National Aeronautics and
Space Administration

Mission to Mt. Sharp

Habitability, Preservation of Organics, and Environmental Transitions

Senior Review Proposal Sections 1 and 2

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Executive Summary

The Mars Science Laboratory (MSL) prime mission has been a tremendous success and the rover is in excellent health. Within its first year of operation, Curiosity traversed over stream-rounded pebbles to a site where mud accumulated in an ancient lake. The mudstones drilled and comprehensively analyzed there yielded evidence for long-lived fresh water, the major elemental building blocks of life, and a source of chemical energy capable of sustaining microbial life. With the discovery of these key characteristics of a habitable environment, MSL satisfied its primary mission goal. The mission has fulfilled all of its diverse science objectives and Level 1 requirements, providing a number of additional discoveries of major significance to NASA's Mars Exploration Program, such as the absence of atmospheric methane, evidence for early massive atmospheric loss, and the first *in situ* rock and surface exposure age dating on another planet. After 19 months of operation, MSL team members have published (or have in press) 42 papers in major scientific journals, including 16 in *Science*, with two covers. With evidence for an ancient habitable environment in hand, the mission is poised to explore the foothills of Mt. Sharp to ask the next logical question in the search for life on Mars: what geological settings and environmental conditions have been conducive to preserving evidence of carbon and other biomarkers? The answers will be Curiosity's legacy to future missions seeking to identify traces of life on Mars or within samples returned to Earth.

Although the ancient river, lake, and groundwater system near Curiosity's touchdown point has proven the worth of Gale Crater as Curiosity's landing site, the mission's full potential will not be realized until the rover is able to access and study the foothills of Mt. Sharp. The mission has focused the second year of its operations on reaching the numerous ancient environments recorded in its varying mineralogy and landscapes. Employing the analytical techniques proven during the prime mission on these new environments will address two new science objectives: (1) identifying the subset of habitable environments capable of preserving organic compounds, and (2) characterizing major environmental transitions recorded in the geology of Mt. Sharp's foothills and adjacent plains.

From the base of Mt. Sharp, Curiosity will explore four unique geologic units, in ascending stratigraphic order: basal rocks with a "paintbrush" texture; overlying and younger hematite-bearing rocks; even younger clay-bearing rocks; and magnesium sulfate-bearing rocks that extend to the upper reaches of the foothills (Figure ES-1). Having the opportunity to study such a varied and extensive stratigraphic record, and the changing planetary environments that it reveals, is a rare opportunity on Mars. Terrestrial and astrobiological studies suggest that clay-bearing rocks at 6 km may provide the highest potential for preserving organics. Reaching the sulfates at 8 km would allow us to test organic preservation models across one of the great environmental transitions in Martian history, when the fresh-water era that favored clay deposition changed to the drier, more acidic conditions that favor sulfates.

