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

M.R. Balme, M.C. Curtis-Rouse, S. Banham, D. Barnes, R. Barnes, A. Bauer, C.C. Bedford, J.C. Bridges, F.E.G. Butcher, P. Caballo, A. Caldwell, A.J. Coates, C. Cousins, J.M. Davis, J. Dequaire, P. Edwards, P. Fawdon, K. Furuya, M. Gadd, P. Get, A. Griffiths, P.M. Grindrod, M. Gunn, S. Gupta, R. Hansen, J.K. Harris, L.J. Hicks, J. Holt, B. Huber, C. Huntly, I. Hutchinson, L. Jackson, S. Kay, S. Kyberd, H.N. Lerman, M. McHugh, W.J. McMahon, J.-P. Muller, T. Ortner, G. Osinski, G. Paar, L.J. Preston, S.P. Schwenzer, R. Stabbins, Y. Tao, C. Traxler, S. Turner, L. Tyler, S. Venn, H. Walker, T. Wilcox, J. Wright, B. Yeomans

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# 1 **The 2016 UK Space Agency Mars Utah Rover Field**

## 2 **Investigation (MURFI)**

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28

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## 29 Abstract

30 The 2016 Mars Utah Rover Field Investigation (MURFI) was a Mars rover field trial  
31 run by the UK Space Agency in association with the Canadian Space Agency's 2015/2016  
32 Mars Sample Return Analogue Deployment mission. MURFI had over 50 participants from  
33 15 different institutions around the UK and abroad. The objectives of MURFI were to  
34 develop experience and leadership within the UK in running future rover field trials; to  
35 prepare the UK planetary community for involvement in the European Space  
36 Agency/Roscosmos ExoMars 2020 rover mission; and to assess how ExoMars operations  
37 may differ from previous rover missions. Hence, the wider MURFI trial included a ten-day  
38 (or ten-'sol') ExoMars rover-like simulation. This comprised an operations team and control  
39 center in the UK, and a rover platform in Utah, equipped with instruments to emulate the  
40 ExoMars rovers remote sensing and analytical suite. The operations team operated in 'blind  
41 mode', where the only available data came from the rover instruments, and daily tactical  
42 planning was performed under strict time constraints to simulate real communications  
43 windows. The designated science goal of the MURFI ExoMars rover-like simulation was to  
44 locate in-situ bedrock, at a site suitable for sub-surface core-sampling, in order to detect  
45 signs of ancient life. Prior to "landing", the only information available to the operations  
46 team were Mars-equivalent satellite remote sensing data, which were used for both  
47 geologic and hazard (e.g., slopes, loose soil) characterization of the area. During each sol of  
48 the mission, the operations team sent driving instructions and imaging/analysis targeting  
49 commands, which were then enacted by the field team and rover-controllers in Utah.  
50 During the ten-sol mission, the rover drove over 100 m and obtained hundreds of images  
51 and supporting observations, allowing the operations team to build up geologic hypotheses

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

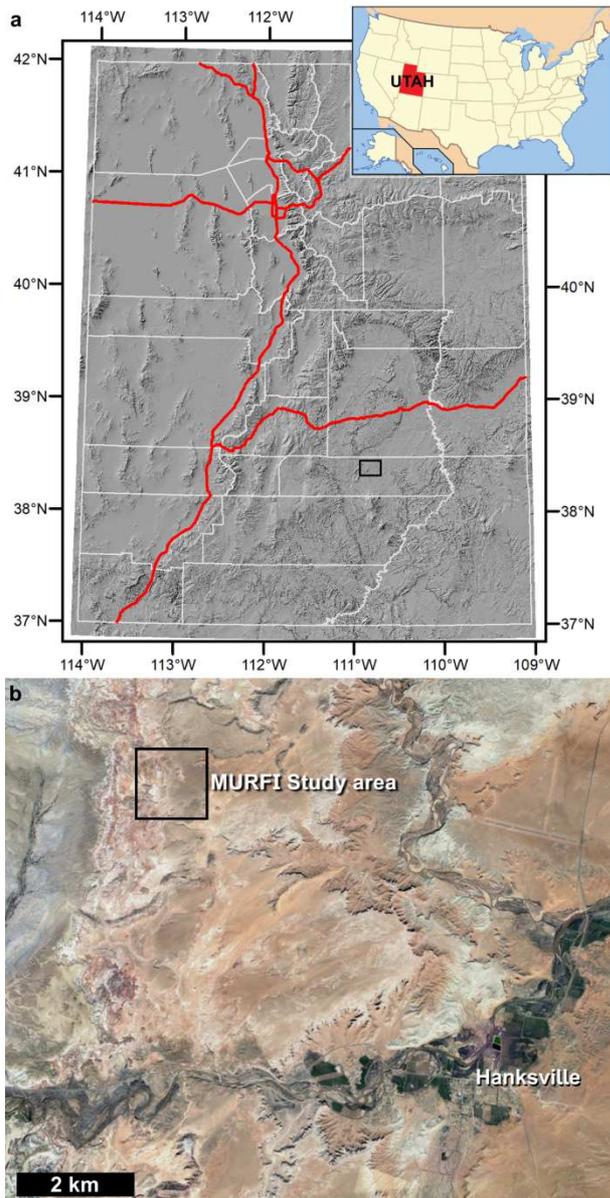
## 68 **1. Introduction**

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



82

83 *Figure 1. The MURFI 2016 rover: a 'Q14' platform with PanCam emulator 'AUPE' (Harris et al., 2015)*84 *attached. The large "eyes" contain the filter wheels for the PanCam emulator. Field team for scale.*85 *Image credit: Mike Curtis-Rouse*



86

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

### 91 **1.1 MURFI investigation objectives**

92 MURFI 2016 had three primary objectives: (i) to develop the logistical and leadership  
 93 experience in running field trials within the UK; (ii) to provide members of the Mars science  
 94 community (especially early career scientists) with rover operations experience, and hence

95 to build expertise that could be used in the 2020 ExoMars rover mission (Vago et al., 2017),  
96 or other future rover missions, and (iii) by running an ExoMars rover-like mission simulation  
97 to explore how operations for the ExoMars rover (which aims to drill up to 2 m into the  
98 subsurface), might differ from past experiences from, for example, the twin Mars  
99 Exploration Rovers (MERs; e.g., Crisp et al., 2003) and the Mars Science Laboratory (MSL;  
100 e.g., Grotzinger et al., 2012).

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

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

119           The ExoMars rover is a partnership between the European Space Agency (ESA) and  
120 the Russian Roscosmos agency. The mission will launch in 2020 and has the explicit goal of  
121 looking for signs of past life (Vago et al., 2017, 2015). It has a mass of 310 kg and is expected  
122 to travel several kilometers during its seven-month mission (Vago et al., 2017). The ExoMars  
123 rover drill has the capability of sampling from both outcrops and the subsurface, with a  
124 maximum reach (i.e. depth) of 2 m. The subsurface sampling capability means that material  
125 that has escaped alteration by the martian surface environment (e.g., Kminek and Bada,  
126 2006; Parnell et al., 2007; Summons et al., 2011) can be sampled, providing the best chance  
127 to sample well-preserved chemical biosignatures for analysis. The ExoMars rover (Vago et  
128 al., 2017) will be different to the preceding MSL and MER rover missions in that it has the  
129 capability for the deepest sub-surface sampling of any Mars rover to date. However, a  
130 trade-off of this drill capability is the lack of an instrumented robotic arm. This means that  
131 any information relevant to understanding the geological context of the landing site must be  
132 obtained from stand-off instruments (at least, up to the point at which a drill sample is  
133 obtained and ingested into the rover for in-situ analysis). Having the best possible  
134 understanding of the geology of the landing site is vital for making the best decisions about  
135 where to drill, as drilling is potentially a time consuming and hazardous procedure.

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

## 143 **1.2 MURFI investigation overview**

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

163 Secondly, the ExoMars-like mission part of MURFI 2016 was run as a “blind” mission  
164 from the perspective of the MOC science team. The team were not permitted to see any  
165 information other than Mars-equivalent remote sensing data, or data returned by the rover  
166 itself. For the MOC team, this also meant blocking the social media accounts of the field

167 team members, disallowing access to online remote sensing services, and requesting MOC  
168 team members to do no background research into the geology of the field site. Those  
169 members of the team with pre-existing knowledge of the site were chosen to form the field  
170 team, supporting the operations in Utah.

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

186 Finally, the MURFI ExoMars rover-like mission itself was given a science goal for the  
187 team to meet within the 10 sol time limit. Mirroring the real ExoMars rover science goal  
188 *"to search for signs of past and present life on Mars"* (Vago et al., 2017), the MURFI ExoMars  
189 rover-like mission goal, was: *"to locate suitable areas in the field site that have sedimentary  
190 geology indicative of an ancient habitable environment, then to drill into the surface to*

191 *acquire a sample from those materials and, finally, to examine this sample with the*  
192 *analytical instruments available onboard the rover.”* Key elements of the mission goal were  
193 (i) the necessity to sample ‘ancient’ environments, which was interpreted by the team to  
194 mean sampling in-situ bedrock within the stratigraphy, rather than loose surficial fines of  
195 poorly-known provenance; (ii) the requirement to drill, which also meant that the drill site  
196 would have to be well characterised prior to drilling; and (iii) the interpretation of ‘habitable  
197 sedimentary geology’ to mean deposits laid down in water in a low-energy environment  
198 such as a lake or slow moving water –given the MURFI field site, this meant looking for fine-  
199 grained or clay-rich materials within the stratigraphy.

200

## 201 **2. Field site and Mission Operations Center (MOC)**

### 202 ***2.1 Field site***

203 The Utah field site (Figure 2) was chosen based on the collaboration with the CSA and its  
204 Mars-like local geology. It was used by the CSA in 2015 for Mars Rover trials (Dupuis et al.,  
205 2016), and in 2016, several teams (see, for example, Hipkin et al., 2017) used the site, each  
206 with their own designated working areas. The description that follows provides an overview  
207 of the geology of the site, but to maintain the integrity of the trial, this information was not  
208 allowed to be seen by the MURFI MOC team prior to the ExoMars rover-like mission.

209 The field site is in the Canyonlands section of the Colorado plateau, a geologically  
210 stable terrain that represents a crustal block of relatively undeformed rock covering an area  
211 of 337,000 km<sup>2</sup>. The plateau is bounded by the Basin and Range province to the west and  
212 the Uintas Mountains and Rocky Mountains to the northeast and east. To the south west,

213 the plateau is bounded by the Mogollon highlands. The stratigraphy of central Utah is  
214 dominated by Mesozoic rocks (with large inliers of Permian-age strata), which represent a  
215 predominantly continental succession, with several significant marine incursions (Stokes,  
216 1986). The area local to Hanksville consists of Jurassic- to Cretaceous-age strata, with dips <  
217 10°, recording continental conditions during the Jurassic. The field study site is within the  
218 Late-Jurassic (Kimmeridgian) Morrison Formation. This Formation is divided into three  
219 Members: The Tidwell Member, which represents lakes and mudflats; The Saltwash  
220 Member, which represents coarse alluvial sediments (average 63% net sand), and the  
221 Brushy Basin Member, which represents finer-grained (average 10% net sand) alluvial  
222 deposits (Heller et al., 2015). The study site was located solely within, but near the base of,  
223 the Brushy Basin Member, which locally has an exposed thickness of ~100 m.

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

233 In the study area, slope-forming sections of outcrop can be capped by cliff-forming  
234 units between 2-5 m thick. These units are characterized by cross-bedded sandstones and  
235 angular matrix-supported conglomerates, within channelized fluvial architectural  
236 components. When viewed in planform, these cliff-forming cap rocks have high aspect-

237 ratios (widths of 20-50 m, and lengths of hundreds of metres to kilometres) and are  
238 curvilinear. These features have been described as inverted channels and are documented  
239 throughout the Morrison Formation (Clarke and Stoker, 2011; Williams et al., 2009, 2007).

240 Light-colored, very poorly sorted, structureless layers of bentonitic volcanic ash, 5 –  
241 20 cm thick can be found at various levels in the silty flood plain deposits and are  
242 interpreted as airfall deposits due to the lack of laminations within the layers. They have U-  
243 Pb zircon ages of 149 Ma (Kowalis et al., 1998; Kowallis et al., 2007). The presence of clays is  
244 evidenced by the shrink-swell weathering of the mud- to silt-grade material, as well as the  
245 presence of well-developed desiccation cracks in the present-day ground surface. These  
246 clays might have been sourced from the volcanic ash layers (Heller et al., 2015). The  
247 Morrison Formation contains abundant macroscale 'biosignatures' in the form of fossils and  
248 ichnofossils. Overall, the palaeoenvironment of the Brushy Basin Member is characterised as  
249 the distal part of a distributive alluvial fan system that drained toward the north-east from  
250 the system's fan apex on the Mogollon Highlands (Owen et al., 2015).



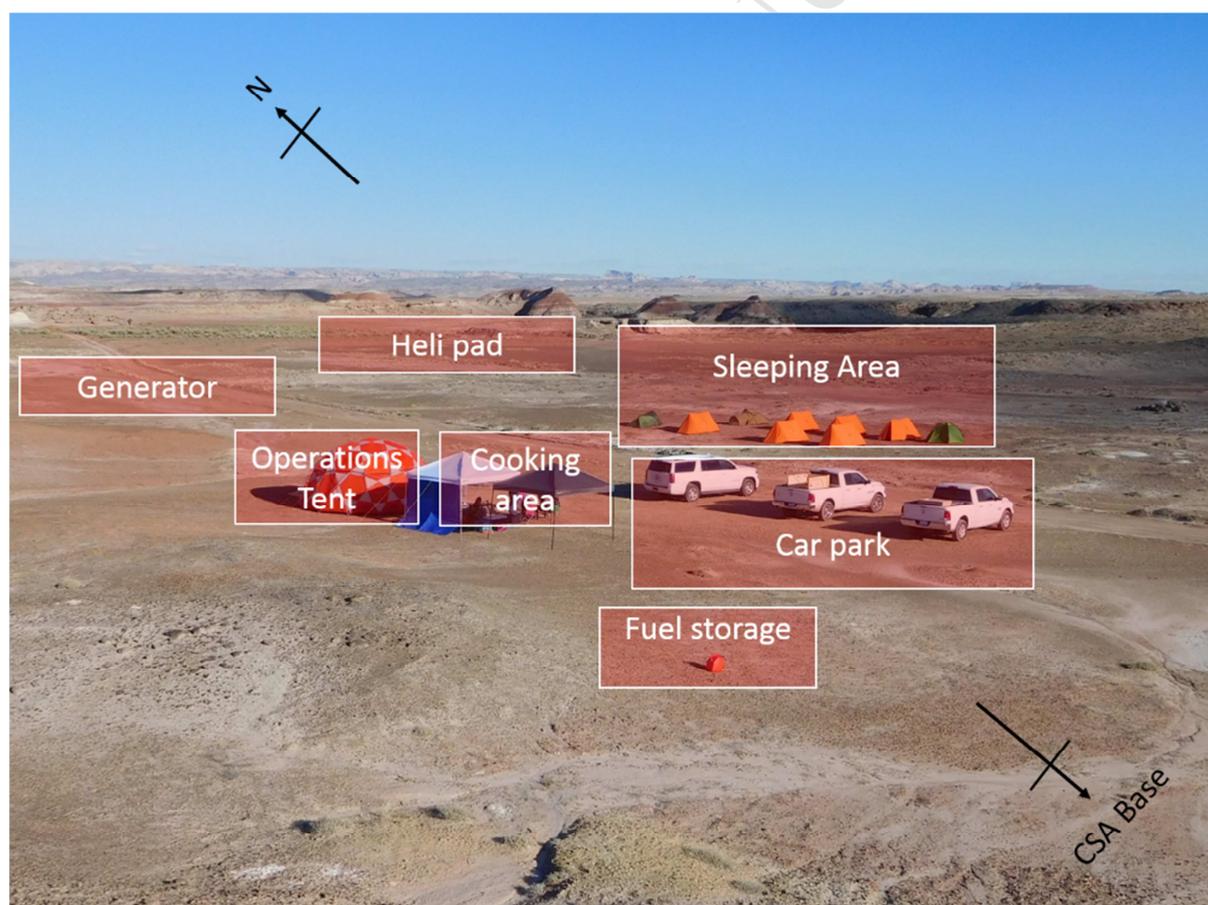
251

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

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

## 263 **2.2 Field logistics**

264 The MURFI base camp was intentionally co-located close to the area of science operations  
265 for several reasons: (i) to reduce transit time between accommodation and working areas,  
266 (ii) to ensure that equipment deployed was secured at all hours of the day, and (iii) to  
267 facilitate collaboration with the other agencies who were working nearby. The basecamp  
268 was divided into three areas; sleeping, food preparation and storage, and operations (Figure  
269 4).



