CHAPTER 11

The NASA Mars 2020 Rover Mission and the Search for Extraterrestrial Life

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From Habitability to Life on Mars
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11.1 INTRODUCTION

Beginning over 40 years ago with the Viking missions, the National Aeronautics and Space Administration (NASA) strategy for the exploration of Mars has centered on the question of whether that planet ever hosted life. The lack of compelling positive results from the Viking biology experiments (Klein et al., 1976; Klein, 1998), together with an emerging understanding of past and present Mars surface conditions, has shifted the focus from extant to ancient life. The current surface of Mars is extremely inhospitable, whereas habitable conditions were apparently widespread in the distant past when Mars had a denser atmosphere and an abundant surface water (Grotzinger et al., 2014; Arvidson et al., 2014; Arvidson, 2016 and references therein; Wordsworth, 2016). NASA's strategy for Mars exploration has evolved in recent years from a "follow the water" approach by the Mars Exploration Rovers (MER; Squyres et al., 2004), to a search for ancient habitable environments by the Mars Science Laboratory (MSL; Grotzinger et al., 2012), to a search for signs of ancient life by Mars 2020 (MEPAG, 2015). The analogous search for the earliest evidence of life on Earth is fraught with ambiguity (e.g., French et al., 2015; Schopf and Packer, 1987; Schopf, 1993; Brasier et al., 2002, 2015; Schopf and Kudryavstev, 2012), in part due to active geologic processes that—over eons—destroy rocks or alter their records beyond recognition. Although preservation processes have acted differently on Mars where plate tectonics, metamorphism, and modern-day weathering are reduced or absent, the burden of proof for the confirmation of extraterrestrial life will be high. Compelling confirmation of a past martian biosphere may not be possible with in situ (remote robotic) science alone, which motivates collection of samples by Mars 2020 for possible Earth return. Beyond possible paradigm-shifting advances in the field of astrobiology, sample return could revolutionize our understanding of Mars' early geologic, geochemical, and climatic evolution relative to other terrestrial planets and the solar system as a whole. A sample return campaign would also offer compelling demonstrations of key technical capabilities required for eventual human exploration.

This chapter was written and published before the mission's planned launch in 2020, during a time of rapid development and against a backdrop of ongoing science and engineering trades. Although accurate at the time of writing, details herein must be considered in this context—this is a snapshot in time of a mission in development by NASA, the Jet Propulsion Laboratory, and the Mars 2020 project to explore the surface of Mars, seek evidence of ancient life, collect a returnable cache of samples, and prepare for future exploration. Collection of returnable samples by Mars 2020 represents a critical first step toward a potential multimission Mars sample return (MSR) effort. Mars 2020 is the only mission related to MSR that is currently approved or funded, and as such, all references in this document to the overarching sample return effort must be considered conceptual. The National Research Council recommended that the highest priority for large planetary science missions in the decade 2013–22 should be to "initiate the Mars sample return campaign" (NRC, 2011, e.g., p. 258). With this in mind, the Mars 2020 team is developing and will conduct the mission in a way that maximizes the prospects for eventual sample return.

11.1.1 Background and Previous Missions

The possibility of life on Mars has captivated the human imagination for centuries and has been a key scientific driver for NASA's exploration of that planet since the early Mariner missions. The search for evidence of life on the martian surface was a primary mission objective of the twin Viking landers in 1976. The Viking biological investigation was a groundbreaking scientific and technical achievement that continues to inform planetary missions, but the result is generally considered to have been negative (Klein et al., 1976; Klein, 1998). The observation of $^{14}CO_2$ that evolved during the labeled release experiment remained an anomalous and equivocal element of the Viking biological investigation until the detection of perchlorate in martian regolith by the Phoenix lander (Hecht et al., 2009) provided direct evidence supporting an abiotic explanation (Zent and McKay, 1994; Yen et al., 2000; Navarro-González et al., 2010; Quinn et al., 2013) consistent with other Viking results.

With the widely publicized—and highly debated—claim of potential ancient biosignatures in martian meteorite ALH84001 (McKay et al., 1996) and the successful demonstration of the first Mars rover Sojourner by the NASA Pathfinder mission a year later, interest in life on Mars was powerfully reinvigorated. Distinct from that of the Viking era, the emphasis of the new age of Mars surface exploration is a search for evidence of *ancient* life. While it is not impossible that Mars is currently inhabited in the relatively deep subsurface where stable liquid water is possible, Mars was a far more habitable planet in the distant past prior to the loss of its atmosphere and, along with it, widely clement surface conditions. Furthermore, the search for extant life on Mars introduces a number of planetary protection considerations that make the delivery of highly capable scientific payloads (and the engineering systems required to deploy and operate them) extraordinarily challenging. By contrast, the search for geologic evidence of ancient life in areas of Mars currently uninhabitable by known Earth life relaxes planetary protection concerns. As an additional benefit, exploration of ancient environments in search of ancient biosignatures yields valuable scientific knowledge about the long-term evolution of Mars as a planetary system.

The exploration strategy for the new wave of Mars surface missions beginning in 2004—the MER Spirit and Opportunity—was to "follow the water." The requirement for liquid water unites all known life forms, and it was thus reasoned that past liquid water was the primary prerequisite for the past life on Mars. Indeed, MER found multiple lines of evidence confirming the past presence of liquid water including trough cross stratification and diagenetic hematite concretions termed "blueberries" (Squyres et al., 2004) and the iron sulfate mineral jarosite (Klingelhöfer et al., 2004).

MSL *Curiosity* followed 8 years later with a new and larger rover platform carrying a more complex and capable scientific payload. With the intention to explore a Noachian-Hesperian sedimentary sequence at Mount Sharp in Gale Crater, Curiosity sought evidence of habitability beyond the presence of liquid water and continues to explore an environment that presumably records the *loss* of widespread surface habitability that occurred as a result of atmospheric loss and the "great drying" of Mars. Early in the mission, *Curiosity* explored an ancient lacustrine mudstone at Yellowknife Bay and uncovered the most robust and comprehensive evidence yet assembled for a habitable extraterrestrial environment. Work at Yellowknife Bay revealed lithologic and textural evidence for abundant surface water with geochemical and mineralogical evidence of its circumneutral pH and available redox couples to support chemoautotrophic microbial metabolism at the time of deposition (Grotzinger et al., 2014). Among its many other scientific and technical achievements, MSL further advanced the understanding of the evolution of habitability on ancient Mars with the discovery of a record of sustained deposition in a fluvio-deltaic-lacustrine setting (Grotzinger et al., 2015), a deuterium/hydrogen measurement of Hesperian clay hydroxyls in Yellowknife Bay sediments demonstrating deposition prior to complete atmospheric loss (Mahaffy et al., 2015) and direct measurements of the depositional and exposure ages of Yellowknife Bay via the first radiometric dates from the surface of another planet (Farley et al., 2013). MSL has also made the first detections of organic molecules on the surface of Mars in the form of chlorobenzene (150–300 ppb) and C_2–C_4 dichloroalkanes (up to 70 ppb). These molecules are interpreted as reaction products of martian chlorine (e.g., as oxychlorine) with organic matter synthesized on Mars or delivered via meteoritic infall (Freissinet et al., 2015). MSL has made major advances in the study of extraterrestrial habitability, including an exploration model for organic molecules that focuses the search for instances of "scarp retreat" in order to access the most recently exhumed rock that has been protected from destructive, ionizing radiation (Farley et al., 2013). However, the lack of any clear biosignatures observed by *Curiosity*'s extremely capable scientific payload in an environment known to have been habitable underscores the challenges associated with the key objective of Mars 2020 to seek the signs of ancient life.

11.2 MISSION OBJECTIVES

Mars 2020 has an ambitious set of objectives that are derived from the recommendations of the Planetary Decadal Survey (NRC, 2011) and the Mars 2020 Science Definition Team report (Mustard et al., 2013). These objectives build upon the successes of MSL and the earlier Mars surface missions, though Mars 2020 is distinguished by its objective to make progress toward MSR by assembling a cache of scientifically selected samples that could be retrieved and returned to Earth by future missions. Mars 2020 brings an extremely capable payload to the surface that will facilitate sample selection by documenting the geologic and astrobiological context of the landing site, effectively assembling the "field notes" for the sample set. The exploration process required to document field context for a returnable sample set will generate important new scientific discoveries about Mars, past and present. These discoveries will advance planetary science, of course, but they also lay important new groundwork for future human exploration of the surface of Mars.

The Mars 2020 mission objectives are as follows, taken from the Program Level Requirements Appendix (PLRA), the agreement between NASA and JPL establishing the level 1 requirements for the mission:

(A) Characterize the processes that formed and modified the geologic record within a field exploration area on Mars selected for evidence of an astrobiologically relevant ancient environment and geologic diversity.

