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The CanMars Mars Sample Return analogue mission

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ABSTRACT

The return of samples from known locations on Mars is among the highest priority goals of the international planetary science community. A possible scenario for Mars Sample Return (MSR) is a series of 3 missions: sample cache, fetch, and retrieval. The NASA Mars 2020 mission represents the first cache mission and was the focus of the CanMars analogue mission described in this paper. The major objectives for CanMars included comparing the accuracy of selecting samples remotely using rover data versus a traditional human field party, testing the efficiency of remote science operations with periodic pre-planned strategic observations (Strategic Traverse Days), assessing the utility of realistic autonomous science capabilities to the remote science team, and investigating the factors that affect the quality of sample selection decision-making in light of returned sample analysis.

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CanMars was conducted over two weeks in November 2015 and continued over three weeks in October and November 2016 at an analogue site near Hanksville, Utah, USA, that was unknown to the Mission Control Team located at the University of Western Ontario (Western) in London, Ontario, Canada. This operations architecture for CanMars was based on the Phoenix and Mars Exploration Rover missions together with previous analogue missions led by Western with the Mission Control Team being divided into Planning and Science sub-teams. In advance of the 2015 operations, the Science Team used satellite data, chosen to mimic datasets available from Mars-orbiting instruments, to produce a predictive geological map for the landing ellipse and a set of hypotheses for the geology and astrobiological potential of the landing site. The site was proposed to consist of a series of weakly cemented multi-coloured sedimentary rocks comprising carbonates, sulfates, and clays, and sinuous ridges with a resistant capping unit, interpreted as inverted paleochannels.

Both the 2015 CanMars mission, which achieved 11 sols of operations, and the first part of the 2016 mission (sols 12–21), were conducted with the Mars Exploration Science Rover (MESR) and a series of integrated and hand-held instruments designed to mimic the payload of the Mars 2020 rover. Part 2 of the 2016 campaign (sols 22–39) was implemented without the MESR rover and was conducted exclusively by the field team as a Fast Motion Field Test (FMFT) with hand-carried instruments and with the equivalent of three sols of operations being executed in a single actual day. A total of 8 samples were cached during the 39 sols from which the Science Team prioritized 3 for "return to Earth". Various science autonomy capabilities, based on flight-proven or near-future techniques intended for actual rover missions, were tested throughout the 2016 CanMars activities, with autonomous geological classification and targeting and autonomous pointing refinement being used extensively during the FMFT. Blind targeting, contingency sequencing, and conditional sequencing were also employed.

Validation of the CanMars cache mission was achieved through various methods and approaches. The use of dedicated documentarians in mission control provided a detailed record of how and why decisions were made. Multiple separate field validation exercises employing humans using traditional geological techniques were carried out. All 8 of the selected samples plus a range of samples from the landing site region, collected out-of-simulation, have been analysed using a range of laboratory analytical techniques. A variety of lessons learned for both future analogue missions and planetary exploration missions are provided, including: dynamic collaboration between the science and planning teams as being key for mission success; the more frequent use of spectrometers and micro-imagers having remote capabilities rather than contact instruments; the utility of strategic traverse days to provide additional time for scientific discussion and meaningful interpretation of the data; the benefit of walkabout traverse strategies along with multi-sol plans with complex decisions trees to acquire a large amount of contextual data; and the availability of autonomous geological targeting, which enabled complex multi-sol plans gathering large suites of geological and geochemical survey data.

Finally, the CanMars MSR activity demonstrated the utility of analogue missions in providing opportunities to engage and educate children and the public, by providing tangible hands-on linkages between current robotic missions and future human space missions. Public education and outreach was a priority for CanMars and a dedicated lead coordinated a strong presence on social media (primarily Twitter and Facebook), articles in local, regional, and national news networks, and interaction with the local community in London, Ontario. A further core objective of CanMars was to provide valuable learning opportunities to students and post-doctoral fellows in preparation for future planetary exploration missions. A learning goals survey conducted at the end of the 2016 activities had 90% of participants "somewhat agreeing" or "strongly agreeing" that participation in the mission has helped them to increase their understanding of the four learning outcomes.

1. Introduction

The human exploration of Mars remains a long-term goal for the Canadian and international planetary exploration communities. Recent and ongoing robotic missions have revolutionized our understanding of the Red Planet (e.g., Squyres et al., 2004a; b; Grotzinger, 2013), as has the continued study of martian meteorites (e.g., McCoy et al., 2011). The martian surface preserves evidence of a complex geological history, including a variety of processes that likely involved liquid H_2O and that may have been conducive to supporting life. While Earth has lost almost all its earliest record of geological history, Mars is believed to retain this record reflected in the preservation of its most heavily cratered surfaces. As such, it may even hold the key to understanding the origin of life on Earth and in the Solar System. Indeed, determining the habitability of past and present martian environments continues to be the focus of current and future missions to Mars. However, the results from orbital and in situ surface robotic missions alone are not sufficient to fully answer the major questions about the potential for life, past climate, and the geological history of Mars. Even if an orbital or in situ mission were to discover putative evidence for the existence of past or present life on Mars, confirming these results would necessitate that samples be collected, returned to Earth, and verified by multiple rigorous laboratory analyses on Earth. Thus, it is widely acknowledged that the next critical step in the exploration of Mars, both to advance science and to prepare for eventual human exploration, is the return of samples from known locations (GES, 2007; MEPAG, 2008a). Such a Mars Sample Return (MSR) mission will be one of the most challenging planetary exploration missions to date and it is widely accepted that this will be an international effort.

Several studies over the past decade have been conducted with the goal of defining science objectives for MSR (NRC, 2007, 2011; MEPAG ND-SAG, 2008b; MEPAG MRR-SAG, 2010; MEPAG, 2010, 2015), with the concept that the first phase of a Mars Sample Return mission campaign would be a MSR cache rover mission. The most recent report to specifically address MSR science objectives was conducted by the MSR End-to-End International Science Analysis Group (E2E-iSAG) (McLennan et al., 2012). In developing science objectives and priorities for MSR, this group identified four overarching science themes:

1) Life and its organic chemical precursors;
2) Surface materials and the record of martian surface processes;
3) Planetary evolution of Mars and its atmosphere; and
4) Potential for future human exploration.

The E2E-iSAG then defined 8 specific scientific objectives that could be addressed through the analysis of returned materials (McLennan et al., 2012). In *prioritized* order, the 8 objectives are:

1) Critically assess any evidence for past life or its chemical precursors, and place detailed constraints on the past habitability and the potential for preservation of the signs of life;
2) Quantitatively constrain the age, context and processes of accretion, early differentiation and magmatic and magnetic history of Mars;
3) Reconstruct the history of surface and near-surface processes involving water;
4) Constrain the magnitude, nature, timing, and origin of past planet-wide climate change;
5) Assess potential environmental hazards to future human exploration;
6) Assess the history and significance of surface modifying processes, including, but not limited to: impact, photochemical, volcanic, and Aeolian processes;
7) Constrain the origin and evolution of the martian atmosphere, accounting for its elemental and isotopic composition with all inert species;
8) Evaluate potential critical resources for future human explorers.

The current scenario for MSR is a series of 3 missions: sample cache, fetch, and retrieval. The NASA Mars 2020 mission represents the first cache mission and is the focus of the analogue activities described in this paper. The Mars 2020 Science Definition Study (Mustard et al., 2013) built on the E2E-iSAG and other previous reports, further developing objectives for this mission:

1) Explore an astrobiologically relevant ancient environment on Mars to decipher its geological processes and history, including the assessment of past habitability;
2) Assess the biosignature potential preservation within the selected geological environment and search for potential biosignatures;
3) Demonstrate significant technical progress towards the future return of scientifically selected, well documented samples to Earth;
4) Provide an opportunity for contributed HEOMD (Human Exploration and Operations Mission Directorate) Participation, compatible with the science payload and within the mission's payload capacity.

Under an analysis for the third mission objective, the report proposed geological environments most likely to address the highest priority science objective related to past life, as sub-aqueous sediments or hydrothermal sediments, or, rocks altered by hydrothermal or low temperature fluids. Appendix 8 of Mustard et al. (2013) also highlighted the specific challenge of designing successful science operations that could achieve mission objectives in a fixed mission duration, and the need for innovation with respect to current science mission operations practice.

In order to position Canada to participate in a future MSR mission a series of ground prototypes for surface mobility and associated science instruments and other peripheral elements were developed through the Canadian Space Agency's (CSA) Exploration Surface Mobility project. Requirements for the prototypes and instruments were derived from the International Mars Architecture for the Return of Samples study in which CSA participated, and a 2009 CSA Mars Sample Return Analogue Mission Science Definition Team that followed. In 2013, the CSA entered into a 4-year partnership with the Centre for Planetary Science and Exploration (CPSX) at the University of Western Ontario (Western) – as part of the Natural Sciences and Engineering Research Council of Canada (NSERC) Collaborative Research and Training Experience Program (CREATE) project "Technologies and Techniques for Earth and Space Exploration" (http://create.uwo.ca) – to conduct a series of annual MSR mission simulations to develop and test planetary surface operational requirements for science instruments, science support equipment and mission platforms in a realistic scenario. The main driver of the CREATE project was to provide a unique training experience for Canadian students and postdoctoral fellows to prepare them for participation in future planetary exploration missions. The goal from the outset was that these simulations would increase in complexity and realism each year.

The 2013, 2014 activities were carried out at the simulated Mars terrain at the CSA headquarters in St. Hubert, Quebec, Canada (Fig. 1). The 2013 deployment was carried out over one week in August 2013 and used the teleoperated Juno rover platform (Fig. 1a and b), which was equipped with onboard stereo and navigation cameras. Three other science instruments were used, all of which were operated by the human field team (Fig. 1b): an X-Ray Fluorescence (XRF) spectrometer, a Raman spectrometer, and a Microscopic Imager (MI) in the form of a digital single-lens reflex (DSLR) camera. The mission control structure comprised Science and Planning teams and was adapted from the Sudbury Lunar Analogue Mission (SLAM) deployment led by Western (Marion et al., 2012; Moores et al., 2012). Both the Science and Planning teams were located at the CSA in Montreal but not in visual range of the Mars terrain.

The 2014 deployment was conducted over two weeks in August 2014 and had a more refined goal of determining the optimum instrument suite and operations architecture required to characterize a sample for return. The major changes for 2014 were the use of the Mars Exploration Science Rover (MESR) rover (Langley et al., 2012) (Fig. 1d; Table 1) – built and supported by MacDonald Dettwiler and Associates Ltd. (MDA) – the switch to have the Science and Planning teams at Western (London, Ontario) (Fig. 1e), and the addition of two other instruments: the Three-Dimensional Exploration Multispectral Microscopic Imager (TEMMI) (Doucet et al., 2012; Bourassa et al. this issue) and a Mini-Corer, both of which were integrated with a robotic arm mounted on the MESR platform (Fig. 1d). Both deployments yielded valuable lessons learned that enabled the CSA and the Western-led CREATE team to prepare for the ambitious CanMars analogue missions.

A priority for the 2015 and 2016 CanMars simulated MSR mission was to conduct operations at a realistic, scientifically interesting, and relevant analogue site. Terrestrial analogues can be defined as places or spaces on Earth that approximate, in some meaningful respect, the geological, environmental and putative biological conditions and/or setting(s) on a particular planetary body, either at the present-day or sometime in the past (Farr et al., 2002; Osinski et al., 2006). Through a competitive process, Western was contracted by CSA in a separate study in 2014 to identify a suitable site for the 2015 and 2016 CanMars activities, seeking accessible terrain for a large rover deployment and a 'habitable environment' suitable for MSR science. While there are many scientifically relevant Mars analogue sites in Canada (Osinski et al., 2006), logistics, weather and seasonal access, were significant considerations that resulted in CSA confirming a site near Hanksville, Utah, USA, for the 2015 and 2016 campaigns. The selected site was relevant to the Mars 2020 target geological environment of subaqueous sediments with a paleochannel feature similar to features observed at candidate landing sites on Mars. Site selection is discussed in more later in this paper and further details of the site are provided by Tornabene et al. (this issue).