270

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

272

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

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

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

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

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

309

### 310 ***2.3 The Rover Mission Operations Centre (MOC)***

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

318 allow the display of datasets (e.g. remote sensing products) across the whole screen in very  
319 high definition.

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



325  
326 *Figure 5. MOC setup. a) The large video wall. The desktop view of one workstation could be stretched*  
327 *over the whole wall, as here, or several workstation desktops could be split across the screen ‘on the*  
328 *fly’. b) The tiered workstations for the SWT stations. Image credit: Andrew Griffiths.*

## 329 **3. Field equipment**

### 330 ***3.1 Rover platform***

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

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

### 348 ***3.2 Rover Instrumentation***

349 The Pasteur payload (Vago et al., 2017) of the ExoMars Rover consists of 11 panoramic,  
350 contact, and analytical instruments. Of this suite, four were emulated for MURFI and were

351 either integrated onto the rover platform, or available as standalone instruments that could  
352 be operated in the same way, as perceived by the MOC team, as if integrated into the rover.  
353 The instruments emulated were the stereo-panoramic/high resolution camera imaging suite  
354 'PanCam' (Coates et al., 2017), the infrared spectroscopy instrument, 'ISEM' (Infrared  
355 Spectrometer for ExoMars; Korablev et al., 2017), the close-up imaging camera, 'CLUPI'  
356 (CLOse UP Imager; Josset et al., 2017) and the Raman spectroscopy system (Rull et al., 2017)  
357 that is part of the ExoMars rover's Analytical Laboratory Drawer. In addition, the MURFI  
358 investigation could simulate ExoMars's drill capabilities.

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

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

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

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

396 To simulate the ExoMars rover's ability to drill to depths of up to 2 m and obtain a  
397 core sample, the field team were equipped with a hand-held core drill and hand tools to

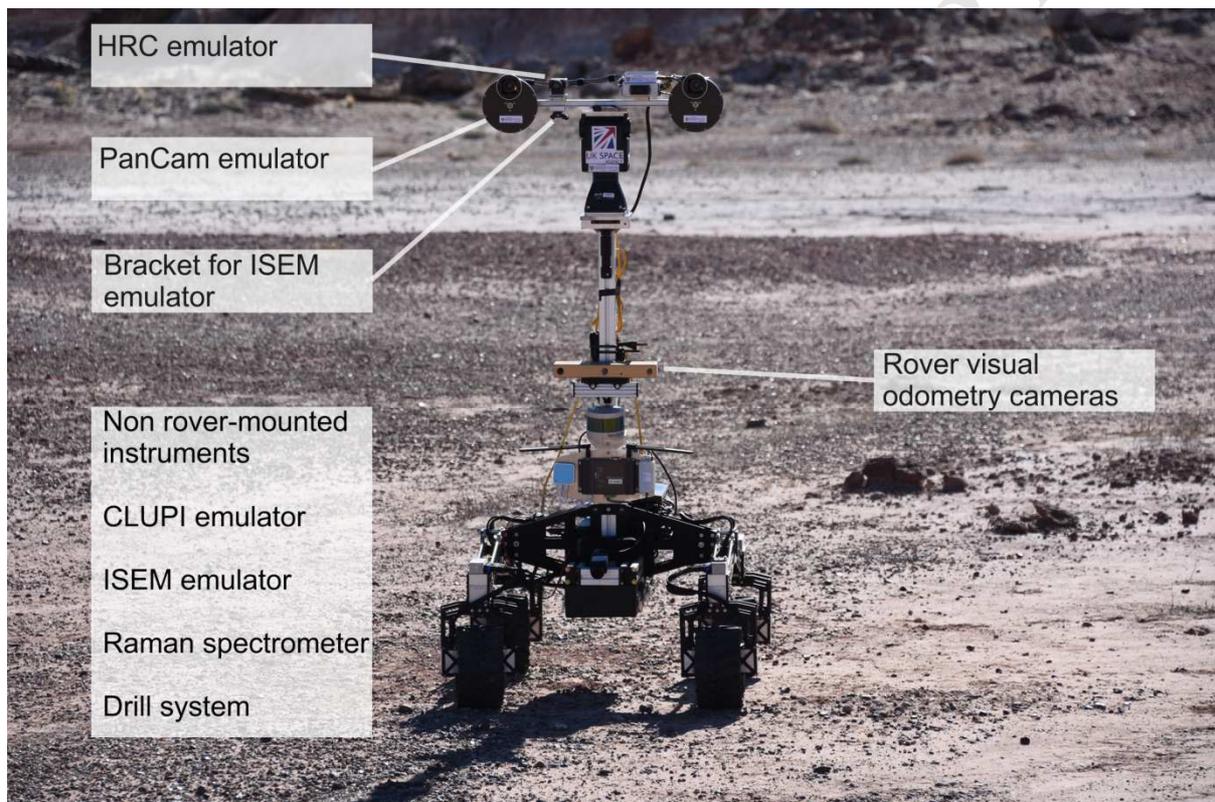
398 extract an ExoMars-like core from a depth specified by the MOC team. This allowed sub-  
399 surface samples to be extracted and then analyzed by instruments representing those in the  
400 Analytical Laboratory Drawer of the ExoMars rover (Vago et al., 2017).

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

419         The primary ExoMars ‘geology instruments’ lacking from the MURFI payload  
420 included the ground penetrating radar (WISDOM; Ciarletti et al., 2017) and the fuller suite of  
421 instruments within the drill package and in the Analytical Laboratory Drawer. We hope to

422 include emulators for these instruments in the future – especially WISDOM, which provides  
 423 sub-surface information – but to meet the overall goals of MURFI 2016 within the limited  
 424 time available for planning, only the stand-off instruments that allow characterization of the  
 425 geological setting and determination of drill location, and the Raman spectrometer, were  
 426 used in this trial.

427



428

429 *Figure 6. The MURFI rover platform showing the rover instruments. The main imaging instruments*  
 430 *were rover-mounted, but the spectrometers were mainly used demounted from the rover for the*  
 431 *convenience of the field team. The ISEM emulator could be used mounted or demounted. See Figure*  
 432 *1 for scale. Image credit: Mike Curtis-Rouse*

433

#### 434 **4. ExoMars rover-like mission operations**

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

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

443

444 *Fig. 7. MOC mission timeline overview.*

#### 445 **4.1 Roles in MOC and in field**

446 The structure of the MOC staff was determined in consultation with advisers who had  
 447 experience of the NASA MSL mission and previous CSA trials (Dupuis et al., 2016; Osinski et  
 448 al., 2017). However, out of necessity, the operations structure was also shaped by  
 449 availability of personnel. The roles of the MOC team and field team are summarized in  
 450 tables 1 and 2 respectively. The MOC personnel swapped in and out of the team based on

451 availability, with the total number of team members in the MOC usually being between 8  
452 and 12 people.

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

455

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.
----------------------------	---

456 *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.

457 *Table 2. Field team responsibilities.*

## 458 **4.2 Mission schedule**

### 459 **4.2.1. MOC team schedule**

460 The field team positioned the rover at the 'landing point' on Sol 0, in a location they decided  
461 would maximize the possibilities for the mission, and from that point onwards a new tactical  
462 plan was generated each sol by the SWT (the sol N plan). The daily planning deadline was  
463 13:00 UK time, meaning that the time zone difference between the UK and Utah allowed  
464 the field team to receive the command plans early in the morning and execute it, and then  
465 to return data to the UK before the start of the next sol's tactical planning schedule. The  
466 first five sols of the mission consisted of using the rover instruments to characterize the  
467 local geology and drives towards outcrops. The next three sols were devoted to  
468 characterizing a possible drill target, with the command to drill being given on sol 8. Post-  
469 drilling observations and CLUPI/Raman analyses of the drill sample were returned on sol 9  
470 for later analysis. This is probably a much more rapid drilling time than is likely for a deep  
471 drill on ExoMars, but simulating a slower drill process was not deemed useful for the MURFI  
472 mission. No planning was done on sol 9 and it was used to discuss the final data sets  
473 returned and for a MOC-team debrief.

474 The MOC SWT followed the same fixed schedule each day (Table 3). The day began  
475 with the Mission Scientist designating roles within the team, a report from the Mission  
476 Manager, including 'flagging' problems or issues on the rover or for the field team, and  
477 confirmation of the rover data that had been downlinked from the field. After a period of  
478 data processing, tactical planning discussion began, and the sol N plan proposed, discussed,  
479 and finalized. After the planner submitted the Sol N plan to the Mission Manager the  
480 commands were 'uplinked' to the field team. After a lunch break, the SWT returned and

481 begun more wide-ranging, free-form science discussions based on the data obtained in the  
482 mission so far. Later in the afternoon another formal planning session, led by the Mission  
483 Scientist, began. During this session, the current longer term plan was discussed and  
484 modified, as well as an outline sol N+1 plan created for use as the basis for the following  
485 day's sol N planning. Daily activity at the MOC was completed by the MS and MM creating  
486 an archive backup copy of all the documentation and data generated during the day. After  
487 dinner, the MS produced a summary of activities and targets from the day for distribution to  
488 all team members, and various team members updated blog posts and social media  
489 accounts.

490 During the daily planning cycle, several formal documents were produced and  
491 archived to keep a record of the operations. These are numbered in Table 3 and included:

492 (1) *Sol N Rover Status Report*: localization results and GIS shapefiles provided by the TML  
493 team, and data downlink lists from the MM.

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

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

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

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

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

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

512 (8) *Rapporteurs Minutes*: describes the day’s discussions for later use.

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

<b>Time (local)</b>	<b>Item</b>	<b>Responsibility</b>
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.
<b>Deadline:</b> 13.00	Mission plan for sol N sent to Utah field team (4). <i>Set to arrive no later than 6am Utah local time so dependent on time- difference.</i>	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.

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

### 517 **4.2.2 Field team schedule**

518 The field team arrived in Utah on 24<sup>th</sup> October, and the basecamp was fully operational by  
 519 the 28<sup>th</sup> October. The field team spent several days ensuring the rover and instrumentation  
 520 were fully functional, as well as performing geological reconnaissance of the operations  
 521 area, and deciding where to position the rover to maximise the return from the exercise.  
 522 The field team began regular daily operations (Table 4) on sol 1 of the ExoMars rover-like  
 523 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.

524 *Table 4. Field team daily schedule*

### 525 **4.3 Data processing and/or software**

526 The majority of the data returned to the MOC by the field team was images. These included  
 527 daily NavCam (panchromatic WAC images taken using the visible light filter) panoramas, and

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

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



551

552 *Figure 8. PRo3D example outputs. a) Near-field view showing annotations made onto the PRo3D*553 *scene. b) Distance measurements, useful for drive planning, made using PRo3D – in this case, to the*554 *'weekday rocks' using sol 1 data.*

## 555 **5. ExoMars rover-like mission summary**

### 556 ***5.1 Preliminary Landing Site Assessment***

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

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

575 The preliminary analysis was performed by five team members who had Mars  
576 remote sensing experience. All targets, units, contacts etc. were digitized using ArcGIS

577 software, and outputs produced for the wider team to analyse. The various maps produced  
578 were displayed and referred to often during the ExoMars-like mission trial.

ACCEPTED MANUSCRIPT

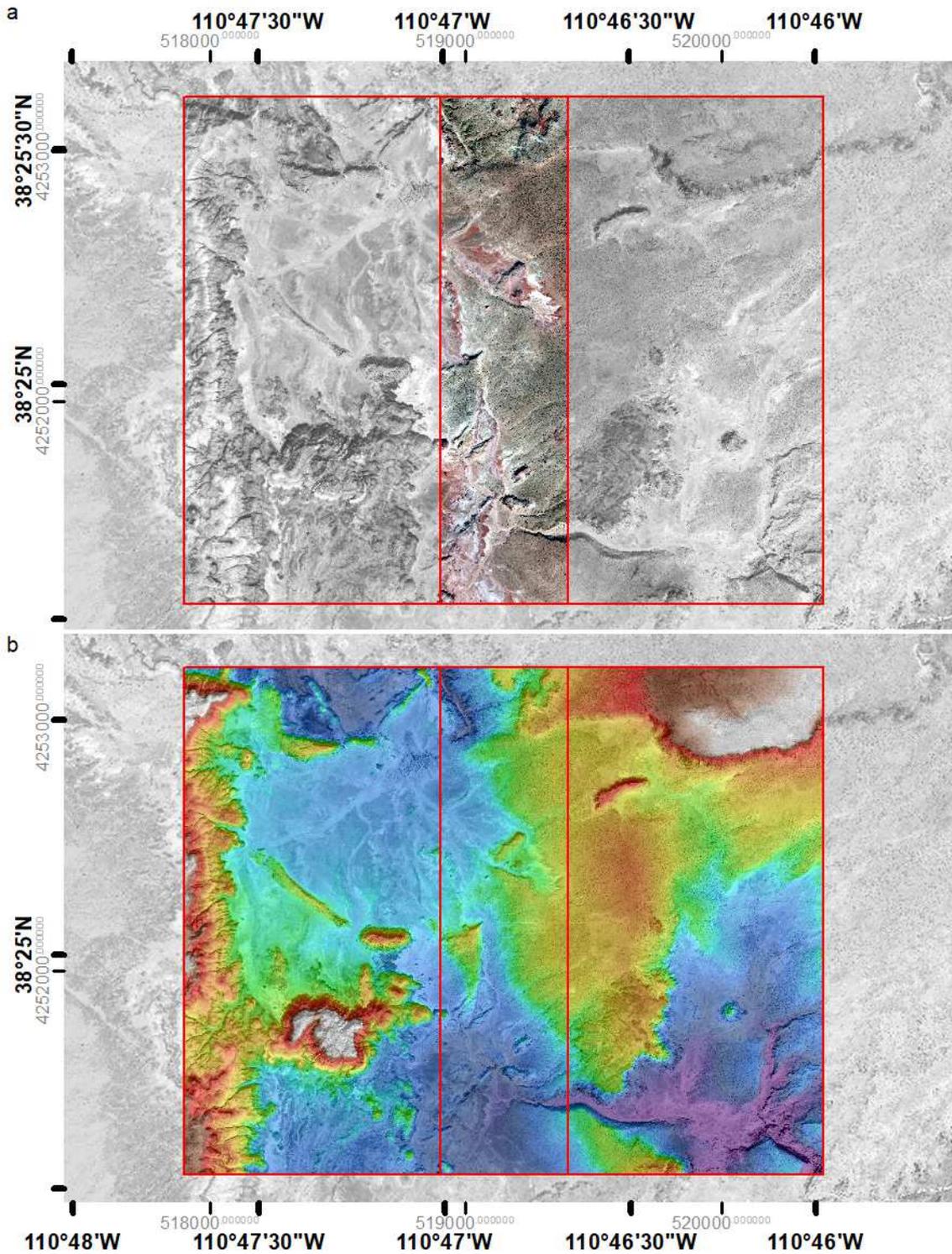
Mars dataset emulated (spectral range and pixel size)	Earth data used (spectral range and pixel size)	Processing	'Mars like data' (spectral range and pixel size)
HiRISE <sup>1</sup> (RED, RGB; 0.25 m)	World View 2 <sup>2</sup> (0.39 m RGB)	Export Red channel Clip central RGB strip	0.39 m RED 0.39 m RGB
HiRISE Digital Terrain Model (DTM) <sup>3</sup> (~1 m)	NAIP* <sup>4</sup> 5 m DTM [3]	none	5 m DTM
CTX <sup>5</sup> (Panchromatic; 6 m)	NAIP* <sup>6</sup> 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 <sup>7</sup> (12.5 m Panchromatic, 50 m RGB)	LANDSAT 8 <sup>8</sup> 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 <sup>9</sup> IR daytime surface temperature (12.17 $\mu$ m – 12.98 $\mu$ m)	LANDSAT 8 band 11 (11.5 $\mu$ m – 12.51 $\mu$ m, 30 m/pixel)	Band 11, resample to 100 m/pixel, rescale pixels from 16 bit to 8 bit	100 m (11.5 $\mu$ m-12.5 $\mu$ m)