(B) Perform the following astrobiologically relevant investigations on the geologic materials at the landing site:
  - **(1)** Determine the habitability of an ancient environment.
  - **(2)** For ancient environments interpreted to have been habitable, search for materials with high biosignature preservation potential.
  - **(3)** Search for potential evidence of past life using the observations regarding habitability and preservation as a guide.

(C) Assemble rigorously documented and returnable cached samples for possible future return to Earth:
  - **(1)** Obtain samples that are scientifically selected, for which the field context is documented, that contain the most promising samples identified in objective B and that represent the geologic diversity of the field site.
  - **(2)** Plan for compliance with expected future needs in the areas of planetary protection and engineering so that the cached samples could be returned in the future if NASA chooses to do so.

(D) Contribute to the preparation for human exploration of Mars by making significant progress toward filling at least one major Strategic Knowledge Gap (SKG). The highest priority SKG measurements that are synergistic with Mars 2020 science objectives and compatible with the mission concept are as follows:
  - **(1)** Demonstration of in-situ resource utilization (ISRU) technologies to enable propellant and consumable oxygen production from the martian atmosphere for future exploration missions.
  - **(2)** Characterization of atmospheric dust size and morphology to understand its effects on the operation of surface systems and human health.
  - **(3)** Surface weather measurements to validate global atmospheric models.

(4) A set of engineering sensors embedded in the M2020 heat shield and backshell to gather data on the aerothermal conditions, thermal protection system, and aerodynamic performance characteristics of the M2020 entry vehicle during its entry and descent to the Mars surface.

The primary scientific question that integrates science objectives A–C is whether Mars was ever inhabited. In situ exploration using the scientific payload immediately provides new insights for Mars geology and planetary science (objectives A and B) while guiding the selection of and providing the critical scientific context for a cache of samples (objective C) that has the potential to revolutionize our understanding of life, terrestrial planets, and evolution of the solar system. The mission also supports NASA's goal to send humans to Mars in the coming decades: the more that is known about the martian environment, the better prepared humankind will be to send people to the surface and return them safely to Earth.

11.3 MISSION OVERVIEW AND COMPARISON TO MSL

The Mars 2020 mission began development in early 2013, just a few months after the MSL *Curiosity* rover's spectacular landing success at Gale Crater. Mars 2020 builds directly on MSL, relying heavily on its design and verification data and in many cases using flight-spare hardware. This "heritage" approach reduces new engineering development and associated uncertainty and is expected to yield as a dividend a substantially lower overall cost and shorter development cycle.

The major technical advances required for Mars 2020 to accomplish its goals of seeking the signs of ancient life and to prepare samples for possible Earth return include a new suite of seven scientific instruments and a sophisticated robotic system to collect, seal, and cache samples. Both are described more fully in the following sections. Mars 2020 will also be outfitted with strengthened wheels to eliminate the damage experienced by *Curiosity* as it drove across rock-strewn martian surfaces (Arvidson et al., 2017).

Mars 2020 will launch from Cape Canaveral sometime within a ~30-day window in July and August of 2020 (hence the current mission name; the rover will likely be renamed before launch). It will arrive at Mars after a 7.5-month cruise in February of 2021. The fundamental design of the cruise and the entry, descent, and landing (EDL) systems remain unchanged from MSL, but a microphone and new high-definition cameras on the rover and the descent stage will acquire unique sound and video to document the EDL process.

Mars 2020 will have a prime mission duration of at least 1 Mars year or approximately 2 Earth years. Due to the expected challenges of accomplishing a robust program of in situ exploration comparable with MSL while also assembling a cache of samples during the prime mission, the project has elected to qualify flight hardware for an additional half Mars year (i.e., beyond the qualification for MSL). Like MSL, the Mars 2020 project includes a multimission radioisotope thermoelectric generator (MMRTG) that is expected to yield sufficient power for rover operations substantially exceeding the length of the primary mission.

11.4 SCIENCE PAYLOAD AND IN SITU INVESTIGATIONS

The science payload was carefully selected to support the mission's science goals and represents a mixture of fundamentally new instruments and enhanced versions of instruments on board *Curiosity*. Sensing units for two of the instruments are mounted on the Remote Sensing Mast (Mastcam-Z and SuperCam), and two are mounted to the turret located at the end of the robotic arm [Planetary Instrument for X-ray Lithochemistry (PIXL) and scanning habitable environments with raman and luminescence for organics and chemicals (SHERLOC)]. The Radar Imager for Mars' Subsurface Experiment (RIMFAX) antenna is mounted on the underside of the rover, while Mars Environmental Dynamics Analyzer (MEDA) has sensors distributed around the rover. The Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE) is located inside the rover, as are the most temperature-sensitive electronics components of the other instruments. Configuration of instruments and other key components on the rover is shown in Fig. 11.1.

11.4.1 Mastcam-Z

Mastcam-Z features a stereo pair of multispectral, color zoom cameras. Maximum image size is 1600 × 1200 pixels (~2 megapixels), and maximum pixel scale at 2 m is about

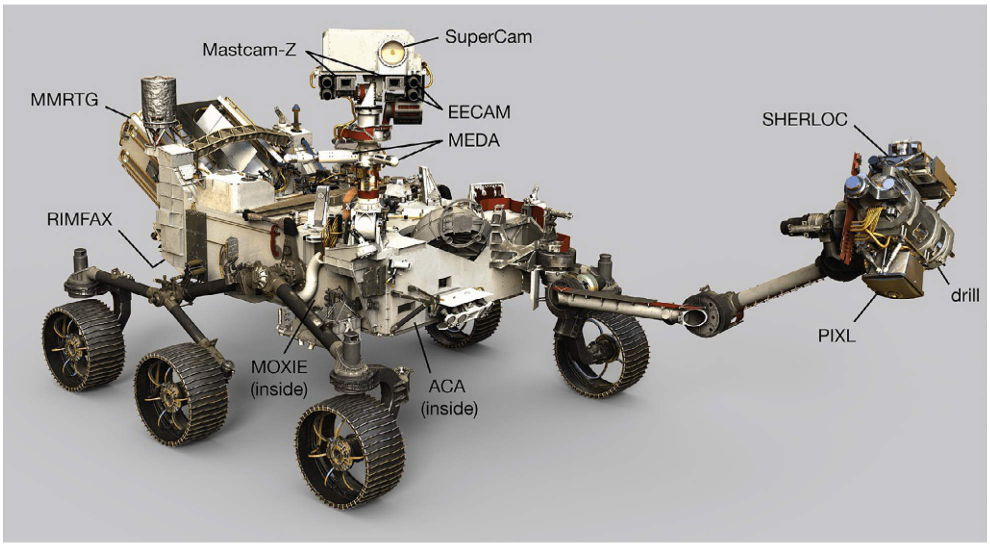

Fig. 11.1 Artist's concept of the Mars 2020 rover with key elements indicated as discussed in the text.

150 μm per pixel (enabling features of ~0.5 mm to be distinguished). Mastcam-Z shares strong heritage with the MSL Mastcam instrument, but includes new multispectral filters and a new zoom capability that significantly enhances stereo imaging flexibility. "Wide-angle" Mastcam-Z stereo panoramic images are crucial to understand geologic structures in the exploration environment, and "telephoto" images of individual targets and the robotic arm workspace immediately in front of the rover are key data products to evaluate lithology and support scientific targeting by other instruments.

11.4.2 RIMFAX

The RIMFAX, contributed by Norway, is a ground-penetrating radar with a frequency range of 150–1200 MHz and a penetration depth >10 m depending on surface materials. Although ground-penetrating radars have orbited Mars (MARSIS on Mars Express and SHARAD on Mars Reconnaissance Orbiter), RIMFAX is a completely new technology for Mars surface missions. Ground-penetrating radar will enable the science team to trace geologic structures observed on the surface into the subsurface, enhancing reconstructions of local and regional stratigraphy. RIMFAX also has the capability to detect water and ice in the subsurface, although landing sites with orbital evidence for ice or liquid water within 5 m of the surface will be avoided for planetary protection reasons.

