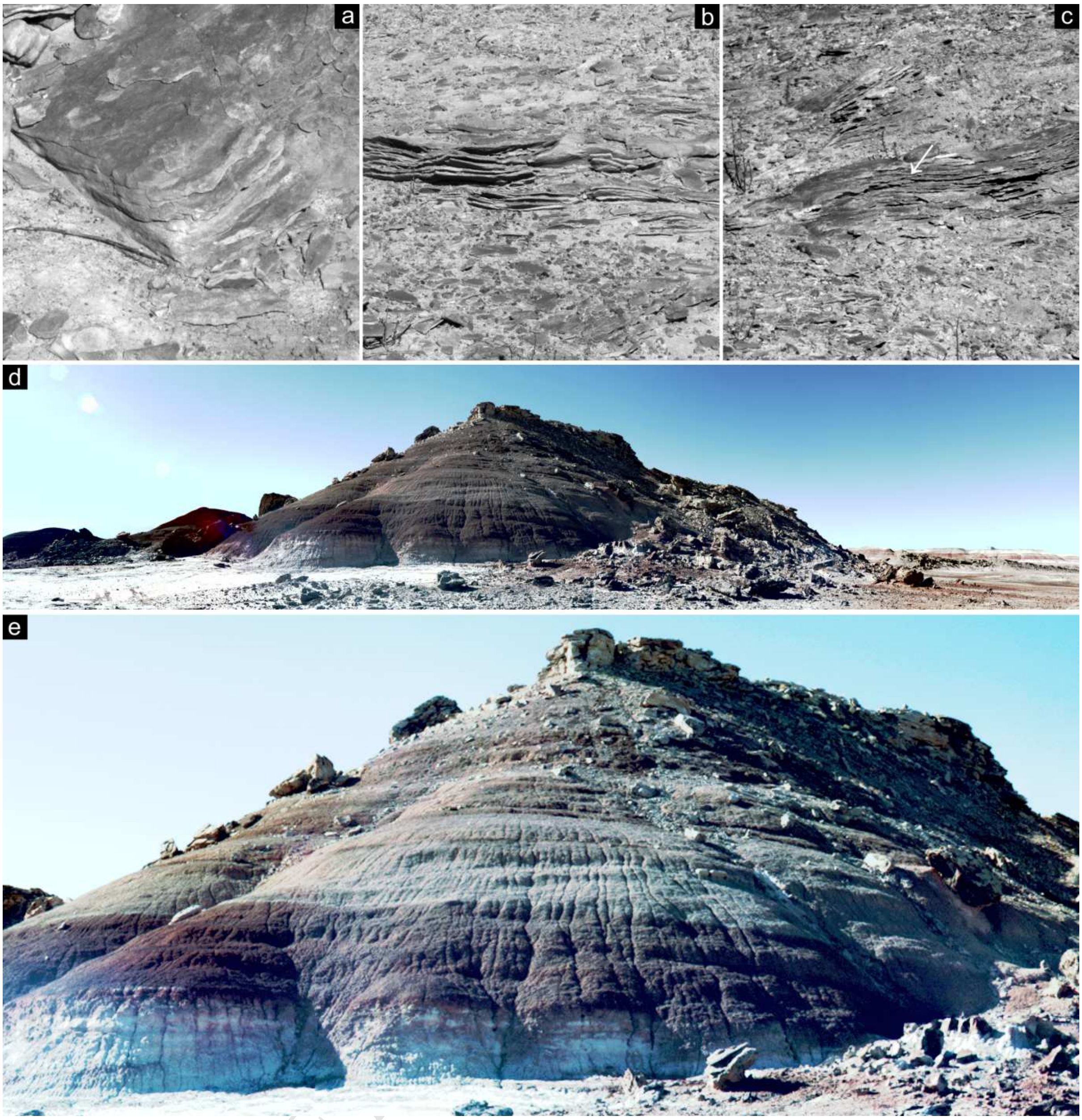

Fig. 18. Examples of science outcomes. a) HRC image of a portion of the 'Cransford' target, a layered outcrop of areas of soil overlying areas of apparently in-situ bedrock. The bedrock areas comprised 15-20 cm thick (based on PRo3d measurements) layered exposures, each composed of thickly laminated or finely bedded material interpreted to be sandstone. b) HRC image of another part of Cransford showing recessive interbeds. c) HRC image of a third area in Cransford, showing possible cross cutting, non-parallel bedding (arrowed), and possible subtly undulating bedding (right of arrow) d) WAC color mosaic of Big Mesa, showing the Resistant Formation (top, and materials shed to the sides) and the Layered Formation (lower part of outcrop, showing bands of whitish, brown and red

material; interpreted to be much finer material), making up for the majority of the scene. At the far right of the scene are similarly colored layers in the distance. Note that sun-angle was consistently poor for imaging Big Mesa. e) Color-stretch close-up of the layering in Big Mesa, showing at least four different tonal-types, and highlighting the modern rill-forms that incise the outcrop. Big Mesa is ~ 22 m high.