$\mu\text{m}$ ; 100 m)			
CRISM <sup>10</sup> (400 nm – 4000 nm wavelength range; 16m)	HYPERION <sup>11</sup> (250 nm – 2500 nm; 30 m/pixel)	Resample pixels to 32 m	½ spectral range & spatial resolution

579 Table 5: Mars like data sets made from available terrestrial counterparts\*NAIP = National  
580 Agriculture Imagery Program. <sup>1</sup>High Resolution Imaging Science Experiments (McEwen et al.,  
581 2007), <sup>2</sup>DigitalGlobe (<https://www.satimagingcorp.com/satellite-sensors/worldview-2/>),  
582 <sup>3</sup>Kirk et al. (2008), <sup>4</sup>NAIP DTM ([https://gis.utah.gov/data/elevation-terrain-](https://gis.utah.gov/data/elevation-terrain-data/#AutoCorrelatedDEM)  
583 [data/#AutoCorrelatedDEM](https://gis.utah.gov/data/elevation-terrain-data/#AutoCorrelatedDEM)), <sup>5</sup>ConText Imager (Malin et al., 2007) <sup>6</sup>NAIP RGB  
584 ([https://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-](https://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/)  
585 [programs/naip-imagery/](https://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/)), <sup>7</sup> High Resolution Stereo Camera (Neukum and Jaumann, 2004)  
586 <sup>8</sup>US Geological Survey (<https://landsat.usgs.gov/landsat-8>), <sup>9</sup> Thermal Emission Imaging  
587 Spectrometer (Christensen et al., 2004), <sup>10</sup> Compact Remote Imaging Spectrometer for Mars  
588 (Murchie and the CRISM Science Team, 2007), <sup>11</sup>US Geological Survey  
589 (<https://eo1.usgs.gov/sensors/hyperion>)

### 590 5.1.1 Physiography of the Landing Site

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



597

598 *Figure 9. The MURFI field site area mapped using Mars-like remote sensing data (cf. black box*599 *showing study area in figure 2b). An area ~ 2 by 3 km was mapped. a) A simulated HiRISE image*600 *(Worldview 2), including the central color strip and the lateral greyscale areas. b) 5 m resolution DTM*601 *showing topography. Note that this DTM actually has lower resolution than the best Mars DTM data*

602 *(5 m/pixel vs 1 m/pixel). Graticule and grid show WGS (World Geodetic System) 1984 latitude and*  
603 *longitude and UTM (Universal Transverse Mercator) zone 12N projection scale information. Image*  
604 *credits: see Table 5.*

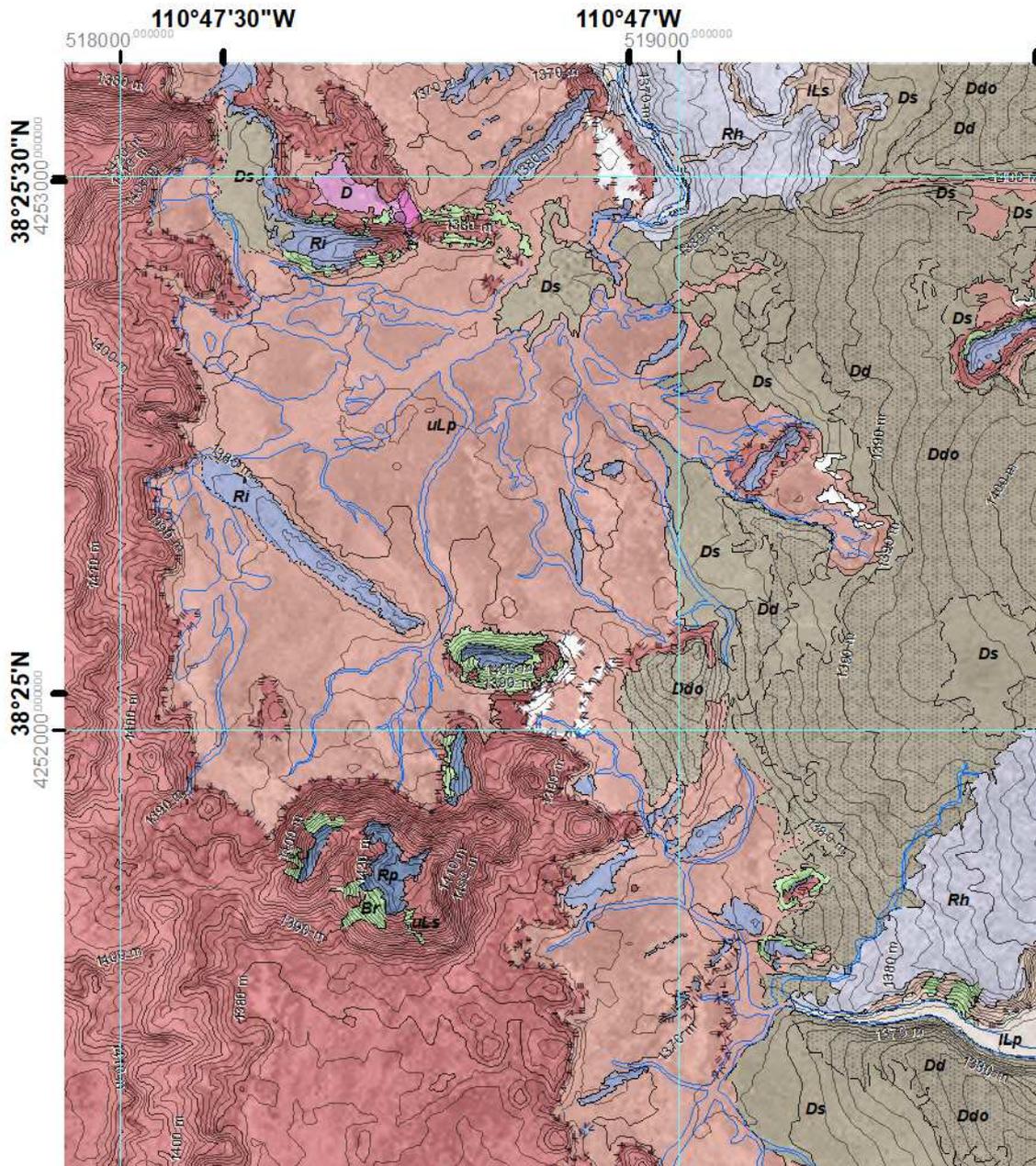
605

### 606 **5.1.2 Photogeological mapping.**

607 The photogeological map (Figure 10) covered an area of 2 x 1.75 km and was digitized at 1:  
608 1,000 scale over three days in the style of the USGS astrogeology program (Tanaka et al.,  
609 2011). The mapping used a HiRISE-equivalent base layer, with color data available only in  
610 the central portion. CTX, HRSC, and THEMIS equivalents (Table 5) were used for regional  
611 context. Hyperion data were only available later in the mission: CRISM-like summary  
612 products were generated but did not provide significant additional information that altered  
613 the mapping.

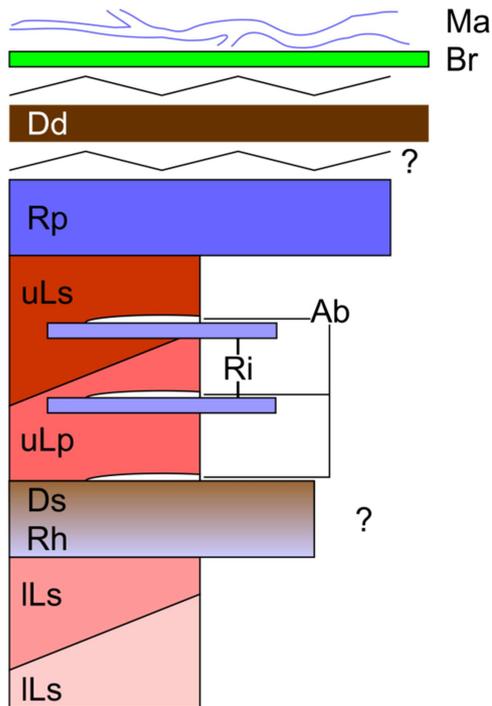
614 At the time of mapping, the SWT did not know where in the mapped region the  
615 rover would 'land', hence it was important to build up a consistent geological interpretation  
616 for the region. This 'rapid mapping' approach has relevance to the ExoMars rover mission as  
617 quickly building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

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



625

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



632

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

640

641 The Resistant Formation consists of three units characterised by a tendency to crop  
 642 out as ridges or flat caps on top of mesas and plateaus. Sub-curvilinear ridges of resistant  
 643 material from this formation are set within the stratigraphy and form the 'Resistant  
 644 Interbedded Unit' (Ri). Examples of this unit were found on top of mesas and hills close to  
 645 the MURFI rover landing point. Based on the mapping and the geomorphology observed in  
 646 the highest resolution images, we interpreted them to be resistant materials composed of

647 the upper parts of inverted fluvial channels. Hence, our hypothesis was that they were  
648 fluvial sandstones or similarly coarse-grained sedimentary materials.

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

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

### 666 **5.1.3 Hazards.**

667 As part of the preliminary landing site assessment, rover traversability hazards were  
668 evaluated. This exercise is directly relevant to the ExoMars rover mission; very similar  
669 analyses were performed at the landing ellipse scale for ExoMars landing site selection, and

670 detailed traversability maps will be needed as soon as the landing position of the ExoMars  
671 rover is determined to allow for drive planning.

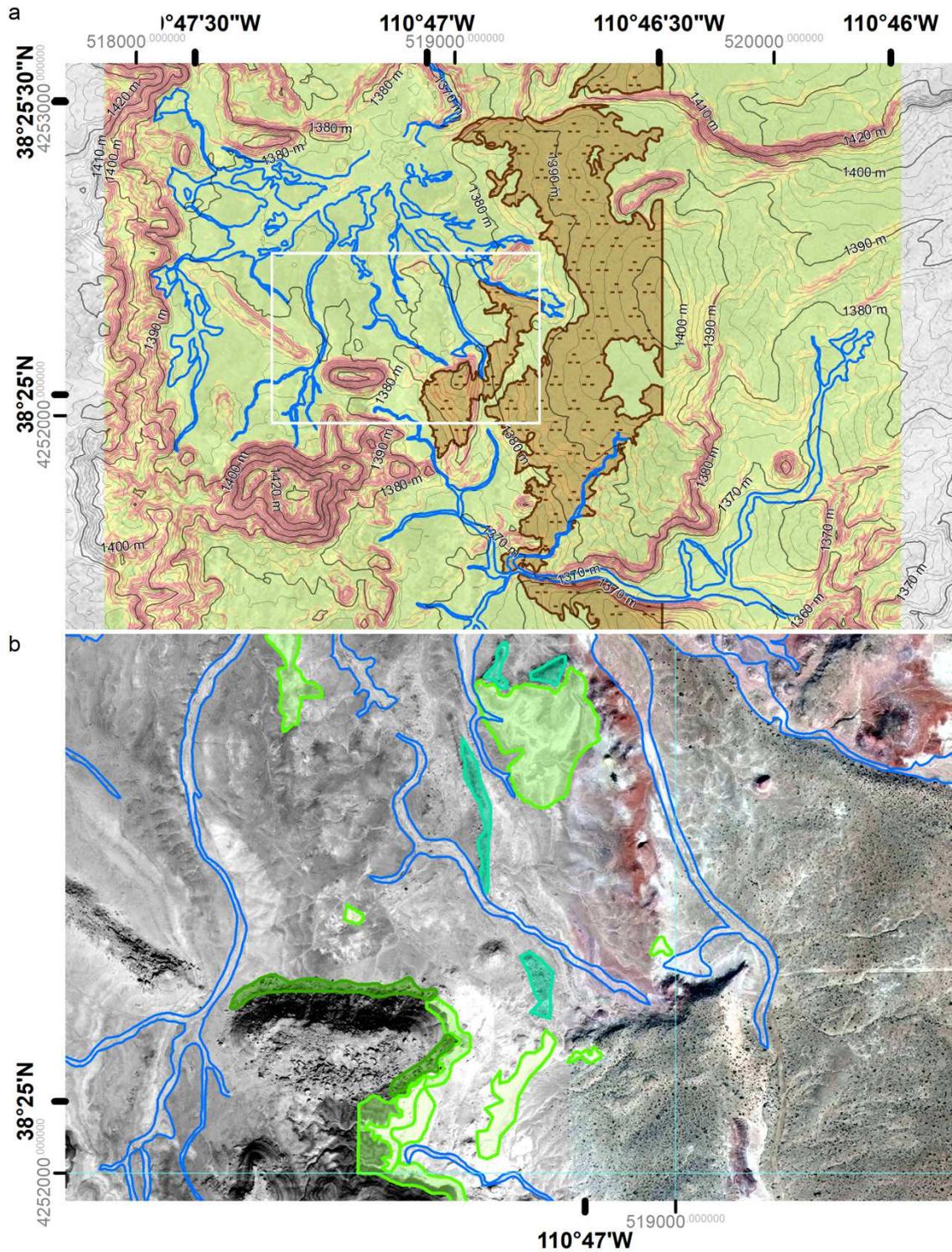
672 The resulting hazard maps (Figure 12a) were used to place constraints on the routes  
673 the rover could traverse and which targets were accessible. Four types of hazard were  
674 identified and mapped:

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

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

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

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



698

699 *Figure 12 – Hazard and science target mapping. a) Hazards within the wider mapping region.*700 *Modern Alluvial hazards are outlined in blue. In the background, slopes < 5° are colored green, slope*701 *5° -10° are yellow, slopes of 10-15° are orange, and slopes >15° are red. The brown area is the 'Dark*702 *Dappled Unit', Ddu – interpreted to be densely covered with boulders and vegetation. White box*

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

#### 709 **5.1.4 Science targets.**

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

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

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

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

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

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

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

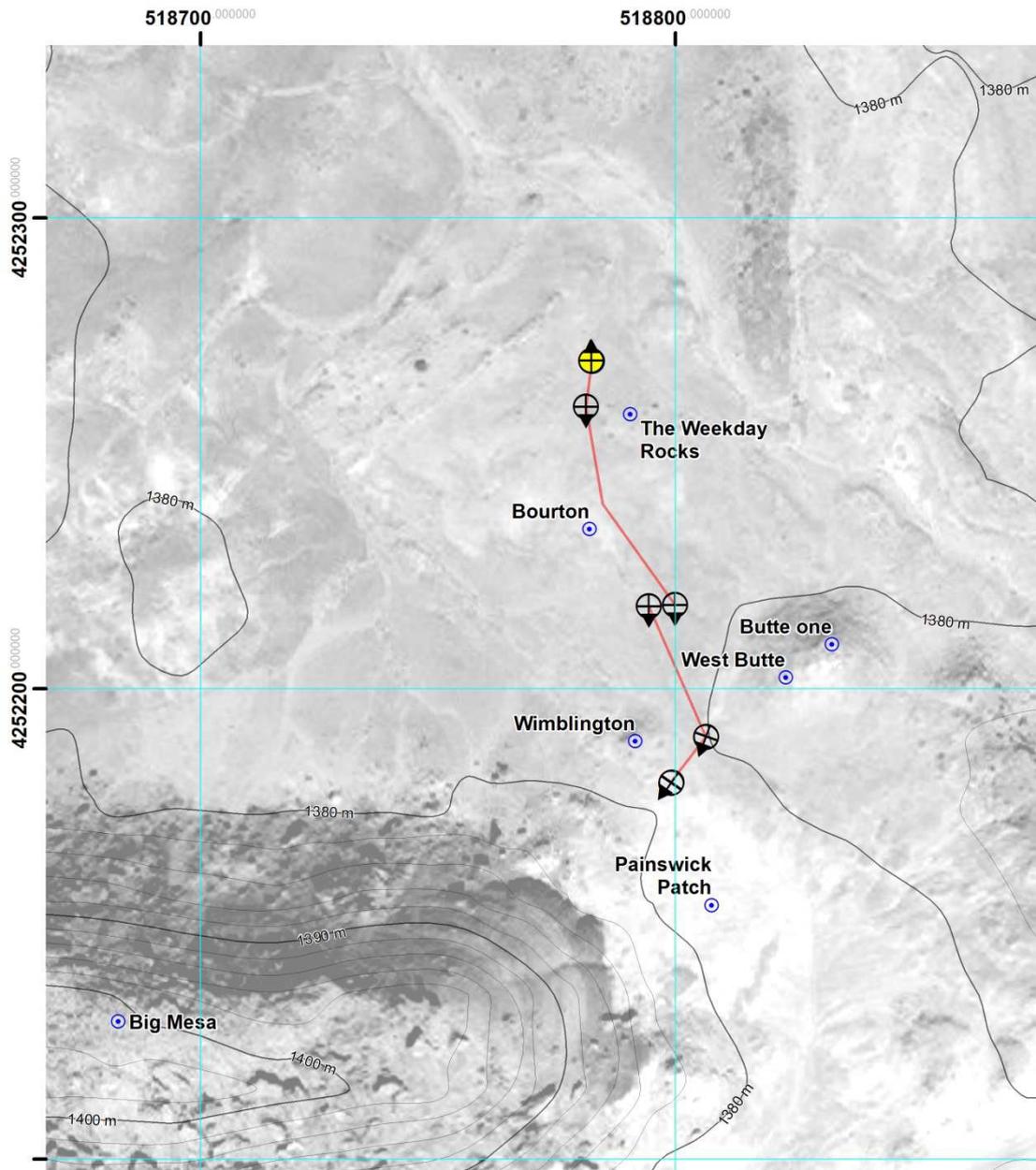
## 735 ***5.2 Traversability, Mapping and Localization (TML)***

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

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

748 In any rover mission it is imperative to know where the rover is, both relative to  
749 science targets and potential hazards, but also to its previous position to determine how  
750 successful the last commanded drive has been. This was especially important on the first sol  
751 of the mission. To localize the rover, we used distal and proximal trigonometry based on  
752 objects seen on the horizon or in the near field, and that could be located in remote sensing  
753 images. Where possible, proximal localization and planning within the meter-scale  
754 workspace was done using the PPro3D tool described above. The 3D scenes were created  
755 from AUPE panchromatic mosaics acting in 'NavCam' mode. The PPro3D scene close to the  
756 rover was used to characterize the workspace surface topography and hence fine tune the  
757 rover position for drill core acquisition.

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



767

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

### 772 **5.3 Daily mission operations log**

773 The following describes the sol-to-sol activities of the MURFI ExoMars rover-like mission. In  
 774 general, each sol's tactical plan involved a science block (targeted observations using one or

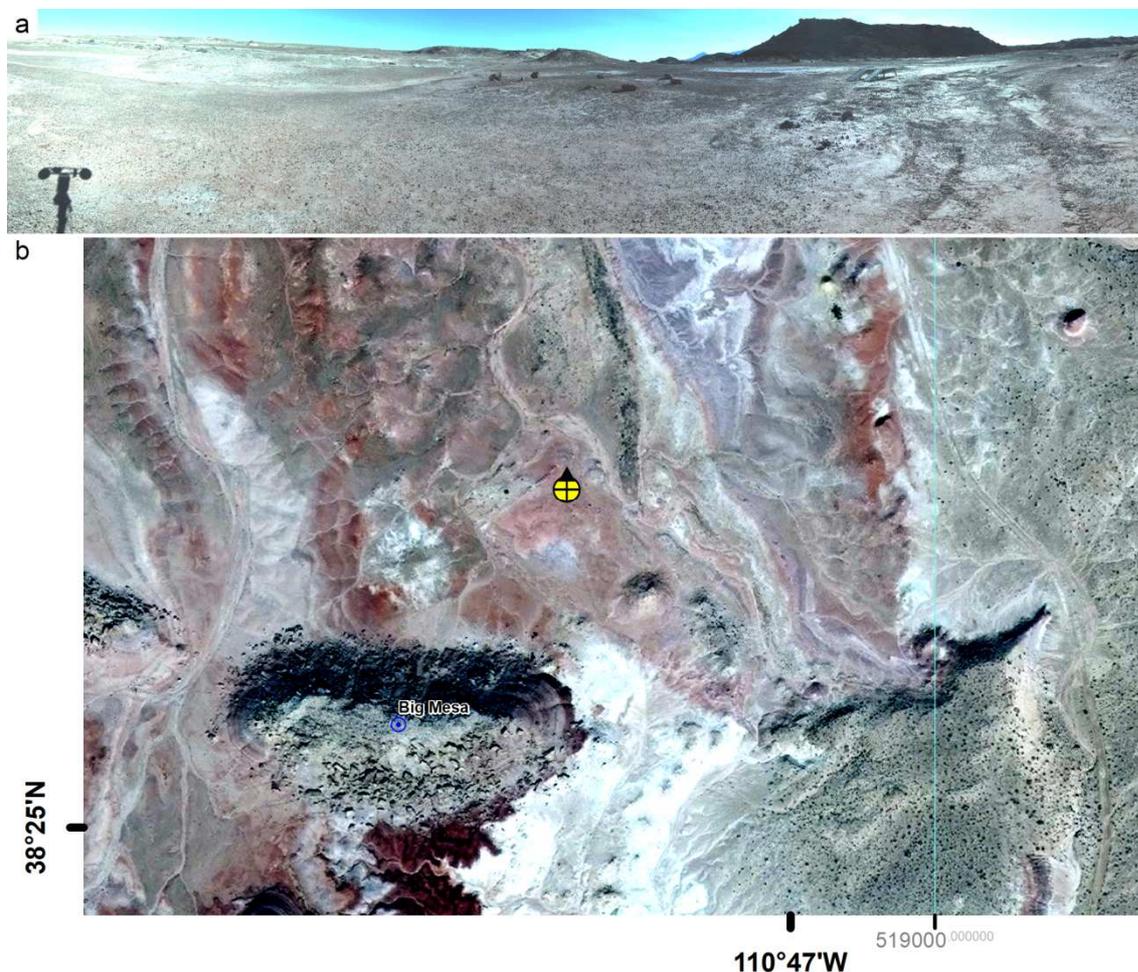
775 all of the standoff instruments), then a drive block. A NavCam emulator panorama  
776 acquisition was included as a standard post-drive imaging command. The post-drive  
777 panoramas were either 180° or 360° depending on data volume available and/or planning  
778 needs, and allowed choice of the next sol's targets from the panorama.

779 **Sol 1. (3<sup>rd</sup> November 2016) – first drive.**

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

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

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



801  
 802 *Fig 14. a) AUPE full color, stereo panorama data returned after sol 0. b) Position of rover at start of*  
 803 *Sol 1, as determined by the TML team. Image credits: see Table 5.*

#### 804 **Sol 2. (4<sup>th</sup> November 2016) – moving towards science targets**

805 Data returned on Sol 2 showed that the rover had successfully avoided the Weekday Rocks  
 806 and moved ~ 10 m south towards the Big Mesa. The SWT wished to characterise 'Bourton, a  
 807 small patch of high albedo material immediately south of the rover, for which two working  
 808 hypotheses existed: (i) an inlier of high albedo bedrock, and (ii) an area of higher albedo

809 surficial material. The team did not want to 'waste' a sol examining this area further if it was  
810 surficial material, but if it were bedrock this could provide a promising target for drilling. It  
811 was also suggested that this material could be a possible rover traversability hazard if it  
812 were loose sand. The outcome of discussion in the SWT was that a two-part drive, first to  
813 the edge of Bourton, then skirting to the east and then southeast of it, was appropriate. An  
814 untargeted right-looking imaging sequence of the centre of Bourton using WAC, HRC and  
815 ISEM emulator acquisition was planned to occur before the second drive. If Bourton was  
816 found to be bedrock, the rover could then retrace its drive back to this area on future sols.  
817 Additional pre-drive targets included several HRC mosaics of the buttes and mesa in the  
818 area to search for sedimentary structures, and an HRC/ISEM emulator study of a bright  
819 patch of soil and a small rock (possibly bedrock) near the rover.

### 820 **Sol 3. (5<sup>th</sup> November 2016)**

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

### 823 **Sol 4. (6<sup>th</sup> November 2016) - targeted instrument analyses**

824 Due to scheduled changeovers in the field Platform Team, no driving was possible on sol 4.  
825 The returned HRC and WAC data showed strong evidence for the Big Mesa being composed  
826 of sedimentary material, based on observations of albedo, texture and layering at smaller  
827 scale than visible in the remote sensing data. HRC images showed inclined strata,  
828 interpreted as being cross-bedding in the Resistant Formation materials, both in situ and in  
829 debris at the base of the slopes. The data also showed further patches of high albedo  
830 material to the east and north of the Big Mesa. The SWT proposed these to be bedrock  
831 examples of the Anomalously Bright Unit of the Layered Formation, and so might be

832 possible future targets for drilling. The data obtained on sol 2 revealed that Bourton was  
833 composed of surficial material so sol 4/5 drives were planned towards the south to bring the  
834 rover into an area with more outcrop and drill targets. The targeting strategy was to build  
835 up more information about the geology by observing outcrops in the local area. Sol 4 targets  
836 included (i) HRC mosaic of 'Painswick Patch' the bright terrain west of Big Mesa, (ii)  
837 Wimblington, an area of jumbled debris north of Big Mesa, and (iii) 'Weeting' and  
838 'Swanland' patches of brighter terrain on the rover's southward drive path.

### 839 **Sol 5. (7<sup>th</sup> November 2016) – long drive towards region of interest**

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

845 Sol 5 contained a few examples of logistical and communication problems. First, the  
846 planned drive for sol 5 brought the rover to the edge of the MURFI 'working space', agreed  
847 between the UK SA and CSA field teams. The working spaces were relatively close together  
848 for communications and logistics reasons. Unbeknownst to the MOC team, the CSA rover  
849 was working just a few tens of meters further south and there were worries that the  
850 presence of two field teams working so close to one another would compromise both  
851 investigations. The field team did not know that this was likely to be the last long drive  
852 performed by the MOC team, as the strategic plan for sols 6-9 included detailed studies of  
853 the locations near the rover to prepare for drilling, rather than further long drives. The  
854 problem was resolved after field and MOC team communicated directly via satellite phone,

855 reassuring the field team that the MURFI rover would not be progressing much further  
856 south into the CSA workspace. This incident demonstrates the need for well-defined  
857 working spaces and reinforces the necessity of readily available communications between  
858 MOC and field.

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

#### 864 **Sol 6. (8<sup>th</sup> November 2016) – characterizing possible drill site**

865 Sol 6 saw a change in the pace of the mission: the team transitioned from “observing and  
866 driving” to “characterising and deciding about drill sites”. The SWT were aware that sol 6  
867 would be the last driving sol, if drill workspace characterisation was to be performed on sol  
868 7, and the command to drill being given on sol 8. This meant that tactical planning on this  
869 day would finalise which of the several possible drill sites were chosen.

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

877 lithologies and potential for future drilling, and an HRC mosaic was taken of the  
878 Skinningrove area.