11.4.3 SuperCam

SuperCam builds upon the strong heritage and scientific success of the MSL ChemCam instrument and is developed primarily in partnership between the United States and France. SuperCam is a remote sensing instrument comprising a remote micro imager (RMI) and a laser-induced breakdown spectroscopy (LIBS) similar to MSL ChemCam (Wiens et al., 2012, 2015, 2017; Maurice et al., 2012, 2016) but now with color RMI. New capabilities for SuperCam include visible-infrared (VISIR) and remote Raman spectroscopy. The latter technique uses a pulsed laser at 532 nm (green Raman) to interrogate samples over a very short period of time (~5 ns) and uses a time-gated intensified detector to minimize interference from ambient light and fluorescence. SuperCam's VISIR spectroscopy consists of an infrared (IR) spectrometer that covers the 1.3–2.6 μm range and the 0.4–0.85 μm range with the spectrometers used for LIBS and Raman spectroscopy. SuperCam includes a scientific microphone that will remotely determine physical properties of the targets from the acoustic signal of the (LIBS) laser interaction with the surface and can also be used for characterization of atmospheric turbulence (wind gusts and dust devils).

Coboresighted VISIR and remote Raman spectroscopies enable a more balanced mineral characterization and more confident identification than either one technique alone. For example, Raman spectroscopy easily identifies feldspar minerals, which are difficult (at best) to identify with VISIR, while VISIR spectroscopy may offer better sensitivity than Raman for certain minerals such as hydrated silicates. These two techniques together can observe silicates, carbonates, sulfates, phosphates, sulfides, and organic molecules. The combination of both elemental and mineral signatures provides strong synergy in characterizing any target. Like ChemCam, elemental compositions are obtained for all major elements to high precision, and minor and trace elements including Li, B, C, N, Cr, V, Mn, Ni, Cu, Rb, Sr, and Ba will be detected and quantified (Wiens et al., 2015; Maurice et al., 2016). An added advantage to all techniques is that the LIBS analysis removes surface dust, enabling a clear view of the surfaces.

The SuperCam mast unit contains a Nd:YAG laser that provides both LIBS (1064 nm) and Raman (532 nm) interrogation, a telescope to project the laser light and collect the light for all techniques, the RMI camera, and the IR spectrometer, microphone, and electronics. Light for the LIBS, the Raman, and the VIS portion of the VISIR spectra is transferred to the rover body by a fiber optic cable. The body unit contains three spectrometers to cover these observations, along with electronics to control the instrument and communicate with the rover. The mast unit is provided by the French Space Agency (CNES), while the body unit is built by Los Alamos National Laboratory under contract with NASA. An extensive calibration target assembly with some 28 targets—including mineral separates, rock, and glasses that have been crushed and flash sintered for homogeneity (Cousin et al., 2017)—is mounted on the back of the rover. The assembly is a Spanish contribution, while the targets themselves are a multinational effort involving France, Denmark, Canada, Spain, and the United States.

With LIBS capability extending to a distance of ~7 m, Raman to ~12 m, VISIR up to 10 km, and RMI to infinity, SuperCam offers a diverse toolkit to guide exploration at a distance. Analytic spot sizes vary by technique and with distance but at 2 m are expected to be ~400 μm for LIBS, 1.4 mm for Raman, and 2.2 mm for IR. An IR "long raster" mode, with SuperCam rapidly analyzing ~100 locations across a transect, will reveal mineralogical distinctions at the outcrop scale. A single-spot, submillimeter-scale analytic resolution at a distance of ~2 m in the rover workspace enables rapid interrogation of individual grains or clasts, matrices, veins, and alteration rinds—key components to reconstruct formation and alteration processes in the exploration environment. Using fine-scale targeting, SuperCam will be able to analyze compositions within the drill hole itself, which will be an important feature for understanding the nature of the samples that could later be returned to Earth.

11.4.4 PIXL

The PIXL is a robotic arm-mounted X-ray fluorescence (XRF) spectrometer and micro-context camera system that will be used to measure the elemental chemistry of rocks and soils and to map chemical variations in relation to visible fine-scale textures and microstructures. PIXL follows the highly successful alpha particle X-ray spectrometer (APXS) instruments on previous Mars rovers that measured the average elemental composition of rocks and soils over an area of several square centimeters. With the capability to analyze elemental lithochemistry with spatial sampling of ~100 μm, PIXL will allow scientists to accurately link chemical variations to small-scale features such as individual grains, laminae, and interstitial cements.

The turret-mounted PIXL sensor head uses a 28 kV X-ray tube and polycapillary X-ray focusing optic to produce a ~100 μm-diameter, high-flux X-ray beam on a target 25 mm away. The high-intensity beam causes X-ray fluorescence that is measured with dual silicon drift detectors, enabling measurement of major and minor elements in as little as 10 s. The sensor head is mounted on a hexapod motion system that can be used to precisely scan the instrument in three dimensions. Using the hexapod to raster the beam across the surface of a rock, PIXL can acquire square-centimeter-scale elemental maps with submillimeter-scale spatial resolution in a matter of hours. For rapid analyses, line and grid scans can be performed. Scans can be performed on both flat surfaces and uneven surfaces with several millimeters or more of surface topography. However, maps are best acquired on flat surfaces. A ~45 mm-diameter abrasion tool and dust removal tool on the rover turret will create a flat surface where desired and provide access to less weathered rock.

PIXL's element data can be used in multiple ways to gain detailed insights to the nature of geologic materials encountered. Examples include the following:

(1) Use spatial covariations of elements to constrain mineralogy.
(2) Use element maps to recognize textures or microstructures that aren't apparent in visual images, for example, due to tool markings from the interaction of the abrading bit with the rock surface.
(3) Determine the chemical makeup of individual features such as sedimentary grains, igneous crystals, laminae, veinlets, and interstitial cements.
(4) Identify spatial variations in the relative abundance of elements to recognize and characterize alteration gradients, alteration rims on grains, zoned cements, and crystals.
(5) Sum spectra together to determine the bulk rock chemistry of a scanned area.

Thus, in addition to providing the bulk rock chemical analyses to which Mars scientists have become accustomed on past rover missions, PIXL will also enable true petrologic analysis of martian rocks.

11.4.5 SHERLOC

The SHERLOC instrument is a noncontact robotic arm-mounted spectrometer with two imaging systems (Beegle et al., 2015). SHERLOC provides high-spatial-resolution (15 μm/pixel) imaging coregistered with hyperspectral maps of mineral and organic composition acquired over approximately square centimeter areas using a ~100 μm beam diameter.

SHERLOC's 248.6 nm deep ultraviolet (DUV) scanning laser generates fluorescence emission from aromatic organics and DUV resonance Raman scattering from aliphatic and aromatic organics and astrobiologically relevant minerals. When using a DUV light source, the weaker Raman scattering takes place in a wavelength range (253–274 nm) that is outside the otherwise obscuring fluorescence range that starts beyond 270 nm and extends into the visible. This enables detection of both Raman scattered photons and stimulated fluorescence emission on the same CCD. The SHERLOC CCD is identical to those used for MSL ChemCam and Mars 2020 SuperCam (Wiens et al., 2012). Detectable organic functional groups include the C—H, CN, C=O, and C=C bonds, and detectable mineral species include carbonates, perchlorates, sulfates, and phyllosilicates. Expected detection limits are as low as 10^{-6} (w/w) for aromatic organics and 10^{-3} for aliphatic organics, and mineral spectra from grains as small as 50 μm can feasibly be recognized.

SHERLOC employs two imaging systems: the Wide Angle Topographic Sensor for Operations and Engineering (WATSON) and the autofocus and context imager (ACI). WATSON is a reflight of the MSL Mars Hand Lens Imager (MAHLI) camera head (Edgett et al., 2012). WATSON will provide color images with a spatial resolution sufficient (at closest approach) to distinguish sand from silt and smaller-sized grains—an important sedimentologic distinction in the evaluation of habitable environments and potential biosignature preservation. Like MAHLI, WATSON also images rover hardware for engineering capabilities including monitoring of wheel wear and produces rover "selfies" for education and public engagement. The ACI enables focusing of the DUV laser for standoff analysis from a distance of 48 ± 7 mm above a target and is coboresighted with the laser scanning system to document the visible context for fluorescence and Raman maps.

SHERLOC DUV fluorescence and Raman maps will be coregistered with WATSON images and PIXL maps (see above), providing a depth of petrographic information about martian materials previously only available from analyses of meteorites in Earth-based laboratories. Such coordinated, grain-scale observations of elemental, mineral, and organic compositions in their textural and stratigraphic context powerfully support mission objectives to document rock formation and alteration processes, evaluate habitability, seek signs of ancient life, and select sampling targets with high potential to preserve signs of life and planetary evolution.

11.4.6 MEDA

The MEDA is contributed by Spain, led by the Centro de Astrobiologia (CAB), with support for the US investigation team members from the NASA Science Mission and Human Exploration and Operations Mission Directorates. MEDA is an integrated suite of sensors providing in situ near-surface weather measurements and dust characterization.