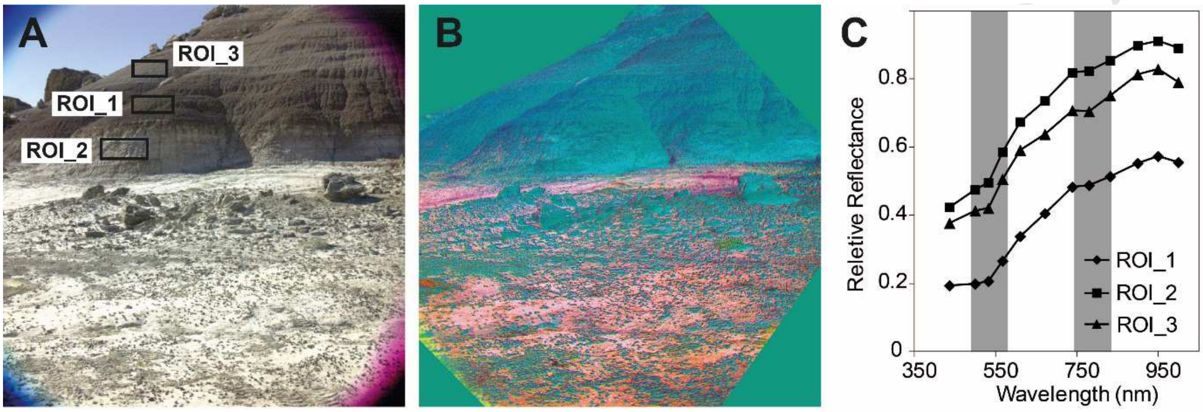

Figure 19. WAC Multispectral results. a) Enhanced color AUPE WAC image of Big Mesa showing location of Region of Interest (ROI) targets. b) Principal Component Analysis (PCA) false-color Left-WAC AUPE image using RGB filters, revealing Big Mesa to comprise spectrally-similar material. c) AUPE spectra extracted from the three ROI targets, all with a strong absorption at 530 nm and a weak absorption at ~800 nm.

Much of the surface of the Layered Formation had been modified by modern erosional processes, and many rills incise it (Figure 18e). Most surfaces are covered in weathering products (and even when the field team scraped away this surface they found significant alteration to several cm's depth). Hence, it was difficult for fresh surfaces to be analsyed. The SWT working hypothesis by mission-end was that the Layered Formation is made up of mudstones, clays, or marls, which are all formed in low-energy environments. The Layered Formation was thus considered to have formed in a more effective environment for preserving biomarkers and organic materials than the Resistant Formation (probably a sandstone) and therefore sampling material from the Layered Formation was the agreed goal for the drilling. The overall paleoenvironmental working hypothesis for the site, based on both the satellite remote sensing and rover observations, was that the Resistant Formation represents the deposits of an ancient fluvial channel, while the Layered Formation represents an associated flood plains environment.

6.1.2 Spectrometer results

Data from the ISEM emulator (Figure 20) revealed ~ 2.21 and ~ 2.34 µm absorption bands in material analyzed from the accessible, Anomalously Bright unit in the 'Painswick Patch' area chosen for drilling. The 2.21 µm feature is characteristic of Al-bearing phyllosilicates such as montmorillonite and kaolinite, whereas the 2.3 µm band is typical for Fe/Mg-bearing smectite clays such as nontronite and saponite (e.g., Bishop et al., 2008). While it is not possible to distinguish between these phases using these bands alone, the strength of the absorptions and their presence in the majority of targets analyzed suggest that phyllosilicates form a core component of the Anomalously Bright Unit. Finally, ISEM emulator data (Figure 20) identified the same Fe^{3+} absorption band at 0.53 µm as the ferric absorption slope identified in the AUPE multispectral data from Big Mesa (Figure 19c). This spectral consistency further supports the hypothesis that the brighter surficial material has the same source as the surrounding mesas.