In addition to enabling comparative planetary geological studies that provide ground-truth for robotic spacecraft data and extreme environments that enable a greater understanding of the limits of habitability (Farr et al., 2002; Osinski et al., 2006), terrestrial analogues also allow for the development and testing of technologies, software and operations architectures and in the training of personnel for future missions. One of the lengthiest and in-depth series of analogue mission activities to date was NASA's 2010 Desert Research and Technology Studies (DRATS). This series of campaigns focused predominantly on testing technology and operation architectures for human exploration, including human-robotic systems and extravehicular equipment (e.g., Bell Jr. et al., 2013; Bleacher et al., 2013; Eppler et al., 2013; Gruener et al., 2013; Ross et al., 2013; Young et al., 2013). In terms of robotic missions, numerous individual analogue missions have been conducted over the years. Notable Pre-MER activities include the Nomad Rover Field Experiment conducted in the Atacama Desert, Chile, in 1997 (Cabrol et al., 2001a, 2001b) and the 1999 Marsokhod rover mission simulation at Silver Lake, California (Stoker et al., 2001). In preparation for the 2003 launch of the twin MER

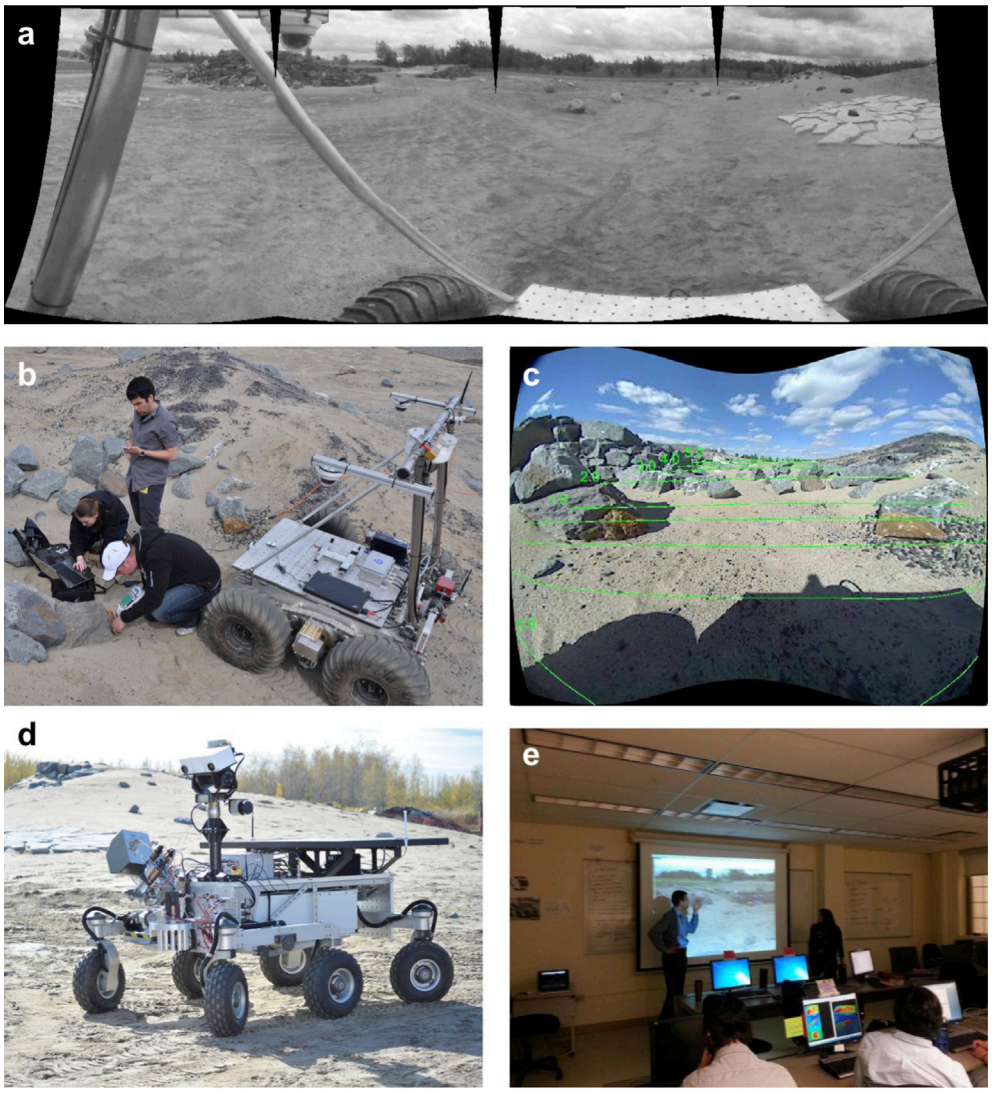

Fig. 1. Images from the 2013 and 2014 MSR analogue campaigns. (a) View of the CSA Mars terrain during the 2013 deployment from the built in camera onboard the Juno rover platform. (b) Image of the Juno rover and field personnel during the 2013 deployment. As the Juno rover had no integrated science instruments, this was the typical set up of field data collection. After the rover was commanded to a position by the Science Team, the field team would collect the required data. Here the field team is collecting XRF data using a Bruker GeoTracer. (c) Screen capture of the CSA rover software interface that was available to the Science Team. (d) The MESR platform in the CSA Mars terrain during the 2014 deployment. Visible on the left of the MESR body is the TEMMI microscope. (e) The Mission Operations room at Western during the 2014 mission.

Table 1
MESR key performance characteristics.

Parameter	Specification
Wheelbase	180 cm
Track width	145 cm
Ground clearance	45 cm
Ramp breakover angle	68°
Angle of approach	>40°
Angle of departure	>40°
Rollover threshold	36°
Ground pressure	28 kPa
Gradeability (terrain)	16°
Gradeability (hard surface)	>31°
Maximum speed	12.5 cm/s
Braking distance	<5 cm
Maximum obstacle	40 cm (slow speed)
Rock hazard	10 cm (all speeds)
Minimum radius of curvature	0 (continuous steering down to point turn)
Payload capacity	70 kg

spacecraft, a series of analogue activities using the Field Integration Design and Operations (FIDO) prototype Mars rover were conducted (Arvidson et al., 2002; Haldemann et al., 2002; Jolliff et al., 2002; Li et al., 2002; Moersch et al., 2002; Stoker et al., 2002). With a focus on the integration of orbital, descent, and rover-based data and on traverse science and sample collection, the 2-week FIDO campaign carried out in 2000 is one of the closest models to our approach for CanMars. More recently, in the Moon Mars Analogue Mission Activities Mauna Kea 2012 (MMAMA, 2012) field test, the emphasis was on comparing products and science results derived from a rover versus those produced by geologists on the ground using traditional field techniques (Yingst et al., 2015). During this analogue mission the operations architecture was adapted from MER and MSL. Other activities have focused on the development and testing of technology and operations for lunar site surveys (e.g., Fong et al., 2006) and semi-autonomous lunar rover operations (e.g., Yingst et al., 2014).

This contribution provides an overview and synthesis of the preparation, execution and follow up scientific studies related to the CanMars MSR analogue mission. Other contributions in this special issue that deal with specifics of certain aspects of the CanMars campaign are referenced in the appropriate sections. CanMars represents an analogue mission that not only entailed an integrated set of activities that simulated the cache component of an MSR mission, but that was also driven by science questions at a Mars-relevant analogue site that was unknown to the mission control team. To our knowledge, CanMars is the most in-depth and high-fidelity analogue mission with an explicit focus on Mars Sample Return and the upcoming NASA Mars 2020 rover mission.

2. CanMars overview

CanMars was conducted over two weeks in November 2015 and continued over three weeks in October and November 2016 at an analogue site in Utah, USA (Fig. 2a), that was unknown to the mission control team located at Western, London, Ontario, Canada. An overview of the site selection process and the details of the site are provided in Section 4. The MESR platform as well as the operations and resource constraints remained the same for both years (see Pilles et al., this issue). As described further below, there were slight differences in the instrument payload (see Section 3 and Table 2) and structure of the Mission Control Team (see Section 5). The objectives of the 2015 and 2016 analogue missions were not, however, identical. In 2015, a landing ellipse of ~1.6 × 5.2 km was defined (Fig. 2a and b) and the Science Team was provided with the following mission goals: 1) to collect a minimum of one sample, and 2) satisfy two sub-goals from the MEPAG objectives for Goals I and III; Habitability and Crustal Processes, respectively. As with an actual mission, characterization of the landing ellipse region was conducted before the analogue mission commenced (see Morse et al., this issue, and Tornabene et al., this issue) and included the derivation of a set of hypotheses for the geology and astrobiological potential of the site (see Section 7 and Caudill et al., this issue, a). Eleven sols of operations were achieved in 2015 (where a sol is a solar day on Mars, which is 24 h, 39 min on average) (Fig. 2c).

In 2016, the CanMars mission formed part of the larger Canadian Mars Sample Return Analogue Deployment (MSRAD). MSRAD 2016 included a cache rover mission simulation (i.e., CanMars), and a Mars Fetch Rover technology demonstration; the latter is described in Gingras et al. (2017). The specific objectives for MSRAD were to:

- Develop and strengthen partnerships and position Canada for future contributions;
- Advance MSR science operations and sample targeting;
- Advance selected rover autonomy and arm positioning technologies;
- Attract and inspire the public in STEM (science, technology, engineering, and mathematics) subject matter;
- Provide valuable learning opportunities to students.

CSA also extended an invitation to other space agencies through the International Mars Exploration Working Group (IMEWG) to participate in parallel analogue deployment tests taking advantage of site knowledge and infrastructure established by CSA, with consideration of developing future, more closely co-ordinated, analogue campaigns. Details of the UK Space Agency (UKSA)-led Mars Utah Rover Field Investigation (MURFI) are detailed in Balme et al. (this issue). For the 2016 campaign, CSA also invited input from other space agencies and partners to design the Science Plan, including specific input from the Mars 2020 project to the design of tests for operational approaches. To further engage Canadian scientists, CSA also provided competitive grants opportunities through CSA's Flights and Fieldwork for Advancement of Science and Technology (FAST) program, and Space Exploration Science Definition Studies (SDS) for investigations within the framework of the CSA-coordinated 2016 analogue campaign. One FAST grant was awarded to the University of Winnipeg (PI: E. Cloutis) and two SDS grants to McGill University (PI: L. Whyte) and Western (PI: G. R. Osinski) were awarded. Members of the University of Winnipeg and McGill University groups conducted fieldwork independent of the CanMars mission; several members of the Western group participated in the mission operations and subsequent field validation.

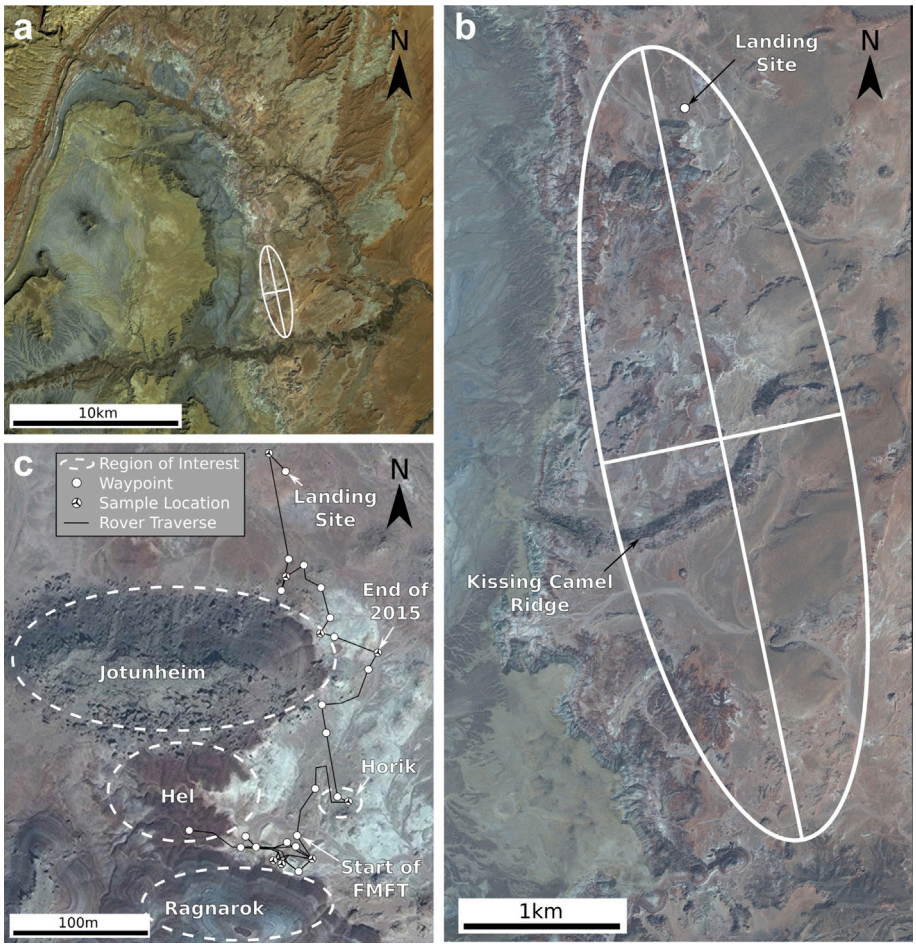

Fig. 2. (a) LandSat-8 image of the site of the CanMars analogue mission in Utah. The landing ellipse is marked by the white oval. (b) Quickbird-2 satellite image of the CanMars landing site (white dot) located at the northern end of the landing ellipse. The prominent sinuous ridge near the centre of the ellipse is "Kissing Camel Ridge". (c) Close-up of the Quickbird-2 satellite image focusing on the region of CanMars operations in 2015 and 2016. The rover traverse is marked as a black line with waypoints displayed as white points. The names of important topographic/geomorphologic features referred to in the text are labelled. The extent of these named regions is indicated by the white dashed lines.