### 879 **Sol 7. (9<sup>th</sup> November 2016) – positioning for drilling**

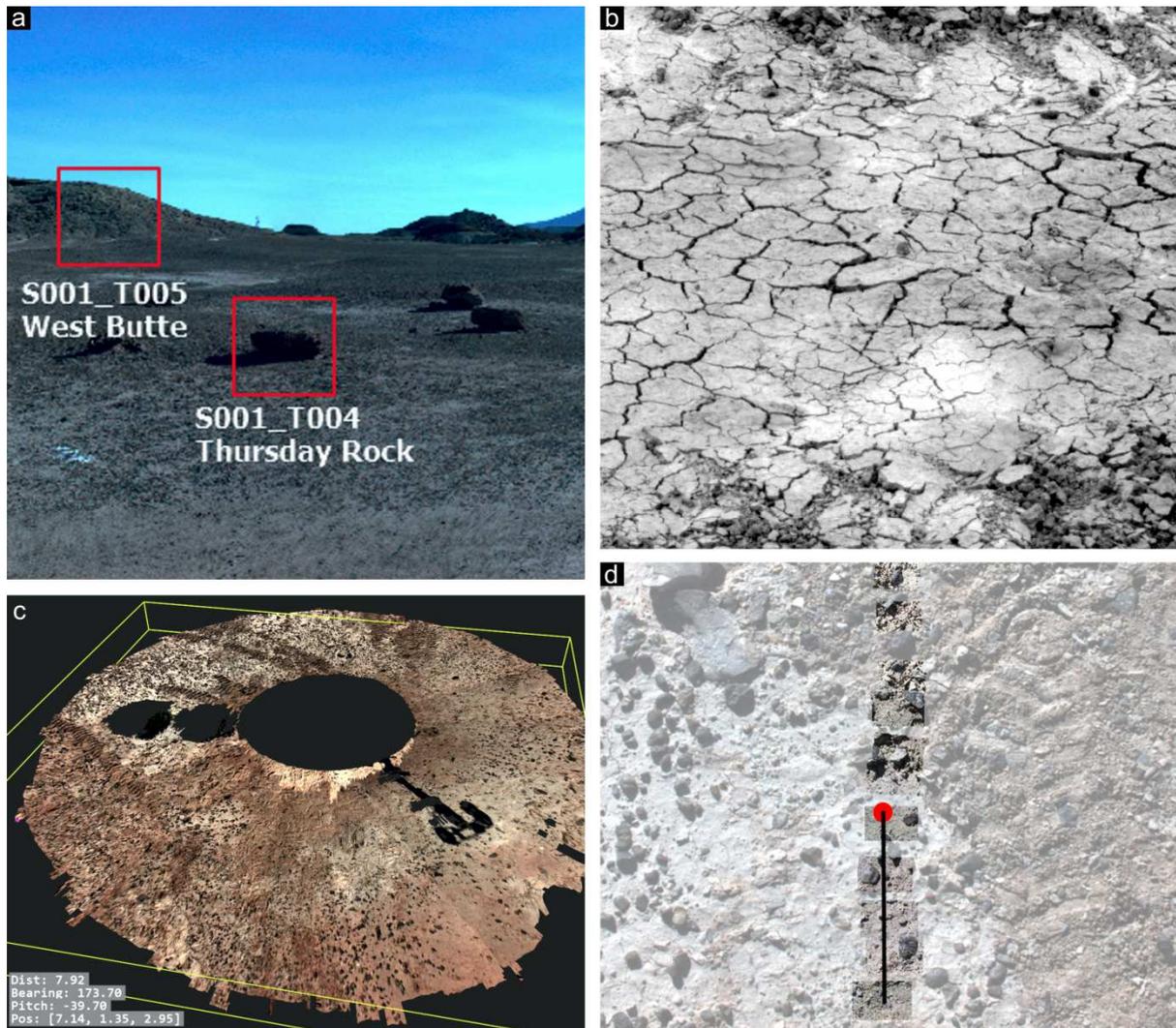
880 Following the sol 6 drive, the rover was correctly positioned at the Skinningrove target in an  
881 area of loose sediment with a light cover of small (cm-scale) pebbles and cobbles. The aim of  
882 the sol 7 plan was to characterize the location in detail, prior to making a decision exactly  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

895         The SWT devised a CLUPI-based tactical plan that enabled a reasonably large area of  
896 ground near the rover to be imaged, but which retained the ability for the rover to return to  
897 the chosen location precisely. The plan involved moving the rover backwards ten times in 10  
898 cm steps, acquiring a vertically-targeted CLUPI emulator image at each step. The aim was to  
899 create a long swathe-like mosaic of CLUPI images that would allow the surface to be

900 analyzed, and so that any location chosen in that swathe could be returned to simply by  
901 driving the rover forward with no turns (the most accurate driving mode) a certain distance.  
902 In addition to this CLUPI emulator mosaic, several ISEM emulator measurements of the  
903 surface near the rover were planned in order to analyze the mineralogy of the surface  
904 materials. The final targeting request was for an early morning full color WAC mosaic of the  
905 Big Mesa to image it in optimal lighting conditions.

### 906 **Sol 8. (10<sup>th</sup> November 2016) – drilling and observation of drill tailings**

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

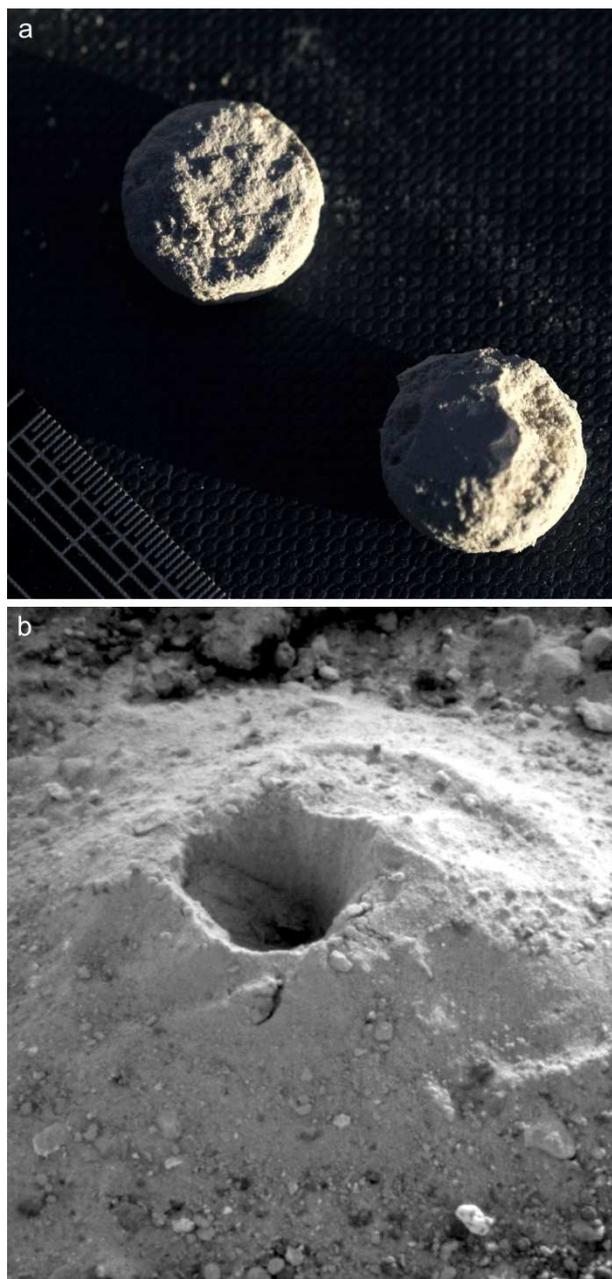


923

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

932 **Sol 9. (11<sup>th</sup> November 2016) – post drill analysis**

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



937

938 *Figure 16. Results of drilling. a) Small parts of drill core obtained. Scale bar lower left is in mm. The*

939 *CLUPI emulator image of the drill core pieces showed that they contained many fine sand-sized*

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

946

## 947 **6. Rover science results**

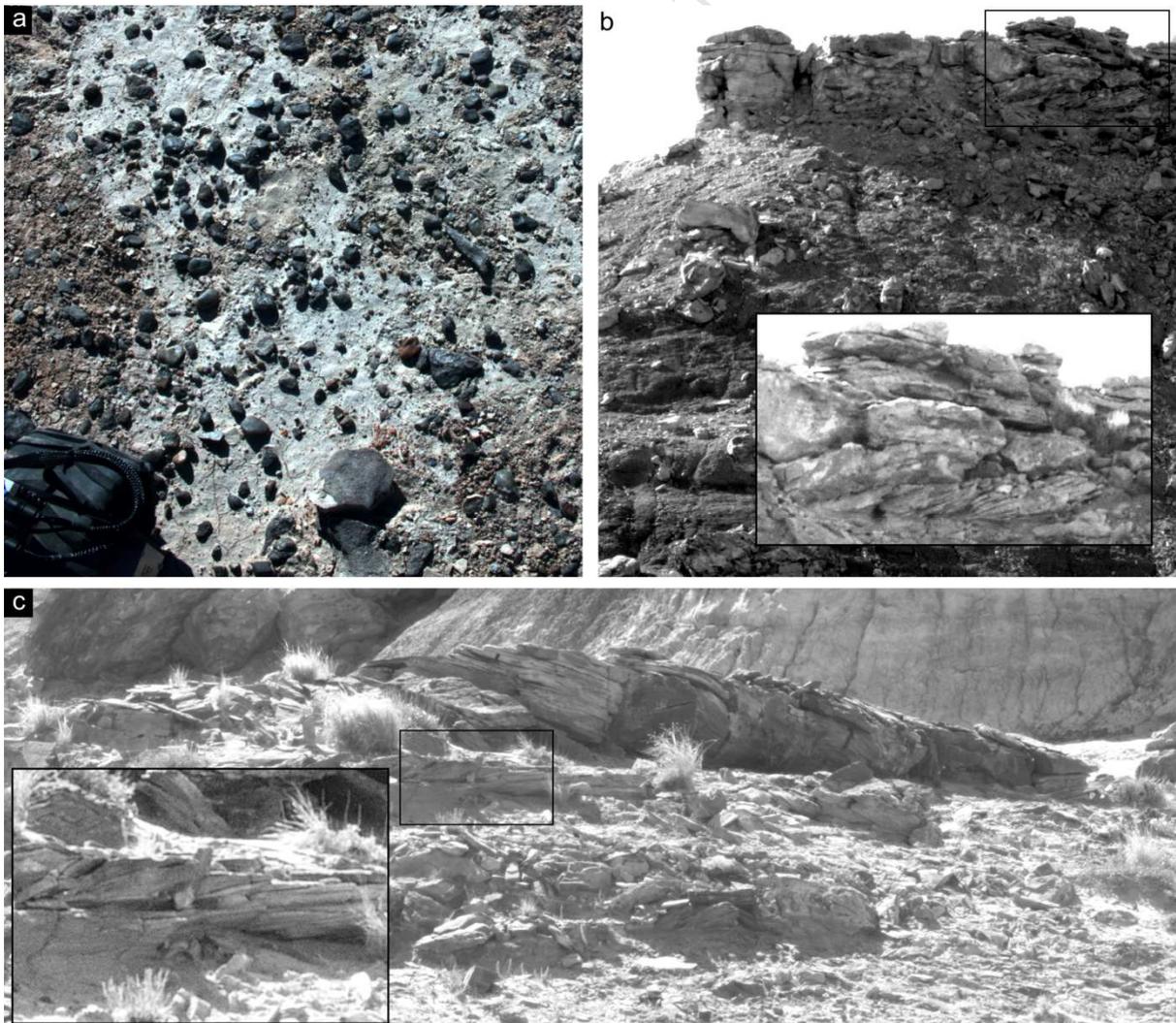
948 During the 9 sols of the ExoMars rover-like mission, the MURFI platform traversed ~100 m  
949 and made multiple observations and measurements that were discussed and analyzed by  
950 the SWT. These discussions built upon the current working hypotheses from the pre-mission  
951 satellite mapping.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

### 958 ***6.1 Key mission observations from stand-off instruments***

#### 959 **6.1.1. Imaging instruments**

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

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



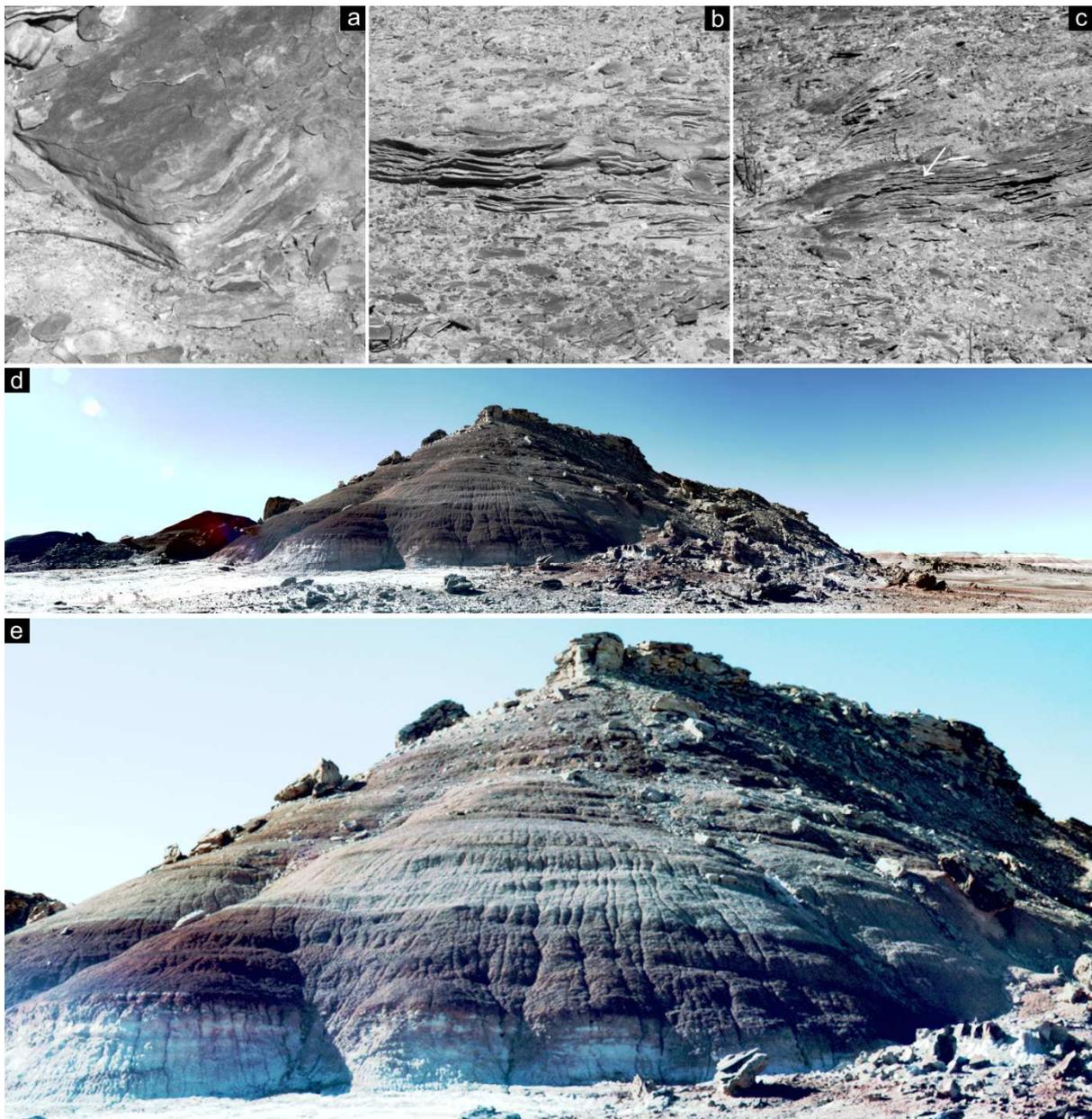
972 *Figure 17. Example science observations and interpretations. a) AUPE image of float rocks and*  
973 *surface texture. Note rover wheel for scale. b) HRC image of resistant material on top of Big Mesa.*  
974 *Layering can be seen, as well as probable crossbedding (inset). This material was therefore*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

977

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

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

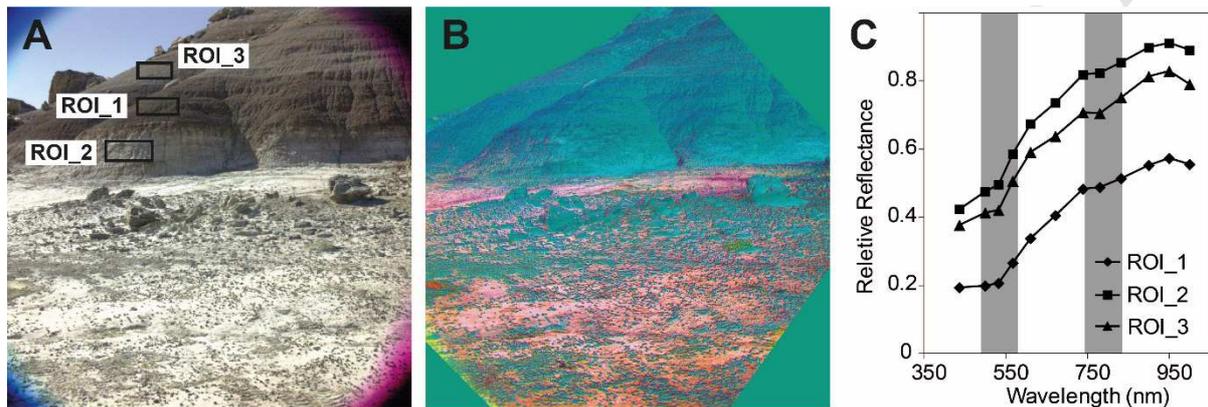
998 (3) Within the Layered Formation that is exposed at the edges of Big Mesa and the more  
999 distant ridges (Figure 18d), layering is visible at the scale of the outcrops (meter-scale), but  
1000 finer scale bedding or laminations are not observable. Color variations (Figure 18e) between  
1001 white and dark – sometimes reddish – layers within the Layered Formation suggest  
1002 geochemical (e.g.,  $\text{Fe}^{3+}$  content) or lithological variations between the layers, possibly due to  
1003 different depositional environments. However, AUPE multispectral data (Figure 19) revealed  
1004 spectral consistency across the face of Big Mesa, despite the apparent color differences. The  
1005 dominant spectral feature observed was the  $\text{Fe}^{3+}$  crystal field absorption band  
1006 superimposed on a steep ferric absorption slope between 350 and 1000 nm. These features  
1007 are present in all layers in Big Mesa.



