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CanMars mission Science Team operational results: Implications for operations and the sample selection process for Mars Sample Return (MSR)

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ABSTRACT

The CanMars Mars sample return (MSR) analogue mission was conducted as a field and operational test for the Mars 2020 sample cache rover mission and was the most realistic known MSR rover analogue mission to-date. A rover — similar in scale to that of rover planned for NASA's Mars 2020 mission — was deployed to a scientifically relevant Mars-analogue sedimentary field site with remote mission operations conducted at the University of Western Ontario, Canada; the mission aim was to inform on best practices and optimal approaches for sample acquisition modeled on the Mars 2020 rover mission. The daily operational procedures of the CanMars Science Team were modeled on those of current missions (i.e., Mars Science Laboratory tactical operations), serving as a study of known operational workflows and as a testbed for new approaches. This paper reports on the operational results of CanMars with best-practice recommendations. CanMars was designed as a Mars 2020 mock mission and thus carried similar science objectives; these included (1) advancing the understanding of the habitability potential of a subaqueous sedimentary environment through identifying, characterizing, and caching drilled samples containing high organic carbon (as a proxy for preserved ancient biosignatures) and (2) advancing the understanding of the history of water at the site. The *in situ* science investigations needed to address these science objectives were guided by the Mars Exploration Program Analysis Group goals. Effective and efficient Science Team operational procedures were developed – and many lessons were documented – through daily tactical planning and science investigations employed to meet the sample acquisition goals. In addition to the documentation of the CanMars operational procedures, this paper provides a brief summary of the science results from CanMars with a focus on recommendations for future analogue missions and planetary sample return flight missions, providing specific value to operational procedures for the Mars 2020 rover mission.

1. Introduction

Robotic exploration of the surface of Mars has transformed our understanding of past and present processes on the Red Planet. Perhaps more importantly for the future of exploration of the solar system, rovers have provided a human-level view of the surface, sparking public imagination about discoveries and forging a path for human exploration. A highly successful sequence of Mars surface missions (e.g., Mars rovers Spirit, Opportunity, and Curiosity) has provided science results supporting the habitability potential of early Mars and have motivated Mars Sample Return (MSR) as the next major phase for Mars exploration (Beaty et al., 2019). These missions have also led to increasing

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sophistication in robotic science operations, which MSR will build on. The Viking landers were the first successfully landed assets on Mars and operated from 1976 to 1982 (Klein, 1998). Viking 1 landed in Chryse Planitia and Viking 2 in Utopia Planitia, both conducting soil analyses and collecting weather data. The Viking missions were critical to test the feasibility of science operations via landed assets on the Martian surface. In 1997, the Mars Pathfinder Sojourner rover demonstrated a low-cost mission, returning weather data and images for an extended, nearly 3-month mission, critically demonstrating the value of mobility with respect to achieving science objectives (Golombek et al., 1997). Then in 2004, the Mars Exploration Rovers (MER) Spirit (Arvidson et al., 2006) and Opportunity landed (Squyres et al., 2006); Spirit landed in Gusev Crater, finding evidence of past water before it became stuck in a sand trap to end the mission in 2010; Opportunity landed in Meridiani Planum on January 24, 2004, immediately finding hematite “blueberries”, the source of the iron signatures that had been observed by Mars Global Surveyor. The discovery of these iron concretions, as well as festoon cross-lamination indicative of shallow subaqueous flows, revealed that subsurface water had likely been substantial in Mars’ past (Grotzinger et al., 2005; Squyres et al., 2006). Having roved more than 33 km, Opportunity arrived at Endeavor Crater in 2011, exploring a water-carved valley feature until the mission ended on June 2018. The Phoenix lander mission successfully completed a 5-month mission in 2008 studying polar processes (Smith et al., 2009). The only currently active landed mission on Mars is the Curiosity rover (or Mars Science Laboratory, MSL) which landed in August 2012 as a next-generation rover (Grotzinger et al., 2012). It landed in Gale Crater to explore hypothesized fluvial and lacustrine deposits of a mounded sedimentary section known as Mount Sharp. MSL has made key discoveries such as the detection of organic material (that is, molecular structures containing carbon) and is still exploring Mount Sharp (Freissinet et al., 2015).

The goals of the next NASA Mars rover mission are focused on identifying and acquiring samples of astrobiological significance. The NASA Mars 2020 rover mission is is tasked with studying the habitability potential of ancient Mars (during the first billion years of its history) and searching for evidence of past or present life (Mustard et al., 2013), and is the first in a series of planned missions for Mars Sample Return (MSR). Similarly, the guiding science objectives of the ESA ExoMars rover, also set for launch in 2020, are focused on the search for past or present life and characterization of water/ice and its geochemistry if present (Vago et al., 2017). The ExoMars rover will be capable of drilling 2 m into the subsurface, a depth at which it is thought that organic molecules are shielded from detrimental surface oxidative processes and cosmic radiation, thus enabling their detection (Kminek and Bada, 2006). The search for organic compounds is key for astrobiological investigations, as these structures make up the basic building blocks of all known life processes.

Pre-mission analogue studies are necessary to ensure that procedures are thoroughly vetted and the most efficient approach to mission operations are determined; efficiency is paramount as ground operations timetables for Mars rover missions require shortened time-critical observations, results, and interpretations. The 2015–2016 CanMars Mars Sample Return Analogue Deployment (MSRAD) employed Mars 2020-simulated instrumentation — also mimicking rover power and uplink/downlink data constraints — with the same basic mission goals as Mars 2020 to test new and current operational and workflow procedures. An overview of the analogue mission campaign and team structure, which included Mission Control (Science and Planning Team operations; Pilles et al., 2019) at Western University, the Canadian Space Agency (CSA) Mars Exploration Rover (MESR) Operations Team (rover uplink at CSA headquarters Saint-Hubert, Quebec), and the field team (on-site operations in Hanksville, Utah Caudill et al., 2019) is detailed by Osinski et al. (2019). Here, we outline the procedural and workflow operations of a rover mission Science Team and detail how the daily derived science influenced sol-by-sol plans, thus resulting in targeting and acquiring samples for cache. Assessment of the accuracy of the data and interpretations reached by the remote Science Team was assessed in four ways:

- After the mission activity was completed, members of the remote Science Team visited the field site to walk the rover traverse, detailing the variances between rover-derived science and interpretations and field observations (Caudill et al., 2019);
- Samples were collected from the field site which were then analyzed with gold-standard laboratory instrumentation and compared with rover-derived results (Caudill et al., 2019);
- The Field Validation Team independently investigated the site using traditional field geology methods, which were compared to the remote robotic methods with important geologic and operational outcomes (Beaty et al., 2019), and;
- Documentarians recorded the activities of both the Science and Planning teams, documenting data-based interpretations and the subsequent decisions made throughout the mission; this documentation was assessed post-mission (and is available for future analogue or real missions) for assessments of decision complexities, team dynamics, and overall efficacy (Bednar et al., 2019).

2. Science operations construct

The CanMars-MSRAD analogue mission was built as a collaboration between the Centre for Planetary Science and Exploration (CPSX) at the University of Western Ontario (Western) and Canadian Space Agency (CSA). Past CPSX-led planetary analogue missions have been held across North America focused on advancing the science to influencing operations of robotic and future human exploration (e.g., (Marion et al., 2012; Osinski et al., 2010). The CanMars deployment was conceived as a 5-week field and operational test (held in November 2015 and November 2016) for the Mars 2020 sample cache rover mission, resulting in the most realistic known MSR rover analogue mission to-date (Osinski et al., 2019). The MSL-scale Mars Exploration Rover (MESR) was deployed to a scientifically relevant Mars analogue sedimentary field site (detailed in Tornabene et al., 2019), with integrated mast-mounted imagers, a robotic arm equipped with a micro-imager and sampling system, and integrated and stand-in instruments. Osinski et al. (2019) provide a comprehensive overview of the MESR platform and science instruments used. Briefly, the science instruments included: a Raman spectrometer stand-in for the Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals (SHERLOC); an X-ray fluorescence (XRF) spectrometer stand-in for the Planetary Instrument for X-ray Lithochemistry (PIXL) with micro-focus camera (Simpson et al., 2017); three separate instruments as stand-ins for SuperCam, namely a Raman (Mittelholz et al., 2016), Laser-induced breakdown (LIBS; Svensson et al., 2017), and visible-infrared (VIS-IR; Bina et al., 2017) spectrometers; and a remote micro-imager (RMI) and mast-mounted cameras (Godin et al., 2017). The SHERLOC stand-in Raman is capable of detecting potential biomarkers *in situ*, with the suite of spectrometers used to test and evaluate the depositional model at each new site to understand habitability potential. CanMars flight rules for the SuperCam stand-ins Raman, LIBS, and VIS-IR allowed usage as remote instruments, meaning data could be acquired on targets up to 12 m away (similar to the expected range for Mars, 2020 SuperCam Raman and VIS-IR) and 7 m (the maximum range of MSL ChemCam LIBS) from the rover (Francis et al., 2016a,b). Out-of-simulation field operation of these instruments is documented by Caudill et al. (2019).