Table 2
CanMars instruments and their Mars 2020 equivalents.

Mars 2020 Instrument	Details	CanMars 2015 Instrument	CanMars 2016 Instrument	CanMars specifications
MastCam	Stereo camera with zoom capabilities	MastCam (Zoom Camera)	MastCam (Zoom Camera)	Horizontal FOV: 75.5°. Vertical FOV: 56.6°. Max resolution 3264 × 2448 pixels. Optical Zoom: 10x
SuperCam	LIBS	XRF (Bruker GeoTracer)	LIBS (SciAps Z500 GEOChem	1064 nm, 5 mJ laser with 50 μm diameter beam; all elements except H, N, O, Cl, Br, Rb, Ce, K
	Raman & TRF	Raman (DeltaNu Rockhound)	Raman (DeltaNu Rockhound)	785 nm 120 mW laser. Resolution of detection is 8 cm-1
	Visible and Infrared reflectance spectroscopy	N/A	ASD FieldSpecPro HR spectrometer	Spectral acquisitions from 350 to 2500 nm. Spectral resolution ranges between 3 and 7 nm at 1 nm intervals.
	Remote micro-imager	DSLR with Macro lens	DSLR with Macro lens	
PIXL	Micro focus XRF	XRF (Bruker GeoTracer)	XRF (Bruker GeoTracer)	All elements above Mg in periodic table
	Camera	DSLR with Macro lens	DSLR with Macro lens	
SHERLOC	Raman	N/A	Raman (B&WTek i-Raman-532-S)	175-4000 cm-1 range, ~4 cm-1 resolution at 614 nm. 532 nm–50 mW solid state diode laser. 0.08 nm spectral resolution CCD detector
Drill	Rotary percussive drill	Mini corer	Mini corer	Solid Core: 10 mm diameter, 25 mm max depth, Loose Soil: 13 mm diameter, 50 mm max depth
HazCams	Six hazard detection cameras	Belly Cam	Belly Cam	3 wide angle cameras. Horizontal FOV: 112.5°, Vertical FOV: 84.4°, Res: 640 × 480 pixels

The Science Plan was finalized at a pre-mission workshop held at Western in coordination with CSA and other partners and grantees. The Science Plan objectives were:

1) To test the accuracy of selecting samples remotely using the partial context available to mission scientists using rover-based field operations, compared to the full context available to a traditional human field party;
2) To test the efficiency of remote science operations with periodic pre-planned strategic observations compared to including strategic and tactical considerations in the tactical plan;
3) To assess the utility of realistic autonomous science capabilities to the remote science team, to understand how such autonomy improves the effectiveness and rate of progress of the science mission, and to learn which strategies of exploration emerge from the availability of these capabilities, including in a downlink-constrained environment;
4) To make a preliminary determination of the factors that affect the quality of sample selection decision-making in light of returned sample analysis.

The CanMars 2016 cache mission was implemented in two parts representing different operational configurations that allowed different operations strategies to be tested, and best use of the limited duration of the analogue deployment. Part 1 was conducted with the MESR rover platform (Fig. 3). In this scenario, 1 day = 1 sol, as with the 2015 campaign and indeed, the MESR rover started the 2016 campaign at the exact spot it ended the 2015 campaign (see Fig. 2c). During Part 1 of the mission (sols 12–21) 10 command-cycles were planned and executed using MESR. In addition, two Strategic Traverse Days were pre-planned with activities involving long rover traverses and post-drive imaging. Part 2 was implemented without the MESR rover and was conducted exclusively by the field team with hand-carried instruments and sample acquisition equipment. This portion of the mission was conducted as a Fast Motion Field Test (FMFT) with the equivalent of three sols of operations being executed in a single actual day (i.e., 1 day = 3 sols). A single plan was used to execute the 3 sols, such that the same remote science team planning cycle was used in Part 2 as for Part 1. The purpose of the FMFT was to enable the team to complete a longer planning cycle, extending the operational activities of the 2016 mission and allowing for a more realistic mission scenario; this extra planning test thereby enhanced the opportunities for experiential training by the participants, providing more time for a better understanding of the geologic context via a synthesis of image and data, and thereby improved sampling opportunities. Details on the Strategic Traverse Days and FMFT are provided in Pilles et al. (this issue).

A final goal of the Western-led Science Definition Study (carried out in collaboration with JPL) for the 2016 CanMars analogue mission was to test and further develop rover science autonomy capabilities, based on flight-proven (e.g., the Autonomous Exploration for Gathering Increased Science (AEGIS) system; Francis et al., 2017) or near-future techniques intended for actual rover missions). A series of experiments implemented blind targeting, Visual Target Tracking (VTT), precise return, autonomous geological classification and targeting, autonomous pointing refinement, contingency sequencing, and conditional sequencing and are described in Francis et al. (this issue).

3. Rover platform and instrumentation

The CanMars mission used a suite of off-the-shelf "stand-in" and integrated instruments onboard the MESR rover platform, which is an end-to-end prototype of a Mars science-class rover system (Langley et al., 2012), capable of supporting science instruments and payloads (Fig. 3; Table 1). MESR is a 6-wheeled rover featuring all-wheel drive, with the four corner wheels being independently steerable. It features a passive walking beam suspension that provides platform stability and obstacle climbing capability. Three low-resolution cameras on the underside provide situational awareness views of all six wheels. The MESR platform is equipped with a sensor head mounted on a mast that is ~1.7 m above ground. This sensor head is equipped with a pan-tilt unit (PTU), featuring a stereo-camera, zoom camera and a line-scanning LIDAR. This arrangement allows 360° imaging of the rover surroundings in 3D and provides panorama-imaging capability. A sun sensor and inclinometer are also included in the sensor head and are used for rover localization. Further specifics of the MESR platform are summarized in Table 1 and in Langley et al. (2012).

As noted above, the CanMars analogue mission sought to replicate as closely as possible the NASA Mars 2020 mission (Farley and Williford, 2017); this is reflected in the instruments and operational architecture. In order to achieve this, science instruments were used in a realistic way. In other words, it was determined that decisions made using acquired data

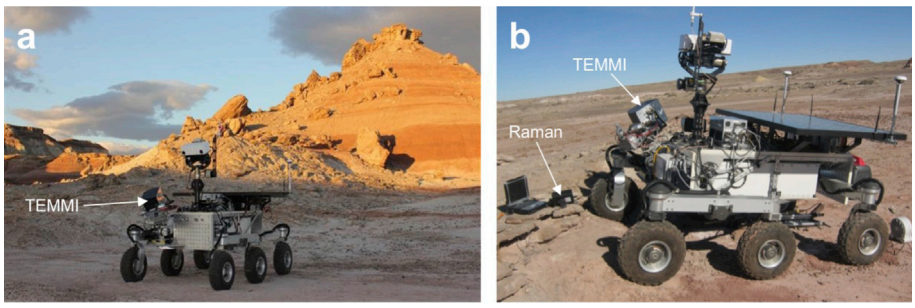

Fig. 3. The MESR rover at the CanMars analogue site in Utah. (a) MESR with the prominent Jotunheim ridge in the background at right. The TEMMI microscope mounted on the end of the robotic arm (stowed) is labelled. (b) View of the MESR rover at a waypoint. The Raman was not integrated with the rover and is shown on the outcrop following an analysis.

and decisions about which data to acquire next, must be plausible with regards to what can be achieved with a remotely-operated robotic mission. To this end, task dependencies, resource costs, and other 'flight rules' constraining mission planning were carefully considered prior to the deployment and tested in a dry run prior to the mission. The design of these rules is described in Francis et al. (this issue), and the resource costs are summarized in Pilles et al. (this issue).

Science activities planned by the mission control team were of three types, each with different constraints and flight rules. Imaging with mast-mounted cameras required the mission control team to specify pointing angles in either rover-relative or 'local level' (site geographic) co-ordinates, by azimuth and elevation. Autofocus and autoexposure were assumed. This allowed the team to take targeted images of features of interest (FOI), if the rover had not moved since the features were seen, or to take images with estimated pointing of new, as-yet-unseen locations post-drive. Use of remote, targeted science instruments required the team to choose specific points on the terrain to measure. Doing so required imagery of sufficient resolution to identify points of interest, an estimate of the range to the target and its position relative to the rover (as derived from LiDAR). As for remote science, 3D information and high-resolution imaging of the measurement site was a prerequisite for acquiring contact science measurements and/or samples. These prerequisite observations were required to be from the same rover worksite – not from a previous drive location – since any error in target localization from rover motion could be catastrophic for instrument placement. The actual reachability constraints of the rover's arm were used for arm-mounted instruments; the sampling system, and reachability rules similar to those expected for Mars 2020 were applied.

The scientific instruments used during the CanMars mission are summarized in Tables 2 and 3, along with their links to the Mars 2020 rover instruments. As CanMars flight rules were closely constrained by those necessary for MSL operations and as planned for Mars 2020, instruments were simulated as both contact and having remote-acquisition capabilities. A key difference to the 2013 and 2014 analogue deployments that this team carried out was the inclusion of remote science capabilities during the 2015 and 2016 CanMars analogue mission for the first time. This was deemed critical from the outset given the success of the ChemCam instrument on the Mars Science Laboratory mission (Maurice et al., 2012). In addition to proving extremely important in shaping the investigations and decision processes used in exploring Gale Crater, ChemCam data is obtained at relatively low resource cost – in particular in terms of mission time and power – compared to contact instruments, such that it has, and continues to be, used to inform decisions about where to conduct more resource intensive activities such as sampling or multi-sol imaging/contact science campaigns (Francis et al., 2017). It is anticipated that SuperCam (Perez et al., 2017) will play a similar role during the Mars 2020 mission. For this reason, the CanMars analogue mission included remote geochemical instruments in the simulation. Since a remote LIBS/Raman/IR spectrometer was not available for integration aboard the rover, this capability was simulated using handheld instruments (see Table 2). The use of the CanMars Mars 2020 stand-in instruments, including their calibration, is described in detail in Caudill et al. (this issue, a,b).

Additional instruments used in the CanMars mission, but with no direct match to the Mars 2020 rover were a LiDAR and a 3D microscope, TEMMI (Table 3). The Three-Dimensional Exploration Multispectral Microscopic Imager (TEMMI) was integrated onto the robotic arm mounted to MESR (Fig. 2). TEMMI is an advanced prototype and consists of a monochrome camera mounted to a microscope objective. Attached are three identical LED-based illumination units making TEMMI independent of natural lighting as well as a digital light processor (DLP)-based video projector with a white LED and an objective. The images obtained by TEMMI during the CanMars mission provided the team with the highest resolution images available to discern micron-scale rock textures. The TEMMI images that were acquired provided fundamental data for characterizing the samples, placing constraints on the types of rocks present (e.g., clastic vs non-clastic; sedimentary vs volcaniclastic) (see discussion in Caudill et al., this issue, a). Details of TEMMI and its use during the CanMars analogue mission are provided in Bourassa et al. (this issue).

While it has not yet been used for past or ongoing rover missions, a Canadian LiDAR instrument successfully flew on the Phoenix mission as part of the Meteorological Station (Whiteway et al., 2008) and is under consideration for future robotic missions. For rover missions, LiDAR has typically been considered in the context of guidance, navigation, and control (e.g., Dupuis et al., 2008), and this was the original purpose of the mast-mounted LiDAR on MESR used during the CanMars mission. However, LiDAR has also been proposed as a scientific tool for planetary exploration (Osinski et al., 2010) due to the superior visual 3D record of

Table 3
Additional MESR CanMars instruments.

Instrument	Details		Specs	
LiDAR	Ranging, elevation, slopes, scale; navigation, localization, 3D morphology, texture and spatial relationships		Horizontal FOV: 360°, Vertical FOV: −45 to +45°, Range: 50 m	
TEMMI	Positioning of TEMMI is restricted to the Small Manipulator Arm (SMA) workspace	Number of focus point: 1 Focusing: Manual or auto, Colour resolution: 12 bits, Illumination: 8 wavelengths, 455 nm–850 nm	At Low resolution Res (pixel): 4.4 μm Res (optical): ≤10 μm Field of view: 5.7 × 4.3 mm^2 Image size in pixel: 2592 × 978	At High resolution Res (pixel): 2.2 μm Res (optical): ≤5 μm Field of view: 5.7 × 2.1 mm^2 Image size in pixel: 1296 × 972

the terrain and the wealth of geometric and structural information that can be obtained from LiDAR scans. LiDAR intensity data also has the potential to provide qualitative, and potentially quantitative, mineralogical information about planetary surfaces (Telling et al., 2017).