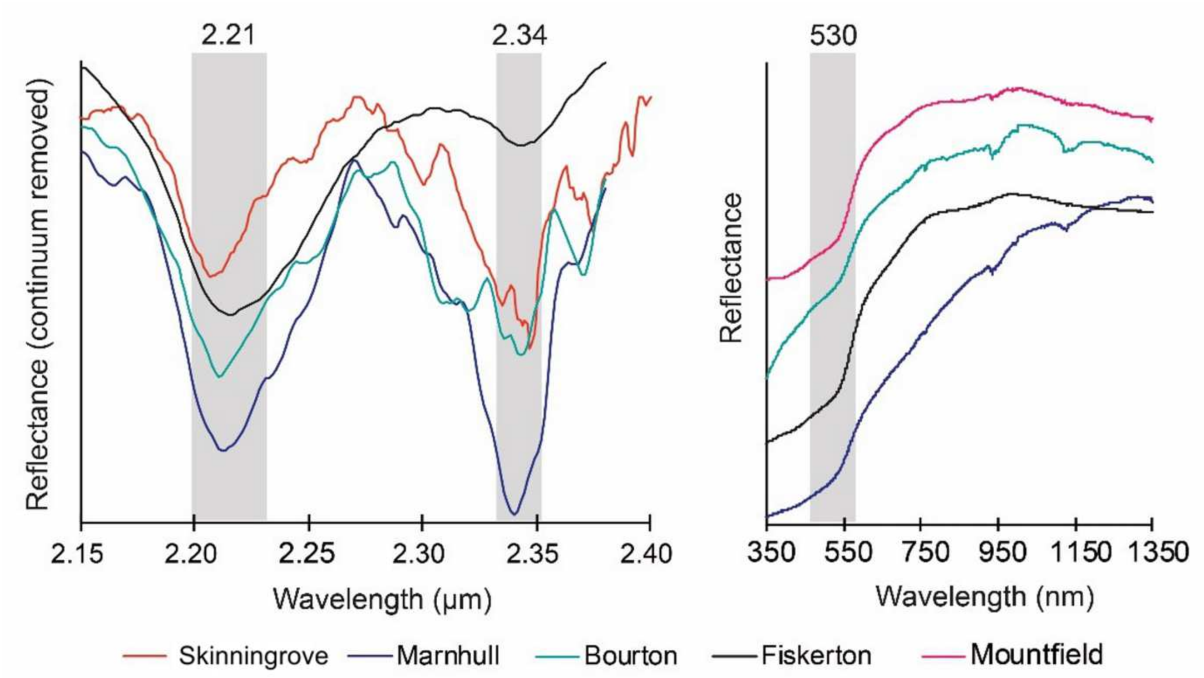

Figure 20. ISEM emulator reflectance spectra in the short-wave infrared (left) and visible to near-infrared regions (right) for a variety of targets. Fiskerton is a ground-surface target of soils containing mud-cracks analyzed on sol 1; Marnhull is a small boulder set within soils, Mountfield an area of anomalously high albedo soils, and Bourton a large patch of high albedo material analyzed during the 'drive-by' analysis – all were analyzed on sol 2; Skinningrove is an area of ground containing the drill site, analyzed on sol7.

6.2 Drill site selection and science outcome

The last commanded activities of the ExoMars rover-like mission were to drill into the 'Skinningrove' target in the high albedo Painswick Patch area, and to analyze the returned sample. Based on rover observations, the SWT developed three working hypotheses to explain this material and its relationship to the Layered Formation: (i) it is bedrock, and part of the Layered Formation; (ii) it is surficial material, possibly an evaporite formed above a low permeability layer, and (iii) it is surficially altered bedrock (a combination of the first two hypotheses). The detection of montmorillonite, which can form as a weathering product, here was important, as it was consistent with either of the latter two working hypotheses. The SWT thought that the third option was most likely, and chose this area for the drill site: the justification for this decision being that if this area contained clay-rich mudstones (accessible at the surface or just beneath the weathered surface) they would then be an ideal environment for biomarker preservation and concentrating organic material, making them good sites for drilling (as discussed in Vago et al., 2017).

The core returned was observed with the CLUPI emulator instrument and then analyzed using the Raman spectrometry instruments. In the CLUPI emulator images, the core extracted did not appear to be a mudstone, or other very fine grained rock, as translucent rounded grains were visible – suggestive of quartz sand grains. Although the core was visibly friable (being fractured into small pieces, and not maintaining a core-like shape), it was impossible to tell how competent the material really was, so the inference, based on CLUPI images, was that this material was a poorly-cemented sandstone.

As the final action of the MURFI ExoMars rover-like mission, Raman spectrometry of the core sample was performed on site. The sample was divided into three pellets, each of which were measured with 30 acquisitions using 1 second acquisition times. The Raman spectra showed two distinct minerals within the sample material (Figure 21). Each pellet showed a strong quartz band with the characteristic sub bands. The main band of calcite was visible with drill core 2, also showing the clearest sub bands to confirm the identification. Further observation points on the sample surface did not reveal any other distinct mineralogy, showing either quartz or calcite or a combination of the two.

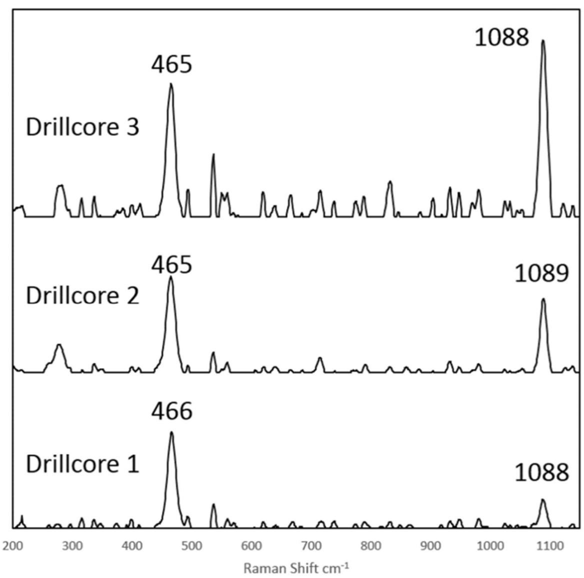

Figure 21. Representative Raman spectra from the three drill core pellets. Spectra have background and fluorescence subtraction with all negative values set to 0. Wavenumber 466 cm^{-1} indicates quartz, will 1088/1089 cm^{-1} indicates calcite.

The results from both the CLUPI and Raman emulator instruments supported the inference that the drill core was a quartz-rich sandstone, not the predicted mudstone or siltstone. Hence, we assumed that either the assumptions made about the bright material composing the Layered Formation were incorrect, or that the drill did not penetrate into bedrock associated with the Layered Formation, instead sampling a more modern deposit, such as a salt pan or poorly cemented juvenile sediments. However, post-mission laboratory-based Scanning Electron Microscope-Energy Dispersive X-ray (SEM-EDX) analyses of the core samples showed different results: SEM-EDX analyses on the drill core confirmed the calcite and quartz identification and, in addition, revealed the presence of substantial amounts of a Potassium/Aluminium-rich clay – possibly Illite. These results suggest that the sample consists of fine grained quartz sand, cemented by both abundant calcite and clay, so potentially a more interesting astrobiological target than first thought. However, given the limitations of the MURFI instrument suite, it was still not possible to determine if this material was bedrock derived, or simply a poorly consolidated recent deposit, perhaps some form of salt and clay pan which encloses fine sand.

For the purposes of MURFI, the extraction and Raman analysis of the sample was considered mission success. With more time, and perhaps a fuller range of emulated instruments, it is likely that similar conclusions could have been drawn from the MURFI analyses as those obtained from the lab-based analysis, and perhaps even a better understanding of the lithology of the sample material. This conclusion once again highlights the difficulties of performing sample acquisition and analysis remotely, compared with laboratory-based analyses using more flexible and more easily deployed analytical tools.