Rover-derived data and Science Team analysis and interpretations drove the daily, or sol-by-sol, plan; this analogue mission was therefore high fidelity as real-time, remote spectroscopic (geochemical, mineralogical, and imaging) data was integral to the simulation. The construct of this analogue mission was built on current MSL mission operations and traverse strategies, while acting as a test-bed for further development of those procedures for future missions. The mission scenario included various constraints modeled after MSL, including rover traverse limitations and resource costs as well as strict adherence to data uplink and downlink 'windows' and operational schedules. Although the Science Team did not adhere to Mars time (common for the start of Mars rover missions to maximize operations during daylight), a daily schedule of morning (7:00–10:00) and evening (19:00–22:00) operations was held for three weeks each in November 2015 and November 2016. The 2016 mission deployment was a continuation of the 2015 deployment. The knowledge transfer supporting the continuation of the mission was conducted through: individual team member and instrument team reports; conference abstracts; archived data and interpretations and results presentations; pre-mission training sessions to prepare new team members, and; the use of Slack in both deployments.

2.1. Science objectives

The CanMars mission was science-driven and thus, the main goals can be summarized as two main science objectives: 1) collect and rank samples for cache and return with highest potential for preservation of organic-rich carbon (using Total Organic Carbon (TOC) as a proxy for evaluation of this test); and 2) assess paleoenvironmental habitability potential and history of water at the site. These science objectives are derived from Mars (2020) science objectives (Mustard et al., 2013) which itself is based on the E2E-iSAG report (McLennan et al., 2011). CanMars entailed similar mission objectives to that of Mars (2020), including the characterization and cache of samples with the most significant contributions to the understanding of life and its chemical precursors, surface materials and processes, and planetary and atmospheric evolution. CanMars was also a field-test for Mars 2020 operations and sought to advancing the operational concepts of a MSR mission. The CanMars instrumentation, tasks, and goals are related to the MEPAG goals as shown in Fig. 1. Full mission success was outlined as collecting two or more scientifically significant samples guided by *in situ* investigations as outlined in the Mars Exploration Program Analysis Group (MEPAG, 2015) document. MEPAG provides a methodology to address the

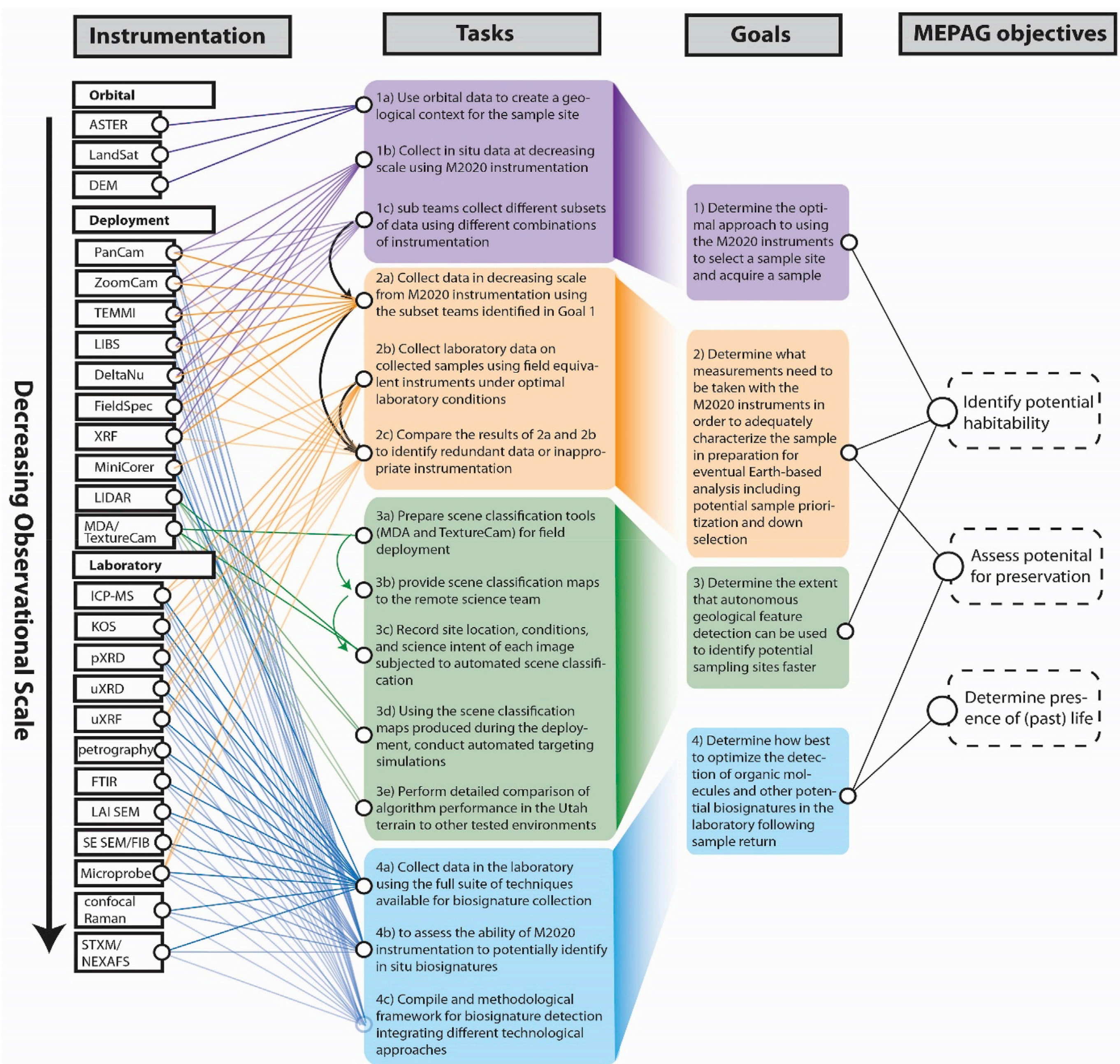

Fig. 1. Summary of proposed instrument linkages to the CanMars mission requirements and overall MEPAG objectives.

high-level goals of habitability (MEPAG goal 1; Mars, 2020/E2E-iSAG objective A) and history of water (MEPAG Goal III, Mars, 2020/E2E-iSAG objective B), including the following sub-goals:

- 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.

It should be noted that the MEPAG document also outlines the need to determine if environments are currently habitable coupled with investigations of evidence for extant life. In keeping with a realistic analogue scenario with its potential impact to future Mars missions, only ancient habitability was considered, and current life at the analogue site was discounted.

3. Pre-mission planning

Several months prior to "landing" and the official analogue mission start in 2015, the mission control team (including Science and Planning Teams) met for several planning meetings to identify and then investigate potential Regions of Interest (ROIs) within the landing ellipse (a ~5.2 by 1.6 km-area). The team developed a number of working geological hypotheses based on remote sensing datasets (see Morse et al., 2018; Tornabene et al., 2019). The Science Team was provided with a set of regional (covering a 15 km^2 area) and landing site-specific data, mimicking the datasets that would be available for remote science of a landing site on Mars. These datasets served as the only guide for initial operations and site research; the field site was concealed from the mission control team so that the analogue mission scenario remained fully in-simulation, or "in-sim". These datasets, their Martian equivalents, and spectroscopic processing are detailed by Tornabene et al. (2019); briefly, datasets available to the Science Team included: Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER; 15–90m/pixel) datasets (Fig. 2a); multispectral visible to thermal infrared Landsat 8 Operational Land Imagery (OLI; 15–60m/pixel) (Fig. 2b); a 10 m/pixel digital elevation model (DEM) (Fig. 2c); and a high-resolution visible-near infrared Quickbird image (60cm/pixel) (Fig. 2d and e). Here we summarize the general use of those datasets to inform pre-mission science and strategic planning.

The Landsat enhanced bands 7, 5, 3 (Fig. 2a) were overlain on the high-resolution Quickbird image as well as the DEM, providing a framework for the regional geologic interpretation. The Landsat data in this band combination is useful as clays and carbonates are highlighted by band 7 (covering SWIR 2.1–2.3 μm range for which minerals in these groups have major absorption features) and band 3 highlights iron oxidation. Band 5 measures the near infrared, or NIR, which is especially important for vegetation as those wavelengths are scattered back into the atmosphere. Note the magenta in the basinal areas, consistent with clays and carbonates, the paucity of green, and the abundance of blue,