During the CanMars analogue mission, LiDAR scans enabled detection of topographic features such as boulders, outcrops and vegetation (Fig. 4). However, the principal use of the LiDAR was for MESR navigation and hazard avoidance, calculation of distances to potential targets for contact science, and estimation of distances to targets for remote science (7 m maximum range for LIBS observations and 12 m for Raman observations). Overall, the extremely detailed surface mapping of objects enabled by the use of LiDAR proved very useful to the Science Team and has implications for science operations (Caudill et al. this issue, a).

4. Site selection and description

The CanMars 2015, 2016 analogue missions were carried out in Utah, USA (Fig. 2). This site was chosen through a site selection process carried out in 2014 by Western under contract to the CSA. The goals of this site selection study were to: 1) identify and characterize a set of viable terrestrial analogue sites that will maximize the CSA's ability to test both engineering and scientific scenarios (specifically the scientific priorities and goals of a MSR mission as summarized by the CSA and the international scientific community) through the utilization of their Exploration Surface Mobility (ESM) ground prototypes and their associated suite of peripheral elements; 2) down-select from the three proposed sites to a final site; and 3) develop a science scenario for a future CSA-lead MSR analogue mission to the final site.

We adopted a modified approach based on the final site selection for the Mars Exploration Rover and Mars Science Laboratory missions (Golombek et al., 2003; Grant et al., 2011). This process took into account the science fidelity, logistics, and terrain requirements from a technology perspective for the analogue site (see also Tornabene et al., this issue). Ultimately, a region of Utah was chosen for the CanMars expeditions in an area well-known for previous analogue activities (e.g., Chan et al., 2011; Foing et al., 2011). This field site locality is situated at ~1300 m above sea level ~8 km to the northwest of Hanksville, Utah, USA, at approximately 110° 47′5.39" W, 38° 25′6.28" N. This is a desert climate on the Colorado Plateau and shares many similarities to the surface of Mars (Fig. 1). This is due to its brightly coloured rocks (both oxidized and reduced), lack of vegetation and arid environment. The geology of this region locally consists of a variety of clastic and chemical precipitates. The clastic rocks include conglomerates, sandstones, shales and mudstones ranging from Jurassic to Cretaceous in age (Hintze and Kowallis, 2009). Both conglomerates and mudstones have recently been observed on Mars by the Mars Science Lab (MSL) rover within Gale Crater (Vaniman et al., 2014; Williams et al., 2013). There are also carbonate and iron oxide concretions at this locality (Battler et al., 2006); the latter being analogous to the "blueberries" observed by Opportunity at Meridiani Planum (Squyres et al., 2006); carbonates have also been observed in some martian meteorites (e.g., Bridges et al., 2001) and as a component of the martian surface, through both in situ spectral and remote orbital analysis (e.g., Ehlmann et al., 2008; Morris et al., 2010). This region also includes pervasive bentonite clays that comprise a major portion of the vegetation-poor regolith (Fig. 2). Bentonite clays are derived from aqueously-altered silicic volcanic ash deposits that were delivered by winds during volcanic eruptions from calderas to the west and southwest of the field site (Demko et al., 2004). These altered ash deposits provide an excellent analogue for the investigation of clay-rich regions on Mars.

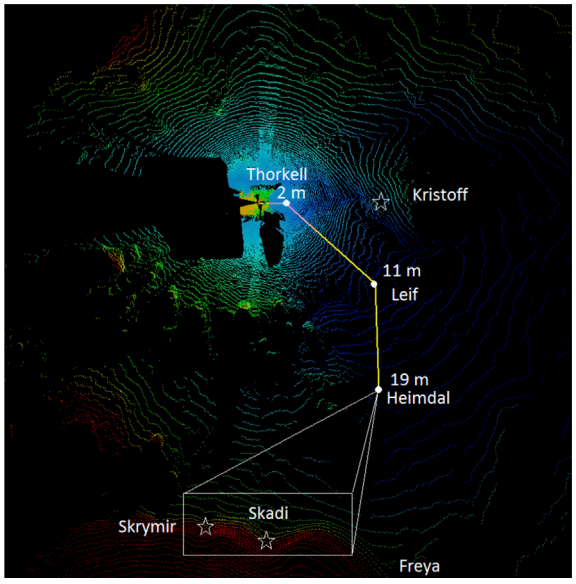

Fig. 4. LiDAR point cloud acquired on Sol 6, coloured by elevation relative to rover (blue = low, red = high). The path in yellow shows the planned traverse for Sol 7 that avoids the rubble south of Thorkell. The stars indicate features of interest and the white square indicates the approximate location of a post-drive zoom image. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

In addition to these analogue aspects, there are numerous "sinuous ridges" (Fig. 2) – including Kissing Camel Ridge itself – that are known to be inverted channels (i.e., "fossilized" stream beds) (Clarke and Stoker, 2011). Inverted channel deposits are relatively common on Mars (e.g., Burr et al., 2010; Weitz et al., 2008). Mars landing sites containing inverted channels are/were also being considered as potential landing sites for ExoMars 2020 (e.g., Aram Dorsum; Balme et al., 2016) and Mars 2020 rovers (e.g., Melas Chasma; Davis et al., 2015). There is very little doubt that water once flowed across the surface of Mars (Carr, 1996); however, the details of the events that lead to features such as channels, deltas and paleolakes – such as volume, intensity and duration of surface water – remain largely speculative and unconstrained from orbit. This analogue site thus presents an ideal opportunity to develop and test protocols and analysis approaches in preparation for MSR. Furthermore, given the geology of this site, there is the potential to sample the 3 highest priority MSR sample suites; namely sedimentary, hydrothermal, and low temperature alteration suites.

5. Team structure and roles

Over 60 people from multiple organizations were divided into three teams for the CanMars analogue mission. The Mission Control Team was responsible for the science planning, processing, and interpretation, and was based at Western (Fig. 5). The CSA Team, with responsibility for the MESR rover operations was based at the CSA headquarters in St. Hubert. The Field Team, which included the MESR platform and handheld instruments, was deployed in Utah, and consisted of personnel from the CSA, Western and MDA.

The CanMars Mission Control Team was further split into Science and Planning sub-teams. This operations architecture was developed based on the Phoenix and MER missions together with previous analogue missions led by Western, including the Sudbury Lunar Analogue Mission (SLAM) – which was a lunar sample return simulation carried out in 2011 (Moores et al., 2012) – and the 2013 and 2014 MSR activities carried out at the simulated Mars terrain at the CSA headquarters in St. Hubert. The *Planning Team* was responsible for planning the rover traverses and producing sol-by-sol activity plans compliant with the data, energy, and time budgets. The *Science Team* was responsible for processing and interpreting the scientific data and producing a science-driven plan each sol. Necessarily, the Planning team developed treed activity plans to accommodate for potential targets desired by the Science team; likewise, the Science team developed "if-then" sol + n plans based on the daily science return (see Fig. 6 in Caudill et al., this issue, a). Table 4 provides a

Fig. 5. Mission control at the university of Western Ontario.

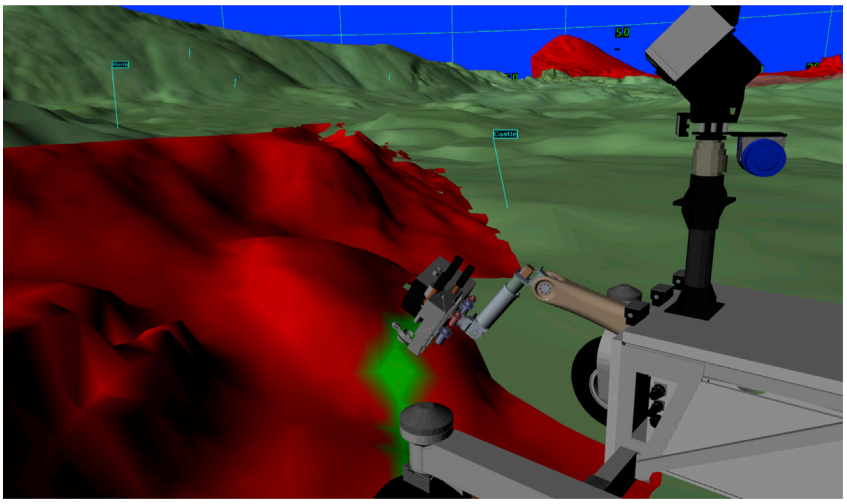

Fig. 6. Screenshot of the Apogy software from sol 17 during a rock abrasion operation.

description of each role in both teams. Both teams had a Team Lead to manage the activities of the team and lead discussions and a Documentarian to record all activities and decisions made. As noted at the outset of this contribution a major emphasis of CanMars was on training so most positions were held by graduate students and post-doctoral fellows with both science and engineering backgrounds, as well as some undergraduate students.

A *Tactical Team* was also included at the start of the 2015 mission. This team comprised 5 main roles: (1) Team Lead; (2) Uplink; (3) Sequencing Integrator; (4) Downlink and Data Management; and (5) Tactical Documentarian. The tasks of the Uplink role were to integrate all instrument sequences received from the Science Team to be uplinked to the MESR, as well as uplink complete daily operational sequences to the CSA Team. The Sequencing Integrator ensured that all instrument sequences received from the Science Team were properly integrated and uplinked to the CSA Team. The Downlink and Data Management roles were responsible for all downlink data products and ensuring that these were available to the Science Team. The primary tasks of the Tactical Documentarian were to document all the activities of the team, record Team discussions (decisions made and rationale), and work closely with the Team Lead. The core responsibilities of the Tactical Team Lead included managing the activities of the Tactical Team, monitoring health and performance of the rover, and approving all commands sent to the rover, and to participate in daily teleconferencing communication with the Engineering Team in Utah.

During the first week of the 2015 CanMars mission (sols 0–5) it became clear that a separate Tactical Team was not needed: the data management tasks (Uplink, Downlink and Data Management) or Sequencing Integrator required input from the Planning Team, which left only the Team Lead and Documentarian operating roles that were independent of the Planning Team. During the second week of operations in the 2015 deployment, the Tactical Team was, thus, absorbed into the Planning team, a process which had already begun, in a practical sense, in the first week. This transition was further eased by the fact that senior operations personnel had significant experience in previous analogue mission simulations.

In addition to the Science and Planning Team roles specified in Table 4, there were several other roles and participants in the Mission Control Team. In addition to the Project Lead (the first author of this contribution), who led the overall mission execution, a Mission Operations Manager (MOM) was critical for ensuring the success of the CanMars analogue mission. This person was responsible for the pre-deployment team planning, staffing, overseeing day-to-day operations, and acting as the main point of contact between the Mission Control, CSA, and Field teams. There was also an Education and Public Outreach (EPO) lead, who coordinated all education and public outreach activities, acted as media liaison for the team, organized the social media campaign, and coordinated the blog.

It is important to note that the Project Lead, MOM, and EPO lead did not participate in the mission operations; they provided guidance and

Table 4
CanMars roles.