MEDA is an evolution of the MSL Rover Environmental Monitoring Station (REMS; Gómez-Elvira et al., 2012) and PanCam/HazCam (Bell et al., 2003). It will measure wind speed and direction, atmospheric pressure, air and ground temperature, relative humidity, radiation fluxes near the surface of Mars, and optical properties of dust. These environmental measurements will inform Mars climate models and support eventual human exploration.

MEDA includes a pressure sensor that shares direct heritage with REMS. The relative humidity sensor, like the pressure sensor, is contributed by the Finnish Meteorological Institute and incorporates a new sensor membrane for increased dynamic range. The wind sensor emerges from a collaboration between the CAB; the Universitat Politècnica de Catalunya (UPC); the Seville Institute for Microelectronics (IMSE); and the Computadoras, Redes e Ingeniería (CRISA). Details of the sensor design have been changed to increase mechanical robustness and consume less power, and the number of hot plates has been doubled to increase functional redundancy.

The air temperature sensor (ATS), developed by CAB, consists of five sets of triple thin wire thermocouple sensors based on the concept used by Mars Pathfinder and Viking. Three ATS sensors are located around the rover mast at around 278 mm height from the rover deck (1458 mm from the ground) and 120° from each other to ensure that one sensor is always upwind of the mast. The other two sets of thermocouples are positioned at the sides of the rover and about 880 mm above the ground. This vertical distribution of the ATS will help characterize the temperature gradient on the surface layer above the regolith.

The Thermal Infrared Sensor (TIRS), by CAB and CRISA, has upward and downward pointing thermopiles using similar detectors as on REMS but sampling different wavelength ranges. In addition to surface temperature, the TIRS will measure downward and upward radiation in the 6.5–30 μm range to document net radiative TIR fluxes forcing the atmosphere at the surface of Mars. It also provides atmospheric temperature of the low layer above the rover location averaged over a few tens of meters, constraining vertical temperature gradients that drive convection.

The radiation and dust sensor (RDS), developed by the Instituto Nacional de Tecnica Aeroespacial (INTA), represents an evolution of two sensors previously flown to Mars. The first sensor, Skycam, is a JPL-provided CCD camera that inherits the electronics of the MER HazCams and incorporates a new lens to minimize internal reflections and stray light. Skycam also includes a neutral density filter to enable direct observation of the sun with minimal blooming and a ring mask to compare direct with scattered sunlight. Skycam will measure the rate of irradiance decay as a function of the distance to the sun disc, and its comparison to radiative transfer models will give a constraint on atmospheric particle-size distribution. Side-looking photodiodes on the RDS will measure scattering properties related to particle shape. Uplooking photodiodes will characterize optical opacity of the atmosphere as a function of wavelength from the UV to the near IR.

11.4.7 MOXIE

The MOXIE is a ~1% scale model of an oxygen processing plant that is intended to support a human expedition sometime in the 2030s. A technology demonstrator, MOXIE ingests the thin CO_2 that comprises 96% of the martian air and produces O_2 as a primary product. On a future mission, such a process could produce ~30 t of liquid oxygen for ascent vehicle propellant in the 16 months preceding launch of a human crew to Mars, representing ~78% of the propellant mass needed for a CH_4/O_2 propulsion system. To bring this amount of oxygen from Earth would otherwise require four to five heavy lift launches (Drake, 2007).

MOXIE's solid oxide electrolysis (SOXE) stack for converting CO_2 to O_2 is designed and built by Ceramatec, Inc. (Hartvigsen et al., 2015). Its working elements are stacked, scandia-stabilized zirconia electrolyte-supported cells with thin screen-printed electrodes, coated with a catalytic cathode on one side and an anode on the other. When CO_2 flows over the catalyzed cathode surface at ~800°C under an applied electric potential, it is electrolyzed according to the reaction $CO_2 + 2e^- \Rightarrow CO + O^-$. The resulting oxygen ions are electrochemically drawn through the solid oxide electrolyte to the anode, where they are oxidized ($O^- \Rightarrow O + 2e^-$) to produce gaseous O_2. A scroll pump developed by Air Squared, Inc. collects and compresses the CO_2 for the reaction.

In development at the Jet Propulsion Laboratory, MOXIE is expected to produce ~10 g/h of O_2 on Mars with >99.6% purity (Hoffman et al., 2015). Oxygen production is expected to be limited both by the compressor capacity and by the external conditions that determine the density and quantity of air that can be drawn in. On Mars, autonomous MOXIE operations will be optimized, and degradation mechanisms will be studied.

11.4.8 Returned Sample Science

A unique aspect of Mars 2020 is the inclusion of returned sample science (RSS) as a distinct investigation. RSS is not associated with any one instrument, but rather is concerned with maximizing the scientific value of samples to be collected during the surface mission. The reasons why a set of martian samples would be valuable if returned to Earth have been described in multiple reports in the literature, and the interested reader is referred to Mustard et al. (2013), E2E-iSAG (McLennan et al., 2011), and NRC (2011) and references therein. Of particular significance is E2E-iSAG (McLennan et al., 2011), which describes specific scientific objectives for a sample return enterprise and translates that into terms that are useful for a project development team, such as how many samples are needed, the physical attributes (e.g., mass, volume, and mechanical integrity) needed in order to support the requisite measurements as currently envisioned, and how the collection could be organized into suites.

To represent the needs and interests of the future sample analysis community during the development phase of the Mars 2020 project, a "Returned Sample Science Board" (RSSB) comprising 14 scientists was selected by NASA from a pool of applicants. As part of the Mars 2020 science team, the RSSB has participated in landing site selection discussions, consulted on key science-engineering trades (e.g., RSSB, 2016) at the request of Mars 2020 project science, and is represented along with the selected payloads on the Project Science Group (PSG). Many of the questions put to the RSSB during the period 2015–17 related to the degree of importance of certain factors that relate to sample quality, such as temperature, contamination, and fracturing. In addition, the RSSB contributed to the development of the project's contamination knowledge strategy (Farley et al., 2017).

The term of the RSSB extends until the participating scientist selection process, projected to complete prior to launch. Some participating scientists will be selected specifically for their expertise in returned sample science, and these individuals will join the Mars 2020 science team in an integrated approach to scientific decision making in support of in situ exploration and returned sample science during the surface mission.

11.5 SAMPLING AND CACHING SYSTEM

The major new development for the Mars 2020 flight system is the Sampling and Caching System (SCS). The Mars 2020 SCS represents an unprecedented set of technical challenges and is critical to the success of the Mars 2020 mission and to the progress toward MSR. Although a number of previous missions have had surface preparation and sample collection capabilities—for example, MSL *Curiosity* has an advanced drilling and sample handling system (Anderson et al., 2012)—the Mars 2020 SCS is a fundamentally new design that enables surface preparation and core acquisition, as well as sealing, onboard storage, and release of sample tubes to the surface, all bound by a set of organic, inorganic, and biological cleanliness requirements more stringent than those for any prior planetary mission. Key elements of the Mars 2020 sampling and caching system are shown in Fig. 11.2.

11.5.1 Sample-Related Requirements

Mars 2020 is designed to meet an ambitious and stringent set of scientific requirements on the samples to be cached (Table 11.1). The mission will be capable of acquiring at least 31 samples, each consisting of about 15 g of rock or regolith. The desired mass of each sample was derived from estimates of how much mass is likely required for analysis and archiving of returned samples (McLennan et al., 2011), while the total number of samples is dictated by the duration of Mars 2020's surface investigation and notional lift capabilities of a return mission. Each rock sample will consist of a cylindrical core about 1 cm in diameter from the uppermost ~5 cm of the rock and will be drilled directly into an individual ultraclean sample tube. Unconsolidated material such as regolith will be collected through a specialized sampling bit that allows particles to flow by gravity into the sample tube.