7. Public Engagement

Public engagement during the MURFI investigation was carried out directly by the MURFI team with assistance from the UK SA and the UK Science and Technology Facilities Council (STFC). Mission planning from the outreach perspective also included engaging with the CSA, and in particular obtaining clearance and support to use the MURFI mission patch.

The use of the MURFI logo and mission patch (Figure 22) was one of the successes of the mission. The value of a good logo cannot be understated, as it provided both a vehicle for the whole team to get behind, and also a key mechanism for engaging with the public. The mission patch was also included by the UK SA and STFC as part of their 'National Colouring Book Day' contribution during the summer of 2017, encouraging children to reimagine the patch design and learn about the missions behind it.

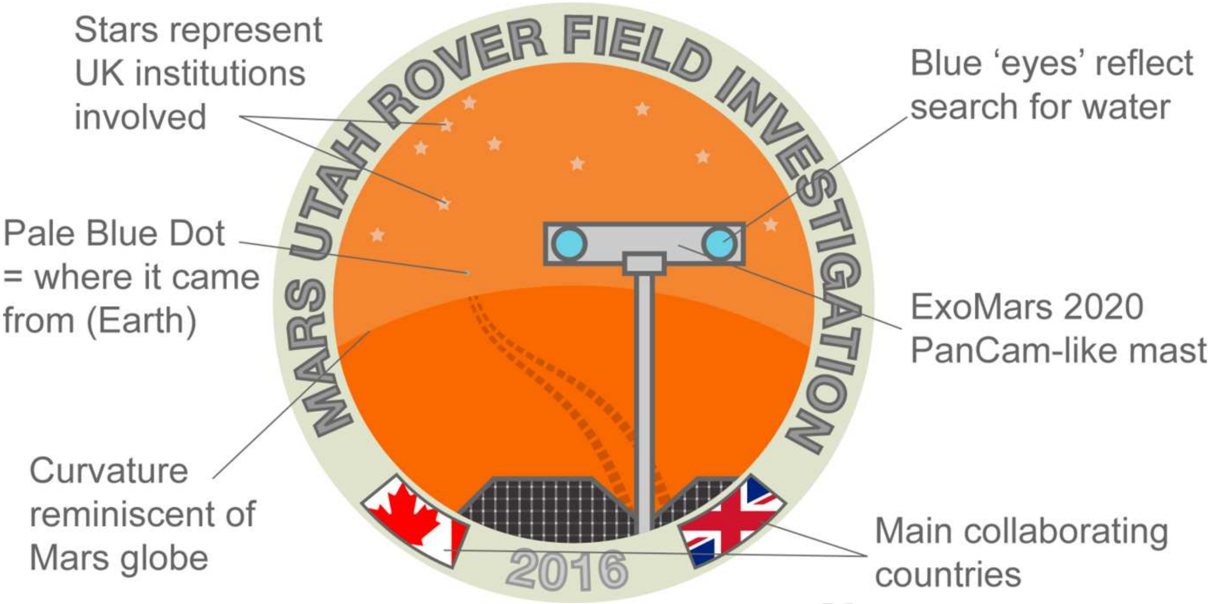

Fig. 22 The MURFI 2016 Logo, including annotations describing the design philosophy.

During the ExoMars mission phase a blog was generated which saw over 20 posts and 5000 views from 1000 visitors in 24 countries to the site (https://murfiblog.wordpress.com/). Additionally, the field trial used a Twitter hashtag (#MURFI). Again the mission name and logo proved extremely valuable in making connections to the wider public. The twitter feed had over 185 posts by 77 different users across the UK planetary science community, achieving a reach of 352,105, and nearly 800,000 impressions. Media coverage of the mission included mentions and feature articles published online through the BBC, The Guardian, New Scientist, Space.com, the UK SA blog, Medium, the TED Blog, and Science Made Simple, whilst the BBC's Sky at Night filmed the MOC operations for their November Mars edition.

There were several visits to the MOC by a variety of different organisations. This was encouraged by the location of the MOC within the larger building – the MOC has a transparent wall (although this can be made opaque) such that operations could be observed by any visitors to the building. Some of the organisations visiting, planned or otherwise, included chancellors of several universities, the Chilean Minster for Science, two NASA technologists, observers from ESA and numerous other organisations based on the Harwell Campus.

At the field site in Utah, visitors included representatives of several other space agencies, representation from Salt Lake City, US government departments and military units in the vicinity, as well as many tourists in the region, both US and foreign.

8. Discussion and lessons learnt

The MURFI trial was very successful both in terms of delivering a mission-like operations experience and learning about the logistics of planning future rover field trials. The site chosen for the trial allowed a range of activities and had a suitable variation of geological features to make it interesting. MURFI benefitted greatly from being a joint activity with the CSA MSRAD trials, and their logistical assistance was a large part of MURFI's success.

8.1 Use of rover-based instrumentation during the MURFI ExoMars rover-like mission

The way the team used the MURFI instruments provides insight for how the instrument suite might be used during the ExoMars rover mission, and also for future field trials. Like rover missions sent to Mars, the acquisition of stereo NavCam panoramas at the end of each drive was vital for planning target acquisitions for the next sol, especially when data downlink limits precluded the use of full color stereo AUPE panoramas. The MURFI SWT requested multi-filter AUPE images only of smaller areas, when there was a science need for multispectral data, or when there was sufficient data downlink availability. HRC was widely used in the MURFI ExoMars rover-like mission. The use of HRC image mosaics of the Resistant Unit allowed inferences about the lithology to be made from observations of the bedding. HRC mosaics were used to analyze the landscape in the medium to far field, and individual HRC images were also used in the near field to analyze the local area to prepare for drilling, or obtain more detailed information about outcrops. HRC was a vital tool for MURFI, and its variable focal length made it useful for both strategic level decision-making (which general direction to head in) and for daily tactical planning (where exactly to set the rover to obtain a drill core). Single HRC images were also used to check the location and orientation of the rover against panorama images.