Role Title	Role Description	Daily Deliverables/Tasks
Planning Team		
Planning Lead	Manage the activities of the Planning Team and tactical activities; monitor progression of daily and long-term plans with consideration of overall Mission goals; monitor health and performance of Rover; approve all commands sent to Rover	Sign off on all planning tasks detailed below
Daily Activity Planner	Ensure daily requested Science plan is in line with available time, power, bandwidth budgets	Communicate between Sequencer, LIDAR/Localization and Instrument Teams regarding how many samples can be planned and where; deliver annotated images from Instrument Teams to sequencer. Conduct long-term planning: sketch out how decisions for today's sol impact future sols; provide inputs into science planning based on different multi-sol activities
Environment and Localization, LiDAR	Monitor physical environment along planned and actual Rover traverses; advise Science about feasibility of potential routes; localization based on LIDAR	Provide localization during science planning (evening session), indicating rover movement and daily distance and obstacle constraints
Rover Planner	Complete instruction sets for the rover; includes operation of the robotic arm.	Complete rover instruction sets, which are integrated into the plan sequence
Autonomy Specialist	Coordinate the use of the autonomy systems, which involves: knowing the rules about what is in play; knowing how the above are to be commanded; advising on options to meet the science team's goals (both tactical and strategic); preparing the commands for the autonomous science systems; integrating the commands for the instruments those systems will control	Draft (or at least advise) the portions of the plan where the rover is working on its own
Sequencing Integrator	Monitor sampling constraints and capabilities of the rover and environment, and their compatibility with Science requests and overall Science goals; integrate all instrument sequences received from Science to be uplinked to Rover	Sequence commands in evening; compile annotated images for sample acquisition
Documentarian	Document all the activities of the Planning team; record Team discussions (decisions made and rationale)	
Science Team		
Science Lead	Manage the activities of the Science Team; lead Science team to a consensus on daily and long-term science goals; adjust long term (weekly) requested Science plan relative to current (daily) progress	Lead science and ongoing interpretation discussion in morning; keep team working toward MEPAG and MSRAD mission goals while on mission and daily timelines
Imagery (Mastcam, TEMMI, RMI, WATSON) SuperCam LIBS SuperCam VIS-IR SuperCam Raman, SHERLOC PIXL (XRF)	Oversee the operation of instrument on Rover; inform team of constraints and capabilities of instrument; [Uplink] integrating requests from other Science team members create daily instrument sequence; [Downlink] verify health of all expected and received data products; [Processing] create accessible data products for use in Science and Planning discussions; [Interpretation] provide preliminary scientific interpretations and hypotheses for recent results and overall mission results	Evening: process data and present data products to present findings. Morning: short presentation with data summary to this point in mission and larger interpretations
GIS, Nomenclature	Process and calibrate all remote sensing data products received and make them available for Science and Planning discussions; create maps recording proposed and requested Rover traverses; create maps/annotated images of requested Sample locations; localize daily position of rover and actual traverse completed; localize position of samples collected; integrate daily received data from rover into site maps	Morning session briefing for Localization using annotated images and data products for use in morning briefing and science discussion.
Documentarian	Document all the activities of the Science Team; record Science Team discussions (decisions made and rationale)	

mentorship when needed and coordinated logistics with the CSA and Field teams. In addition, there were a series of observers who acted as mentors and who helped guide discussions when needed, but who did not participate in the decisions made by the Science and Planning teams. In 2016, this mentoring was formalized with the addition of a Simulation Assurance Manager (SAM) who had previous leadership experience on analogue missions and MSL mission operations. SAM played an integral role in guiding the MC team, through teaching mission operations principals and clarifying flight rules and rover capabilities.

In preparation for the CanMars 2015, 2016 campaigns an intensive week of training for all Mission Control personnel was held one month before the mission. This training included the following: (1) an introduction to Apogy, the environmental simulation software designed by CSA, which was used to visualize MESR (see section 6.2); (2) a half-day dry-run using the MESR platform in the CSA Mars Yard, for Mission Control members to practice their roles and the daily workflow; and (3) a science workshop for all Mission Control members and stakeholders, to cover mission rationale, scientific and operational goals, mission schedule and daily timelines. In 2016 this workshop was expanded and included discussion on approaches to sample collection, rover autonomy, and the use of a strategic traverse route to facilitate strategic days, as well as a review of the CanMars 2015 mission. Additionally, the Mission Control team met for 3 weekly training sessions, which included: a half-day pre-planning workshop for the Science and Planning teams to review the mission operational schedule, aims, and in-simulation goals; a half-day science workshop to formulate a preliminary, pre-mission, overall traverse plan; and various instrument presentations.

6. Operations

6.1. Operational workflow

The CanMars daily operational workflow procedures (Table 5) were modified from recommendations by Francis et al. (2012) and Moores et al. (2012), which were in turn based on MER and Phoenix operations. Daily Planning Team operations for sol n commenced with the downlink of the data from sol n-1 at 19:00 on sol n-1, which usually consisted of a combination of image and science instrument measurements. Initial planning for the sol n depended on motivations from previous sols, including factors like the ease of access to and/or distance from a target or a preliminary investigation of scientific value for a target (Pilles et al., this issue). The Science Team then formulated an initial plan based on objectives and desired outcomes for sol n (Caudill et al., this issue, a). Science team operational procedures proved to have a direct impact on

the timelines, focus, and relevancy of sol-by-sol data interpretation, and hence discussion and the development of subsequent sol plans. During the evening shift beginning at 19:00 on sol n-1, science team members were tasked with processing all n-1 data, synthesis and interpretation of all combined data, and sol n planning. These tasks were time-sensitive to meet the data uplink "window" at the end of the morning shift the following day, making each shift a practice in managing time, details, and mission goals. Data were received by downlink at 19:00, marking the beginning of the evening shift and the time at which instrument and imaging teams began processing and synthesizing data. The individual science instrument teams (e.g., Raman, XRF) had the task of processing the large datasets acquired from the previous sol, analyzing the data in bulk to find trends and important outliers, in just over an hour. This was accomplished most efficiently and effectively with all Science Team members in one room together, where real-time collaboration aided in culling the data and expediting interpretations (discussed in Bednar et al., this issue, and Caudill et al., this issue, a). Individual Science teams prepared one or two slide presentations for the rest of the science team with interpretations that could be summarized in just a few sentences and that would have relevance to the n-1 target as well as potential sol n targets. These science team presentations led to discussions involving the entire team, focused on observations and interpretations aimed at planning sol n targets, with each sol n plan intentionally moving the rover toward future outcrops which were deemed valuable or mission critical.

The Planning Team worked in parallel with the Science Team, providing input as to which science targets were viable on sol n based on the constraints of MESR and its instrumentation and available images and 3D LiDAR scans projected with the 3D environment simulation software Apogy (see section 6.2). This led to a dynamic interplay between the two teams (Bednar et al., this issue), and essentially every team member was important in moving the plan forward for each sol. At 21:00 on sol n-1 the plan was finalized and the team began creating sequencing documents which informed the field and CSA teams what activities were to be executed on sol n.

Table 5
CanMars operational schedule. for the 2015 and 2016 analogue mission cycles.

Time (EST)	Regular Operations (sols 1–21)	Fast Motion Field Test (sols 22–39)
19:00	Sol n-1 downlink due	Sol n-3, n-2, n-1 downlink due
19:00	Tactical planning	Tactical planning
	Process and assess data, intermittent science discussion as necessary	Process and assess data
	Group science discussion structured and led by STL, review vehicle localization status led by PTL, confirm FOIs, sampling targets, and general n+1 plan	Review status of instruments at end of n-1, confirm general plans for n, n+1
	Discussion between Science and Planning team to confirm feasibility of target selection and validate plans, prepare final n+1 plan	
	Prepare sequencing documents containing detailed targeting parameters. Upload files to Data Manager.	Prepare plans for n, n+1, n+2
22:00–07:00	Crew rest	Crew rest
07:00	Plan walkthrough	
08:00	Uplink to CSA (deadline)	Plan walkthrough
08:30	Science plan review conference	
09:00		Uplink to field lead (deadline)
09:15	Sol n+1 pre-planning (science and	
09:30	planning collaboration), science discussion, science presentations,	Science plan review conference
10:15	depositional model focus	Sol n+1 pre-planning, science discussion
11:00–19:00	The rover carries out the commands	The rover carries out the commands

Instrument teams were responsible for generating instrument-specific sequencing documents after converging on a sequenced plan (Caudill et al., this issue, a). These documents provided specific details related to the operations of that instrument on the sol. It was then the responsibility of the Planning Team to collate the necessary annotated images and information from each instrument into the sequencing document. Additionally, the intention for each activity in the plan was given to remove any ambiguity for the field team. Frequently, deficiencies would be identified in these documents and their associated images during the plan walkthrough, which was at the end of the shift in the evening. If revisions to the plan were necessary, they were made at the start of the next morning shift. The Planning Team began to make minor changes as necessary with experience as the mission progressed, and created templates for common activities such as traverses followed by post-drive imagery or the deployment of the arm and acquisition of contact science and/or samples. A final plan walkthrough was completed the morning of the sol on which activities would be carried out prior to plan uplink with the CSA rover team and field team. Additionally, clarifications were made during the morning CSA teleconference. After locking in the plan, discussions began for the sol n+1 planning based on the assumed rover position and activity completion.

6.2. Strategic traverse days and the fast motion field test

As noted above, novel operational strategies were tested during the 2016 CanMars mission which altered the daily operation workflow described above. Two pre-planned operations (Strategic Traverse Days) were executed on sols 15 and 20 to test the efficiency of remote science operations with pre-planned strategic observations. During these Strategic Traverse Days the rover was commanded to drive towards a predetermined feature of interest and acquire post-drive imagery and remote science measurements. No tactical input from the Science Team at Western was required for these operations, thus allowing them to focus on an in-depth science discussion. In the case of the CanMars analogue mission, the intent was to have a fully pre-developed plan which was prepared several days ahead of time, and independent on events in the mission between when it was planned and when it would be executed. This innovative strategy provided the Science Team with additional time to interpret the scientific data, but also hindered their potential plans because a long traverse was pre-allotted to a particular sol. The full impact of the implementation of Strategic Traverse Days during the CanMars analogue mission is discussed in Pilles et al. (this issue).

Additionally, the Fast Motion Field Test (FMFT) simulated multi-sol planning on a real Mars mission and allowed the team to collect additional samples during the last week of analogue activities (starting on sol 22). During this time, each Earth day corresponded to 3 sols' worth of activities, executed by a human field team in place of the MESR rover. Each sol retained the same limitations regarding data, budget, and time, however, because activities were completed without the use of the MESR rover, the Field Team was able to execute 3 sols' worth of activities in a single Earth day. Creating 3-sol plans introduced complexities that necessitated careful long-term planning that is described in Pilles et al. (this issue). The idea of a "walkabout-first" strategy (Yingst et al., 2017) was an important component of the FMFT. The multi-sol plans also introduced predictive planning for the Science Team, where potential targets, each with science rationale and working hypotheses, were outlined on a white board to track priority targets and planning traverse strategies (see Caudill et al., this issue, a).

During the 2016 activities, autonomy capabilities were used by the Mission Control Team where they provided an advantage to the proposed daily plan (see Francis et al., this issue, for details). In brief, it is notable that autonomous geological classification and targeting was used extensively on the Strategic Traverse Days and during the FMFT. This allowed the team to explore a large and diverse area in a reduced number of command cycles. Furthermore, a rich suite of instrument measurements on the desired units allowed the Science Team to conduct a

thorough exploration of a complex geological setting (Caudill et al., this issue, a). Contingency sequencing was used on four occasions and was used primarily to recover time in the plan for operations where the team anticipated difficulties (e.g., when attempting challenging drives). Contingency sequencing also proved extremely useful during the walkabout phase, when several 3-sol plans were drawn up. These plans involved several activities contingent on sampling; if sampling failed, the planned post-sampling activities were skipped, the arm stowed, and the rover directed to move on to the rest of the plan (Francis et al., this issue). As described by Francis et al. (this issue), only one conditional sequence was uploaded, but it had a major role in determining the selection of the final sample at the end of the CanMars mission. In summary, the sol 34 plan focused on 3 sites, two of which had been visited previously, and one new site. The plans included conditional sequencing whereby autonomous decisions on sampling were made based on the presence or absence of Raman peaks at two specific wavelengths. Details of this sol 34 plan are discussed in Francis et al. (this issue).

6.3. Apogy

The Apogy (previously known as Symphony) software package developed by the CSA is a tool designed to plan, validate, execute, and monitor integrated operations to support analogue mission planning (Fig. 6). In this respect it is broadly analogous to the Maestro Science Activity Planner (Norris et al., 2005) and Mars Science Laboratory InterfaCE (MSLICE) (Powell et al., 2009) tools used by the MER and MSL teams, respectively, to plan mission science. During CanMars, Apogy was used by the Planning Team to evaluate the requests of the Science Team and convert them into instructions that could be implemented by the Engineering Team. The component-based architecture allows for instrument and rover integration to model systems, telemetry, and the 3D environment. The worksite consisted of a Digital Terrain Elevation Model (DEM) formed the basis of the 3D environmental simulation within a worksite reference frame (Fig. 6). Within the Apogy workspace, a project folder was created for each Sol containing the Features of Interest (FOIs), location and orientation of MESR, as well as data products such as 3D lidar point clouds, zoom images, and TEMMI images that could be projected onto the DEM. Line-of-sight maps and slope maps indicating no-go areas in terms of loss of communication and traversable slopes, respectively, could be easily generated and draped onto the DEM. The Trajectory Picking and Ruler Tools were used to plan different paths that avoided non-driveable terrain identified by the line-of-sight and slope maps for the upcoming sol based on the desired drive locations identified by the Science Team. Adjustable time sources and Earth-sky interface projects lighting conditions for any given time point, past or future, for image planning purposes. Once the Science Team had chosen a specific scientific target, the Planning Team used Apogy to determine the rover-relative pointing angles required to point the instruments at specified FOIs.