1008

1009 *Fig. 18. Examples of science outcomes. a) HRC image of a portion of the 'Cransford' target, a layered*  
 1010 *outcrop of areas of soil overlying areas of apparently in-situ bedrock. The bedrock areas comprised*  
 1011 *15-20 cm thick (based on PRo3d measurements) layered exposures, each composed of thickly*  
 1012 *laminated or finely bedded material interpreted to be sandstone. b) HRC image of another part of*  
 1013 *Cransford showing recessive interbeds. c) HRC image of a third area in Cransford, showing possible*  
 1014 *cross cutting, non-parallel bedding (arrowed), and possible subtly undulating bedding (right of arrow)*  
 1015 *d) WAC color mosaic of Big Mesa, showing the Resistant Formation (top, and materials shed to the*  
 1016 *sides) and the Layered Formation (lower part of outcrop, showing bands of whitish, brown and red*

1017 material; interpreted to be much finer material), making up for the majority of the scene. At the far  
 1018 right of the scene are similarly colored layers in the distance. Note that sun-angle was consistently  
 1019 poor for imaging Big Mesa. e) Color-stretch close-up of the layering in Big Mesa, showing at least  
 1020 four different tonal-types, and highlighting the modern rill-forms that incise the outcrop. Big Mesa is  
 1021 ~ 22 m high.



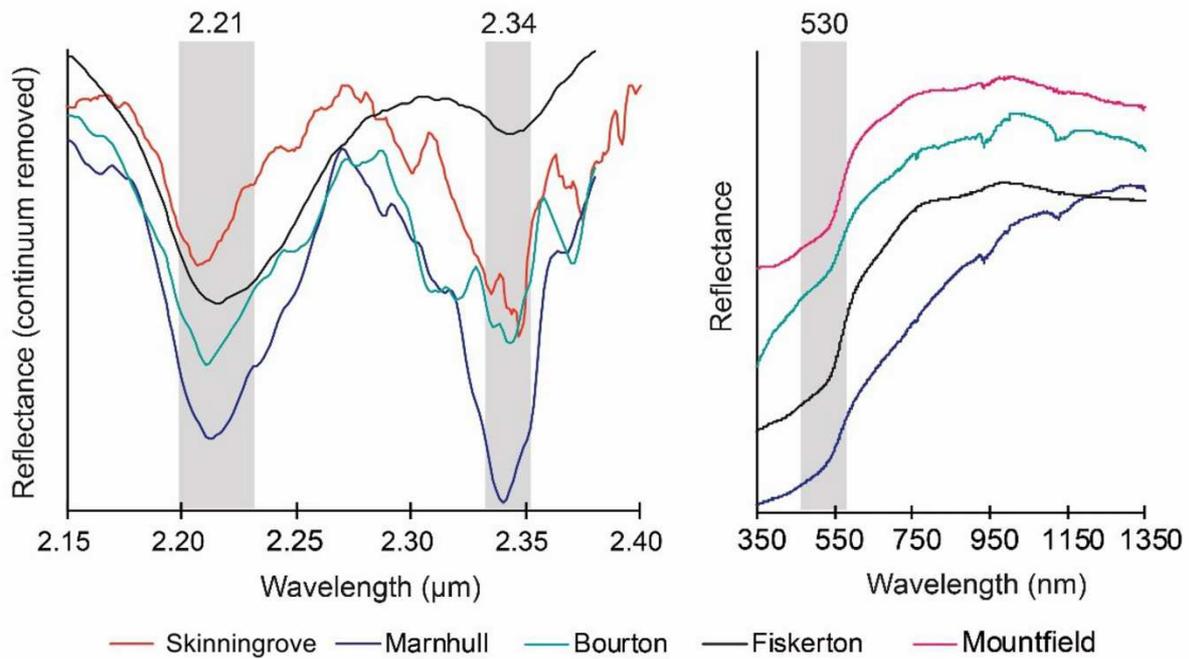
1022  
 1023 Figure 19. WAC Multispectral results. a) Enhanced color AUPE WAC image of Big Mesa showing  
 1024 location of Region of Interest (ROI) targets. b) Principal Component Analysis (PCA) false-color Left-  
 1025 WAC AUPE image using RGB filters, revealing Big Mesa to comprise spectrally-similar material. c)  
 1026 AUPE spectra extracted from the three ROI targets, all with a strong absorption at 530 nm and a  
 1027 weak absorption at ~800 nm.

1028  
 1029 Much of the surface of the Layered Formation had been modified by modern erosional  
 1030 processes, and many rills incise it (Figure 18e). Most surfaces are covered in weathering  
 1031 products (and even when the field team scraped away this surface they found significant  
 1032 alteration to several cm's depth). Hence, it was difficult for fresh surfaces to be analysed.  
 1033 The SWT working hypothesis by mission-end was that the Layered Formation is made up of  
 1034 mudstones, clays, or marls, which are all formed in low-energy environments. The Layered  
 1035 Formation was thus considered to have formed in a more effective environment for  
 1036 preserving biomarkers and organic materials than the Resistant Formation (probably a

1037 sandstone) and therefore sampling material from the Layered Formation was the agreed  
1038 goal for the drilling. The overall paleoenvironmental working hypothesis for the site, based  
1039 on both the satellite remote sensing and rover observations, was that the Resistant  
1040 Formation represents the deposits of an ancient fluvial channel, while the Layered  
1041 Formation represents an associated flood plains environment.

### 1042 **6.1.2 Spectrometer results**

1043 Data from the ISEM emulator (Figure 20) revealed ~ 2.21 and ~ 2.34  $\mu\text{m}$  absorption bands in  
1044 material analyzed from the accessible, Anomalously Bright unit in the 'Painswick Patch' area  
1045 chosen for drilling. The 2.21  $\mu\text{m}$  feature is characteristic of Al-bearing phyllosilicates such as  
1046 montmorillonite and kaolinite, whereas the 2.3  $\mu\text{m}$  band is typical for Fe/Mg-bearing  
1047 smectite clays such as nontronite and saponite (e.g., Bishop et al., 2008). While it is not  
1048 possible to distinguish between these phases using these bands alone, the strength of the  
1049 absorptions and their presence in the majority of targets analyzed suggest that  
1050 phyllosilicates form a core component of the Anomalously Bright Unit. Finally, ISEM  
1051 emulator data (Figure 20) identified the same  $\text{Fe}^{3+}$  absorption band at 0.53  $\mu\text{m}$  as the ferric  
1052 absorption slope identified in the AUPE multispectral data from Big Mesa (Figure 19c). This  
1053 spectral consistency further supports the hypothesis that the brighter surficial material has  
1054 the same source as the surrounding mesas.



1055

1056 Figure 20. ISEM emulator reflectance spectra in the short-wave infrared (left) and visible to  
 1057 near-infrared regions (right) for a variety of targets. Fiskerton is a ground-surface target of  
 1058 soils containing mud-cracks analyzed on sol 1; Marnhull is a small boulder set within soils,  
 1059 Mountfield an area of anomalously high albedo soils, and Bourton a large patch of high  
 1060 albedo material analyzed during the ‘drive-by’ analysis – all were analyzed on sol 2;  
 1061 Skinningrove is an area of ground containing the drill site, analyzed on sol 7.

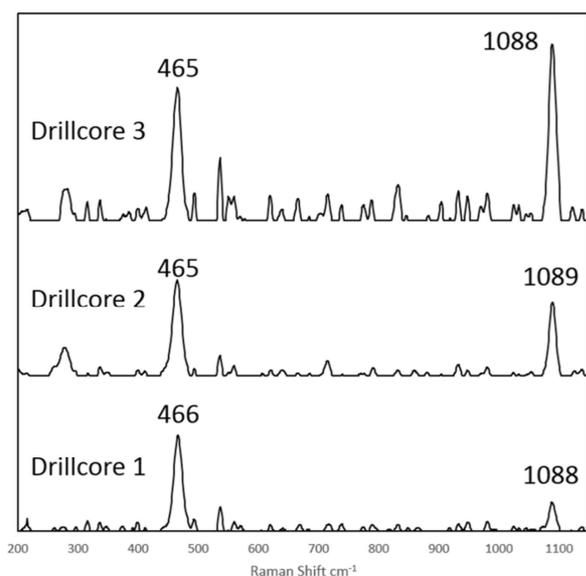
## 1062 **6.2 Drill site selection and science outcome**

1063 The last commanded activities of the ExoMars rover-like mission were to drill into the  
 1064 ‘Skinningrove’ target in the high albedo Painswick Patch area, and to analyze the returned  
 1065 sample. Based on rover observations, the SWT developed three working hypotheses to  
 1066 explain this material and its relationship to the Layered Formation: (i) it is bedrock, and part  
 1067 of the Layered Formation; (ii) it is surficial material, possibly an evaporite formed above a  
 1068 low permeability layer, and (iii) it is surficially altered bedrock (a combination of the first  
 1069 two hypotheses). The detection of montmorillonite, which can form as a weathering

1070 product, here was important, as it was consistent with either of the latter two working  
1071 hypotheses. The SWT thought that the third option was most likely, and chose this area for  
1072 the drill site: the justification for this decision being that if this area contained clay-rich  
1073 mudstones (accessible at the surface or just beneath the weathered surface) they would  
1074 then be an ideal environment for biomarker preservation and concentrating organic  
1075 material, making them good sites for drilling (as discussed in Vago et al., 2017).

1076 The core returned was observed with the CLUPI emulator instrument and then  
1077 analyzed using the Raman spectrometry instruments. In the CLUPI emulator images, the  
1078 core extracted did not appear to be a mudstone, or other very fine grained rock, as  
1079 translucent rounded grains were visible – suggestive of quartz sand grains. Although the  
1080 core was visibly friable (being fractured into small pieces, and not maintaining a core-like  
1081 shape), it was impossible to tell how competent the material really was, so the inference,  
1082 based on CLUPI images, was that this material was a poorly-cemented sandstone.

1083 As the final action of the MURFI ExoMars rover-like mission, Raman spectrometry of  
1084 the core sample was performed on site. The sample was divided into three pellets, each of  
1085 which were measured with 30 acquisitions using 1 second acquisition times. The Raman  
1086 spectra showed two distinct minerals within the sample material (Figure 21). Each pellet  
1087 showed a strong quartz band with the characteristic sub bands. The main band of calcite  
1088 was visible with drill core 2, also showing the clearest sub bands to confirm the  
1089 identification. Further observation points on the sample surface did not reveal any other  
1090 distinct mineralogy, showing either quartz or calcite or a combination of the two.



1091

1092 *Figure 21. Representative Raman spectra from the three drill core pellets. Spectra have background*  
 1093 *and fluorescence subtraction with all negative values set to 0. Wavenumber 466 cm<sup>-1</sup> indicates*  
 1094 *quartz, will 1088/1089 cm<sup>-1</sup> indicates calcite.*

1095

1096 The results from both the CLUPI and Raman emulator instruments supported the inference  
 1097 that the drill core was a quartz-rich sandstone, not the predicted mudstone or siltstone.

1098 Hence, we assumed that either the assumptions made about the bright material composing  
 1099 the Layered Formation were incorrect, or that the drill did not penetrate into bedrock

1100 associated with the Layered Formation, instead sampling a more modern deposit, such as a  
 1101 salt pan or poorly cemented juvenile sediments. However, post-mission laboratory-based

1102 Scanning Electron Microscope-Energy Dispersive X-ray (SEM-EDX) analyses of the core  
 1103 samples showed different results: SEM-EDX analyses on the drill core confirmed the calcite

1104 and quartz identification and, in addition, revealed the presence of substantial amounts of a  
 1105 Potassium/Aluminium-rich clay – possibly Illite. These results suggest that the sample

1106 consists of fine grained quartz sand, cemented by both abundant calcite and clay, so

1107 potentially a more interesting astrobiological target than first thought. However, given the

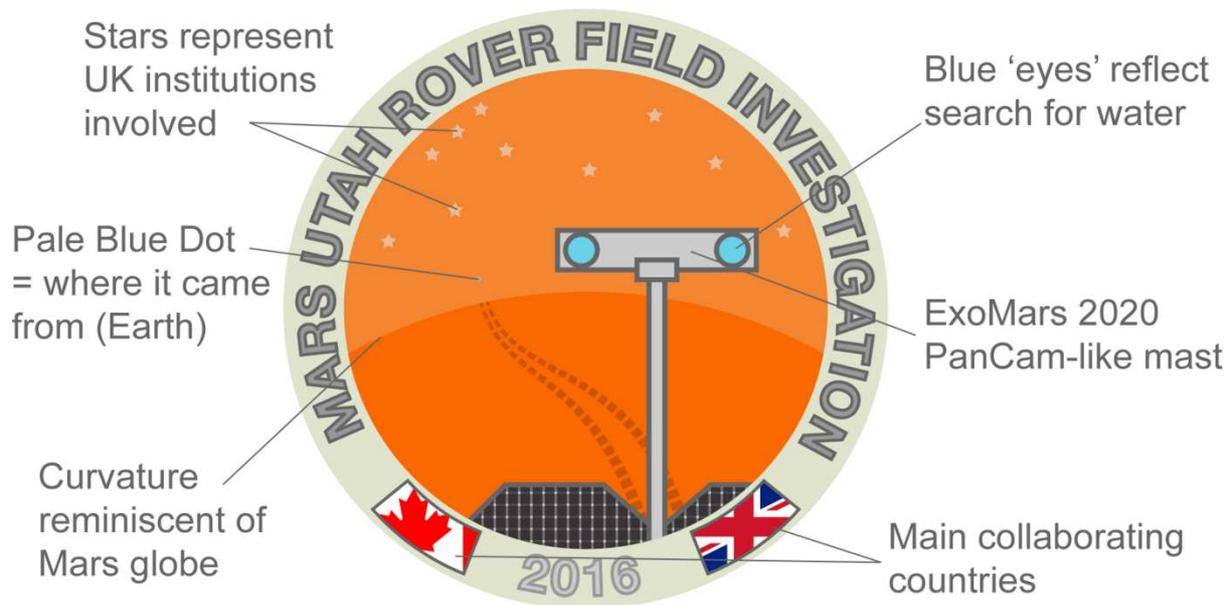
1108 limitations of the MURFI instrument suite, it was still not possible to determine if this  
1109 material was bedrock derived, or simply a poorly consolidated recent deposit, perhaps some  
1110 form of salt and clay pan which encloses fine sand.