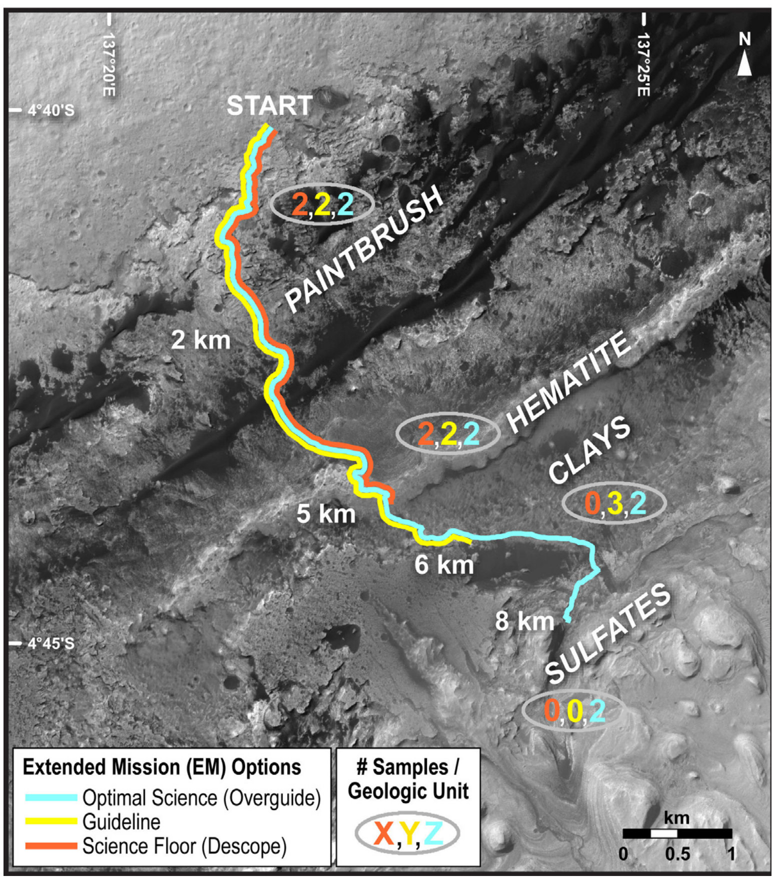

Figure ES-1. *EM1 example science scenarios offer strong EM1 mission possibilities toward accomplishing science objectives.*

Curiosity's progress toward Mt. Sharp has been impeded by hazardous terrain, damaging its wheels at an unanticipated high rate. In response, the team has minimized the impact of this terrain through new routes and drive strategies. In addition, the team implemented an innovative "rapid-drive" operational concept in January 2014, recovering some of the lost progress. Testing and analysis to date indicate that wheel degradation will have minimal impact on the rover's mobility in Extended Mission 1 (EM1) and does not pose a significant risk to our ability to accomplish EM1 objectives.

We present three mission options and their associated scenarios, based on performance to date. These scenarios evaluate the time it will take to access each region and the number of samples that we can acquire and analyze at each. The Overguide option (Optimal Science) accomplishes EM1 science objectives across all four units and is the only option that can reach the environmental transition recorded at the clay-sulfate boundary. This option is also strong in its flexibility to respond to discovery-driven changes, allowing for more margin to accomplish the science objectives in the clay unit, previous units, or unanticipated sites. The Guideline option accomplishes EM1 science objectives across the first three units: paintbrush, hematite, and clay. A strength of the Guideline option is the ability to characterize the clay unit, which has a high potential for organic preservation. The Descope option (Science Floor) provides access to and sampling of the paintbrush and hematite units. This option leaves the study of the critically important clay unit to a future EM, but still provides essential context for understanding the stratigraphy of Mt. Sharp.

Curiosity's performance during EM1 will be comparable to that achieved in its prime mission, but at lower cost, due to the team's continuing success in increasing science and operations effectiveness, while maintaining acceptable risk. Monthly operational costs have been reduced 50% since landing through FY14 and will be reduced another 15% in the Guideline budget option. The vehicle is in excellent health and all systems are capable of supporting the planned EM1. In addition, the rate at which Curiosity's power subsystem is degrading will not have an impact on science until after EM1. As such, a dollar invested in Curiosity's first extended mission has more science buying power than a dollar invested in any future MSL extended mission.

- *The MSL prime mission has achieved all mission and science objectives, including the overall goal of assessing a habitable environment.*
- *Guided by the Decadal Survey, EM1 will address two new science objectives: (1) identifying the subset of habitable environments capable of preserving organic compounds, and (2) characterizing major environmental transitions recorded in the geology of Mt. Sharp's foothills and adjacent plains.*
- *EM1 will explore the foothills of Mt. Sharp, where diverse rock units offer multiple opportunities to test hypotheses for habitability, preservation of organics, and environmental transitions.*
- *Operations teams and processes have reduced in cost by 50% since landing, and will reduce another 15% in EM1 under the Guideline budget, while providing increased overall mission performance.*
- *Now is the best opportunity to invest in new science objectives, as Curiosity's systems and payload will remain fully capable throughout EM1.*
- *With its powerful analytical laboratory, Curiosity's feed-forward discoveries will maximize the probability of success of future Mars missions by identifying the best types of places on Mars to search for samples of the greatest scientific interest for possible return to Earth.*