The team made extensive use of downward-looking CLUPI images for drill targeting, but sideways looking CLUPI images were also used to examine outcrops and the landscape in general, when rover pointing allowed. The high resolution and full color capability of CLUPI images were particularly suited for analyzing outcrops to determine grain size and detailed sedimentary structure.

Although almost all observations were made via targeted, precise direction of the instruments based on their position within the NavCam mosaic or a PRo3D scene, the SWT also commanded a single untargeted imaging session of the Bourton area as part of a 'drive-by' tactical plan: this was very useful for testing ways to maximize the efficient use of limited time resources.

Overall, we found that the stand-off instruments used on MURFI had complementary strengths and different weaknesses, such that targeting them as a suite gave a huge benefit. We feel that rehearsals and trials such as the MURFI ExoMars rover-like mission, in which the instruments were together, and with targeting performed holistically across a wide working group, are vital for allowing a rover team to work out how to operate efficiently and effectively.

8.2 MURFI ExoMars rover-like mission: assessment of geological interpretations and planning decisions made by the SWT

8.2.1. Initial satellite remote sensing mapping

The hypotheses built using the Mars-equivalent satellite remote sensing data were vital for the mission and provided a framework to test other observations against. After the MURFI mission, we compared the satellite remote sensing observations with field observations provided by the MURFI field team, the results of past studies of the geology of the MURFI site in the literature, and direct observations made during a post-mission visit to the MURFI site by some members of the SWT. The interpretations made from the satellite remote sensing broadly matched those made by the field team, as well as the conclusions from the literature: the overall interpretation of the landscape comprising inverted fluvial channels and flood plains deposits was confirmed.

The prediction made from satellite remote sensing of layered plains with interbedded resistant layers was also broadly correct, matching previous observations of the Brushy Basin Member of the Morrison Formation (Heller et al., 2015). One hypothesis put forward during satellite remote sensing mapping was that the Layered Formation is a mudstone, with significant geochemical variation. However, this was not supported by either the MURFI drill results or rover observations (which found many the Anomalously Bright Unit to be composed of sandy material, and little variation in WAC multispectral images across the colored layers). Furthermore, based on MURFI rover data, the color differences in the Layered Formations did not appear to be strongly associated with significant differences in mineralogy or the depositional environment. However, the color differences are actually indicative of palaeosol weathering variations that reflect complex variations in local and regional paleoclimate and paleoenvironment (Demko et al., 2004). It is possible that similar conclusions could have been reached using the MURFI instruments and platform, given a long enough mission and the collection of multiple samples. However, it is unlikely that orbital remote sensing analyses using Mars-like data alone could be expected to tease out these details. *Lesson learnt: geology is complicated, and satellite remote sensing conclusions can obscure these complications. However, a combination of satellite remote sensing and rover-scale observations is needed to interpret the geology of landing sites correctly (see also, for example, Stack et al., 2016).*

The difference in the image resolution between satellite remote sensing data and rover observations meant that detail was easily overlooked at the start of the mission. For example, the initial direction in which to drive was determined mainly on satellite remote sensing interpretations, primarily that Big Mesa outcrops might show lithological, geochemical or mineralogical variation, and possible layered bedrock. However, several small outcrops visible in the initial panorama and close to the rover would have provided clearer indicators of the palaeoenvironment. These outcrops were actually visible in the Mars-like remote sensing data, but the small-scale of mapping required to cover the whole landing site meant that they were amalgamated into a larger unit, rather than being highlighted as specific bedrock areas. *Lesson learnt: to provide the best possible chance to make good strategic decisions, large-scale geological, science target and hazard mapping using full-resolution satellite images of the area around the landing location should be conducted as rapidly as possible, as soon as the landing location is known.*

The initial landing site assessment included analysis of rover-scale hazards such as slopes, modern fluvial channels, loose materials, and boulders and rocks. Even with the sub-meter pixel size images available, we could not measure the distribution of loose material or small cobble-grade rocks (potentially relevant to rover traversability), as they are below the pixel size. During post mission field observations we were consistently surprised by the distribution and diversity of surface textures (some traversable, some not) compared with the satellite remote sensing images. For example, in the field we have observed soft ground with a lag of 2-3 cm diameter pebbles, cloddy friable ground, and regions of densely packed cobble-sized clasts, all of which appeared featureless, although of different colours, in the highest resolution satellite data. *Lesson learnt: a robust practical understanding of the rover platform traversability capabilities, tested against as wide a variety of analog surfaces as possible, is essential, because even 25 cm/pixel (HiRISE) data provide little information about the true surface type. Hence, stand-off ground-based observations will be more important for determining whether or not an area is traversable.*

8.2.2. Rover-based observations

The interpretations made from the satellite remote sensing data were broadly supported by observations from the rover-based instruments, and in general our working hypotheses developed during MURFI were supported by post-mission fieldwork and previous field studies. As mentioned above, the largest area of misinterpretation was in the identification of the layered terrains as being probable mudstones, when post-mission field work showed that they contain many examples of sand-grade materials and only mud/silt-stone beds to a much lesser extent. *Lesson learnt: grain size of a sedimentary rock – a vital measurement for* *inferring depositional environment – is difficult to measure from a rover, and nearly impossible from orbit.*