The Apogy software was important for integrating the Science and Planning Teams through localization and visualization of engineering and activity constraints. A major benefit was that the worksite viewer allows for instantaneous modeling of FOIs and provides immediate feedback to the science team regarding the feasibility of planned operations. This feedback reduced the need for iterative communication between the Planning and Science Teams, thus expediting the planning process to maximize resources towards data analysis and integration. For contact science, visualization of the rover arm workspace volume allowed for targets to be chosen, checked for accessibility, and down selected. Combined with the ability for high resolution images to be projected onto the DEM within the 3D environment, the Apogy software improved the accuracy and fidelity of FOI selection.

Some limitations of Apogy included the limited set of data products that could be integrated into the environmental simulation, and the lack of normalized data product naming conventions between users both within and between field mission control teams, which rendered Apogy integrated data products time-intensive to create and use. Although the software was necessary for directing the activities of MESR, the usefulness of Apogy in daily mission planning activities was hindered by its poor reliability. In particular, the tools used to project zoom images on the DEM and reposition MESR in the 3D environment often failed to work entirely. These difficulties occasionally forced the Planning Team to target images using the DEM's relatively coarse resolution (0.5 m), which resulted in missing the intended target on three occasions. Another common issue was that the workspace could not be reliably saved. Despite the shortcomings with the Apogy software, it was an integral part of the planning process. The software allowed the team to plan safe traverse routes for MESR prior to visiting the site, allowed for accurate pointing of cameras and stand-off instruments, and allowed the Planning Team to determine if it was safe to position the arm for contact science.

7. Science objectives and overview

In preparation for the 2015 CanMars mission, the Science Team was provided with the following mission objectives: 1) to collect a minimum of one sample, and 2) satisfy two sub-goals from the MEPAG objectives for Goals I and III; Habitability and Crustal Processes, respectively. As discussed above, for the 2016 CanMars mission, a detailed Science Plan was drawn up that described constrained science objectives in order to focus science team decision-making and help derive lessons from the operations tests, and with direct relationship to Mars 2020 objectives. These objectives were: 1) To advance understanding of the habitability potential of sub-aqueous sedimentary environments: learn how to seek, identify and characterize samples containing high organic carbon; and 2) to advance understanding of the history of water at the site. Caudill et al. (this issue, a) provides a detailed overview of the science objectives for this analogue mission and their evolution from pre-mission hypotheses to in situ science. Below we present a scientific overview for the 2015 and 2016 CanMars missions as they evolved from pre-mission science to testable scientific hypotheses addressed through in situ science data products.

7.1. Pre-mission science

In advance of the 2015 deployment, the Science Team was barred from information regarding the landing site, but was provided with a set of regional and landing site-specific data, chosen to mimic datasets available from Mars-orbiting instruments which are available to Mars rover mission planners pre-mission. These datasets, detailed by Tornabene et al. (this issue), include: multispectral visible to thermal infrared Landsat Operational Land Imager (OLI) (15–60 m/pixel) and Advanced Spaceborne Thermal Emission Radiometer (ASTER) (15–90 m/pixel datasets as substitutes for the THEMIS (Thermal Emission Imaging System), OMEGA (Visible and Infrared Mineralogical Mapping Spectrometer) and CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) instruments; a visible to near-infrared pan-sharpened Quickbird-2 image (60 cm/pixel) (Fig. 2b and c) as a proxy for HiRISE (High Resolution Imaging Science Experiment); and a 5 m/post digital elevation model (DEM), was intended to approximate a HiRISE or CTX (Context Camera) stereo image derived-DEM.

Although the team was kept from knowing the exact location for the “landing site”, they were encouraged to investigate potential terrestrial analogues, again, preparing for the mission much like that of a real Mars mission. Based on the data sets provided, the team suggested that the Painted Desert, Arizona was a working morphologic and mineralogic analogue for the field site. The team proposed that the region was the result of extensional tectonics, which produced uplifted topography to the east, and a lower elevation erosional basin present within the landing ellipse (Fig. 2a and b). Interpretations on a local-scale suggested that the sedimentary basin was comprised of a series of blue, purple/red, and white repeating layers in mounds or hills, with carbonates, sulfates, and likely clays, and sinuous ridges with a coherent capping unit. The

sinuosity of the ridges were quantified morphometrically, and found to have metrics as described for paleochannels in the US southwest. If the environment was indeed analogous to the Painted Desert, the team suggested a lacustrine and fluvial basin environment would support that these features were ancient inverted paleochannels. It was further proposed that the putative paleochannels were preserved through the deposition of an erosion-resistant cap rock as evident in the available imagery, though the coherent material forming the cap rock could not be determined based on remote sensing. The team suggested that the cap rock was fluvial channel deposits or lava flows, both of which have been documented elsewhere in Utah. Nominal traverse plans were made during the pre-mission team meetings. For the 2016 mission cycle, these

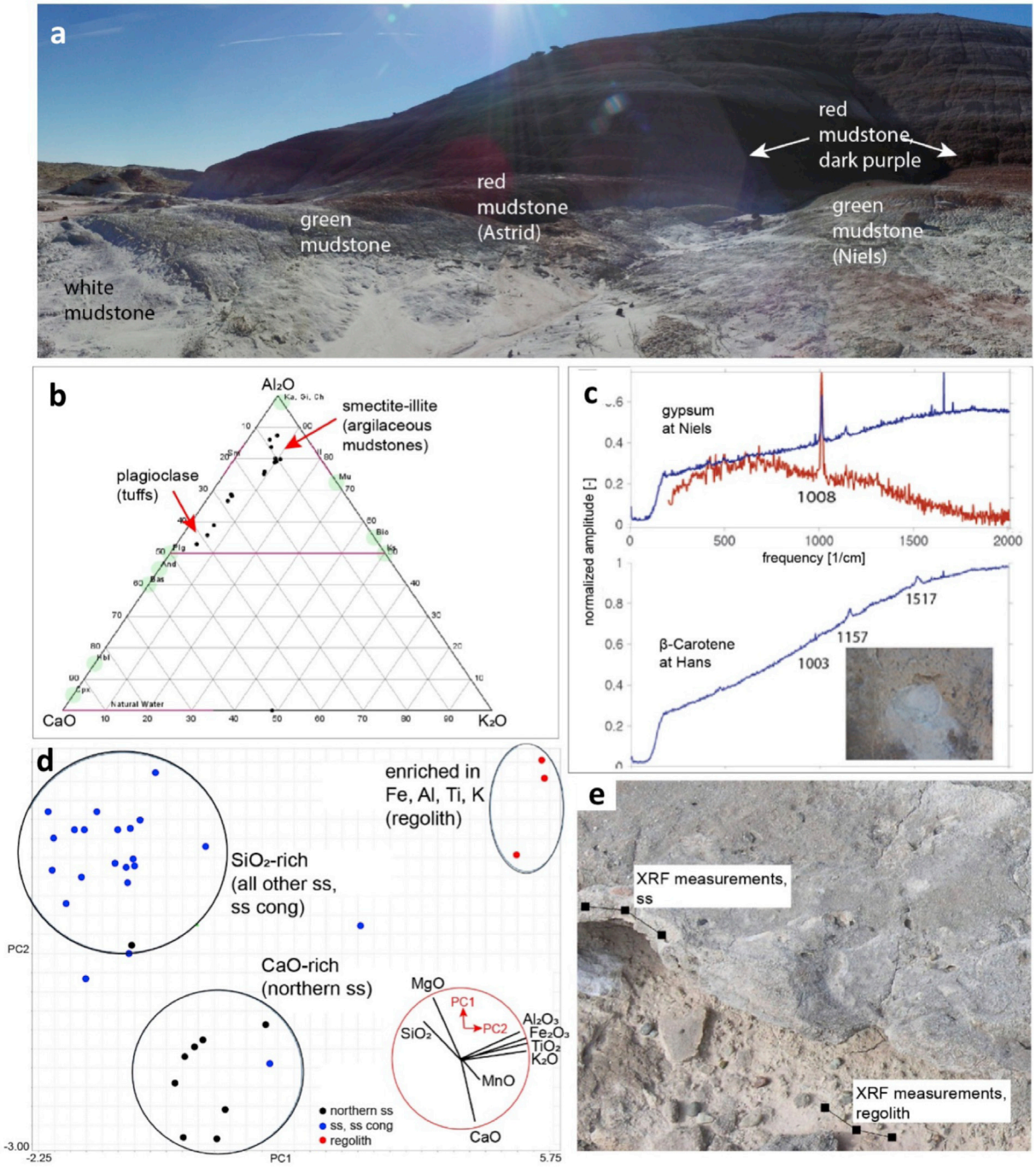

Fig. 7. a) Rover-acquired panorama showing the mudstone sequence. White-green and green unit (showing Niels sample location) is overlain by the red/purple (e.g., Astrid sample lithology) lacustrine units. b) Alkalis ternary diagram with rover-acquired XRF geochemical data from tuffs ("potatoes") and mudstone units are plotted, indicating a feldspathic and smectitic composition, respectively. c) XRF-acquired geochemical data from sandstones and regolith is represented in a PCA diagram to display geochemical trends. Oxides are shown on the bottom right with their relative direction of increase and relative weight. The sandstones which dominated the basin were geochemically distinct from the sandstone outcrop in the northern area of the field site; these are both distinct from the geochemistry of the regolith. d) Rover-acquire Raman spectrum collected using 532 nm laser (upper, blue spectra) and 785 nm laser excitation (lower, red spectra) at Niels. Both show a strong gypsum peak at 1008 cm-1. Raman collected on target Hans after abrasion, showing ß-Carotene signatures. Collected using 532 nm laser excitation. e) An example of XRF measurements planned for acquisition on a sandstone and local regolith. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

plans were based on the hypotheses and ground-work from the 2015 mission cycle. Four potential traverse paths were considered, with one favoured as the nominal path.

7.2. In-mission science

During the 2015 mission, the rover traversed a total of 253 m over 11 Sols (Fig. 2c) and the team collected four samples (3 rock samples and 1 regolith). A sandstone outcrop near the landing site, called Alfheim (Fig. 2c), proved to be an arkose-based sandstone, with fine, sub-rounded grains and was relatively unaltered, indicating that the sandstone was relatively immature. This outcrop was sampled within the first few days of the mission as a "safety" sample, ensuring at least one sample was acquired in the case of an unforeseen rover catastrophe which would end the mission. Upon reaching Jotenheim on Sol 4, which was the closest hill having the blue, red/purple, and white layers, plus the capping unit (Fig. 2), layering and the possible presence of sedimentary structures as revealed by a MastCam panoramic image, suggested that the capping unit was not igneous in origin. One of the samples acquired was from a boulder derived from the capping unit of Jotenheim; once imaged and analysed with onboard instruments, the team identified the cap unit as a clastic sandstone or conglomerate, and clearly not a volcanic rock.

One of the most interesting discoveries of the 2015 mission was the identification of additional resistant units cropping-out further to the south in an area called Ragnarok (Figs. 2c and 7). The deposits were visually similar to the capping units explored thus far, but importantly, were non-continuous. The interpretation by the Science Team was that the capping unit is the result of the insinuation of braided channel deposits draining from the higher stratigraphy to the west during regression events. Overall, the landing ellipse region was interpreted to have been that of either a deep inland sea, experiencing several transgression/regression events, or lacustrine and fluvial environments as water tables fluctuated over time, where a large amount of sediment was deposited under low energy conditions. This type of environment would have been highly favourable for microorganisms and result in the burial and preservation of significant amounts of organic matter.

The 2016 deployment picked up at the same spot where the rover ended the 2015 campaign. During the 2016 mission the geological interpretation of the site was further refined with the development of a depositional model of the field site based on image and data acquisition and interpretation (see Caudill et al., this issue, a). The depositional model was critical to guide traverses, sampling, and overall mission planning to meet mission science goals. The data and imagery from the field site allowed a continual refinement of this model, for example: geochemical and mineralogical data showed a lack of evidence of an ancient sea deposit; the layered deposits had an influx of volcanic ash that mixed with variably oxidized and/or reduced low-energy deposits; imagery of the basin interior revealed another generation of extensive, isolated lenticular sandstones, which were interpreted as representing a braided channel environment at the base of a lacustrine regime (represented by the layered deposits). The landing ellipse therefore was interpreted as a catchment basin for various fluvial regimes, where inverted paleochannels with erosion-resistant cap rock preserved an underlying lacustrine sequence. At the base of Ragnarok, the Science Team identified a green lithology, perhaps due to minerals from microbially-mediated reduced iron (Fig. 7); this lithology became the focus of our priority sampling efforts described below.