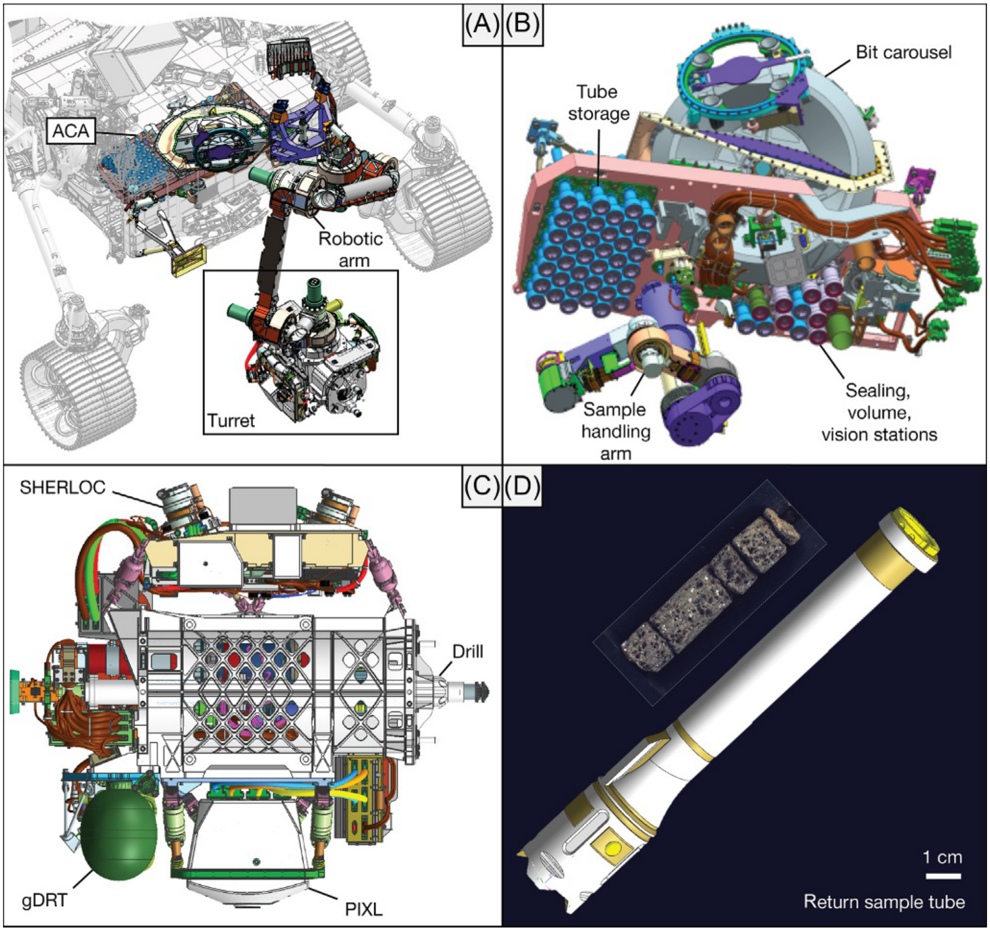

Fig. 11.2 Mars 2020 sampling and caching system, including a front view of the rover (A) with turret, robotic arm, and adaptive caching assembly (ACA) indicated; a view of the ACA from below (B); another view of the turret (C) showing PIXL, SHERLOC, and drill (one stabilizer shown; bit is retracted); and a drawing of a sample tube (D) with a representative test core shown to scale.

Scientific integrity requirements exist to minimize rock fragmentation that would preclude identification of structures (especially biosignatures), to restrict sample temperature to <60°C during drilling and storage on Mars, and to minimize volatile loss via hermetic sealing of each tube immediately after acquisition. The most demanding requirements on sample integrity are those that limit terrestrial contamination. These include a requirement of absolute sterility (less than one viable organism per sample tube), restrictions on the abundance of many elements critical for geochemical study, and extraordinarily stringent requirements on organic contamination.

Table 11.1 Requirements on the samples to be prepared for caching by the Mars 2020 mission

Category	Requirement
Number of samples	Capable of at least 31 in total, with 20 in the primary mission
Sample mass (each)	10–15 g cylindrical cores
Contamination limits	
Inorganic	Limits on 21 key elements based on typical concentrations in martian meteorites
Organic	<10 ppb total organic carbon <1 ppb of 10 critical marker compounds
Biologic	<1 viable terrestrial organism per sample
Drilling and storage temperature	$<60°C$ at all times including during depot on Mars surface
Individual sample tube sealing	Hermetic (to prevent volatile loss and contamination)
Sample disaggregation	Maintain large pieces to allow structure investigations during drilling, storage, and possible Earth return

Separate from sample cleanliness requirements, the Mars 2020 mission will acquire detailed contamination knowledge covering all relevant stages of the mission. This knowledge will be critical for confirming the martian origin of any potential biosignatures detected in the returned samples. Prior to spacecraft assembly, witness plates and spacecraft swabs will be used to characterize vapor-deposited and particulate organic and biological contamination. This includes a thorough genetic inventory of potential microbial contaminants in relevant development environments. Also during this phase, lot-identical spacecraft components, including a planned "contamination model" of the drilling system, will be archived for future analysis.

Once the spacecraft is assembled, it is no longer possible to directly measure Earth-sourced contamination until samples are returned, so Mars 2020 will feature a system designed to accumulate contaminants during Mars surface operations and the roundtrip flight. Six sample tubes ("witness tubes") will be modified to carry a witness plate assembly (WPA) featuring ultraclean surfaces and meshes that will trap molecular and particulate contaminants. The witness tubes will be stored and processed identically to sample-containing tubes, with the exception of bit-on-rock contact. By carrying six such tubes, it will be possible for the science team to devise appropriate strategies for when to expose and seal these tubes as the contamination environment aboard the rover evolves.

If specific organic compounds or organisms are someday detected in returned samples, a comparison between the preflight contaminant analyses and the witness tube measurements can be made to assess whether there is evidence for an Earth source. If necessary, the contamination model of the drill can be used to assess the role of bit-on-rock contact in sourcing and possibly modifying organic compounds. In the end, it may be necessary to make spatially resolved measurements (i.e., compare interior portions of sample with exterior portions) to compellingly confirm a martian source of potential biosignatures.

11.5.2 Design of the Sampling and Caching System

The Mars 2020 sampling and caching system (SCS) is a dual-purpose subsystem supporting both in situ exploration and sample acquisition and storage. Features of the SCS that support sampling include a rotary-percussive drill similar to MSL but modified to generate cores rather than cuttings, a rotating bit carousel containing multiple bits for rock coring and regolith collection, and an adaptive caching assembly (ACA) with its own robotic sample handling arm (SHA) enabling filled sample or witness tubes to be photographed, sealed, stored, and eventually placed on the surface of Mars. The SCS supports in situ science investigations with a gas-based dust removal tool (gDRT) and drill bits designed for surface abrasion. The abrading bit is used to prepare a ~4 cm-diameter patch of rock to facilitate proximity science including imaging and mapping by the PIXL and SHERLOC instruments. The gDRT uses a high-velocity jet of nitrogen gas to remove dust and abrasion fines that might otherwise obscure surface targets.

To collect a rock sample, the SHA inserts an empty sample tube into a coring bit, and this bit is rotated into docking position for insertion into the drill. The drill containing the coring bit is placed onto the desired target and preloaded, a "hole start" routine is run, and coring continues in either rotary-percussive or rotary-only mode, depending upon the mechanical characteristics of the rock. An eccentric race at the end of the sample tube facilitates core breakoff, the drill is removed from the borehole, and the robotic arm docks again to the bit carousel, which removes the bit and rotates, presenting the rear portion of the bit to the ACA. The filled sample tube is removed from the bit by the SHA and taken through a number of stations including imaging, volume estimation, and sealing prior to storage in its original location.

11.5.3 Sample Caching and Potential Return

In order to maximize flexibility and minimize risk, Mars 2020 has adopted an approach called "adaptive" caching by which multiple sealed sample tubes will be dropped by the ACA onto the surface of Mars (e.g., Beaty et al., 2015). This is in contrast to an approach in which all samples are stored on board the rover in a single container until a decision is made to transfer the container—the monolithic cache—on to the martian surface. Evaluation of the relative benefits of these two basic caching architectures dates back at least as far as early MSR concepts emerging in the years following Mars Pathfinder. The main advantage of the adaptive approach adopted by Mars 2020 is that it allows the mission to offload its sample cargo at opportune times, thereby eliminating the possibility that all of the samples (e.g., in a monolithic cache) get stranded in a disabled rover. Adaptive caching also permits the potential return mission to select the highest value samples for return rather than to take all samples in the monolithic cache.

The current notional strategy is that multiple samples will be deposited at a "depot" site selected to optimize relocation by the retrieval mission and where dust accumulation is expected to be minimal. A likely scenario for depot caching is as follows. A first region of interest (ROI 1) is explored, approximately half (~10) of prime mission samples are collected, and the rover drives to ROI 2 with samples stored on board. Prior to exploring ROI 2, a suitable depot location is identified nearby, and the samples from ROI 1 are dropped in a collection. This offloads the risk associated with further transport of the sample cargo. ROI 2 is explored, ~10 more samples are collected, the rover returns to the depot, and the samples from ROI 2 are added to the initial collection. At this point, the team is free to pursue higher risk exploration near ROI 2 or at a third ROI some distance away. Once more, samples are collected; the team will face the decision of whether to return to the first depot or to establish a new depot. An obvious risk of establishing multiple depots is that the retrieval mission may not be designed to traverse among far-flung depots.