Another area where, post-mission, the MURFI field team advised the MOC SWT that a mistake had probably been made, was in the failure of the SWT to better investigate a rocky ridge only a few meters to the northwest of the landing site as their first priority. In fact, the SWT did not request any further targeted data of this feature other than the original sol 0 panorama. Post-mission field work confirmed that this feature, composed of cross-bedded sandstones and conglomerates, would have provided definitive information about the palaeoenvironment (i.e., this was a fluvial sandstone, so deposited in a river). This omission was partly due to the perception that the variety of textures seen in the larger Big Mesa outcrop to the south would provide answers about more elements of the landscape, but also due to the smaller features appearing to be composed of out-of-situ blocks in the panorama. In fact, the SWT should probably have realized that even if these blocks were not in-situ, their meter-scale size meant that they probably were local to emplacement source, and so could have provided important information. *Lesson learnt: small outcrops can provide important information, and spectacular, larger outcrops can deflect attention from more important targets. A balance must be struck that can probably only be determined during the mission itself – but field trials can give important training for making these decisions.*

A similar issue identified by the field team was that, although the SWT used HRC image targeting very effectively to search for sedimentary structures, several opportunities to identify sedimentary structures and layering – and even cross-bedding – were missed. One example of this was a feature called ‘West Butte’, in which the HRC targeting missed the cross bedding hinted at in the WAC panorama. *Lesson learnt: even though tactical* *planning is time-constrained, all images should be examined carefully to avoid loss of potentially informative targeting opportunities. Making time for whole-team science discussions during a planning day is vital.*

Post-mission, some of the MOC SWT 'walked the MURFI traverse' in the field. One of the biggest surprises was how close targets appeared when viewed in situ, compared with when examined in panorama images returned by the rover. This was partly compensated for by using PRo3D, but it was still very hard to get a correct sense of scale and distance. This problem also probably contributed to the rocky-ridge and West Butte issues mentioned above. *Lesson learnt: the projection of panorama summary products can be misleading, and wider use of 3D visualization, and even virtual reality viewing platforms, should be made.*

8.3 Lessons learned from MURFI for ExoMars rover operations.

The mission style, pre-mission geological mapping, the instrument suite deployed, and data returned during the MURFI ExoMars rover-like mission were sufficiently close to the real ExoMars rover payload and mission to give the team insight into how the ExoMars rover might operate. A key responsibility of the ExoMars science team will be to characterize the local geology well enough to provide the mission with the best possible targets for sampling, such that science questions can be answered to further the overall objectives.

The satellite remote sensing mapping provided vital context for the MURFI ExoMars rover-like mission, and, once the landing site point was determined, provided specific constraints about how the mission might progress, as it highlighted possible science targets and likely hazardous areas. Also, although the satellite remote sensing mapping was done in a very short time period, the relatively small size of the area mapped and the high degree of planetary mapping experience available within the team allowed useful maps to be generated quickly. Almost complete HiRISE coverage of both candidate ExoMars landing sites is now available, so very high resolution mapping should be possible for ExoMars once the landing location is known. *Lesson Learnt: once the rover landing position is known, rapid, high quality geological mapping, at full HiRISE-resolution scale, will provide a vital resource for shaping the mission.*

A corollary to the previous point is that although the satellite remote sensing interpretations were broadly correct, the rover-based measurements demonstrated some mistakes or misidentifications in the satellite image based mapping. Also, the initial decisions of the SWT to head south to Big Mesa, rather than focussing on small outcrops nearby was perhaps a mistake, and may have been exacerbated by the satellite remote sensing focus on mapping the whole study area before the precise landing position was known, and so by necessity omitting some detail in the local area. *Lesson Learnt: satellite remote sensing can only provide certain types of information, and a combination of wider context mapping, and very highly detailed local mapping is preferred. Still, care must be taken to examine ground-based images before making decisions based on satellite remote sensing data.*

During the ExoMars rover-like mission, a challenge that quickly became apparent on MURFI was that of discriminating grain size without an arm-mounted, close-up imager. Although HRC was often used to search for sedimentary structures, both at centimeter scale in the near field and decimeter scale in the far field, it cannot resolve grains smaller than fine sand, even in the nearest field. This was a challenge when, for example, trying to discriminate whether observed cross bedding was occurring in an aeolian or fluvial sandstone. CLUPI, although possessing the required spatial resolution has a more limited field of view, with fixed positions with respect to the rover. Thus, obtaining close-up images of specific outcrop targets required rover movements, costly in power, time and planning resources. While this is not an insurmountable problem, it is an important lesson to learn: as the rover approaches outcrops, positioning it at the end of the drive in such a way that CLUPI will have the best opportunity for immediate observation will be important to save 'wasted' days of planning and rover movement. Here, the MURFI team felt that HRC played a complementary role: targets that would be imaged with CLUPI can be identified from range the sol before the rover approached. Also, the availability of Pro3D terrain models was a great help in planning these sorts of drives. *Lesson learnt: CLUPI can be used in a variety of modes that will be useful for understanding the local geology. However, the lack of close-up imager on an arm could be a challenge. The challenge can be lessened by careful rover positioning at the end of outcrop-approach drives, and use of HRC and 3D models of the workspace can assist greatly.*