The combination of the rover's current capabilities and its impending arrival at the unexplored terrains at the foot of Mt. Sharp offers enormous potential for new and groundbreaking science. The vehicle and payload are in the best state to perform this mission now, and the MSL team is committed to continued cost reductions and operational improvements while appropriately managing risk. Because potential sample return missions in development lack Curiosity's analytical laboratory capabilities, this is our best opportunity to search for organic carbon and the environments that may preserve it. This next phase of exploration will bring the science community and the public a step closer to understanding whether life ever arose on Mars.

1 Current Mission Objectives and Historical Accomplishments

1.1 Curiosity's Science Goals, Objectives, and Approach

Curiosity has accomplished its overall science goal (quantitatively assessing a habitable environment) and each of its prime mission science objectives (Table 1-1).

The mission's overall science goal is to assess the present and past habitability of environments within the Gale Crater field site (the foothills of Mt. Sharp and the surrounding plains), as codified in the mission's Level 1 science objectives (Table 1-1). Loosely defined, a habitable environment is one that has water, a source of carbon and other vital elements (to build cellular structures), and a source of energy (to fuel organism metabolism)—in other words, the essential ingredients for life as we know it on Earth. Each of Curiosity's ten science instruments contributes to multiple science objectives, and most of the science objectives involve contributions from several instruments. The major accomplishments of MSL to date are summarized in Tables 1-1 and 1-2, and Appendix C. These discoveries satisfy prime mission science objectives and, as such, meet several core requirements for Mars research described in the 2012 Decadal Survey. Two "Special Sections" of *Science* magazine have been dedicated to MSL results. The first featured results related to the first 100 sols of operations, with emphasis on the Rocknest soil deposit, while the second covered sols 100–360, with emphasis on the results from drilling the Sheepbed mudstone at Yellowknife Bay.

Curiosity allows the MSL Science Team to study materials and properties not observable from orbit, and to undertake sophisticated experiments that enable the reconstruction of ancient aqueous conditions and processes. For instance, at Yellowknife Bay, we were able to quantitatively ascertain that not only did water exist there as a lake, but that it had near neutral pH (indicated by the precipitation of clay minerals and Ca-sulfates, determined by Chemistry and Mineralogy (CheMin)), low salinity (determined by the Alpha Particle X-ray Spectrometer (APXS) and Chemistry and Camera (ChemCam)), and variable Eh (indicated by presence of sulfate and sulfide minerals, as well as magnetite and akaganeite, determined by CheMin and Sample Analysis at Mars (SAM)). Furthermore, we know that C, H, N, O, P, and S were all present in the aqueous environment and that C might have been present as both inorganic and organic species (as determined by SAM, CheMin, APXS, and ChemCam). SAM has detected a simple distribution of chlorinated organics, probably of Martian origin. Image data constrain the depositional environment as fluvial and lacustrine (Mast Camera (Mastcam), Mars Hand Lens Imager (MAHLI)). SAM also showed that the rocks preserving these environments have only recently been exhumed in the past ~ 80 million years; levels of present-day ionizing radiation measured by the Radiation Assessment Detector (RAD) place severe constraints on preservation, but recently exhumed rocks would be less impacted.