Because follow-on sample return missions are not yet confirmed, the length of time the samples collected by Mars 2020 must retain their integrity on the surface is unknown. Mars 2020 is verifying that sample tubes and seals will last at least 10 years on the surface of Mars and 10 years in Mars orbit.

11.6 EXTANT LIFE AND PLANETARY PROTECTION

The combination of low and widely varying temperature, low atmospheric pressure, low water activity, and high ultraviolet and ionizing radiation environment at the surface of modern Mars is extremely inhospitable for life. Geologic evidence and models of planetary evolution suggest that similarly inhospitable conditions have prevailed for most of Mars history—probably for >3 billion years (3 Ga; Carr and Head, 2010)—and martian life has not been detected by any previous mission. It thus seems unlikely, but not impossible, that present-day Mars supports a biosphere. If martian life does exist today, it would likely be confined to subsurface environments that are protected from deleterious radiation and where liquid water is stable. These caveats notwithstanding, the precautionary principle has led to policies for planetary protection designed to limit "forward" contamination of extraterrestrial environments by Earth organisms and "backward" contamination of Earth by extraterrestrial organisms.

Samples collected by Mars 2020 will be sealed in tubes and placed on the surface of Mars where their exteriors will be in contact with the martian environment (and possible martian organisms). Further, containment of samples in such a way that Earth is protected from accidental release of a possible martian organism would be the responsibility of follow-on missions. The Mars 2020 project is working with future mission planners to design a system that would enable future missions to meet planetary protection responsibilities and will be archiving information about Mars 2020 that future missions would need to demonstrate that samples are safe to return.

Surface environments on Mars "within which terrestrial organisms are likely to replicate" (e.g., with water activity between 0.5 and 1.0 and temperature above − 25°C) have been designated "special" or "uncertain regions" (Rummel et al., 2002, 2014; Committee to Review the MEPAG Report on Mars Special Regions et al., 2015; COSPAR, 2015). Mars 2020 will not target special regions because its goal is to look instead at the potentially far more habitable environments of pre-3 Ga Mars. As was the case for MSL, the Mars 2020 strategy to prevent forward contamination responds to NASA policy for Mars surface missions that do not access special regions. MSL met the biological cleanliness (or "bioburden") requirements to prevent forward contamination with significant margin (Benardini et al., 2014). Mars 2020 will use a heritage approach with limited improvements to ensure compliance with high confidence.

11.7 LANDING SITE SELECTION

Following previous practice (e.g., Golombek et al., 2012), the selection of a landing site for Mars 2020 will occur late in mission development to ensure that the greatest amount of orbital data has been acquired before a decision is made. Previous landing site selection efforts, additional orbital data acquired since the MSL site selection process, and heritage engineering approach used for Mars 2020 have enabled more thorough and rapid scientific and engineering safety analyses of landing sites than ever before. Landing site selection criteria are different for Mars 2020 than for previous rover missions. With objectives to seek evidence of ancient life and prepare a cache of samples, strong evidence for habitability and conditions conducive to biosignature preservation in the depositional environment and lithologic diversity assumes new importance.

The bulk of the record of life on Earth derives from sedimentary rocks deposited in relatively shallow, subaqueous settings. Experience studying the Earth's sedimentary rock record also provides a clear and robust model to guide the search for biosignatures in fluvio-deltaic or lacustrine environments on Mars. For these reasons, many in the Mars science community favor a landing site with clear evidence for large, standing bodies of water, for example, geomorphic evidence for a delta, often accompanied by mineralogical evidence for hydrous minerals.

However, questions remain whether habitable environments present at the Mars surface subsisted long enough to allow life to gain a recognizable foothold. Current thinking suggests that life on Earth emerged among the diverse and abundant chemical disequilibria (including abiotic organic synthesis) that result from energetic water-rock interaction in subsurface hydrothermal systems (e.g., Russell et al., 2014). The great significance of Earth's "deep biosphere" (organisms living >1 m below the surface; Edwards et al., 2012) has been appreciated only relatively recently (e.g., Kallmeyer et al., 2012). While there is nothing to suggest that the deep biosphere is a recent phenomenon, very little is known about its distribution and extent throughout Earth's history—and of particular relevance to the Mars 2020 mission—and how it may be preserved in the rock record. The influence of a magnetic field on the habitability of surface environments on Mars is also unknown. Most sites considered for Mars 2020 appear to have been deposited after the magnetic field was lost. For these reasons, the most ancient (early Noachian) landing sites featuring evidence for hydrothermal activity enjoy strong community support.

In addition to past habitability, the ideal Mars 2020 landing site would feature geologic diversity adequate to satisfy the needs and desires of the community of scientists who would someday analyze returned samples. There is a great diversity of investigations to which returned samples are likely to be subjected, and many investigations have specific target lithologies. For example, there is strong and obvious interest in analyzing igneous rocks to better understand the nature and timing of early planetary differentiation and in sedimentary rocks that may carry a record of ancient climatic evolution. Also of interest are rocks that may document an early martian magnetic field and those that would provide a radiometrically determined age of a laterally extensive cratered surface to test crater chronology models. Locating a single site that meets *all* of these objectives is unlikely, and prioritization will almost certainly be required.

As of this writing, three Mars 2020 landing site workshops have been held, and the list of possible landing sites has been narrowed to three: Columbia Hills, Jezero Crater, and Northeast Syrtis. Leading hypotheses regarding the geologic origin and potential habitability have been developed for each site. A delta at Jezero Crater samples a lithologically diverse watershed and provides evidence for subaqueous sediment deposition in a crater-filling lake (Fassett and Head, 2005; Ehlmann et al., 2008; Schon et al., 2012; Goudge et al., 2015, 2017). Among a diversity of igneous rocks observed by the Spirit rover near the Columbia Hills in Gusev Crater is a silica deposit interpreted to be the preserved remnants of a surface hydrothermal system (Ruff et al., 2011; Schmidt et al., 2008; Squyres et al., 2008) that could contain biosignatures (Ruff and Farmer, 2016). Northeast Syrtis exposes extremely ancient, early Noachian crust without clear geomorphic evidence for persistent surface water but with mineralogical indicators consistent with past water-rock interaction across a range of temperatures, including phyllosilicates and alteration of olivine to Mg carbonate and serpentine (Bramble et al., 2017; Ehlmann et al., 2008, 2009; Ehlmann and Mustard, 2012) or talc carbonate (Brown et al., 2010).

11.8 MARS 2020 AND THE SEARCH FOR LIFE BEYOND EARTH

11.8.1 Mars 2020 and In Situ Astrobiology

Mars 2020 builds upon previous rover missions' approaches for documenting geologic context and assessing ancient habitability. Upon landing and system checkout, the science team will select an initial exploration area or "region of interest" (ROI), roughly 1 km^2 in area. The first ROI will be selected on the basis of perceived scientific potential and proximity to the rover landing site from a number of previously identified ROIs that will have been mapped and prioritized by the science team based on orbital data (e.g., MRO HiRISE imagery and CRISM spectra). As the rover approaches and arrives at the first ROI, stereo color images from Mastcam-Z and enhanced engineering cameras (EECAMs) at increasing spatial resolution will begin to reveal information about lithology, structure, and stratigraphic relations of geologic units present within the ROI. Radar soundings from RIMFAX will be correlated with image data to extend the structural and stratigraphic investigation into the subsurface. Multispectral imagery from Mastcam-Z, together with LIBS, VNIR, and Raman spectroscopy from SuperCam, will provide information about mineralogy at a distance of a few to tens of meters from the rover, enabling further development of a model for deposition and subsequent diagenesis of rocks in the ROI. As the contextual, ground-based "remote science" dataset is acquired, new understanding of the local geology will be used to refine ROI maps based previously on orbital data alone. Remote science data will lead the team to select scientifically compelling and safely accessible targets for surface preparation and "proximity science" with the turret-mounted instruments PIXL and SHERLOC, whose data will ultimately inform the choice of sampling locations based upon the likelihood of a target to preserve records of ancient life and planetary evolution that could someday be detected in Earth-based laboratories.

Certain elements of Mars 2020 astrobiology exploration strategy are landing site independent. Evidence of past liquid water and its persistent interaction with rock to yield metabolic substrates is the dominant exploration target regardless of habitat type. Potential for and diversity of disequilibria are important components of habitability, so locations with apparently primary mineralogical and morphologic complexity may be preferable to relatively homogeneous locations. Evidence of diagenetic alteration can be favorable or unfavorable, depending upon the circumstance. Oxidizing or acidic fluids can destroy primary elemental or molecular biosignatures (e.g., Sumner, 2004), and recrystallization or impact processes can destroy morphologic biosignatures. From that point of view, rocks that are as mechanically and chemically "primary" are considered to be higher priority targets for potential biosignature preservation. On the other hand, the aforementioned fracture networks can represent important subsurface habitable environments and must not be overlooked. Similarly, impact-generated hydrothermal systems may destroy evidence of earlier life in the host rock while forming their own postimpact habitats (Osinski et al., 2013) and potentially preserving records of subsurface life (Parnell et al., 2010; Sapers et al., 2014, 2015).