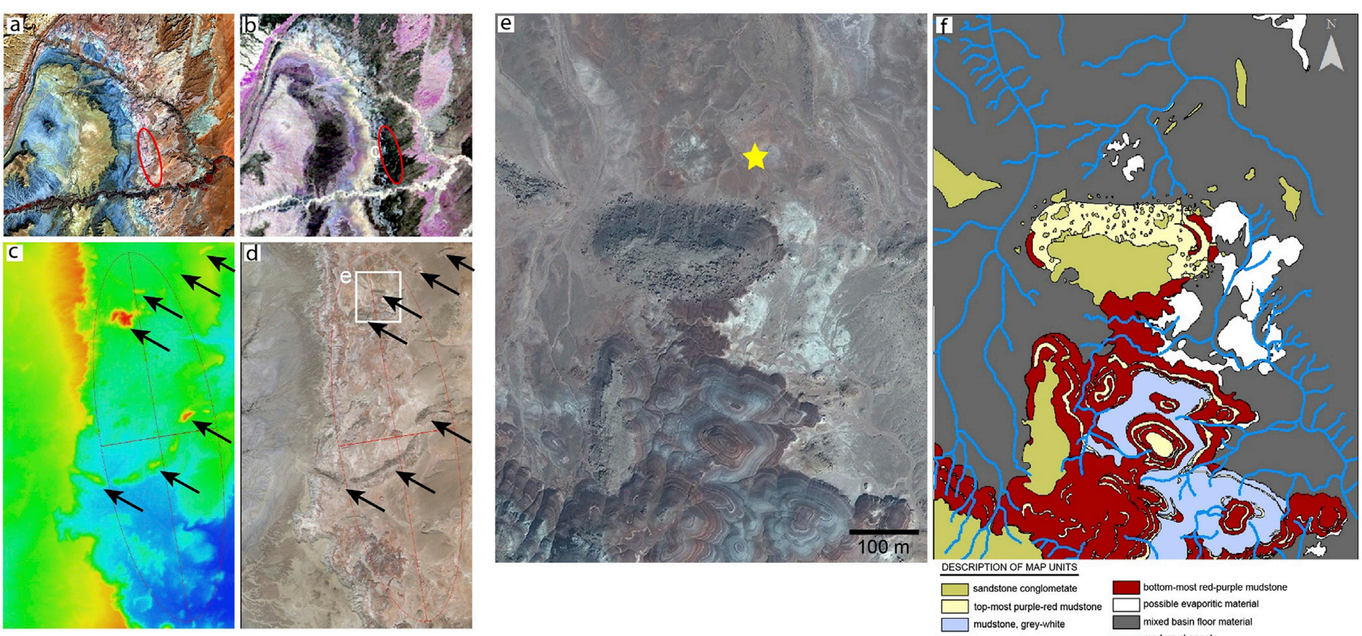

Fig. 2. a) Regional Landsat 8 OLI (15–60m/pixel) with bands 7, 5, 3 color infrared image. A local stretch was applied. Blues indicate the presence of ferric oxides (band 3) and magenta indicates the presence of clays and carbonates (band 7). Note the lack of green, which indicates vegetation (band 5) (See Tornabene et al. (2019) for spectral analysis.). The red circle indicates the landing ellipse, which is ~5.2 by 1.6 km. b) Regional ASTER TIR (15–90m/pixel, bands 10, 11, 12) color composite. Magenta indicates sulfate-bearing; light blue indicates carbonate-bearing; black indicates silica-dominated; light yellow indicates clay-rich. Same scale as (a). See Tornabene et al. (2019) for spectral interpretations. c) and d) The landing ellipse (~5.2 by 1.6 km) is indicated by the red outline, shown on c) a 10 m/pixel DEM and d) a high-resolution Quickbird image (60cm/pixel). Nearly continuous ridges to discontinuous ridge segments are highlighted by black arrows; sinuosity of the ridges features was measured as 1.21 for the northern-most ridge segments and 1.33 for the southern ridge, as indicated in the image. White box in (d) indicates the spatial extent for the immediate landing site shown in (e). e) Close-up of Quickbird image (60cm/pixel) image of the landing site and field area. Yellow star indicates the position of the landing site. f) Geologic map of the field area, following "landing," representing pre-mission data and interpretations and data acquired from the 2015 mission cycle. Same extent and scale as (d). North is up in all images. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

consistent with iron oxidation (Fig. 2a). Based on ASTER TIR emissivity, bands 10, 11, 12 (Fig. 2b), the landing ellipse and its regional surroundings were interpreted to be dominated by a spectral signature consistent with silica-rich materials (indicated by black). ASTER and Landsat multispectral data analyses (covered in detail by Tornabene et al., 2019) led to the interpretation that the landing ellipse had minimal vegetation with silica and carbonate-bearing deposits, abundant ferric oxides, and likely having clays and sulfates. In visible imagery, within the basin, alternating red, white, and blue layers were present underlying sinuous ridges. Geomorphological and morphometrical analyses was performed on the ridges including curvature, continuity of cross-sectional profile across ridge segments, and sinuosity (Fig. 2c and d). The ridges were determined to have a strong morphometric similarity to terrestrial inverted paleochannels (i.e., 1.2–1.5 sinuosity; Williams et al., 2011). Combining with the km-scale data (Fig. 2a and b) with the m-scale morphology provided by the Quickbird image and DEM (Fig. 2c and d), the team hypothesized there was a domed feature (mountain, volcanic edifice, or other feature) to the west of the landing ellipse, with the landing ellipse located in a sedimentary basin having sinuous ridges. Regional extensional tectonism was proposed as a potential mechanism having formed the dome and basin. The team proposed that the ridges were inverted topography, where ancient, inverted paleochannels were likely capped by either resistant fluvial or igneous rocks. The underlying basin materials were thought to be dominated by silica-rich lithologies having various oxidation states, which reflects changes to the environmental conditions over the geologic history of the site (Pontefract et al., 2017). Light-toned whitish deposits are exposed on the basin floor, which the Science Team proposed could be comprised of volcanic ash, lacustrine evaporates, or other diagenetic or alteration products. Shallow sea or lacustrine deposits, both prior to and after the emplacement of a channel system, would indicate a variable influx of water in wetter climates followed by the present-day erosional regime. A geological map, based on remote sensing data and data acquired during the 2015 mission, is provided in Fig. 2f.

As is commonly the case for actual flight missions, the Science Team was permitted to use terrestrial analogues to help support and develop their hypotheses. The dominant terrestrial analogue used for the field site was the Painted Desert, Arizona, which has multi-colored layered lacustrine units indicative of periods of variable fluid and sediment influx (e.g., Harris et al., 1997). Regional uplift and basin and range-style extension contributed to the Painted Desert depositional environment (Hendricks, 1985; Arizona Soils). One hypothesis for the landing site was that regional tectonics similarly resulted in sedimentation and fluvial transport from the higher terrain in the west, draining into the area of the landing ellipse. Until landing and rover investigations during the 2015 mission cycle, the hypothesis of volcanic domes to the west and volcanic infilling of channels to the east could not be ruled out. Following landing in 2015, a portion of an inverted channel was investigated (Fig. 2e). It was found that the capping unit was a fluvial clastic sandstone as opposed to volcanic material (Fig. 2f). However, the team discovered upon ground operation investigations that volcanism was important to the geologic history of the site, present in the form of massive ash fall having comprised at least some component of the siltstone units. The discoveries from remote rover operations are described in the following sections. The putative ancient fluvial and lacustrine systems of our field site were deemed highly favorable for habitability and, with burial and preservation due chiefly to the capping unit, of significance for the preservation of organic matter (Pontefract et al., 2017).

Prior to the start of the 2016 deployment, the mission control team again held a series of meetings to revisit the geological interpretations as determined by investigations of the imagery and the results and interpretations from the 2015 rover operations. The team reviewed the last sol's data (from the previous year) and began planning high-level, treed, potential sol paths – these were long-term mission scenarios that acted as a guide for the mission, to be revisited and updated as the 2016 mission proceeded and new rover data was acquired. This long-term, mission overview planning protocol is similar to Campaign Planning processes currently being developed for Mars 2020 operations, where high-level sol paths are edited as new areas are explored and characterized in depth (Francis et al., 2019).

In the days leading up to both 2015 and 2016 missions, the team participated in a one-day “dry-run” of operations. A mock-scenario was constructed — covering both daily operational shifts — to allow the team to practice the daily operations workflow. Workfows were practiced, assessed, and reformulated within the smaller instrument teams and the larger Science and Planning teams. This exercise was important for allowing team members to understand their roles and responsibilities, and for the leadership to assess any gaps and unmet needs of the mission and team.

4. Science Team operations

4.1. Operational procedures

Science Team operational procedures proved to have a direct impact on the timeliness, focus, and relevancy of sol-by-sol data interpretation, and hence discussion and next sol (or "n+1") plans. The detailed daily operational schedule and related discussion is provided by Osinski et al. (2019). The Science Team worked together in one room, which facilitated discussion even during data processing and interpretation. Geochemistry and spectral/mineralogy datasets on their own are necessarily incomplete to describe the geologic context for a given set of daily targets, which may include rocks of differing lithologies, dust or debris coverings, and/or weathering rinds, as well as soil, dust, or erosional material. Moreover, the synthesis of the massive amount of data acquired daily by the rover is an immense challenge given the daily operational timeline, particularly when several datasets require concurrent analysis. These problems were mitigated by easy, quick consultations between the individual science instrument teams during the initial stages of analysis, essentially building a context for the n-1 scene and narrowing down the data which was most important for that context. For example, while the Raman and VIS-IR spectroscopy teams developed targeted data analysis based on preliminary XRF and LIBS results from those teams, imaging teams provided morphologic, micro-textural, and contextual information, along with mast-mounted camera images giving insight into structures or reference to geologic contacts. The interplay among the instrument teams was critical for timely interpretations. Among the science operational procedures, encouragement of this collaboration during data processing was instrumental in moving the Science Team quickly towards science discussion and meeting the time-sensitive n+1 plan uplink window.