Together with the other prime mission science accomplishments, the comprehensive assessment of Yellowknife Bay demonstrates the potential offered by this remarkable rover for additional discoveries in EM1. *The science results discussed below demonstrate that the payload's capabilities, the rover's mobility and sampling systems, and the operations strategies were sufficient to meet prime mission science objectives, and will be able to meet those proposed for EM1.*

Table 1-1. *Mission science objectives and historical accomplishments.*

Objective #	Mission Science Objectives	New to EM?
Overall	Quantitatively assess past and present habitable environments at Gale Crater.	N
1	Characterize geological features, contributing to deciphering geological history and the processes that have modified rocks and regolith, including the role of water.	N
2	Determine the mineralogy and chemical composition of surface and near-surface materials (including an inventory of elements such as C, H, N, O, P, S, etc., known to be the building blocks for life).	N
3	Determine energy sources that could be used to sustain biological processes.	N
4	Characterize organic compounds and potential biomarkers in representative regolith, rocks, and ices.	N
5	Determine stable isotopic and noble gas composition of the present-day atmosphere *and of ancient H_2O and CO_2 preserved in hydrated minerals* (italicized wording is new; added for clarification).	N
6	Identify potential biosignatures (chemical, textural, isotopic) in rocks and regolith.	N
7	Characterize the broad spectrum of surface radiation, including galactic cosmic radiation, solar particle events, and secondary neutrons.	N
8	Characterize the local environment, including basic meteorology, the state and cycling of water and CO_2, and the near-surface distribution of hydrogen.	N
9	Identify and quantitatively assess "taphonomic windows" for organic carbon (subset of habitable environments also capable of preserving organic compounds, through exposure age dating and refined models for primary facies distributions and diagenesis).	Y
10	Explore and characterize major environmental transitions recorded in the geology of the foothills of Mt. Sharp and adjacent plains.	Y
Objectives Addressed	**Major Historical Accomplishments in the Prime Mission**	
1,2,3,4	Determination of a sustained habitable environment at Yellowknife Bay through geological, mineralogical, and isotopic analyses of clay-bearing Sheepbed mudstone; identification of C, H, N, O, P, S; circum-neutral pH; low water salinity; multiple redox states (microbial energy sources).	
1,2,8	First detailed analysis of clay-bearing materials on Mars; determination of geologic context, provenance, and diagenetic history of Sheepbed lacustrine mudstone.	
1,2	Characterization of Peace Vallis fan, an ancient stream and alluvial fan system; estimates of hydrologic discharge.	
5	Measurement of atmospheric chemical and isotopic composition, revised $^{40}Ar/N_2$ ratio; upper limit on CH_4 abundance.	
5	New constraints on early massive atmospheric loss from atmospheric $^{36}Ar/^{38}Ar$, D/H, $\delta^{13}C$, and $\delta^{18}O$.	
1,2	First identification of a highly evolved alkaline basalt (mugearite) on Mars.	
1,8	Finding that hydration is widespread in dust and in the amorphous component of soils.	
1,4,6,7	First *in situ* determination of radiogenic and surface exposure ages on another planet, relevant for understanding taphonomy of organics at sampling sites.	
4,6,7	Measurement of energetic particle flux in cruise and on surface; relevant for taphonomy of organics and radiation risk to future human explorers.	
8	Acquisition of continuous records of diurnal and seasonal meteorological variables; identification of novel phenomena in pressure tides, slope winds, ground temperatures.	