As the shift in focus of the MSL mission from habitability to taphonomy demonstrates (e.g. Grotzinger, 2014), the element of time is critical in both directions. Long times are important—for a habitat to generate sufficient biosignatures to enable detection, the system must persist long enough for a biome to take hold and produce a relatively robust and recalcitrant environmental expression. Short times are also important—rapid burial and/or rapid crystallization are key to preservation of biosignatures before they can be degraded by ambient environmental processes, and short surface exposure time is important to protect any complex molecular biosignatures from being destroyed (or rendered ambiguous) by ionizing radiation. Each of these requirements for biosignature formation and preservation has implications for the Mars 2020 mission's exploration strategy. Mars 2020 will seek local environments with evidence for relatively persistent water (e.g., lacustrine sediments and nodes in fracture networks), maximal primary chemical diversity, and favorable taphonomic conditions (e.g. rapid burial or entombment by evaporitic minerals and impact glass).

Certain details of the mission's surface exploration strategy are heavily site-dependent. For example, exploration of fluvio-deltaic and lacustrine environments in Jezero Crater might prioritize a search for low-energy distal facies with a high capacity to preserve organic matter and any carbonate-bearing facies nearer to ancient shorelines that could have offered a physical and chemical environment particularly conducive to the formation and preservation of biosignatures in forms recognizable to rover instrumentation (e.g., fossilized microbial mats or stromatolites). By contrast, habitable environments at NE Syrtis were likely in the subsurface where water interacted with rock to generate chemical disequilibria that could have been harnessed by microbial life. The exploration strategy at NE Syrtis might focus on identifying fluid flow networks, perhaps seeking nodes in ancient fracture/vein systems where fluids of varying compositions could have interacted to generate chemically fertile microenvironments. Exploration targets at Columbia Hills have already been identified using ground-based data from the MER Spirit rover. High-silica materials with digitate morphology observed near Home Plate have been interpreted to represent potential biosignatures (Ruff and Farmer, 2016), and a spatially resolved investigation of the elemental and molecular chemistry of these features with PIXL and SHERLOC would be a priority in order to determine whether there is more compelling evidence of ancient life than what MER *Spirit* observed.

11.8.2 Martian Biosignatures

What is a martian biosignature? Will we know it when we see it? Mars rover scientists and engineers often joke about finding "the dinosaur bone," but the modern concept of astrobiology holds that the conditions enabling complex, multicellular life on Earth are probably unique in the solar system, and thus any extraterrestrial life is likely to have been microbial. Rather than the dinosaur bone, then, we may consider the astrobiological "holy grail" of a Mars rover mission to be something like a stromatolite—a finely layered sedimentary rock that may represent a fossil microbial mat. Many stromatolites as we know them from ancient Earth rocks would be readily detectable by Mars 2020 instrumentation, with submillimeter- to centimeter-scale lamination that sometimes exhibits morphologically correlated elemental and molecular heterogeneity (including biotic organic matter preserved on billion year timescales as kerogen and distinctly confined to certain laminae). For example, variably silicified, carbonate stromatolites of the ~3.4 Ga Strelley Pool formation in Western Australia represent some of the oldest widely accepted evidence for life on Earth and show morphologic, elemental, molecular, and isotopic signs of life within a geologic context clearly indicative of deposition in a habitable environment (Allwood et al., 2006, 2009; Bontognali et al., 2012; Lepot et al., 2013; Flannery et al., 2018).

Recently, the Mars 2020 PIXL and SHERLOC teams conducted a coordinated investigation of a particularly well-preserved kerogen- and carbonate-bearing sample of a Strelley Pool formation stromatolite using laboratory development models of the Mars 2020 instruments (Fig. 11.3). PIXL used microfocus X-ray fluorescence to observe features consistent with a variably silicified matrix of original dolomite having spatially

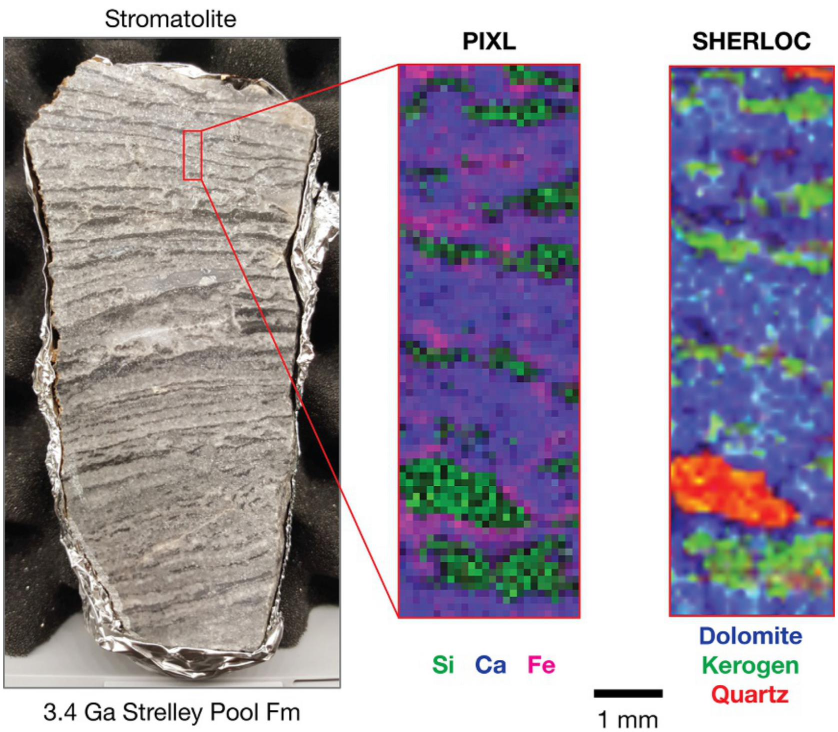

Fig. 11.3 Coregistered X-ray fluorescence (PIXL) and UV Raman (SHERLOC) maps over a ~2.5 × 8 mm laminated region of a stromatolite from the ~3.4 Ga Strelley Pool formation, Western Australia. Leftmost panel is similar to an image acquired from the WATSON camera on SHERLOC; center panel is a PIXL map showing distribution of Si, Ca, and Fe; and rightmost panel is a SHERLOC UV Raman map showing intensity of peaks corresponding to dolomite, kerogen, and quartz.

variable Fe concentrations consistent with earlier observations by Allwood et al. (2009). Coregistered SHERLOC UV fluorescence and Raman measurements confirmed the carbonate mineralogy variably altered to quartz, with kerogen preferentially distributed in zones of silicification. This type of elemental and molecular heterogeneity in correlation with primary morphology (in this case, millimeter-scale laminae) represents an important class of biosignature clearly detectable by the Mars 2020 payload.

In general, we suggest that potential biosignatures can be defined as (1) co-occurring concentrations of biologically important elements, molecules, and/or minerals; (2) exhibiting heterogeneity correlated in space with complex or otherwise biologically suggestive morphologies; (3) observed within a geologic context consistent with habitability; and (4) the likelihood of biogenicity dependent upon the relative parsimony of any abiotic explanations for the sum of the observed phenomena.

11.8.3 Astrobiologic Considerations for MSR

Mars 2020 has the tremendous opportunity and profound responsibility to provide the in situ geologic and environmental context for what would be among the most precious samples in the history of science if successfully returned to Earth. The ability to achieve scientific consensus about any evidence for ancient life observed in samples returned from Mars strongly depends on the quality of science conducted during the Mars 2020 mission. To this end, the science team is developing a three-part approach to contextualization of samples.

The first component of sample contextualization will include a set of data and interpretations largely independent of the decision to collect any particular sample. Using an approach similar to previous rover missions, Mars 2020 will explore the landing site, conducting an analysis of representative materials that is as comprehensive as possible in order to generate interpretive models explaining the emplacement and alteration of rocks exposed at the surface. This work will be in service of planetary science generally—the science team will pursue and communicate discoveries related to the evolution of Mars as a system, including its capacity to support life. This process will also guide the eventual selection of samples that are themselves dominantly contextual. In addition to any primarily "astrobiology" samples with high potential to preserve biosignatures, future scientists will need access to a representative set of "context" samples collected primarily for this purpose. These samples would be of high scientific value in their own right, selected as faithful recorders of the conditions of deposition/emplacement, the nature of the most significant alteration events, and a time series of environmental change encompassing the interval represented by astrobiology-oriented samples.