The Science Team discussion for n+1 planning was guided by the Science Team Lead (STL), who took arguments and interpretations into account while ensuring that mission goals were addressed with every targeting and sample selection campaign. New targets were chosen based on observations and interpretations provided by the ongoing data synthesis of previous sols; repeat targets were often discussed but rarely planned, balancing mission goals — including thorough geologic characterization at each location with the ever-present push to traverse toward new terrain for sampling opportunities. Upon choosing new targets, the distance and traversability were determined using the CSA MESR software Apogy (Sapers et al., 2016; Pilles et al., 2019; Osinski et al., 2019), which allowed for planning of the next or multiple next sols based on rover constraints. Data and energy constraints were considered for the desired use of any instruments or sampling functions. We found that a procedural deadline was necessary for this nominal plan, as discussion of next sol planning was often heated and lengthy. Upon delivery of a nominal plan to the Planning Team, they offered a number of possible traverse scenarios given time, data, energy, and traversability constraints (see Pilles et al., 2019). Discussion followed to produce a final plan by 10 p.m. that satisfied the science goals of the mission within engineering constraints.

4.2. Strategies for best Science Team operations

The most productive operational procedures in terms of priority sampling opportunities came about from Science and Planning teams independently constructing multi-sol, long-term plans as decision trees (e.g., Fig. 2). Preparation for sampling required ground-in-the-loop (localization and data gathered from consecutive sols) as a Light Detection and Ranging (LIDAR) cm-scale resolution workspace was generated for precise rover arm placement opportunities on the following sol (Zylberman et al., 2016). Sampling via the drill corer or scoop and analyses with contact instruments, such as the XRF and micro-focus camera stand-in for the rover arm-mounted Mars 2020 PIXL instrument, required a LIDAR workspace for such precision activities. Consequently, use of these tools and instruments was costly in terms of mission time, often requiring multiple sols of data collection to sufficiently characterize a lithology before sampling was considered. A "walk-about" traverse strategy, rover exploration reconnaissance involving long traverses with minimal data acquisition as detailed by Pilles et al. (2019), cleverly mitigated the potential waste of precious mission time due to activities that required human decision-making. In this strategy, multiple remote science targets were visited per sol with the autonomous capability to end the drive with the construction of a LIDAR workspace at a precise location, which prepared for next-sol sampling while returning data on future potential sample sites, as is shown in the sample planning diagram in Fig. 3. Preparation for sampling during "walkabouts", therefore, required the Science Team to develop strategic multi-sol plans (e.g., Fig. 3) that included multiple targets and sampling sites with "if-then" decision trees based on priority sample ranking. The sample ranking was based on mission goals, where we determined the potential for a sample to have total organic carbon (TOC) from previous sols data return and the depositional model. Once these complex and multi-sol nominal plans were detailed, an effectual interplay between the science and planning teams lead to the final walk-about plans.

When choosing scientifically significant targets for n+1 sol or multi-sol plans, the Science Team had other tactical allowances in-play that allowed us to meet mission goals. For example, imaging and "blind targeting," where autonomous data was collected at a known location but on an unknown target, both utilized rover-relative and site geographic coordinates by azimuth and elevation (see also Pilles et al., 2019). This allowed post-drive imagery (e.g., panoramas, zooms, or higher resolution images) as well as targeted remote science (e.g., XRF or Raman). As discussed by Francis et al. (2016a,b) and Francis et al. (2019), such autonomous targeting allowances for the CanMars mission constraints was modeled after MSL visual target tracking (VTT) and actual ChemCam capabilities (Francis et al., 2016a,b). The Science Team used this strategy to collect data on lithologies, soils, and erosional material for geologic characterization, essential to our understanding the history of fluvial processes and climate of the site. Along with acquiring scientifically significant samples, such collection of data enroute to potential sample sites allowed the Science Team to achieve "full success" by meeting multiple MEPAG goals. These tactical strategies were critical for collecting data during consecutive days dedicated to driving and served as a data-rich approach to filling the energy and data budget of a time and distance-limited plan.

4.2.1. Pre-planned strategic traverse days

Strategic planning days were used during the CanMars mission to give the team a break from tactical planning to focus on the huge volume of

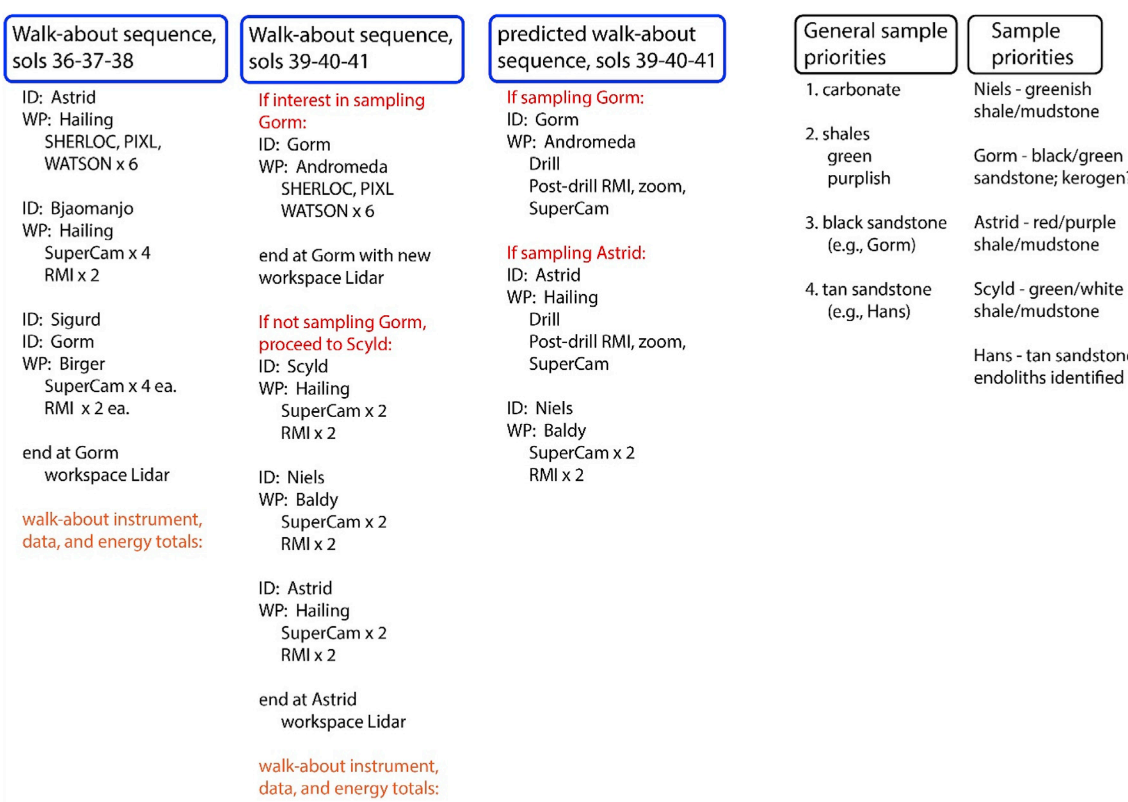

Fig. 3. In-sim treed, multi-sol plans with sample priorities, representing a typical whiteboard sketch of planning and pre-planning during each shift. "ID" is the name given of a feature of interest (FOI), generally a rock, outcrop, or specific spot in the regolith. "WP" is the waypoint, or the name given for the location of the rover from which the analyses or image is taken. FOI locales are indicated in Fig. 3. Walk-about planning allows for many sites to be investigated with pre-planned end-of-sol at a potential sampling FOI. Notes that workspace LIDAR is requested at the end of the multi-sol plans, as this sets up for use of contact instrumentation (e.g., SHERLOC Raman, drill) which requires ground-in-the-loop. Sample priorities, as formed through the site depositional model and defined by the science objectives, are always indicated to guide plans. The sample priorities acted as scientific hypotheses and were continually edited with acquisition of new data and interpretations as the mission progressed.

data return and develop and strengthen depositional mode1 and working hypotheses. During each strategic day, pre-planned activity sequences covering a full sol were uplinked to the rover (see Pilles et al., 2019). Strategic traverse days were built into the mission plan, but were necessarily kept as flexible calendar days, to be implemented to coincide with long traverses or other scenarios that were easily pre-planned with a minimum of data return (Pilles et al., 2019). During these days, both the Science and Planning teams broke from normal operations and met in groups with the intention of bringing together multiple perspectives (e.g., science, engineering) and therefore fresh insights to the mission-acquired observations and interpretations. Each group was given a set of tasks based on the experience and specialization of members in the group. Panoramas, zooms, and mast-mounted camera images were stitched and overlain for the purposes of making facies and geomorphological maps, measuring the true height of outcrops, and determining fluvial-lacustrine successions with basin geometries. Primary sedimentary textures and structures such as bedding, cross-bedding (e.g., mapping shown in Fig. 3 for outcrops in units #1 and #7), grains, clasts, and apparent porosity were mapped. At the end of the shift, the entire team met to present results, for discussion, and to further develop the depositional model (Fig. 3), discussed in the following section. Although the data return from the rover's activities was sparse on these days, the model and stratigraphic columns developed informed sample selection decisions throughout the mission.