Table 1-2. *Prime mission Level 1 requirements accomplished.*

Level 1 Requirements: All Objectives Met	
Launch a mobile surface mission to Mars during 2009 opportunity from the Eastern Test Range.	Launched 11/26/11 after slip of one launch opportunity.
Deliver a flight system to be launched on a launch vehicle competitively selected under the NASA Launch Services contract, compatible with both Atlas V and Delta IV intermediate-class launch vehicles.	Launched on Atlas V.
Shall be able to land at altitudes of up to +1.0 km relative to the Mars Orbiter Laser Altimeter (MOLA) areoid. The threshold for altitude capability is 0 km.	Landed at −4.5 km elevation. System design met threshold altitude capability of 0 km.
Shall be capable of landing and operating at sites between 45°N and 45°S latitude selected as late as one year before launch without compromising overall mission safety. The threshold for latitude capability is between 30°N and 30°S.	Landed at 4.6°S. System design met threshold capability of 30°S to 30°N.
Shall be able to land with an error of < 10 km radially from a designated point on the Martian surface (excluding any uncontrolled effects of winds during parachute descent) using a guided atmospheric entry. The threshold for landing error capability is < 20 km radially from a designated point on the Martian surface.	Landed 2.4 km (< 1 sigma) from designated point. System design achieved 9.5 × 3.5 km (semi-axes) 3-sigma ellipse.
Shall provide data communication throughout critical events, at a rate sufficient to determine the state of the spacecraft in support of fault reconstruction, to relay assets provided by the Mars Program or to the Deep Space Network (DSN).	Near-continuous data demonstrated during launch and entry, descent, and landing (EDL).
Shall acquire scientific data about the rover's local region and conduct mobile *in situ* analysis with the rover and its scientific payload on the surface of Mars for at least one Martian year (669 sols). The threshold for mission duration is one-half of a Martian year (335 sols).	Active for 580 sols (to date).
Shall deliver to Mars a rover with the capability of a total traverse path length of at least 20 km. The threshold for total traverse capability is 10 km path length.	~ 6 km traverse distance to date. 20-km capability met by design.
Shall be able to select, acquire, process, distribute, and analyze at least 74 samples of rock, rock fragments, and/or regolith. The threshold capability is at least 28 samples.	Acquired four samples to date. 28-sample capability met by design.
Shall conduct near real-time public release of imagery and other science/technology via the Internet and will provide regular releases for public information purposes.	Compliant. Raw imagery released within 1 day of receipt. Regular public releases of news and processed imagery.
Shall archive copies of all verified, validated, and calibrated data acquired by the mission to the Planetary Data System (PDS) within six months after receipt on Earth.	Compliant. Archive volumes delivered to the Planetary Data System ranging in age from 3 to 8 months—consistent with NASA HQ agreement.

1.2 Early Discoveries: Bradbury Landing to Rocknest

Within 100 sols of landing, Curiosity was able to characterize an ancient river system, identify igneous rocks with an unanticipated, Earth-like composition, and reveal the detailed composition of a typical soil.

Curiosity was sent to explore a field site located within Gale Crater where a broad diversity of materials was observed from orbit, including evidence for aqueous environments of significance for habitability. However, the mission's science objectives also include characterizing the geologic diversity of the landing site at all scales—encompassing loose surface materials such as impact ejecta, soils, and windblown accumulations of sediment. Such characterization provides a broader context for local observations related to habitability and, in certain cases, may even provide constraints on the evolution of the planet as a whole.

The first outcrop Curiosity encountered was a sedimentary conglomerate, interpreted as ancient stream gravel, exposed in a scour formed by MSL's descent engines. Mastcam and ChemCam Remote Microscopic Imager (RMI) images of cemented rounded pebbles (2–40 mm diameter) and sand grains constitute the first confirmation of sedimentary conglomerate on another planet (Williams et al. 2013). These conglomerates occur in isolated, thin outcrops exposed in the lowlands between Mt. Sharp and the Gale Crater wall. Rounded pebbles in the conglomerates indicate substantial fluvial abrasion. These water-transported pebbles support decades of orbiter-based research documenting ancient, water-carved surfaces and provide *in situ* constraints on the hydrology of this class of flows from scoured bedrock channel systems.

The float rock Jake_M is a dark, macroscopically homogeneous igneous rock representing a new Martian magma type. In contrast to the relatively unfractionated, Fe-rich, Al-poor tholeiitic basalts typical of Martian igneous rocks, it is highly alkaline and fractionated (Stolper et al. 2013). No other Martian rock is as compositionally similar to evolved terrestrial igneous rocks as is Jake_M (and similar rocks found later); it compares very closely with an uncommon terrestrial rock type known as a mugearite, typically found on ocean islands and in rift zones on Earth.

The composition indicates an origin from magmas generated by low degrees of partial melting at high pressure of relatively water-rich, metasomatized Martian mantle different from the sources of other known Martian basalts.