1111 For the purposes of MURFI, the extraction and Raman analysis of the sample was  
1112 considered mission success. With more time, and perhaps a fuller range of emulated  
1113 instruments, it is likely that similar conclusions could have been drawn from the MURFI  
1114 analyses as those obtained from the lab-based analysis, and perhaps even a better  
1115 understanding of the lithology of the sample material. This conclusion once again highlights  
1116 the difficulties of performing sample acquisition and analysis remotely, compared with  
1117 laboratory-based analyses using more flexible and more easily deployed analytical tools.

## 1118 **7. Public Engagement**

1119 Public engagement during the MURFI investigation was carried out directly by the MURFI  
1120 team with assistance from the UK SA and the UK Science and Technology Facilities Council  
1121 (STFC). Mission planning from the outreach perspective also included engaging with the  
1122 CSA, and in particular obtaining clearance and support to use the MURFI mission patch.

1123 The use of the MURFI logo and mission patch (Figure 22) was one of the successes of  
1124 the mission. The value of a good logo cannot be understated, as it provided both a vehicle  
1125 for the whole team to get behind, and also a key mechanism for engaging with the public.  
1126 The mission patch was also included by the UK SA and STFC as part of their 'National  
1127 Colouring Book Day' contribution during the summer of 2017, encouraging children to  
1128 reimagine the patch design and learn about the missions behind it.



1129

1130

1131 *Fig. 22 The MURFI 2016 Logo, including annotations describing the design philosophy.*

1132

1133 During the ExoMars mission phase a blog was generated which saw over 20 posts and 5000  
 1134 views from 1000 visitors in 24 countries to the site (<https://murfiblog.wordpress.com/>).

1135 Additionally, the field trial used a Twitter hashtag (#MURFI). Again the mission name and

1136 logo proved extremely valuable in making connections to the wider public. The twitter feed

1137 had over 185 posts by 77 different users across the UK planetary science community,

1138 achieving a reach of 352,105, and nearly 800,000 impressions. Media coverage of the

1139 mission included mentions and feature articles published online through the BBC, The

1140 Guardian, New Scientist, Space.com, the UK SA blog, Medium, the TED Blog, and Science

1141 Made Simple, whilst the BBC's Sky at Night filmed the MOC operations for their November

1142 Mars edition.

1143 There were several visits to the MOC by a variety of different organisations. This was

1144 encouraged by the location of the MOC within the larger building – the MOC has a

1145 transparent wall (although this can be made opaque) such that operations could be

1146 observed by any visitors to the building. Some of the organisations visiting, planned or  
1147 otherwise, included chancellors of several universities, the Chilean Minister for Science, two  
1148 NASA technologists, observers from ESA and numerous other organisations based on the  
1149 Harwell Campus.

1150 At the field site in Utah, visitors included representatives of several other space  
1151 agencies, representation from Salt Lake City, US government departments and military units  
1152 in the vicinity, as well as many tourists in the region, both US and foreign.

## 1153 **8. Discussion and lessons learnt**

1154 The MURFI trial was very successful both in terms of delivering a mission-like operations  
1155 experience and learning about the logistics of planning future rover field trials. The site  
1156 chosen for the trial allowed a range of activities and had a suitable variation of geological  
1157 features to make it interesting. MURFI benefitted greatly from being a joint activity with the  
1158 CSA MSRAD trials, and their logistical assistance was a large part of MURFI's success.

1159

### 1160 ***8.1 Use of rover-based instrumentation during the MURFI ExoMars*** 1161 ***rover-like mission***

1162 The way the team used the MURFI instruments provides insight for how the instrument  
1163 suite might be used during the ExoMars rover mission, and also for future field trials. Like  
1164 rover missions sent to Mars, the acquisition of stereo NavCam panoramas at the end of  
1165 each drive was vital for planning target acquisitions for the next sol, especially when data  
1166 downlink limits precluded the use of full color stereo AUPE panoramas. The MURFI SWT  
1167 requested multi-filter AUPE images only of smaller areas, when there was a science need for

1168 multispectral data, or when there was sufficient data downlink availability. HRC was widely  
1169 used in the MURFI ExoMars rover-like mission. The use of HRC image mosaics of the  
1170 Resistant Unit allowed inferences about the lithology to be made from observations of the  
1171 bedding. HRC mosaics were used to analyze the landscape in the medium to far field, and  
1172 individual HRC images were also used in the near field to analyze the local area to prepare  
1173 for drilling, or obtain more detailed information about outcrops. HRC was a vital tool for  
1174 MURFI, and its variable focal length made it useful for both strategic level decision-making  
1175 (which general direction to head in) and for daily tactical planning (where exactly to set the  
1176 rover to obtain a drill core). Single HRC images were also used to check the location and  
1177 orientation of the rover against panorama images.

1178         The team made extensive use of downward-looking CLUPI images for drill targeting,  
1179 but sideways looking CLUPI images were also used to examine outcrops and the landscape  
1180 in general, when rover pointing allowed. The high resolution and full color capability of  
1181 CLUPI images were particularly suited for analyzing outcrops to determine grain size and  
1182 detailed sedimentary structure.

1183         Although almost all observations were made via targeted, precise direction of the  
1184 instruments based on their position within the NavCam mosaic or a PRo3D scene, the SWT  
1185 also commanded a single untargeted imaging session of the Bourton area as part of a 'drive-  
1186 by' tactical plan: this was very useful for testing ways to maximize the efficient use of  
1187 limited time resources.

1188         Overall, we found that the stand-off instruments used on MURFI had complementary  
1189 strengths and different weaknesses, such that targeting them as a suite gave a huge benefit.  
1190 We feel that rehearsals and trials such as the MURFI ExoMars rover-like mission, in which  
1191 the instruments were together, and with targeting performed holistically across a wide

1192 working group, are vital for allowing a rover team to work out how to operate efficiently  
1193 and effectively.

## 1194 ***8.2 MURFI ExoMars rover-like mission: assessment of geological*** 1195 ***interpretations and planning decisions made by the SWT***

### 1196 **8.2.1. Initial satellite remote sensing mapping**

1197 The hypotheses built using the Mars-equivalent satellite remote sensing data were vital for  
1198 the mission and provided a framework to test other observations against. After the MURFI  
1199 mission, we compared the satellite remote sensing observations with field observations  
1200 provided by the MURFI field team, the results of past studies of the geology of the MURFI  
1201 site in the literature, and direct observations made during a post-mission visit to the MURFI  
1202 site by some members of the SWT. The interpretations made from the satellite remote  
1203 sensing broadly matched those made by the field team, as well as the conclusions from the  
1204 literature: the overall interpretation of the landscape comprising inverted fluvial channels  
1205 and flood plains deposits was confirmed.

1206 The prediction made from satellite remote sensing of layered plains with  
1207 interbedded resistant layers was also broadly correct, matching previous observations of the  
1208 Brushy Basin Member of the Morrison Formation (Heller et al., 2015). One hypothesis put  
1209 forward during satellite remote sensing mapping was that the Layered Formation is a  
1210 mudstone, with significant geochemical variation. However, this was not supported by  
1211 either the MURFI drill results or rover observations (which found many the Anomalously  
1212 Bright Unit to be composed of sandy material, and little variation in WAC multispectral  
1213 images across the colored layers). Furthermore, based on MURFI rover data, the color  
1214 differences in the Layered Formations did not appear to be strongly associated with

1215 significant differences in mineralogy or the depositional environment. However, the color  
1216 differences are actually indicative of palaeosol weathering variations that reflect complex  
1217 variations in local and regional paleoclimate and paleoenvironment (Demko et al., 2004). It  
1218 is possible that similar conclusions could have been reached using the MURFI instruments  
1219 and platform, given a long enough mission and the collection of multiple samples. However,  
1220 it is unlikely that orbital remote sensing analyses using Mars-like data alone could be  
1221 expected to tease out these details. *Lesson learnt: geology is complicated, and satellite*  
1222 *remote sensing conclusions can obscure these complications. However, a combination of*  
1223 *satellite remote sensing and rover-scale observations is needed to interpret the geology of*  
1224 *landing sites correctly (see also, for example, Stack et al., 2016).*

1225         The difference in the image resolution between satellite remote sensing data and  
1226 rover observations meant that detail was easily overlooked at the start of the mission. For  
1227 example, the initial direction in which to drive was determined mainly on satellite remote  
1228 sensing interpretations, primarily that Big Mesa outcrops might show lithological,  
1229 geochemical or mineralogical variation, and possible layered bedrock. However, several  
1230 small outcrops visible in the initial panorama and close to the rover would have provided  
1231 clearer indicators of the palaeoenvironment. These outcrops were actually visible in the  
1232 Mars-like remote sensing data, but the small-scale of mapping required to cover the whole  
1233 landing site meant that they were amalgamated into a larger unit, rather than being  
1234 highlighted as specific bedrock areas. *Lesson learnt: to provide the best possible chance to*  
1235 *make good strategic decisions, large-scale geological, science target and hazard mapping*  
1236 *using full-resolution satellite images of the area around the landing location should be*  
1237 *conducted as rapidly as possible, as soon as the landing location is known.*

1238           The initial landing site assessment included analysis of rover-scale hazards such as  
1239 slopes, modern fluvial channels, loose materials, and boulders and rocks. Even with the sub-  
1240 meter pixel size images available, we could not measure the distribution of loose material or  
1241 small cobble-grade rocks (potentially relevant to rover traversability), as they are below the  
1242 pixel size. During post mission field observations we were consistently surprised by the  
1243 distribution and diversity of surface textures (some traversable, some not) compared with  
1244 the satellite remote sensing images. For example, in the field we have observed soft ground  
1245 with a lag of 2-3 cm diameter pebbles, cloddy friable ground, and regions of densely packed  
1246 cobble-sized clasts, all of which appeared featureless, although of different colours, in the  
1247 highest resolution satellite data. *Lesson learnt: a robust practical understanding of the rover*  
1248 *platform traversability capabilities, tested against as wide a variety of analog surfaces as*  
1249 *possible, is essential, because even 25 cm/pixel (HiRISE) data provide little information about*  
1250 *the true surface type. Hence, stand-off ground-based observations will be more important*  
1251 *for determining whether or not an area is traversable.*

### 1252 **8.2.2. Rover-based observations**

1253           The interpretations made from the satellite remote sensing data were broadly supported by  
1254 observations from the rover-based instruments, and in general our working hypotheses  
1255 developed during MURFI were supported by post-mission fieldwork and previous field  
1256 studies. As mentioned above, the largest area of misinterpretation was in the identification  
1257 of the layered terrains as being probable mudstones, when post-mission field work showed  
1258 that they contain many examples of sand-grade materials and only mud/silt-stone beds to a  
1259 much lesser extent. *Lesson learnt: grain size of a sedimentary rock – a vital measurement for*

1260 *inferring depositional environment – is difficult to measure from a rover, and nearly*  
1261 *impossible from orbit.*

1262 Another area where, post-mission, the MURFI field team advised the MOC SWT that  
1263 a mistake had probably been made, was in the failure of the SWT to better investigate a  
1264 rocky ridge only a few meters to the northwest of the landing site as their first priority. In  
1265 fact, the SWT did not request any further targeted data of this feature other than the  
1266 original sol 0 panorama. Post-mission field work confirmed that this feature, composed of  
1267 cross-bedded sandstones and conglomerates, would have provided definitive information  
1268 about the palaeoenvironment (i.e., this was a fluvial sandstone, so deposited in a river). This  
1269 omission was partly due to the perception that the variety of textures seen in the larger Big  
1270 Mesa outcrop to the south would provide answers about more elements of the landscape,  
1271 but also due to the smaller features appearing to be composed of out-of-situ blocks in the  
1272 panorama. In fact, the SWT should probably have realized that even if these blocks were not  
1273 in-situ, their meter-scale size meant that they probably were local to emplacement source,  
1274 and so could have provided important information. *Lesson learnt: small outcrops can*  
1275 *provide important information, and spectacular, larger outcrops can deflect attention from*  
1276 *more important targets. A balance must be struck that can probably only be determined*  
1277 *during the mission itself – but field trials can give important training for making these*  
1278 *decisions.*

1279 A similar issue identified by the field team was that, although the SWT used HRC  
1280 image targeting very effectively to search for sedimentary structures, several opportunities  
1281 to identify sedimentary structures and layering – and even cross-bedding – were missed.  
1282 One example of this was a feature called ‘West Butte’, in which the HRC targeting missed  
1283 the cross bedding hinted at in the WAC panorama. *Lesson learnt: even though tactical*

1284 *planning is time-constrained, all images should be examined carefully to avoid loss of*  
1285 *potentially informative targeting opportunities. Making time for whole-team science*  
1286 *discussions during a planning day is vital.*

1287         Post-mission, some of the MOC SWT ‘walked the MURFI traverse’ in the field. One of  
1288 the biggest surprises was how close targets appeared when viewed in situ, compared with  
1289 when examined in panorama images returned by the rover. This was partly compensated  
1290 for by using P<sub>Ro</sub>3D, but it was still very hard to get a correct sense of scale and distance.  
1291 This problem also probably contributed to the rocky-ridge and West Butte issues mentioned  
1292 above. *Lesson learnt: the projection of panorama summary products can be misleading, and*  
1293 *wider use of 3D visualization, and even virtual reality viewing platforms, should be made.*

### 1294 ***8.3 Lessons learned from MURFI for ExoMars rover operations.***

1295 The mission style, pre-mission geological mapping, the instrument suite deployed, and data  
1296 returned during the MURFI ExoMars rover-like mission were sufficiently close to the real  
1297 ExoMars rover payload and mission to give the team insight into how the ExoMars rover  
1298 might operate. A key responsibility of the ExoMars science team will be to characterize the  
1299 local geology well enough to provide the mission with the best possible targets for sampling,  
1300 such that science questions can be answered to further the overall objectives.