In summary, the strategic traverse days were important for the team to make better short- and long-term tactical decisions; such operational strategies may be beneficial for strategic planning for Mars 2020 and future rover missions operations. The CanMars analogue mission, representing an end-to-end mission scenario, presented an ideal opportunity to experiment with new models and mission approaches that are too costly to test during extraplanetary mission.

4.3. Development of the depositional model

Similar to sedimentary facies models used as basic tools in MER and MSL missions to investigate layered sedimentary sequences (e.g., Edgar et al., 2017), the depositional model developed during CanMars describes the geologic setting of the region and the implications to sampling selection. The depositional model was a synthesis of imagery and digital terrain models, elucidating sedimentary facies, contacts, stratigraphy, and general architecture of the site, through investigations of paleo current or slope indicators, basinal centers and edges, and unconformities. These observations led to interpretations about the influence of diagenetic histories that either promoted or inhibited biologic activity in particular facies or lithologies. Hence, a large volume of data was synthesized into a predictive model that guided Science Team decisions for long-term planning, afforded by the collective teamwork on the strategic traverse days.

The depositional model provided the Science Team with predictive power to strategically plan the general traverse of the mission, focused primarily on a layered, multi-colored siltstone unit that was not reached until the third week of 2016 operations. Based on the mineralogical and geochemical data, geologic context, and textural evidence, the Science Team proposed that the lowermost white and red layers of the siltstone sequence (Fig. 4, unit 4) were likely the same, but influenced by diagenesis, where a variable water table post-emplacement resulted in redox changes. The green layers (Fig. 4, unit 5) were in contact with intermittent, high energy lenticular sandstones (Fig. 4, unit 7), indicating very low energy environment was present before a rising water table increased the fluvial activity and sediment influx rate. Mineralogy of the green siltstone was dominated by smectites, with yellowish alteration, a "popcorn" erosional texture, and gypsum present throughout the unit. The team interpreted that nontronite and the green color of the unit may indicate diagenesis, where microbially-mediated weathering resulted in reduced iron in anoxic sediments. Sparse, isolated, cm-scale white material within the siltstones was found to be evaporitic lenses comprised of gypsum and were interpreted in the model to have formed where water only breached the surface during periods where the water table was lower. As the rover traversed up-section through the landing site, the model predicted that the green and/or red-black layers represented a redox sensitive lake (supported by the presence of evaporites), with a potentially microbially-mediated reducing depositional environment (green) and a potentially very high concentration of organic carbon (purple-black). We suggested that these units experienced low sedimentation rates which tends to increase TOC, and even though some amount of ash fall was introduced, very little clastic dilution took place to lower potential TOC (Ding et al., 2015). With low sedimentation rates, redox conditions become an important factor in the preservation of TOC (Ding et al., 2015).

4.4. Sample priorities

Sample selection for the CanMars mission was governed by two main science objectives: 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

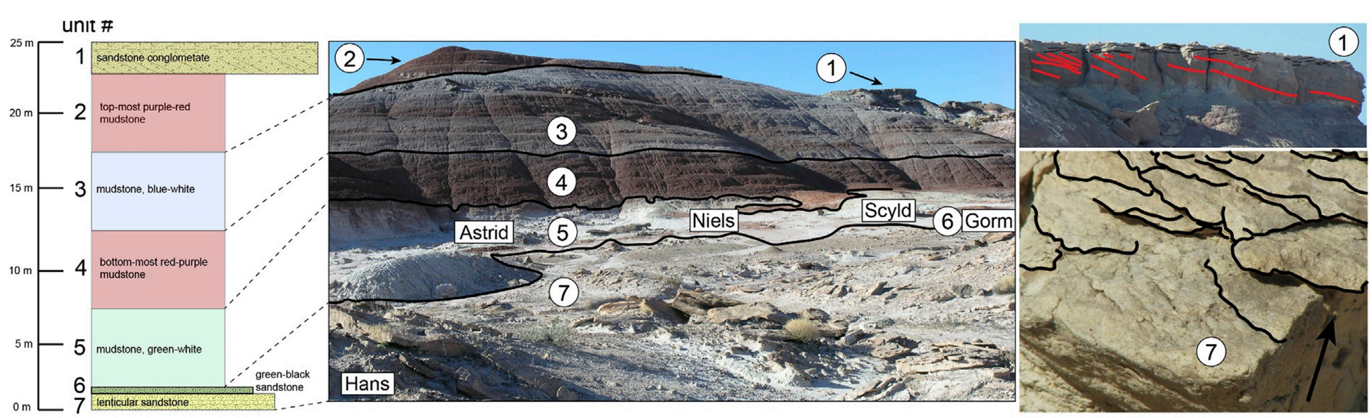

Fig. 4. Final depositional model and stratigraphic column of the analogue site as produced during the mission. This model guided the planning of the rover traverses to reach desired sampling sites. The input of the model included facies and geomorphological maps, outcrop and feature height and extent measurements, and constructing basin geometries. Primary sedimentary textures and structures such as cross-bedding were mapped directly on to zoom or other imagery, as shown for units #1 and #7. Unit #1 shows cross-bedding perpendicular the direction of fluid flow; Unit #7 shows planar cross-bedding (and potentially flaser bedding) as stacked, thin bedding planes, viewed in the direction of fluid flow. Major features of interest (FOIs) and sampling sites are indicated by target name. The model remained fluid, allowing for changes in working hypotheses with regard to lithologic interpretation and boundaries, facies changes, etc. For regional location, see the yellow star in Fig. 1e. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

history of water at the site. Mission requirements regarding sampling (as indicated MSRAD guidelines; see Osinski et al., 2019) indicated one cached sample for minimum mission success, two cached for full success, and three cached as a “stretch”. During the 2015 and 2016 CanMars mission cycles, 8 total samples were acquired and cached (four each cycle). Table 1 describes the samples, their relative rankings for priority return samples, and the science rationale for each sample. The Science Team ranked the siltstones highest priority based chiefly on the geologic context and interpretation of these units as marginal lacustrine facies, as such a depositional environment would most likely to have organic carbon and potentially biosignature preservation (Fig. 5a–c). We were unable to obtain organic carbon signatures in-sim with the Raman, however, and the team recognized that the preservation of ancient biosignatures is highly dependent on the weathering state and general preservation of the lithologies. The sandstone conglomerate (Fig. 5d and e) sample was rated as the third priority return sample (above the older sandstone units) due to the potential to retain micro-paleofossils. Table 1 presents the 8 cached samples and highest priority return samples chosen based on rover-derived observations and analyses, with 1 being highest priority.

Caudill et al. (2019) provides the post-mission laboratory analyses of these samples, including the total organic carbon (TOC) of a sample suite of the field site and the in-sim cached and ranked samples (Table 1). Laboratory Raman revealed that the samples in this study either do not contain kerogen (Raman-detectable form of organic carbon), or do not contain it at detectable levels (Caudill et al., 2019). Solvent extraction Gas Chromatography Mass Spectrometry (GC-MS) showed that the sandstones had the highest TOC of the in-sim cached samples, but the level of TOC (at <0.03 wt%) was 100 times less than is considered organic-rich for sedimentary rock (Boggs, 2006). Potential explanations for the lack of TOC in the field site may include either a low primary productivity due to the oligotrophic nature or anoxic conditions (perhaps with the influx of ash) of the depositional environment, unfavorable preservation conditions (e.g., ash or other inorganic sedimentation influx to the lacustrine siltstone units; high clastic sedimentation rates in the sandstone units preventing biomass accumulation), or both.

4.5. Post-mission site visit

A fundamental advantage of using an actual field site in analogue mission simulations is the ability to physically explore the field site post-mission to assess the validity and understand the limitations of remote science. Following CanMars mission operations in November 2016, the mission control team visited the rover deployment site near Hanksville, Utah, with the intent of geologically assessing the field site. The team first walked the path of the full mission traverse, only then fully comprehending how little ground can be covered by a rover versus a human and how little of the area it is possible to assess via remote science. The overall lack of awareness of the surroundings – which included missing outcrops and other key details that were just out of the view of the rover's imagery – serves as a caution with regard to over-interpretation of remote science. Given line-of-site, time, and traversability limitations, thoroughly investigate a geologic site is a difficult task. Upon visiting the site, the mission control team realized that part of the stratigraphy was missing from the depositional model because it was out of view from the rover traversable terrain. It is important to note that mineralogic, textural, and contextual clues that may be obvious to a field geologist do not always appear evident in spectroscopy data; in available context and scale, imagery is often insufficient for textural and other contextual clues to differentiate lithologies when mineralogy and chemistry are similar (e.g., an ash-fall tuff versus a very fine-grained sandstone; a volcanic breccia versus an impact breccia). Some minerals were only locally present throughout the field site and proved to be difficult to target. For example, the post-mission analysis indicated the presence of jarosite, interpreted as a common alteration product of the white-gray-green lacustrine unit and the source of the orange alteration observed during the mission. Sulfates (gypsum), Ca-phosphates (brushite), and Fe-oxides and Fe-oxyhydroxides are important indicators of paleoconditions and are important for metabolically-significant organisms that can be formed via a biologically-induced and controlled process (Gramp et al., 2010; Lucas and Prévôt, 1984; Mojzsis and Arrhenius, 1998); thus, jarosite may have been an important finding during the mission. Only after the field visit did the team suggest that the siltstone sequence may have formed as an acid-saline lake; jarosite is an important environmental indicator and was important for ancient Mars as conditions became more arid.