7.3. Sampling priorities

In addition to deriving a geological history of the field site, in 2016 the Science Team was provided with the following highest priority mission science goals, with mission success based on acquisition of samples: 1) collect and rank samples for cache and return with highest potential for preservation of ancient biosignatures from organic-rich carbon; and 2) assess paleoenvironmental habitability potential and history of water at the site. The in situ investigations needed to address these goals and identify samples with high Total Organic Carbon (TOC) was guided by relevant investigations described in the MEPAG Goals and Investigations document (MEPAG, 2015). These investigations include:

- Goal I, Investigation A1.2. Constrain prior water availability with respect to duration, extent, and chemical activity;
- Goal I, Investigation A1.3. Constrain prior energy availability with respect to type (e.g., light, specific redox couples), chemical potential (e.g., Gibbs energy yield), and flux;
- Goal I, Investigation A1.4. Constrain prior physicochemical conditions, emphasizing temperature, pH, water activity, and chemical composition;
- Goal I, Investigation A2.1. Identify conditions and processes that would have aided preservation and/or degradation of complex organic compounds, focusing particularly on characterizing. redox changes and rates in surface and near-surface environments;
- Goal III, Investigation A1.1. Determine the role of water and other processes in the sediment cycle;
- Goal III, Investigation A1.3. Characterize the textural and morphologic features of rocks and outcrops.

The 2016 CanMars mission was driven by these investigations in the sense that they helped identify where to look within the analogue mission Region of Interest to identify samples to cache with high TOC. The Ragnarok hill (proposed reduced lacustrine deposits) was therefore the destination of a long traverse, where samples were acquired along the way to fulfil geologic context and more complete characterization (see Fig. 7) (e.g., history of water at the site). The highest priority samples acquired during the CanMars mission were therefore ranked as those that were thought to most likely contain highest organic-rich carbon (Table 6; Fig. 7). Ranking was difficult, as the preservation is highly dependent on the weathering state and general preservation of the lithologies. Although the outcrops were highly weathered, and a fresh sample was not possible to acquire, the Science Team determined that the marginal lacustrine facies of Ragnarok was still most likely to possess the highest amount of organic carbon (samples 1 and 2, Fig. 7, Table 6). The third priority sample was from the conglomerate–clastic sandstone capping unit. Investigations revealed the presence of trough cross stratification and soft sediment deformation features with embedded clasts that were multi-coloured, well-rounded, and of pebble to gravel-sized. These lithologic features alone justified the return of this sample as it fulfilled the goals of assessing the history of fluvial activity at the site as well as well as providing broader geological characterization of the site. In addition, the Science Team thought that this sample could have potentially preserved microfossils, if present. The rationale was that the intergranular porosity provided by the conglomerate could allow for the potential for larger fossils to be preserved, either in chert or carbonate fragments or in cementation between the clasts. For the full list of the eight acquired samples with science rationale, see Caudill et al. (this issue, a).

8. Field and laboratory validation of mission data

An important component of the CanMars mission was the field validation of remote rover observations and subsequent laboratory validation of samples. Indeed, being able to ground-truth observations and interpretations made by a remote Mission Control Team is a major advantage, and motivation for, analogue missions. As a review, as presented at the outset of this contribution, the Science Plan objectives of CanMars were:

1) To test the accuracy of selecting samples remotely using the partial context available to mission scientists using rover-based field operations, compared to the full context available to a traditional human field party;

Table 6
Top priority samples from the CanMars in-simulation mission.

General lithological units	Hypothesis tested	2015 samples	2016 samples	Sampling priorities	Science rationale
Green siltstone	Lithology, depositional environment, and potential organic carbon content was determined by geologic context, colour, and mineralogy. Potential kaolinite, muscovite, and nontronite were observed, and montmorillonite-illite were observed with high confidence. Gypsum was identified (strong peaks, high certainty) with Raman. Smectites indicate the weathering of volcanics. Microorganisms are involved in reduction of iron when soils undergo anoxia (producing the reduced form of the clay), which is hypothesized here.	–	Niels	1	Marginal lacustrine facies are ranked highest for highest total organic carbon (TOC) and biosignature preservation. Ranking is difficult, as the preservation is highly dependent on the weathering state and general preservation of the lithologies. In an attempt to acquire the most 'fresh' sample possible, the surfaces we disturbed using the rover wheels, which provided an exposure deeper than would have been possible with the RAT. High Na levels in bright white material suggests halite may be present; elevated salinity in these environments may encourage chemical stratification, which in turn favours preservation of organic matter. Dysoxic to anoxic conditions result from exhaustion of free oxygen by oxidation of organic matter in the isolated deep zone of the lake. The darker green coloration, geochemistry, and mineralogy indicate a reduced depositional environment, and therefore representative of the best paleohabitability.
Purple/red siltstone	Geochemically, this unit appears to be similar to the underlying white unit. It is clay-rich and very weathered, with the same shrink-swell erosional character. Purple coloration (with geochemistry similar to green layer) may indicate habitability (as black coloration indicates an even more reducing environment than represented by the green shales). Fe-oxides (hematite) and Fe-oxyhydroxides (goethite, ferrihydrite) were observed.	–	Astrid	2	Purple-red siltstones may indicate high TOC and/or oxidized conditions in a low energy environment with possibility to preserve organic matter. Preservation pathways are known in oxide and oxyhydroxide minerals. Purple-black bands may represent cm-scale windows of very well preserved organic carbon, and may indicate habitability as dark coloration indicates an even more reducing environment than represented by the green shales.
Sandstone conglomerate	Geologic context and imaged cross stratification indicates fluvial emplacement.	Thrymheim	–	3	Trough cross stratification and soft sediment deformation features with embedded clasts that were multi-coloured, well-rounded, high sphericity pebble to gravel-sized. Potential for microfossils within the conglomerate clasts. Fulfils goals of assessing the history of fluvial activity at the site and the stratigraphic column for broader geologic characterization.

2) To test the efficiency of remote science operations with periodic pre-planned strategic observations compared to including strategic and tactical considerations in the tactical plan;
3) To assess the utility of realistic autonomous science capabilities to the remote science team, to understand how such autonomy improves the effectiveness and rate of progress of the science mission, and to learn which strategies of exploration emerge from the availability of these capabilities, including in a downlink-constrained environment;
4) To make a preliminary determination of the factors that affect the quality of sample selection decision-making in light of returned sample analysis.

For CanMars, several different validation exercises and approaches were taken. Pilles et al. (this issue) provide a detailed overview of the use of periodic pre-planned strategic observations (objective #3), or Strategic Traverse Days, and lessons learned are summarized below in section 11. Building upon experience from the MER and Curiosity rover missions (Estlin et al., 2012; Francis et al., 2017), the utility of autonomous science capabilities during CanMars (objective #3) is detailed in Francis et al. (this issue), and lessons learned are summarized below in section 11. The remaining two objectives intrinsically require baseline knowledge from traditional field geological approaches and laboratory analysis of returned samples for validation to be conducted. A further requirement to validate these two objectives is the ability to go back and question why decisions were made and whether different decisions would have been made with hindsight. In order to achieve this, we employed a number of documentarians whose job it was to capture deliberative and decision making process in both the Science and Planning teams (see Bednar et al., this issue).

Beaty et al. (this issue) describe a dedicated one day validation exercise that was carried out to compare traditional field geology methods with rover-based remote operations. In comparing the rover and field team results, these authors noted notable differences in the interpretation of stratigraphic thicknesses and the missing of a green marker bed by the Mission Control Team (also discussed by Caudill et al., this issue, a). The most striking conclusion, which is perhaps unsurprising to field geologists, is the value of full context whereby human field geologists can, almost immediately, look around and assemble and integrate the context of everything they see. Beaty et al. (this issue) estimate that, based on the CanMars scenario, a human geologist can be thought to be at least ~50 times more productive than a robotic geologist using current technology, and could be expected to produce higher quality results. (Beaty et al. (this issue) define productivity as include "parameters such as number of targets measured and distances traversed." These are metrics that can be measured, but other important parameters include the time taken to observe the surroundings, the time and "effort" (traverse and data acquisition costs) to identify lithologies and recognize them in sequence, and the accuracy and depth of those observations.) The flip side, however, was that instrumentation allowed the Science Team to generate much more data-rich observations about the mineralogy and geochemistry of the site than was possible by the human validation team (Beaty et al., this issue; Caudill et al., this issue, a).

Further field validation was carried out by the Western Field Team and the Mission Control Team following the completion of CanMars. The field team were provided instructions to conduct an independent geological study of the analogue site over the course of the 3-week 2016 CanMars mission. No detailed geological map existed for this site and so this work included geological mapping and detailed observations, measurement of two detailed stratigraphic sections, and sampling. In addition to the samples selected by the Science Team (see Table 6 and Caudill et al., this issue, a) the field team also collected a much larger number of samples, both to validate Science Team interpretations and decisions

(e.g., outcrops that were analysed with rover instrumentation but from which the Science Team chose not to collect) and also as a thorough geological assessment of the landing site region to provide a baseline for validation. The methods and results of this work are documented in Caudill et al. (this issue, b) and also integrated into the discussion of the CanMars mission science results and optimization for sample selection for Mars Sample Return in Caudill et al. (this issue, a). Finally, over 20 members of the 2015 and 2016 Mission Control Team visited the field at the end of the campaign to understand how their observations and interpretations made through the "eyes" of the MESR matched reality (Fig. 8). This validation is also included in the discussion of Caudill et al. (this issue, a). The laboratory analysis of returned samples is detailed in Caudill et al. (this issue, b). A final field and sample investigation was carried out independently at the CanMars site under another CSA grant and the results are reported in Cloutis et al..

9. Education and public outreach

As with actual space missions, public education and outreach was a priority for this analogue mission. Indeed, one of the 5 primary objectives for both the overall MSRAD campaign, and CanMars specifically, was to "attract and inspire the general public in STEM subject matter". This was achieved through a strong presence on social media (primarily Twitter and Facebook); attention on local, regional, and national news networks; and interaction with the local community in London, Ontario. Below we report on the strategy implemented during the missions and effectiveness in regards to articles produced and people reached for each area of engagement.

9.1. Twitter

Given the length of time between the two missions, continuity was propagated using a common hashtag during both missions; namely #CanMars. The hashtag #CanMars was chosen for its shortness and the emphasis it placed on the Canadian origin of the mission. By using the same hashtag in both missions, we were able to build upon the success of the former year rather than starting from scratch. Two platforms were primarily utilized, Twitter and Facebook, and individual team members were encouraged to tweet and post frequently.

The success of the twitter campaign stemmed from the participation from both the individuals taking part in the mission and organizations running and funding the mission. As the CPSX hosted mission control, the @WesternuCPSX account was used to provide daily updates and an overview of the mission on a day-to-day basis, often retweeting team members to boost visibility of both the participants and information they shared. As noted above, the EPO Lead and other team members who were in control of the CPSX account were considered out-of-simulation and were positioned to post photos and multimedia from the field team that was not taken by the rover. Effort was taken to ensure that scientific information that could have been utilized by the science team was not posted online; however, these posts allowed CPSX to highlight the people working in the field. The CSA (@csa_asc) and NSERC (@NSERC_CRSNG) also provided a greater reach for #CanMars by scheduling tweets and retweeting multimedia shared by the CPSX account. The CSA also posted their own tweets during the 2016 campaign. In addition to the main organizations, trainees in mission control were encouraged to tweet about their experiences with the instruments they were responsible for and data products they had produced through working with other members of the team. By working with both the individuals on the team and organizations in charge of the mission, a narrative was created that allowed the public to see both the high fidelity of science being conducted and the nature of the training aspect of the mission. This worked well when media outlets tweeted about articles they had written after visiting mission control because it allowed the general public to get a sense of the mission before viewing what individuals involved in the mission were doing.

The Twitter results were particularly impressive. From November 15th to December 5th, 1794 tweets utilized the #CanMars hashtag, with a reach of 2,618,818. In 2015 there were 3126 engagements with 122,435 impressions and in 2016, there were 6114 engagements with 322,572 impressions.

Fig. 8. A portion of the Mission Control Team exploring and documenting the area of rover operations. The image is taken on the slope of the feature Ragnarok looking north to Jotunheim.

9.2. Facebook

Due to privacy settings and limited reach of Facebook, CPSX posted new articles and pictures daily; however, less emphasis was placed on this form of social media. Instead, Facebook was used to spread news of the missions and allow trainees to share achievements with family members and friends. The CSA did post several articles throughout the course of both missions and during the 2016 deployment a Facebook Live video was created and streamed on the CSA's Facebook event. This single video has been viewed over 9000 times as of Junu 2018. For the 2016 campaign there were 23,145 engagements and 624,011 impressions for Facebook.