As the drill is fixed to the rover body, positioning the drill precisely requires rover drives. If a post-drive CLUPI image of the surface drill target area shows the rover is already appropriately positioned, this will not be a problem. However, to obtain images of a wider area required rover drives to return to the identified spot. For MURFI, we did not have sufficient information about the driving precision of the ExoMars rover, so to minimise days spent on the imaging, planning, driving, re-imaging cycle, the MURFI team used a series of CLUPI images and very short rover drives to build up a mosaic of images showing the context for the drill location. If the ExoMars rover can return precisely to previous points, then this may not be necessary, but if precision driving is a challenge, or if the desired drill target is small, then the use of this type of multiple CLUPI imaging could be helpful. The WISDOM ground penetrating RADAR was not emulated for MURFI, so data from this instrument would also have to be taken into consideration in planning drill locations. *Lesson* *learnt: the 'CLUPI ladder' technique could be useful for the ExoMars rover to identify the exact spot for drilling, while also making it easy for the rover to return to that spot.*

Several MURFI tactical decisions were made to avoid 'wasting days'. This included the Bourton 'drive-by' imaging, learning to position the rover so that CLUPI would have a good field of view, and using the 'CLUPI ladder' to avoid multiple small 'drive, observe, decide' cycles. Given the high 'per sol' cost of a Mars rover mission (both in terms of actual financial cost, and in terms of counting down days until mission success) every day is vital. *Lesson learnt: a rover field trial team using a realistic mission instrument suite and a realistic mission goal can develop important practices that could improve the efficiency of the real mission.*

Finally, the decision made to drill at the Poddington location within the Painswick Patch area was based on the MOC SWT presumption from mapping and spectral data that the brighter materials seen here (the Anomalously Bright Unit in the mapping) were part of the Layered Formation and so were phyllosilicate-bearing, very fine-grained, fluvial deposits (thought to be flood plains facies) that should have been ideal preservation materials for biosignatures. The decision was also made under extreme time pressure, as the command to drill had to be fitted into the mission schedule. However, the core materials returned were friable, apparently containing sand grade materials, rather than being competent, finer mudstones or silt stones, and were considered by the team to be less high-value targets for an astrobiology mission than hoped for (i.e., not an organic-rich mudstone). Ultimately, laboratory studies showed that the drill sample did contain calcite and clay minerals, again reinforcing the difficulties in interpreting rover-derived data quickly during tactical planning: the MURFI mission only simulated < 10 sols of a wider mission. However, it was still not clear if the drill samples returned were weathered or friable bedrock, or porrly cemented, recently emplaced sediments. Better geological knowledge could have been derived from a longer, more thorough study of the site. This result demonstrates how important adequate geological assessment of the landing site will be to avoid 'wasting' drilling cycles within the mission. *Lessons learnt: (i) understanding local-scale geology is difficult, even with Mars-like remote sensing data and a suite of excellent rover-based instruments. To avoid drilling in the 'wrong place', the local geology must first be very well characterized, and this can require extensive data analysis and discussion within the team, as well as critical reanalysis of satellite data-based hypotheses. (ii) The results of the MURFI drilling also reinforce the benefits of end-to-end rehearsals of the sample acquisition and analysis chain, including laboratory analysis of representative drill samples to provide feedback to the rover-based interpretations.*

8.4 Lessons learned from MURFI for implementing future field trials

As a UK-led Mars rover field trial, the completion of the MURFI mission was itself a success, and a key element of the mission was learning where things had 'failed' or 'gone wrong', so as to enhance the ability of the UK to run future field trials. At the end of the mission, a debrief workshop was held at which participants aired their views about the success or otherwise of the mission. All felt the mission was successful in delivering its goal of providing a 'realistic' rover operations experience to the participants. Several areas for improvement were noted. One of the biggest problems identified was that few of the team could commit several weeks as one block of time, hence travel and accommodation proved a greater than anticipated logistical challenge. Some participants also felt that swapping roles so often was both stressful and inefficient, as they felt there was insufficient time to learn the role adequately to deliver what was needed. Others, however, felt that experiencing different aspects of the tactical planning was rewarding, and that it was important to explore the strengths and weaknesses of team members in a mission setting, outside of the ‘comfort zone’ of everyday scientific working. *Lesson learnt: future trials should ensure less frequent changes of role and require participants to commit to longer, but not too long, time blocks (e.g. 4 days).*

The choice of early- to mid-career scientists for SWTC meant that postdocs and research fellows were able to experience this leadership role. Of the five team members who spent time as SWTC, all agreed that it had helped them learn about their ability to lead a team under pressure, and given them ideas for how to improve their leadership skills. The postgraduate students who participated in the mission were keen that the MURFI investigation should be repeated, as they also were keen to try the SWTC role. *Lesson learnt: keep active daily leadership roles for early/mid-career team members.*

The available preparation time for MURFI was limited, and many participants felt badly prepared for their roles. This was especially true for those who were not able to attend the sol 1 rehearsal days prior to the official sol 1 planning meeting. Some found the technical aspects a challenge (e.g., processing data), while others did not quite understand the rationale of the ExoMars rover-like mission (e.g., why drilling from bedrock was required rather than sampling surficial fines from obviously fluvial environments). This was partly due to the disparate skills-base in the team, including as it did geologists, astrobiologists, planetary scientists and instrument specialists. Although written instructions were available, documentation sent out to the team beforehand, and some degree of mentoring and handover time was provided by more experienced SWT members, daily tactical planning was a high-pressure environment that sometimes made it hard to learn specific skills. All team members agreed that attending a training workshop beforehand would have been very useful for preparing the team better. *Lesson learnt: practical training is necessary to reinforce written instructions for optimum team performance. Future trials should provide a 1-2 day training workshop for all team members that focussed both on the overall rationale, and on providing technical training.*