The second component will include a minimum set of systematic observations to be performed as consistently as possible on or in association with every sampling target. Analytic consistency will support the rapid construction and dissemination of "dossiers" for each sample, the compilation of which will represent an early guidebook to the samples available for return. The third component will include detailed observations specifically tailored to individual samples or sampling locations. These may represent the richest, but most complex and difficult to interpret data from the mission, and their full fruition may not come until sample analysis on Earth. It is in this third realm that any potential biosignatures are likely to emerge, and it is these data that may provide the most compelling rationale for sample return.

Mars 2020 will carry more sample tubes ($\sim$40) than the currently envisioned carrying capacity for a retrieval mission (31). Planning for success, scientists of the future will be able to debate the merits of the Mars 2020 samples after the sampling phase of the mission concludes in order to determine the highest value subset for return to Earth. The Mars 2020 science team is designing the sample documentation program with these future deliberations in mind.

11.8.4 Some Thoughts on Returned Sample Science

Assuming that samples collected by Mars 2020 are successfully returned, the Earth-based phase of returned sample science would begin in earnest with documentation of any conditions associated with touchdown and field recovery of the Earth entry capsule that could impact sample properties. Planetary protection concerns related to returned extraterrestrial samples that could feasibly contain viable extraterrestrial organisms require that extraordinary measures be taken to ensure containment. For example, the return capsule must be designed to survive impact without the aid of a parachute to avoid the unintended and uncontrolled exposure of martian materials to the Earth environment. Upon landing, the return capsule would be removed to a receiving facility with a degree of biological security that may exceed any that exists today. After an initial phase of analysis, it is possible that the samples would be transferred to a separate, lower biosecurity and longer-term curation facility from which subsamples could be distributed to external laboratories for further analysis.

The search for evidence of ancient life in returned martian samples would likely use an approach fundamentally similar to that described in Section 11.8.2, with the addition of a wide variety of analytic techniques not featured by Mars 2020. The analytic possibilities are numerous, and it is likely that approaches not yet imagined would be employed. Here, we offer several examples of existing techniques that would almost certainly play an important role in returned sample astrobiology. Solvent extraction followed by gas chromatography and mass spectrometry is among the most powerful methods available to study the ancient record of life on Earth, and this approach applied to returned martian samples would enable the detection of any organic molecules of sufficient complexity or distributions of molecules in patterns that cannot be explained abiotically (e.g., Summons et al., 2011). Clearly, nondestructive or minimally destructive techniques would be favored whenever feasible for returned sample analysis as they minimize sample consumption and provide data in petrographic context. Careful sample preparation followed by light and electron microscopy would enable a search for microbial fossils and spatially resolved elemental, molecular, and isotopic analysis. Biogenicity assessment of putative microfossils in ancient Earth rocks has a long and controversial history (e.g., Schopf, 1993; Brasier et al., 2002), but criteria for such assessments have evolved considerably over the last several decades (e.g., Schopf and Walter, 1983; Buick, 1990; Sugitani et al., 2007; Wacey, 2009), and similar approaches have been applied to nonmicrofossil biosignatures including putative microbial microalteration textures in igneous rocks (McLoughlin and Grosch, 2015). Recent developments in spatially resolved analysis of organic and mineral matter distinguish morphologically correlated compositional heterogeneities and represent important new capabilities for the confident detection of biosignatures at or below the scale of individual microorganisms (e.g., Williford et al., 2013, 2016; Wacey et al., 2016). In particular, the evolution of techniques such as atom probe tomography (e.g., Miller et al., 2012; Valley et al., 2014) will no doubt be important to the future analysis of returned extraterrestrial samples.

Although the primary astrobiological motivation for Mars 2020 and MSR as currently envisioned is to investigate the possibility of ancient life on Mars, a pristine and scientifically selected set of samples from the surface of that planet would also offer an excellent opportunity to seek signs of extant (living or recently deceased) extraterrestrial life. This search would be complementary to the planetary protection goal to determine whether the samples contain any martian organisms that are hazardous to Earth life. As such and as was the case for the lunar samples returned by the Apollo program, this biological analysis would likely occur early (in part to assess any risks to human workers) and certainly within the high biosecurity receiving facility. Because it would be impossible to conclusively prove the absence of a dangerous martian organism without complete consumption of the sample set (an absurd proposition!), future scientists and policy makers will likely face a decision to either sterilize the samples or contain them in the high biosecurity receiving facility indefinitely (or until human exploration of Mars matures to a degree that existential threats to the biosphere of Earth can be confidently rejected). Removal to a lower security, longer-term curation facility, and distribution to external laboratories may thus require sterilization of the samples and acceptance of any accompanying alterations to sample properties that might result. Workers of the future may have to balance a desire to conduct specific, idiosyncratic analyses in unique individual laboratories against the potential scientific cost of sample sterilization.

How then might extant life be detected in martian samples, and if detected, how could scientists determine conclusively whether the organisms were Earth-sourced contaminants (the obvious null hypothesis) or indigenous martian life? If the contamination could be confidently rejected and the recovery of indigenous martian life confirmed, the implications would be profound. Such a discovery would immediately raise an important second-order question: are the martian organisms the result of an independent origin of life on Mars (independent genesis) or are Earth and Mars life related through impact exchange (panspermia)?

One might imagine (based on the current state of the art for life detection in low biomass terrestrial samples) that the first detection of a possible extant microorganism in a returned martian sample would result from fluorescence or electron microscopy (e.g., Kallmeyer et al., 2008; Morono et al., 2009). If a cell-like entity (CLE) were detected, researchers would face difficult decisions about downstream destructive analysis. Possible choices with the potential to yield a confident determination of biogenicity would include lysis and sequencing (e.g., Gawad et al., 2016) or cryo-electron tomography (e.g., Dobro et al., 2017). Unsuccessful sequencing after lysis would be uninformative unless sufficient unprocessed CLE material remained to permit further analysis. Successful amplification and sequencing showing a match to any known Earth life would suggest contamination. A sequence that did not match any previously known and showed extraordinarily deep divergence (e.g., such that the sequence was unassignable to any of the three domains of Earth life) could be explained by either (1) panspermia or (2) extraordinary convergent evolution to DNA after independent genesis. Successful cryo-EM could show cellular anatomy distinct from any known form of Earth life, but this result would also likely be inconclusive given the current pace of discovery in this field (Dobro et al., 2017). It is possible that a combination of mass spectrometry and crystallography could reveal a system of pseudo/xenoproteins and/or xenonucleic acids that would represent strong evidence for independent genesis on Mars. Regardless of the analytic choice and the result, information from a single CLE would almost certainly be insufficient to disprove the null hypothesis of terrestrial contamination, and a variety of analytic techniques applied on a larger number of CLEs would be required. Therefore, the probable approach prior to any destructive analysis would be to repeat the procedure that yielded the first CLE detection, consuming additional material from the sample in question and/or from other returned samples until either (1) more CLEs were detected or (2) the willingness to expend sample material on the search for extant life was overwhelmed by the desire to pursue the more central goals to understand the evolution of Mars as a system, including the search for evidence of ancient life.

Return and analysis of samples from Mars would represent an important turning point for astrobiology. For a field that has so far been restricted to analysis of Earth-based analogs, models, and remote observations, the opportunity to bring scientifically selected samples of a once habitable planet into the laboratory for interrogation by any technique available on Earth would be transformative. Perhaps the most exciting, but least likely, result (given the current inhospitability of surface environments) of MSR science would be the determination that Mars is currently inhabited by organisms from an independent genesis. More likely and similarly meaningful would be a determination that Mars was inhabited in the ancient past—answering a central motivating question for Mars 2020 and MSR. It may be difficult or impossible to determine whether any evidence of ancient martian life in samples collected by Mars 2020 resulted from independent genesis or panspermia. It is also possible, of course, that Mars was never inhabited or that samples and in situ data collected by Mars 2020 reveal no convincing evidence of life. A complete lack of biosignatures in a diverse and carefully selected set of samples from a clearly habitable ancient environment on Mars could place important constraints on the spatiotemporal ubiquity of life on habitable planets. The explosion of scientific knowledge sparked by the return and analysis of lunar samples demonstrates that, even in the event of this third, astrobiologically negative result, the scientific rewards for MSR would be tremendous.

Regardless of the astrobiology results, successful return and analysis of samples scientifically selected and with geologic context exhaustively documented by Mars 2020 fairly guarantees a revolution in human understanding of our planetary neighborhood. If conclusive martian biosignatures *are* detected, however, a new world opens before us, and future generations can finally leap from the Earthly tree of life to begin exploring the forest.

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