5. Lessons learned – optimal Science Team operational procedures

An important outcome from a procedural standpoint was the collaboration among the various teams. Data analysis and interpretation were heavily communicated between the science instrument and imaging teams, providing holistic and targeted analyses. Mineral identification, lithologic classifications, or other data trends were verified and corroborated by other instrument teams, providing useful and meaningful interpretation. This real-time collaboration also afforded the most efficient data processing and interpretation, which is critical when scientific evidence is intended to dictate next-sol planning. Furthermore, this process allowed the team over time to develop best-strategies to maximize the efficient use of the available instruments in planning, including, for example: the pre-planned use of all reasonable arm-bound instruments when deployed; expending traversable distance and data and time allowance enroute to a target, and; ending a sol plan with remote spectroscopic observations as well as a LIDAR scan to allow sampling if the returned data showed it was warranted (e.g., Fig. 3). A dynamic collaboration between the Science and Planning teams was also vital to the mission success. When coordinating single sol plans, but especially for the complex multi-sol plans, members from the Planning and Science Teams were in direct communication, moving between both control rooms. Combined workflows and advanced hardware and software capabilities are being explored for use in flight missions (e.g., Deans et al., 2012) to allow disparate, remote planetary mission teams to work together in real time. We suggest such research and testing has real power to better integrate dispersed international teams and partners and produce better, more efficient science. Furthermore, we suggest that Science Team Leads (STLs) or other leadership recognize that team members participating remotely (e.g., by phone and/or web-enabled conferencing software) will generally not engage and collaborate as fluidly as those present together in mission control, and strategies should be considered to ensure collaborative space at all levels of participation.

The success of analogue and flight missions depends on team member contribution and participation. Given the intense and difficult science discussions and planning with high-stakes decisions based on limited time and science, it is critical to create a collaborative atmosphere. A culture should be cultivated wherein team members are empowered and expected to speak up about ideas and interpretations, with no penalties for being wrong but accepting of criticism. We suggest that operational schedules include time for instrument team presentations as well as presentations by individuals; this may include scheduled breaks during Tactical planning for individual team members to expand on ideas or prepare graphics to be presented at that planning meeting.

Data processing and interpretation, as well as subsequent next-sol planning, is time-limited both per sol and over the course of a mission; it is thus imperative to implement efficient strategies for Science Team operations and plan implementation. The walkabout rover traverse strategy, along with multi-sol plans with complex decisions trees, was found to be the optimal strategy for choosing sampling sites. Nested decision trees were important for the Science Team, with ranked sample priorities and science rationale for each, to match the traverse scenarios constructed by the Planning Team (e.g., Fig. 3). Pilles et al. (2019) provide further discussion on the walkabout and other traverse strategies. This strategy allowed for exploration and data acquisition of many sites,

Table 1
Priority rankings, descriptions, testable hypotheses, and science rationale of the samples acquired and investigated throughout the CanMars mission. The samples are ranked beginning at most desirable based on the characterization of the lithologic unit. This chart represents the rankings developed by the Science Team throughout the mission; not all desired samples were acquired. See Fig. 4 for location information.

general lithologic units	hypothesis test	2015 samples	2016 samples	sampling priorities	science rationale
potatoes (tuff)	Carbonates or concretions? If a Raman signature for carbonates or kerogen was demonstrated, it would be ranked highest (such signal was not detected).		no sample acquired		Carbonates would be lower than shales in TOC, but preserve organic and inorganic carbon together. A return sample would allow isotopic paleothermometry, and may preserve microbial fossils or mats.
green siltstone	Lithology, depositional environment, and organic carbon potential was determined by geologic context, color, and mineralogy. Potential kaolinite, muscovite, and nontronite were observed, and montmorillonite-illite were observed with high confidence. Gypsum was identified (strong peaks, high certainty). Potential nontronite - indicates the weathering of volcanics with microorganisms involved in reduction of iron when soils undergo anoxia (producing the reduced form of the clay).		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, we disturbed the surfaces with 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 favors 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 (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.
"black" sandstone	Could be an organic rich sandstone. This was targeted for biosignatures, but instead graphite was identified by Raman, and is very different from the kerogen signature that would indicate organic carbon If a Raman signature for kerogen was demonstrated, it would be ranked highest (such signal was not detected). VIS-IR suggested that Fe and Mg-rich clays were present.		no sample acquired		Could be an organic rich sandstone. High TOC sand units in a fluvial environment could be overbank or crevasse splay deposits with potential for organic and biosignature preservation, though ranked lower than marginal lacustrine facies (shales).
sandstone conglomerate	Imaging microfossils and cross stratification possible. Will fulfill goals to study history of aqueous environments at the site.	Thrymheim		3	Trough cross stratification and soft sediment deformation features with embedded clasts that were multi-colored, well-rounded, high sphericity pebble to gravel-sized. Potential for microfossils within the conglomerate clasts. Fulfills goals of assessing the history of fluvial activity at the site and the stratigraphic column for broader geologic characterization.
sandstone	Identify biomarkers identified from endolithic communities.		Hans	4	Carotenes were identified *in situ* with Raman, which are indicative of endolithic communities within the rock. This step-wise approach including identifying a rock likely to have preserved endolithic pigments, abrading the rock with the rock abrasion tool (RAT), then confirming with Raman. The carotene pigments do not represent biomarkers from ancient life (i.e., kerogens), but more recent life (extant or extinct). Desert varnish is observed as a weathering product on the sandstones, indicated by dark coloration, mm-sized thickness of the coating, and very high Fe and Mg.
white siltstone	Lithology, depositional environment, and organic carbon potential to be determined by geologic context, color, and mineralogy.	Gimli		5	Gray shale bleached/weathered and/or volcanic ash – least likely to preserve organic material, but fills the stratigraphic column for geologic characterization.
sandstone	Identify biomarkers identified from endolithic communities (such signal was not detected).	Alfheim		6	Sandstone which would fill out the stratigraphic column for geologic characterization.
white/green siltstone, erosional face	Lithology, depositional environment, and organic carbon potential to be determined by geologic context, color, and mineralogy.		Scyld (with green)	7	The sample was not fresh, but taken from a highly erosional face. Although the underlying lithology might be ranked higher for TOC, the state of preservation likely negatively affected biopreservation.
regolith sample	Sample would fill the stratigraphic column for geologic characterization pertaining to the erosional regime and material transport.	Fenrir		8	The last sample in priority is the regolith sample, as it would not give *in situ* information not is likely to preserve biosignatures.