A challenge inherent in the MURFI ExoMars rover-like mission, and agreed by all in the SWT, was that image processing each morning was difficult and time consuming, and that too few of the team had experience operating the PRo3D software, which is itself still in final stages of development. The production of panoramas and the presentation of the 3D workspace terrain models would benefit from dedicated technical staff. Again, this was partly due to the rapid rate at which MURFI was organized, and also by a lack of trained team members able to take on this role. Also, localization was performed each day, yet on a real mission this job would likely be performed outside of the science team. *Lesson learnt: if resources permit, localization, data preparation and data visualization, are best done by dedicated technical operators, rather than by SWT members.*

The MOC was seen as being an excellent facility, and the large video wall, with the ability to accept feeds from various different workstations, was very useful. However, the two-tiered seating arrangement made it hard to communicate between the rows, especially when team members were referring to the video wall while speaking. In the future, some kind of communication system or a horseshoe shape arrangement would be better. *Lesson learnt: communication within the team is vital, and MOC setup is important for facilitating this.*

The field site was perceived to be very Mars-surface relevant, overall the logistics and planning worked well, and the time difference meant that both teams could work full days on the mission without resorting to antisocial working times. The main improvement that could have been made was more robust field-to-MOC communications. *Lesson learnt: a field site with good cell-phone coverage, mobile wifi, or a regular use of satellite telephone communication is vital.*

9. Conclusions

MURFI demonstrated that the UK has a planetary science and engineering community capable of performing a challenging Mars rover trial. MURFI also demonstrated the benefits of the bilateral collaboration with CSA. While primarily a 'trial for future trials', MURFI 2016 was also a vital training activity for the science team and, perhaps most importantly, produced operations insights that could be relevant to ExoMars rover.

The team learned very quickly to work together, due to the time pressure and common goals, and the changing roles meant there were new challenges for members every day. However, this role-changing also caused problems, and issues arose which could have been avoided if roles changed less often, and also perhaps if objectives, priorities and constraints had been more clearly laid out. An important learning outcome for many in the MOC team was having to perform tactical operations under a tight deadline, with little time to examine the data in full. During debrief meetings, it was found that the MURFI experience was particularly valued by early career scientists, so future rover field trials should aim to include and inspire as many junior members of the community as possible, and especially provide them leadership roles where they can learn 'on the job' while still benefitting from experienced mentors within the team. Providing experience working as a team in this environment was one of the biggest perceived successes of MURFI.

The MOC set-up, schedule, and mission guidelines and the field location and logistical arrangements were all well-suited to a rover mission-simulation trial and, although some improvements could be made, the facilities and logistics provide a template for future field trials. Also, the extensive documentation produced on a daily basis allowed the mission to be analyzed at a later date. The biggest logistical improvements that could be made for a future rover trial would be the provisions of a 1-2 day training workshop for all team members prior to mission-start, additional on-site technical support, better field to MOC communications, more end-to-end sample acquisition training, and more post-mission sample analysis and feedback.

The MURFI ExoMars rover-like mission showed that mission simulation or rehearsal field trials will be useful for the ExoMars rover mission for several reasons: (i) to understand how to operate the instruments as a suite, making best use of their complementary strengths and mitigating weaknesses, and especially learning how to interpret the local geology correctly, and to identify potential drill sites, using stand-off instruments alone, (ii) to build an operations planning team that can work well together under strict time-limited pressure, (iii) to develop new processes and workflows that could save time or improve productivity when implemented on the real ExoMars rover mission, (iv) to understand the limits and benefits of satellite mapping and the differences in scale between satellite and rover images and data, and (v) to practice the efficient geological interpretation of outcrops and landscapes from rover-based data by comparing the outcomes of the simulated mission with post-trial, in-situ field observations.A vital input to the MURFI mission was the satellite remote sensing mapping, and the hazard and science target identification. However, due to the large area covered by the mapping, it could not be performed at a scale equivalent to the full resolution of the best satellite remote sensing images. This also cannot be done for the ExoMars rover until its landing position is known, given the > 100 km by 20 km landing uncertainty ellipse. When localization has been performed, though, rapid high-fidelity geological and hazard mapping of the area around the landing point at full HiRISE resolution will provide an extremely important resource that can be then be built upon using ground-based observations as the mission progresses.

We conclude by noting that although MURFI 2016 was the UK SA's first Mars Rover trial, others have been run by various agencies (e.g., Arvidson et al., 2002; Woods and Shaw, 2014), and the lessons learned in them have allowed Mars rover operations to be rigorously planned (e.g., section 5.3 of Grotzinger et al., 2012) and successfully performed. In fact, it could be argued that much of the Mars rover operations knowledge and expertise residing within the global community was developed during the MER (e.g., Arvidson et al., 2006; Biesiadecki et al., 2006; Squyres et al., 2004) and MSL experiences (e.g., Vasavada et al., 2014). However, while some of the MURFI lessons learnt are generic (e.g., the need for rapid, high quality remote-sensing mapping, while understanding the scale disparity between remote sensing and field observations), they are still important for a team to learn, and important for each new mission to learn – only through hands-on experience can such knowledge be embedded.

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Highlights

MURFI: a UK Space Agency Funded Mars Rover trial

Field site in Utah, USA; Rover control centre in Harwell, UK

Includes a 9-sol ExoMars Rover-like mission element

ExoMars rover-like instrument suite and platform

'Lessons learnt' relevant to future trials and future ExoMars Rover operations