Many other rocks subsequently analyzed by APXS and ChemCam also are alkali-rich (up to 3 wt % K_2O in Bathurst_Inlet, Figure 1-1; Schmidt et al. 2014). Over the first 100 sols of the mission, ChemCam returned > 10,000 laser-induced breakdown spectra (Meslin et al. 2013), helping to characterize the diversity of local materials. ChemCam's laser acts effectively as a microprobe, distinguishing between fine grains and coarser ~ 1 mm grains. Geochemical variations indicate sediments are mixtures between more primitive (low Si, high Mg, Fe) and evolved, Jake_M-like (high Na, Al) basaltic materials (Schmidt et al. 2014; Sautter et al. 2014; Meslin et al. 2013). Igneous float rocks are dominated by feldspar and pyroxene (Sautter et al. 2014), in contrast to the olivine-dominated mineral composition at Gusev Crater. The regional alkali-rich signature points toward alkaline igneous protoliths (Schmidt et al. 2014; McLennan et al. 2014; Sautter et al. 2014) that might be characteristic of Noachian Martian crust (e.g., McSween et al. 2009), but ultimately derive from an incompatible element-enriched domain of the mantle (Stolper et al. 2013; Schmidt et al. 2014).

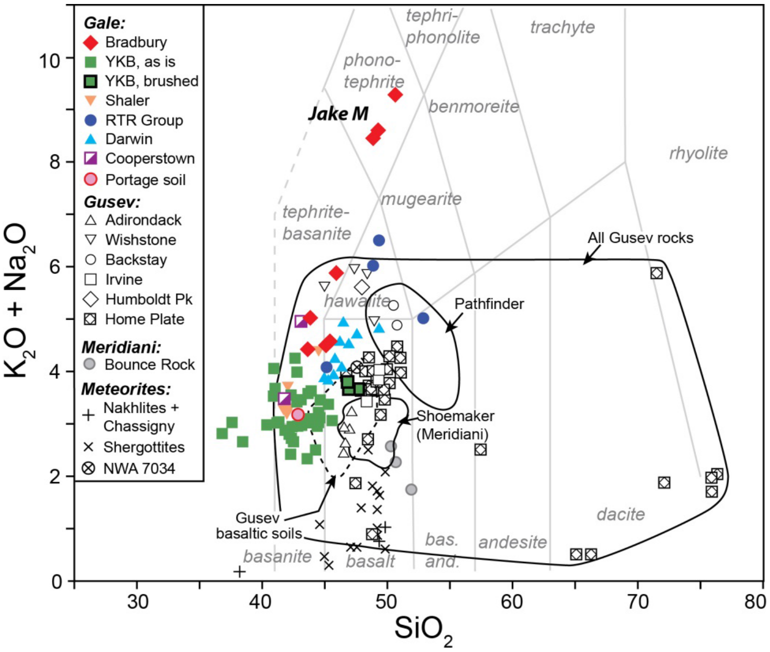

Figure 1-1. *Total alkali versus silica diagram with igneous classification scheme after La Bas et al. (1986). Compositions of Martian rocks (volatile-free) determined by APXS include key bedrock exposures and Portage soil in Gale Crater, relatively unaltered basalts and hydrothermally altered Home Plate rocks from Gusev Crater, and Bounce Rock from Meridiani Planum. Martian SNC meteorites (Shergottites, Nakhlites, Chassignites) are also shown.*

These alkali-rich rocks fundamentally challenge the common perception that the Martian mantle has mainly produced shergottite- or Adirondack-like (low K) basaltic melts (e.g., McSween et al. 2006) and point toward a heterogeneous distribution of alkalis in the Martian mantle. Combined with other mission and meteorite datasets, Gale geochemical data indicate that Mars has produced a diversity of igneous compositions (including some that are uncommon on Earth) and likely will lead to significant revisions to current models of Martian crust-mantle evolution.