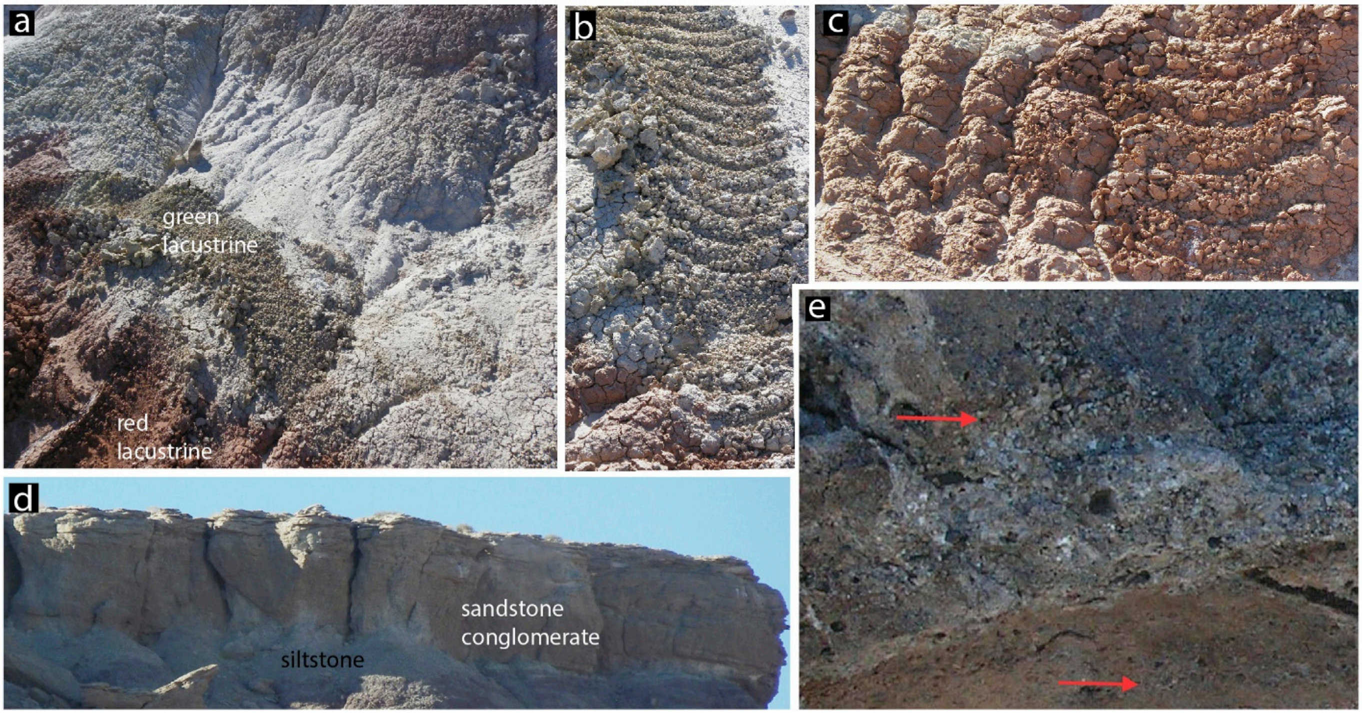

Figure 5. a) Sampling context for the first and second priority samples (Table 1). Rover wheels were used to disturb the surface in an attempt to sample below the cm-thick erosional surface. b) Sampling location for Niels, green siltstone (unit # 5 in Fig. 2). Montmorillonite-dominated green siltstone with yellowish alteration present and a popcorn erosional texture, and gypsum is ubiquitous throughout the unit and as erosional lenses. Potential nontronite as well as the green color may indicator microbially-mediated weathering, producing reduced iron in anoxic sediments. The darker green coloration likely indicates a microbially-mediated reducing depositional environment, and therefore representative of the best paleo-habitability. c) Sampling location for Astrid, red siltstone with dark purple lenses (unit # 4 in Fig. 2. The purple coloration is geochemically and mineralogically similar to green layer (also smectite-rich) and may indicate habitability as dark coloration indicates an even more reducing environment than represented by the green shales. d) Zoom image of the conglomerate – clastic sandstone capping unit (unit # 1 in Fig. 2) showing cross stratification and in contact with siltstones. e) Fallen block of the sandstone conglomerate unit shown in (d) and sampling location of Thrymheim. Two bands of embedded clasts are shown by red arrows, which are multi-colored, well-rounded, high sphericity pebble to gravel-sized clasts. This was sampled for potential for microfossils within the conglomerate clasts and further fulfills goals of assessing the history of fluvial activity at the site and the stratigraphic column for broader geologic characterization.

while setting up for n+1 sampling, and furthermore forcing the Science Team to detail potential sampling sites, providing sampling rationales and ranking the potential samples early in the mission. The walkabout planning approach was also discussed by Yingst et al. (2017) who studied best operational approaches to rover-based site characterization and sample cache and improving overall efficiency. The multi-sol planning scenarios implemented in CanMars are also similar to current the MSL extended mission operations, where 3 to 5 tactical planning days occur per week, facilitating customary terrestrial schedules for the team (that is, not on Mars-time) and necessitating multi-sol planning.

Daily report writing with standardized templates for data interpretations and presentations are one avenue for efficient and fluid daily planning operations. One major lesson from the CanMars experiment is the need for structured reports written by each instrument team and team members in major positions. These reports carry the details of the previous planning day and the context of the larger campaign. Having mechanisms in place for transfer and curation of data proved to equally important; all Science Team members should be able to search for, and understand, the daily data downlink and interpretations from each instrument team. These data documents should be standardized with predictable and readily ingestible formats. During MSL operations, daily report writing is fundamental to the transfer of knowledge from planning sol to the next, written by instrument Payload Downlink Leads (PDLs), Payload Uplink Leads (PULs), and the Long Term Planner. We suggest that a greater number of roles produce daily reports, perhaps every individual participating in operations if only for the next person working the shift of the same role. However, the team found that it would be more beneficial if the reports and data documents were indexable to a database, keyword-enabled and searchable. This is likely far more effective than individual report writing as it allows any team member to search on specific targets, analyses, or interpretations without combing through various reports; one other issue with many reports is that information can be conflict, given the very fast pace of Tactical planning. Organization and ease of access is difficult to overstate given the time constraints on daily rover mission operations.

The strategic traverse days were very well spent, as the development of the depositional model guided the sampling and the ultimate direction of the mission. The model allowed predictive power, extending interpretations up-section through stratigraphy and comprehensively linking individual sites to form a geologic construct. We suggest that future missions consider similar scheduled collaborative space where team members have an opportunity to review planned sol paths, data and interpretations, and assure daily operations are advancing overall mission goals. An analogous process in being implemented for Mars 2020 mission operations, where multiple teams will participate in overview planning sessions removed from Tactical, or daily, rover planning (Francis et al., 2019).

5.1. Lessons learned – instrumentation

The search for evidence of ancient life is one of the most challenging objectives of current and future Mars exploration. During CanMars, Raman spectroscopy provided the unique opportunity to identify biosignatures and mineralogy. Raman results were frequently decisional with respect to selecting destinations and observation sites for the rover, and in one case, Raman spectra were used in a conditional sequencing plan where the detection of kerogen signatures would have triggered actions to set up for sampling at the detection site, had that signal been detected (see Francis et al., 2019). In future missions, a similar conditional sequencing function could offer suggestions on adjusting collecting time and laser power based on the former data quality, for Raman and perhaps other spectrometers – adapting the instrument parameters in real-time as developed by Thompson et al. (2014). This would enhance the quality of data with little use of the daily budget of time and energy, given a remote-sensing Raman instrument as is provided by the Mars 2020 SuperCam instrument (Wiens et al., 2016). Autonomous targeting (e.g., AEGIS, Francis et al., 2016a,b) and other advanced autonomous capabilities and associated workflow adjustments (e.g., multi-sol plans with tiered sampling decision trees; post-measurement high resolution imagery or other target confirmation) is a crucial capability to develop for remote rover operations (Francis et al., 2019). Although the Mars 2020 SHERLOC Raman represents the best instrument for the search of organics, it is a time-intensive arm-mounted proximity instrument requiring ground-in-the-loop.

Remote spectrometers (in this exercise, the stand-in SuperCam LIBS, VIS-IR, and Raman) were used in the plan for nearly every sol, and the arm-mounted instruments were used less frequently. Arm-mounted proximity instruments (the PIXL stand-in XRF and the SHERLOC stand-in Raman, as well the RAT tool and micro-imagers) required ground-in-loop (or, communication with and decision-making by scientists on Earth); thus, arm-mounted instruments were only used where previously acquired data led the team to the decision to plan a LIDAR scan and deploy the arm. The use of these instruments requires careful planning with multi-sol planning operations. Importantly, our study demonstrates that spectrometers having remote capabilities are ideal for use in rover missions, greatly increasing the speed of operations and the amount of data that can be acquired. This has also been the experience of the MSL team, where ChemCam (having LIBS and remote micro-imager (RMI) instruments) has proven to be extremely useful and often the most utilized instrument for geochemical observations (Maurice et al., 2016). This is due in part to its mast-mount and remote capabilities, as well as the capacity to provide geomorphologic context with the RMI. Such remote spectrometry tools further lend themselves well to the increased data throughput that onboard science autonomy can produce (Francis et al., 2017). As suggested by Wiens et al. (2016), the MSL remote instrument suite has proven to be extremely useful in the capacity to provide geomorphologic context and in efficiency.

Given the limited mobility of the rover, additional imagers would always be more beneficial. Micro-imagers are a powerful tool to give geologic context to broader imagery and data observations, and stereo imagery is an important tool for give spatial context for placement of the rover arm. However, we found that multispectral imagers would move rover mission operations forward significantly. With only visible imagery to rely on, it proved easy to misidentify features based on color, or miss small outcrops completely. This limitation was particularly apparent in CanMars when a small, finely-layered green siltstone bed was missed by the rover team due to image resolution and lighting issues; this outcrop was significant as it was a rare “fresh” siltstone outcrop not covered by cm-scale popcorn-textured erosional material. Multispectral imaging would mitigate lighting effects and allow mineralogically distinct outcrops and other features to be more easily detected. The Mars 2020 SuperCam instrument will be an improved version of MSL ChemCam, with an expanded Infrared passive Spectrometer (IRS; Bernardi et al., 2017), and along with the PanCam Infrared Spectrometer (ISEM; Korablev et al., 2017) will provide multi-spectral point data covering 0.3 – 2.8 μm wavelengths, ideal to differentiate clays, carbonates, and sulfates. Although this is a significant step forward for data collection and remote geological assessments, a full VIS–SWIR (0.35–2.5 μm) *imaging* spectrometer would provide the greatest data return for rover-based imaging and spectroscopy, as well as the greatest efficiency in daily decision-making and planning. An imaging spectrometer through the SWIR range allows for pixel-by-pixel mapping of molecular vibrations associated with clays, carbonates, and sulphates. Based on the CanMars mission, we suggest that such a dataset would tremendously increase planning efficiency, though the constraint of data volume is always an issue. Mars 2020's MastCam-Z will provide imaging spectrometry from 0.4 to 1.0 μm (Bell et al., 2016), which provides the spectral range to discern ferric and ferrous iron.

The micro-imager TEMMI was an underutilized instrument in this mission due to its placement on the arm (Bourassa et al., 2019), which therefore required a LIDAR workspace and ground-in-the-loop for its use. However, a longer mission would certainly have allowed heavier use of this instrument, as the textural and morphologic information from micro-imaging provided vital geologic context for interpretations. Imagers should therefore be equipped with remote micro-zoom capabilities to maximize their use. Additionally, imagers having stereo imaging capabilities in this field scenario would have allowed for more expeditious decision-making particularly when assessing outcrops for sampling, mitigating the need for multiple sols to acquire LIDAR workspaces. We suggest that the most useful imagers should be multispectral, micro-zoom, and capable of acquiring stereo images (which are ideally stitched via automated pipeline), while also enabling remote observations (that is, not bound to arm constraints).