9.3. Internet presence

In another attempt to promote the trainees of the mission and the role of their instruments, on each sol of the mission a blog post was created providing an overview of each of the instruments and the experiences that individual trainees had gained during the mission. These blog posts were posted on Western's NSERC CREATE program website (http://create.uwo.ca), which provided a means to not only promote these experiences, but highlight the role of the NSERC in this program. By the end of the two missions every instrument on MESR had been highlighted as well as leads from the tactical and planning aspects of the mission. In addition to this webpage, the CSA dedicated a section of its website (http://www.asc-csa.gc.ca/eng/rovers/analogue-msrad.asp) to the mission and highlighted several aspects of the mission, the site, and team behind it.

9.4. Community engagement

During both years of the CanMars missions, great effort was placed on bringing in external media into the mission control room and creating an opportunity for the public to interact and ask questions about the mission. Given the public nature of the funding of this mission, inviting the media and public to participate in CanMars demonstrated the importance of this work and why we continue to invest in space

exploration.

During both missions, a day was arranged during operations to give members of the press the opportunity to visit mission control. By inviting them into mission control they had an opportunity to get a sense of the mission operations as well as interview members of the team and organizers of the analogue mission. The geographic audience of the media coverage was local, regional, and national, with most of the coverage in print; radio and television interviews also took place. The success of this campaign was clearly demonstrated in 2016 when a graduate student joined the CanMars mission because they had read about the 2015 mission in a local newspaper in Vancouver, Canada.

To further engage the public, open house nights were arranged each year so that the general public could ask questions about the mission and engage with the various team members. The events were divided into two main components. The first component was created specifically for children. The event gave children a sense of how rover missions are conducted by showing them how mission control was organized, while giving them access to fun, interactive activities related to space exploration. The second component was designed for everyone and gave them opportunity to see what types of instruments were being used by the rover team in field, as well as, interact with members of the science team to get a better understanding of the mission and its operations. Both years the event was concluded with a talk given by the Project Lead (GRO) on the importance of this kind of work with regards to space exploration.

In addition to the above education and outreach activities, two experimental immersive technologies were used during the mission as described by Morse et al. (this issue): 1) A Google Cardboard virtual reality headset with motion sensitive stereographically projected versions of panoramic images taken by the rover, and 2) an easily navigable dynamically lit 3D terrain model also projected stereographically through a motion sensitive VR platform. Both technologies were used for education and outreach activities as well as aiding in mission operations (Morse et al., this issue).

10. CanMars as a training experience

As noted at the outset of this contribution, one of the 5 core objectives of CanMars was to "provide valuable learning opportunities to students and post-doctoral fellows". Enabled by the NSERC CREATE project "Technologies and Techniques for Earth and Space Exploration" a unique aspect of the CanMars analogue mission was the involvement of students in all aspects of the mission operations. This included the key leadership roles of Science and Planning Leads and Mission Operations Manager (MOM), which were filled by senior PhD students or post-doctoral fellows during the 2015 and 2016 campaigns. As stated by several of the team members who had actual Mars mission experience, this in no way detracted from the realism of this analogue mission and it was noted that this was a very realistic mission that gave a very accurate representation of the roles, types of activities, and time commitment for actual missions.

In order to quantify the success of CanMars from a learning perspective, immediately upon completion of the 2016 portion of the CanMars mission, each participant was asked to anonymously complete a Learning Goals survey. This survey was designed to assess: the degree to which mission-related *learning outcomes* were met; the *impact of the mission* on the development of interdisciplinary and intradisciplinary teamwork skills and personal and professional development; and other parameters to aid in future mission planning and operations that will not be reported here. The CanMars learning objectives included:

1) Formulating multiple working hypotheses as an effective method to address the mission objectives;
2) Synthesizing multiple datasets to answer a given question;
3) Contextualizing in situ datasets with observable surroundings;
4) Contextualizing in situ datasets with orbital datasets; and
5) Evaluating trade-offs between desired scientific measurements and engineering constraints.

A total of 21 surveys were completed. Results of the learning objectives questions are shown in Fig. 9. Of the five learning outcomes, four were met with at least 67% of participants "strongly agreeing", and 90% of participants "somewhat agreeing" or "strongly agreeing" that participation in the mission has helped them to increase their understanding of the four learning outcomes. The learning objective that was not met was #4, "Contextualizing in situ datasets with orbital datasets". Based on these results, on future missions we plan a full-time role dedicated to management and integration of the orbital datasets with in situ datasets.

Results of the mission impact questions are shown in Fig. 10. Most notably, 100% of participants felt that "Participation in the mission will help [them] with [their] professional development". In answer to all the questions, all respondents "somewhat agreed" or "strongly agreed", and at least 81% of respondents "strongly agreed" that the mission encouraged interdisciplinary and intradisciplinary interactions, and personal development. All participants "somewhat agreed" or "strongly agreed" that they were "satisfied with this simulated mission as a learning activity"; of these, 86% "strongly agreed".

Some noteworthy comments from participants highlighted the importance of interdisciplinary learning: for example "Science and Engineering working side by side was the best part". While this was by far

Participating in this mission has helped increase my understanding of…	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
… formulating multiple working hypotheses as an effective method to address the mission objectives				5	16
… synthesizing multiple datasets to answer a given question			2	5	14
… contextualizing *in situ* datasets with observable surroundings			1	5	15
… contextualizing *in situ* datasets with orbital datasets		1	4	9	7
… evaluating tradeoffs between desired scientific measurements and engineering constraints				4	17

Fig. 9. Results of the 2016 CanMars learning objectives survey questions.

As compared to my pre-mission impressions / level of understanding:	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
The mission encouraged academic and/or professional interactions with other students within my discipline				4	17
The mission encouraged academic and/or professional interactions with other students from other disciplines				2	19
Participating in the mission will help me with my personal development				2	19
Participating in the mission will help me with my professional development					21
Overall, I am satisfied with this simulated mission as a learning activity				3	18

Fig. 10. Results of the 2016 CanMars mission impact survey questions.

the most common type of comment, one participant noted that it wasn't an easy or obvious process: "Working with a group of individuals with diverse skills was challenging. Learning about their skills did not come naturally. By the end we know how to best help each other." This points to a need for more preliminary training on interdisciplinary communication. Other comments emphasized the benefits that students felt participation in the mission would have in their future careers. "Programs like these are indispensable for students. It not only gives us some insights into what true space missions are like, it gives us the connections [to] further our research and personal development and could also lead us to hold positions such as the ones we fulfilled in the mission at established organizations. Training future Canadian space scientists is very important and if this is an example of what students from multiple backgrounds and institutions can accomplish in a short amount of time then I cannot see how this mission isn't worth it."

A final indicator of the success of CanMars as a learning experience is demonstrated by the preparation of a large number of conference abstracts. Indeed, an entire poster session was dedicated to the CanMars analogue missions at the 2016 and 2017 Lunar and Planetary Science Conference, held in Houston, Texas. In 2016, 12 of the 15 abstracts had student or postdoctoral fellows as first authors as did 15 of the 20 abstracts presented in 2017. It is notable that 5 of the papers in this special issue have students as first authors (Bednar et al., this issue; Caudill et al., this issue, a,b; Morse et al., this issue; Pilles et al., this issue).

11. Lessons learned and recommendations

In the following sections, we provide a set of lessons learned from CanMars and recommendations for future analogue missions and for future planetary exploration missions. Both sets of recommendations are, to a lesser or greater extent, also applicable to each other.

11.1. Lessons for future analogue missions

- Well-designed pre-mission tests using a variety of samples (e.g., multiple rock types containing different biosignatures) are essential to better understand the capabilities of instruments, particularly for the detection of biosignatures;
- A thorough review and demonstration of the instruments with the entire Mission Control team is vital for daily planning, ensuring that all team members are aware of the capabilities and limitations of the instruments;
- Thorough laboratory and field testing of all science instruments is essential prior to operations. All team members need to be aware of the capabilities and limitations of the instruments and data collection protocols need to be developed by the field and mission control teams.
- Pre-mission Operations Readiness Tests (ORTs), as with actual space missions, are crucial to allow all team members to be ready for operations on the first day of the mission.
- The Mission Operations Manager (MOM) role is essential to the success of the mission, activing as a link between the mission operations and field teams. This out-of-simulation person needs to be readily available up-to-date with all operations, at all times;
- The value of dedicated documentarians (Bednar et al., this issue) is key to a successful validation of mission results. Both point-form-style documentation, common in current missions such as MSL, and transcription-style documentation are recommended and a mix of experts and non-experts was found to provide an optimum balance.
- All roles and communications protocols need to be fully understood by all team members both in the mission operations and field teams;
- It is difficult to run long days and exhausting schedules for multiple weeks with the same personnel. This is particularly so for analogue missions when there is a motivation to gather as much data in as little time as possible as opposed to actual missions where there is typically a slower pace over months and years.
- The Apogy software was a critical tool for planning the CanMars analogue mission; however, the following recommendations are suggested for increasing the utility of the program for mission planning:
  - A function to "go to" a selected FOI without having to manually enter its matrix values into the rover position field;
  - A selection of default views (e.g., Bird's eye view north facing up, rover POV, etc.);
  - Ability to reposition the rover without resetting and reapplying instances, forgoing the need to project data products each time the rover is moved.

11.2. Lessons for future missions

- Dynamic collaboration between the science and planning teams was vital to the mission success (Caudill et al., this issue, a; Pilles et al., this issue). Analysis and interpretation were heavily communicated between the science instrument and imaging teams, providing holistic and targeted analyses. Real-time planning collaboration allowed the

development of best-strategies to maximize the efficient use of the available instruments in planning.

- As has been the case with ChemCam onboard the Curiosity rover (Francis et al., 2017; Maurice et al., 2012), spectrometers and remote micro-imagers having remote capabilities are ideal for rover missions, greatly increasing the speed of operations and the amount of data that can be acquired.
- Situational awareness of the rover operations area, as noted in previous analogue missions (Antonenko et al., 2013), remains a challenge. The use of data-rich augmented virtual reality (cf., Delgado and Noyes, 2017) offers one possible solution.
- Lessons learned from Strategic Traverse Days:
  - The amount of scientific data returned is immense, and the additional time for scientific discussion provided during the strategic traverse days was essential to allow for meaningful interpretation of the data (the two separate Strategic Traverse days gave the team a total of two full days for extended discussion in the absence of n+1 planning). Furthermore, the development of the depositional model was afforded by the Strategic Traverse Days, which served to drive the entire mission;
  - The rigidity of pre-planned strategic traverses was limiting to the plan, and forced decisions on the Science Team that otherwise would not have been made.
  - Pre-planned traverses *should* be included in rover planning to navigate between predetermined regions of interest that can be modified as new data is received. Only when the science tasks are complete at a particular region (e.g., the intended sample and/or scientific measurement is acquired) should a pre-planned traverse be implemented.
- Lessons learned from the Fast Motion Field Test:
  - Creating multi-sol plans requires detailed long-term planning and a conscious effort to carefully plan the "ground-in-the loop" sols ahead of time so that contact science can be completed at features of interest with high scientific impact.
  - The "walkabout" or "walkabout-first" method of exploration tested during the FMFT is an effective method of rover exploration (cf., Yingst et al., 2017). It allows the Science Team to acquire a large amount of contextual data (in the form of images and remote scientific measurements) in a region and use this data to triage the visited sites down to select the most scientifically interesting locations for further contact science and/or sampling (much like a field geologist). The walk-about traverse strategy, along with multi-sol plans with complex decisions trees, was found to be the optimal strategy for choosing sampling sites.
  - Creating multi-sol plans every day for an entire week is exhausting and results in fatigue that negatively affects the quality of the plans later in the week. Multi-sol plans should be spaced out to avoid this.
- Lessons for science autonomy:
  - The suite of science autonomy capabilities available to the team saw significant use. Each capability was used at least once – some turned out to be central to enabling productive use of time, especially during the FMFT.
  - The AEGIS-like (Francis et al., 2017) autonomous geological targeting capability was extensively used, and its availability enabled complex multi-sol plans gathering large suites of geological and geochemical survey data (from cameras and remote spectrometers). The team innovated a cyclical approach of back-to-back multi-sol plans, in which a series of sites would be imaged, revisited with autonomously-targeted science, and then studied with proximity science and sampling tools, with each site at a different stage in that process in each successive plan. This strategy was enabled by the autonomous targeting capability, combined with flexible longer-term planning.
  - Conditional and contingency sequencing enhances the science return, though complex conditional plans require significant work to produce. When combined with autonomous targeting, they greatly increase the productivity and rate of progress of the mission by saving command cycles.
  - Even with capable onboard autonomy (such as intelligent autonomous targeting) blind targeting and visual target tracking still find uses.
- Lessons learned from use of students in key mission operations roles:
  - Students currently play key roles in downlink and uplink for Mars mission instrument teams, as well as in theme groups and as documentarian. It is clear that trained graduate students are highly capable and bring energy and ideas to mission operations as well as living a mission experience that can prepare them for Co-Investigator and other mission leadership roles.

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Appendix A. Supplementary data

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