Curiosity scooped, processed, and analyzed a small deposit of wind-blown sand/silt/dust (Figure 1-2) at Rocknest that has similar morphology and bulk elemental composition to other aeolian soils studied at other Mars landing sites (Blake et al., 2013). With the first X-ray diffraction (XRD) capability on Mars, the MSL team determined that the Rocknest deposit contains ~ 55% crystalline material of basaltic origin (including plagioclase, olivine, pigeonite, augite, magnetite, quartz, and possibly sanidine), and about ~ 45% X-ray amorphous materials (Bish et al. 2013; Blake et al. 2013). The amorphous component might contain nanophase iron oxide similar to what was observed by earlier rovers. The similarity between basaltic sediment observed at Rocknest and aeolian deposits and soil fines at other Mars sites implies either global-scale mixing of basaltic material or similar regional-scale basaltic source material or some combination of both.

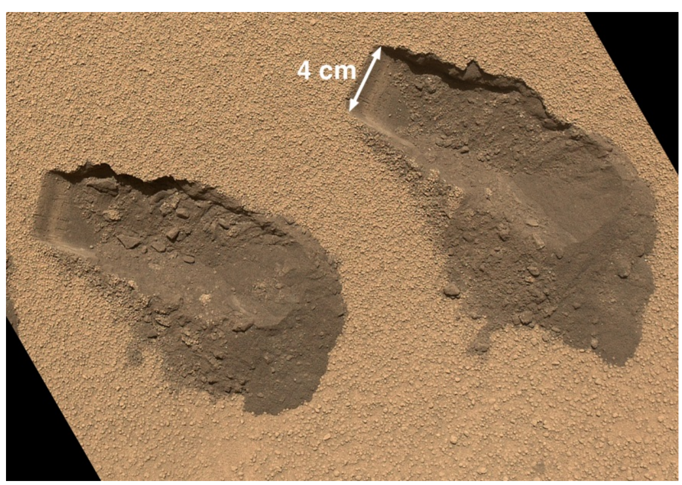

Figure 1-2. *Curiosity used its scoop to collect samples of the Rocknest aeolian deposit. Sand grains 0.5 to 1.5 mm in size armor the deposit's upper surface. These coarse grains are coated with fine dust, giving the deposit an overall light brownish red color. Beneath the coarse sand crust is finer sand, dark brown in color.*

No crystalline hydrated phases were detected by CheMin, while pyrolysis of Rocknest fines using the SAM instrument revealed volatile species, likely in the amorphous component, including H_2O, SO_2, CO_2, and O_2, in order of decreasing abundance (Leshin et al. 2013). The detection of 2% H_2O associated with the globally distributed amorphous component suggests that accessible water is present planet-wide as a resource for future exploration. ChemCam measurements of these materials revealed the presence of H (Meslin et al. 2013). It is likely that H_2O is contained in the amorphous component and CO_2 was liberated via decomposing Fe/Mg carbonates present below the 1–2% XRD detection limit. Isotopic data from SAM indicate that this H_2O, and possibly CO_2 were derived from the atmosphere. SAM analysis also revealed oxychlorine compounds (such as perchlorates) similar to those found by earlier missions, suggesting that their accumulation reflects global planetary processes (Leshin et al. 2013). The detection of perchlorates in the first drilled rock samples analyzed on Mars by SAM will help guide organic detection strategies by Curiosity and future Mars missions.

1.3 Investigation of Yellowknife Bay

1.3.1 An Ancient Habitable Environment

Laboratory analyses and context provided by the remote sensing and contact science instruments determined that early Mars was habitable, and that organic compounds were possibly preserved in the rocks.

Curiosity is designed to test whether ancient aqueous environments had been habitable—in addition to water, did these ancient environments record evidence for the chemical building blocks of life (C, H, N, O, P, S), and chemical/mineralogic evidence for redox gradients that would have enabled microbial metabolism, such as chemoautotrophy? From sols 100–329, Curiosity explored Yellowknife Bay, a topographic depression where it drilled two holes (Figure 1-3) and collected rock powder samples for analysis by the CheMin and SAM laboratories.