As the CanMars field site was in a sedimentary setting, with soft, highly friable lithologies, it became apparent that a scoop would have been beneficial, with the capability to analyze and image the material post-scoop. A scoop tool would have given access to the shallow subsurface in a way that was not within mission parameters; though the Mars 2020 rover will not have a scoop, it will be equipped with a tool for sampling regolith and soft materials. In an attempt to access a fresh surface of the siltstones beneath the several cm-thick popcorn-textured erosional cover, we disturbed the surfaces of green (Fig. 4 unit #5) and purplish-red siltstones (Fig. 4 unit #4) with the rover wheels, which provided an exposure deeper than would have been possible with the RAT. This introduces other issues though, as debated by the Science Team, including possible contamination from the wheels. A rock hammer or rock splitting tool would also have been ideal, but the thick erosional cover of the siltstone units highlights the need for tools to explore soft sediments. As discussed by Backes et al. (2011), drill bits (having several abrading bit types) and a coring and caching system position the Mars 2020 rover well to meet science goals; however, removing larger surfaces (perhaps via scoop) and obtaining a smooth surface (via splitting or percussion tool) is still in need of investigation.

Pre-mission readiness should include instrument tests and instrument training sessions for the entire Science Team. This point is critical for efficient and effective operations and cannot be overstated. Flight missions of course require instrument validation test, but we suggest that analogue missions should operate in the same way. 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. For example, Raman was vital but many of the sites in the field area were dominated by clays, and thus complementary geochemical plots from XRF data and VIS-IR-derived mineralogy proved critical to interpretations. The LIBS instrument was used as a low energy option to remove dust or other materials from the surface, but it can be destructive. Indeed, there was concern during the mission that the heat of many LIBS analyses might influence the reliability of Raman results. (This is still the preferred option, though, as the contact RAT requires ground-in-the loop with multiple sols invested in a target, which is costly for any non-sampling site.) We recommend that both flight and analogue missions include extensive pre-mission training for Science Team personnel and engineers, working closely together under a variety of mission-relevant scenarios, to help the team better understand the context of the data, the broader meaning of results and interpretations, and therefore the best use of the entire instrument suite in exploration and operations to serve their science goals.

The 2016 CanMars deployment saw the preliminary implementation of Virtual Reality (VR) technology in mission control. This technology enabled the creation of an immersive virtual environment based on both the provided remote sensing data and ground-based rover-obtained data. If further developed, this technique for observing remote locations could allow for faster feature recognition, and a better understanding of the scale of observed features by members of the mission control team (Morse et al., 2019). Caudill et al. (2019) describes the post-mission geological study and field validation of the CanMars field site and noted the inherent problem in conceptualizing and discerning scale: the true sense of location and relation of the rover to outcrops, formations, and traversable areas remained abstract to the CanMars Science Team. While VR immersive technology may not likely be feasible for analogue missions, the technology is being developed for use in Mars (2020).

Finally, the development of advanced pre-processing software built-in to the data downlink pipeline would facilitate a faster and more simplified evaluation of data. As management of the Science Team was largely an exercise in managing very limited time budgets and a significant amount of data and details, we deem that such a technological advancement to expedite data processing and interpretation is vital for best outcomes for rover-based missions. These software programs would be instrument-specific, providing the Science Team with a more streamlined data analysis window. Such automated ground segment processing could enhance both the speed of analysis and mission progress, and the completeness of scientific analysis on operational timescales, by providing more complete information to science operations teams quickly. Although pre-processing software is already in use for flight instruments in rover missions, such sophisticated capabilities were not available to CanMars or likely any such future analogue mission. As such, the immense time commitment required for data processing, interpretation, collaboration, preparation for team presentations, and synthesizing these from all instrument teams, should not be discounted. We suggest that future analogue missions carefully consider these time constraints and build in appropriate time to the operational schedule, even if the planning timeline is extended from that of a flight mission.

6. Conclusions

The CanMars analogue mission provided the opportunity for the most detailed, in-depth field and operational trials of an MSR mission to-date, vetting mission management and procedures, workflows, instrumentation, and the complex interplay of multiple teams (Osinski et al., 2019). Laboratory analyses of the "returned" samples as well as a post-mission, *in situ* field analysis revealed that the remote, in-sim mission operations team were able to characterize the lithologies and assess the geologic context and stratigraphic sequence. However, this simulated mission highlights the limitations of rover-based science. Some limitations are inherent (e.g., rover mobility, terrain traversability, line-of-sight) yet others may be mitigated by development of advanced instrumentation and data processing. We suggest the development of pre-processing data pipelines to enhance data return, lessen the daily Science Team workload, and expedite interpretations and next-sol planning. We further suggest that the single most useful additional instrumentation for CanMars would have been multispectral, micro-zoom, and stereo imagers. This would mitigate lighting effects, allowing for the quick and more accurate identification of outcrops of interest, and mitigate the inefficiency of multi-sol ground-in-the-loop to acquire LIDAR workspaces for sampling.

The most valuable asset that the CanMars Science Team had during the mission was each other. Tactical planning for a rover mission is necessarily very difficult – a large team of people with sometimes differing ideas, opinions, and observations must come together to make mission-critical decisions with very little time for science, discussion, or planning. Thus, an intentional operational structure must be employed to maintain a fast-paced flow that still requires all members to participate – intentional space must be created for team members to feel they can voice ideas that are independent of the majority. Real-time collaboration among team members afforded the most efficient data processing and interpretation, which is critical when scientific evidence is intended to dictate next-sol planning. During the CanMars mission, it was found that the optimal approach to remote geologic characterization of a site included a series of autonomous targeting and conditional sequencing functions combined with a walkabout traverse strategy (see Francis et al., 2019; Pilles et al., 2019), built on the development of a depositional model through intentional space for collaborative science (e.g., the strategic traverse days). Fostering an environment of real-time collaborations among the individual Science Teams during processing, interpretation, and presentation of data allowed for a more robust and streamlined approach to daily science operations; close collaborations and synergy between the science and planning teams also was found to be an optimal use of the very limited time of daily planning.

We suggest that closely-simulated end-to-end analogue missions should be implemented for any future planetary rover mission to vet operational procedures, scientific instrumentation, and hardware and software. Such an opportunity further provides training to mission scientists and engineers to make the best use of limited time and resources. Additionally, the geologic characterization of the field site through the CanMars mission highlights the need for terrestrial analogue studies, having mission objectives as well as instrumentation specific to upcoming missions to guide the search for exploration sites. For example, although the site near Hanksville, Utah, utilized in this study is an excellent analogue for inverted channels on Mars (e.g., Williams et al., 2011) a rover-based mission at an analogous exploration site on Mars may have similar difficulties detecting high levels of organic carbon. Investigating redox couples and potential reducing conditions pre-mission in a similar site may mitigate these concerns. Such considerations need urgent attention; it is the hope that this study and similar continued research into analogous environments on Earth and Mars will assist in site selection for best potential biosignature preservation and detection.

Finally, it is clear that beyond vetting operational workflows and instrumentation, closely-simulated, pre-mission training is imperative for science and planning teams. Such training sessions properly prepares the team and ensures full utilization of the team members and their time, and hence vital mission time, and produces the best return on investment from the time of rover deployment. The Mars 2020 Science Team has begun simulated mission training for the Science Team, which was born out of the experience of CanMars and its predecessors. The Rover Operations Activities for Science Team Training (ROASTT) program is designed to prepare the Mars 2020 Science Team for the decision-making processes required to achieve the mission's objectives from the first day of ground operations (Francis et al., 2019). The ROASTT team is developing and implementing a series of field and mission operations training exercises, introducing new operational procedures, including Campaign Planning (high-level sol path planning), Campaign Implementation (strategies and sol path planning on the timeline of one week), and abbreviated Tactical timelines (daily operations and planning is carried out in a shortened timeline, as compared to MSL operations). The training of a team not only supports the best return in the first few days or weeks of a mission but sets up the entire mission for success. We found that a best practice is for early pre-mission simulated or analogue mission training to reveal gaps in operational procedures, staffing, or expertise, experience, or understanding of individual team members. This provides time for all team members to adequately prepare for the complexities of operations and science in a unique mission environment, as they will not likely be afforded the time to do so after the start of the mission. Pre-mission simulations should include: sessions to familiarize the entire team with instrumentation, including presentations with practical examples of the capabilities and limitations of the instruments and data acquired – this is vital to full-team participation in planning and science decision-making; "dry run" planning and walk-through scenarios to allow the team to collectively put this knowledge in play, and; operational simulations true to the real mission working groups and timelines to allow for the leadership to observe team dynamics within the operational construct – this allows a valuable opportunity to change operational procedures as necessary and assess the needs of the team. Ultimately, pre-mission training and analogue missions allow a team to vet operational workflows and procedures, which are best implemented in advance of flight missions.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pss.2019.04.004.

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