1301         The satellite remote sensing mapping provided vital context for the MURFI ExoMars  
1302 rover-like mission, and, once the landing site point was determined, provided specific  
1303 constraints about how the mission might progress, as it highlighted possible science targets  
1304 and likely hazardous areas. Also, although the satellite remote sensing mapping was done in  
1305 a very short time period, the relatively small size of the area mapped and the high degree of  
1306 planetary mapping experience available within the team allowed useful maps to be

1307 generated quickly. Almost complete HiRISE coverage of both candidate ExoMars landing  
1308 sites is now available, so very high resolution mapping should be possible for ExoMars once  
1309 the landing location is known. *Lesson Learnt: once the rover landing position is known,*  
1310 *rapid, high quality geological mapping, at full HiRISE-resolution scale, will provide a vital*  
1311 *resource for shaping the mission.*

1312 A corollary to the previous point is that although the satellite remote sensing  
1313 interpretations were broadly correct, the rover-based measurements demonstrated some  
1314 mistakes or misidentifications in the satellite image based mapping. Also, the initial  
1315 decisions of the SWT to head south to Big Mesa, rather than focussing on small outcrops  
1316 nearby was perhaps a mistake, and may have been exacerbated by the satellite remote  
1317 sensing focus on mapping the whole study area before the precise landing position was  
1318 known, and so by necessity omitting some detail in the local area. *Lesson Learnt: satellite*  
1319 *remote sensing can only provide certain types of information, and a combination of wider*  
1320 *context mapping, and very highly detailed local mapping is preferred. Still, care must be*  
1321 *taken to examine ground-based images before making decisions based on satellite remote*  
1322 *sensing data.*

1323 During the ExoMars rover-like mission, a challenge that quickly became apparent on  
1324 MURFI was that of discriminating grain size without an arm-mounted, close-up imager.  
1325 Although HRC was often used to search for sedimentary structures, both at centimeter scale  
1326 in the near field and decimeter scale in the far field, it cannot resolve grains smaller than  
1327 fine sand, even in the nearest field. This was a challenge when, for example, trying to  
1328 discriminate whether observed cross bedding was occurring in an aeolian or fluvial  
1329 sandstone. CLUPI, although possessing the required spatial resolution has a more limited  
1330 field of view, with fixed positions with respect to the rover. Thus, obtaining close-up images

1331 of specific outcrop targets required rover movements, costly in power, time and planning  
1332 resources. While this is not an insurmountable problem, it is an important lesson to learn: as  
1333 the rover approaches outcrops, positioning it at the end of the drive in such a way that  
1334 CLUPI will have the best opportunity for immediate observation will be important to save  
1335 'wasted' days of planning and rover movement. Here, the MURFI team felt that HRC played  
1336 a complementary role: targets that would be imaged with CLUPI can be identified from  
1337 range the sol before the rover approached. Also, the availability of Pro3D terrain models  
1338 was a great help in planning these sorts of drives. *Lesson learnt: CLUPI can be used in a*  
1339 *variety of modes that will be useful for understanding the local geology. However, the lack of*  
1340 *close-up imager on an arm could be a challenge. The challenge can be lessened by careful*  
1341 *rover positioning at the end of outcrop-approach drives, and use of HRC and 3D models of*  
1342 *the workspace can assist greatly.*

1343 As the drill is fixed to the rover body, positioning the drill precisely requires rover  
1344 drives. If a post-drive CLUPI image of the surface drill target area shows the rover is already  
1345 appropriately positioned, this will not be a problem. However, to obtain images of a wider  
1346 area required rover drives to return to the identified spot. For MURFI, we did not have  
1347 sufficient information about the driving precision of the ExoMars rover, so to minimise days  
1348 spent on the imaging, planning, driving, re-imaging cycle, the MURFI team used a series of  
1349 CLUPI images and very short rover drives to build up a mosaic of images showing the  
1350 context for the drill location. If the ExoMars rover can return precisely to previous points,  
1351 then this may not be necessary, but if precision driving is a challenge, or if the desired drill  
1352 target is small, then the use of this type of multiple CLUPI imaging could be helpful. The  
1353 WISDOM ground penetrating RADAR was not emulated for MURFI, so data from this  
1354 instrument would also have to be taken into consideration in planning drill locations. *Lesson*

1355 *learnt: the 'CLUPI ladder' technique could be useful for the ExoMars rover to identify the*  
1356 *exact spot for drilling, while also making it easy for the rover to return to that spot.*

1357 Several MURFI tactical decisions were made to avoid 'wasting days'. This included  
1358 the Bourton 'drive-by' imaging, learning to position the rover so that CLUPI would have a  
1359 good field of view, and using the 'CLUPI ladder' to avoid multiple small 'drive, observe,  
1360 decide' cycles. Given the high 'per sol' cost of a Mars rover mission (both in terms of actual  
1361 financial cost, and in terms of counting down days until mission success) every day is vital.  
1362 *Lesson learnt: a rover field trial team using a realistic mission instrument suite and a realistic*  
1363 *mission goal can develop important practices that could improve the efficiency of the real*  
1364 *mission.*

1365 Finally, the decision made to drill at the Poddington location within the Painswick  
1366 Patch area was based on the MOC SWT presumption from mapping and spectral data that  
1367 the brighter materials seen here (the Anomalously Bright Unit in the mapping) were part of  
1368 the Layered Formation and so were phyllosilicate-bearing, very fine-grained, fluvial deposits  
1369 (thought to be flood plains facies) that should have been ideal preservation materials for  
1370 biosignatures. The decision was also made under extreme time pressure, as the command  
1371 to drill had to be fitted into the mission schedule. However, the core materials returned  
1372 were friable, apparently containing sand grade materials, rather than being competent,  
1373 finer mudstones or silt stones, and were considered by the team to be less high-value  
1374 targets for an astrobiology mission than hoped for (i.e., not an organic-rich mudstone).  
1375 Ultimately, laboratory studies showed that the drill sample did contain calcite and clay  
1376 minerals, again reinforcing the difficulties in interpreting rover-derived data quickly during  
1377 tactical planning: the MURFI mission only simulated < 10 sols of a wider mission. However, it  
1378 was still not clear if the drill samples returned were weathered or friable bedrock, or poorly

1379 cemented, recently emplaced sediments. Better geological knowledge could have been  
1380 derived from a longer, more thorough study of the site. This result demonstrates how  
1381 important adequate geological assessment of the landing site will be to avoid ‘wasting’  
1382 drilling cycles within the mission. *Lessons learnt: (i) understanding local-scale geology is*  
1383 *difficult, even with Mars-like remote sensing data and a suite of excellent rover-based*  
1384 *instruments. To avoid drilling in the ‘wrong place’, the local geology must first be very well*  
1385 *characterized, and this can require extensive data analysis and discussion within the team,*  
1386 *as well as critical reanalysis of satellite data-based hypotheses. (ii) The results of the MURFI*  
1387 *drilling also reinforce the benefits of end-to-end rehearsals of the sample acquisition and*  
1388 *analysis chain, including laboratory analysis of representative drill samples to provide*  
1389 *feedback to the rover-based interpretations.*

#### 1390 ***8.4 Lessons learned from MURFI for implementing future field trials***

1391 As a UK-led Mars rover field trial, the completion of the MURFI mission was itself a success,  
1392 and a key element of the mission was learning where things had ‘failed’ or ‘gone wrong’, so  
1393 as to enhance the ability of the UK to run future field trials. At the end of the mission, a  
1394 debrief workshop was held at which participants aired their views about the success or  
1395 otherwise of the mission. All felt the mission was successful in delivering its goal of  
1396 providing a ‘realistic’ rover operations experience to the participants. Several areas for  
1397 improvement were noted. One of the biggest problems identified was that few of the team  
1398 could commit several weeks as one block of time, hence travel and accommodation proved  
1399 a greater than anticipated logistical challenge. Some participants also felt that swapping  
1400 roles so often was both stressful and inefficient, as they felt there was insufficient time to  
1401 learn the role adequately to deliver what was needed. Others, however, felt that

1402 experiencing different aspects of the tactical planning was rewarding, and that it was  
1403 important to explore the strengths and weaknesses of team members in a mission setting,  
1404 outside of the 'comfort zone' of everyday scientific working. *Lesson learnt: future trials*  
1405 *should ensure less frequent changes of role and require participants to commit to longer, but*  
1406 *not too long, time blocks (e.g. 4 days).*

1407         The choice of early- to mid-career scientists for SWTC meant that postdocs and  
1408 research fellows were able to experience this leadership role. Of the five team members  
1409 who spent time as SWTC, all agreed that it had helped them learn about their ability to lead  
1410 a team under pressure, and given them ideas for how to improve their leadership skills. The  
1411 postgraduate students who participated in the mission were keen that the MURFI  
1412 investigation should be repeated, as they also were keen to try the SWTC role. *Lesson*  
1413 *learnt: keep active daily leadership roles for early/mid-career team members.*

1414         The available preparation time for MURFI was limited, and many participants felt  
1415 badly prepared for their roles. This was especially true for those who were not able to  
1416 attend the sol 1 rehearsal days prior to the official sol 1 planning meeting. Some found the  
1417 technical aspects a challenge (e.g., processing data), while others did not quite understand  
1418 the rationale of the ExoMars rover-like mission (e.g., why drilling from bedrock was required  
1419 rather than sampling surficial fines from obviously fluvial environments). This was partly due  
1420 to the disparate skills-base in the team, including as it did geologists, astrobiologists,  
1421 planetary scientists and instrument specialists. Although written instructions were available,  
1422 documentation sent out to the team beforehand, and some degree of mentoring and  
1423 handover time was provided by more experienced SWT members, daily tactical planning  
1424 was a high-pressure environment that sometimes made it hard to learn specific skills. All  
1425 team members agreed that attending a training workshop beforehand would have been

1426 very useful for preparing the team better. *Lesson learnt: practical training is necessary to*  
1427 *reinforce written instructions for optimum team performance. Future trials should provide a*  
1428 *1-2 day training workshop for all team members that focussed both on the overall rationale,*  
1429 *and on providing technical training.*

1430 A challenge inherent in the MURFI ExoMars rover-like mission, and agreed by all in  
1431 the SWT, was that image processing each morning was difficult and time consuming, and  
1432 that too few of the team had experience operating the PRo3D software, which is itself still in  
1433 final stages of development. The production of panoramas and the presentation of the 3D  
1434 workspace terrain models would benefit from dedicated technical staff. Again, this was  
1435 partly due to the rapid rate at which MURFI was organized, and also by a lack of trained  
1436 team members able to take on this role. Also, localization was performed each day, yet on a  
1437 real mission this job would likely be performed outside of the science team. *Lesson learnt: if*  
1438 *resources permit, localization, data preparation and data visualization, are best done by*  
1439 *dedicated technical operators, rather than by SWT members.*

1440 The MOC was seen as being an excellent facility, and the large video wall, with the ability  
1441 to accept feeds from various different workstations, was very useful. However, the two-  
1442 tiered seating arrangement made it hard to communicate between the rows, especially  
1443 when team members were referring to the video wall while speaking. In the future, some  
1444 kind of communication system or a horseshoe shape arrangement would be better. *Lesson*  
1445 *learnt: communication within the team is vital, and MOC setup is important for facilitating*  
1446 *this.*

1447 The field site was perceived to be very Mars-surface relevant, overall the logistics and  
1448 planning worked well, and the time difference meant that both teams could work full days  
1449 on the mission without resorting to antisocial working times. The main improvement that

1450 could have been made was more robust field-to-MOC communications. *Lesson learnt: a*  
1451 *field site with good cell-phone coverage, mobile wifi, or a regular use of satellite telephone*  
1452 *communication is vital.*

## 1453 **9. Conclusions**

1454 MURFI demonstrated that the UK has a planetary science and engineering  
1455 community capable of performing a challenging Mars rover trial. MURFI also demonstrated  
1456 the benefits of the bilateral collaboration with CSA. While primarily a 'trial for future trials',  
1457 MURFI 2016 was also a vital training activity for the science team and, perhaps most  
1458 importantly, produced operations insights that could be relevant to ExoMars rover.

1459 The team learned very quickly to work together, due to the time pressure and  
1460 common goals, and the changing roles meant there were new challenges for members  
1461 every day. However, this role-changing also caused problems, and issues arose which could  
1462 have been avoided if roles changed less often, and also perhaps if objectives, priorities and  
1463 constraints had been more clearly laid out. An important learning outcome for many in the  
1464 MOC team was having to perform tactical operations under a tight deadline, with little time  
1465 to examine the data in full. During debrief meetings, it was found that the MURFI  
1466 experience was particularly valued by early career scientists, so future rover field trials  
1467 should aim to include and inspire as many junior members of the community as possible,  
1468 and especially provide them leadership roles where they can learn 'on the job' while still  
1469 benefitting from experienced mentors within the team. Providing experience working as a  
1470 team in this environment was one of the biggest perceived successes of MURFI.

1471 The MOC set-up, schedule, and mission guidelines and the field location and  
1472 logistical arrangements were all well-suited to a rover mission-simulation trial and, although

1473 some improvements could be made, the facilities and logistics provide a template for future  
1474 field trials. Also, the extensive documentation produced on a daily basis allowed the mission  
1475 to be analyzed at a later date. The biggest logistical improvements that could be made for a  
1476 future rover trial would be the provisions of a 1-2 day training workshop for all team  
1477 members prior to mission-start, additional on-site technical support, better field to MOC  
1478 communications, more end-to-end sample acquisition training, and more post-mission  
1479 sample analysis and feedback.

1480         The MURFI ExoMars rover-like mission showed that mission simulation or rehearsal  
1481 field trials will be useful for the ExoMars rover mission for several reasons: (i) to understand  
1482 how to operate the instruments as a suite, making best use of their complementary  
1483 strengths and mitigating weaknesses, and especially learning how to interpret the local  
1484 geology correctly, and to identify potential drill sites, using stand-off instruments alone, (ii)  
1485 to build an operations planning team that can work well together under strict time-limited  
1486 pressure, (iii) to develop new processes and workflows that could save time or improve  
1487 productivity when implemented on the real ExoMars rover mission, (iv) to understand the  
1488 limits and benefits of satellite mapping and the differences in scale between satellite and  
1489 rover images and data, and (v) to practice the efficient geological interpretation of outcrops  
1490 and landscapes from rover-based data by comparing the outcomes of the simulated mission  
1491 with post-trial, in-situ field observations. A vital input to the MURFI mission was the satellite  
1492 remote sensing mapping, and the hazard and science target identification. However, due to  
1493 the large area covered by the mapping, it could not be performed at a scale equivalent to  
1494 the full resolution of the best satellite remote sensing images. This also cannot be done for  
1495 the ExoMars rover until its landing position is known, given the > 100 km by 20 km landing  
1496 uncertainty ellipse. When localization has been performed, though, rapid high-fidelity

1497 geological and hazard mapping of the area around the landing point at full HiRISE resolution  
1498 will provide an extremely important resource that can be then be built upon using ground-  
1499 based observations as the mission progresses.

1500 We conclude by noting that although MURFI 2016 was the UK SA's first Mars Rover  
1501 trial, others have been run by various agencies (e.g., Arvidson et al., 2002; Woods and Shaw,  
1502 2014), and the lessons learned in them have allowed Mars rover operations to be rigorously  
1503 planned (e.g., section 5.3 of Grotzinger et al., 2012) and successfully performed. In fact, it  
1504 could be argued that much of the Mars rover operations knowledge and expertise residing  
1505 within the global community was developed during the MER (e.g., Arvidson et al., 2006;  
1506 Biesiadecki et al., 2006; Squyres et al., 2004) and MSL experiences (e.g., Vasavada et al.,  
1507 2014). However, while some of the MURFI lessons learnt are generic (e.g., the need for  
1508 rapid, high quality remote-sensing mapping, while understanding the scale disparity  
1509 between remote sensing and field observations), they are still important for a team to learn,  
1510 and important for each new mission to learn – only through hands-on experience can such  
1511 knowledge be embedded.

1512

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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