Through laboratory analyses and geologic context provided by remote sensing and contact science instruments, we reconstructed the record of an ancient habitable environment that existed at Yellowknife Bay, where stream waters flowed from the crater rim and pooled in a curvilinear depression at the base of Gale's central mountain to form a lake/stream/groundwater system that might have existed for millions of years (Grotzinger et al. 2014b). Vaniman et al. (2014) constrained these aqueous environments to have moderate to neutral pH, as shown by the presence of Fe-smectite clay minerals and absence of acid-environment sulfate minerals. They also showed that the environment had variable redox due to the presence of mixed valence Fe (e.g., magnetite, akaganeite) and S (sulfide, sulfate) minerals formed within the sediment and cementing rock. McLennan et al. (2014) showed that lake salinities were low due to the low concentration of salt in the lake deposits. Elemental data indicate that clay minerals were formed in the lake environment and that minimal weathering of the parent rocks occurred, suggesting that a colder and/or drier climate was prevalent.

Ming et al. (2014) showed that thermally decomposed rock powder yielded NO and CO_2, indicating the presence of nitrogen and carbon-bearing materials. The CO_2 could have been generated by carbonate and the combustion or thermal decomposition of organic materials. Concurrent evolution of O_2 and chlorinated hydrocarbons indicates the presence of oxychlorine species (Figure 1-4). Higher abundances of chlorinated hydrocarbons in the lake mudstones, as compared to modern windblown materials, suggest that indigenous Martian or meteoritic organic C sources are preserved in the mudstone; however, the possibility of terrestrial background sources brought by the rover itself cannot be excluded. These results demonstrate that early Mars was habitable, and possibly that organic compounds were preserved in the mudstone.

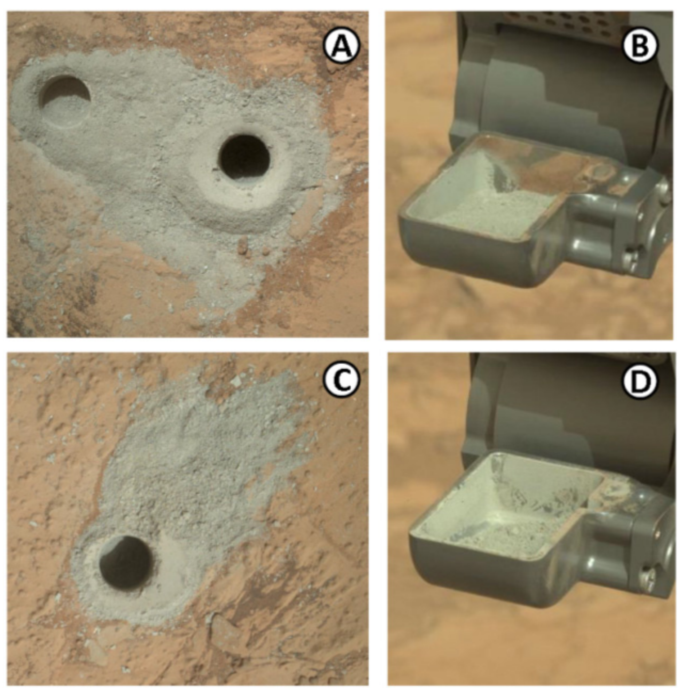

Figure 1-3. *Images of shallow test drill hole (at left in (A)) and sampled drill hole for John Klein, (B) John Klein drill sample in the scoop reservoir, (C) sampled drill hole for Cumberland, and (D) Cumberland drill sample in the scoop reservoir. Notable is the gray color of the subsurface mudstone compared with the reddish weathered surface. Borehole diameters are 1.6 cm. Scoop inner width is 3.8 cm.*

1.3.2 The First In Situ *Planetary Geochronology Experiment*

SAM determined both a cosmogenic (surface exposure) and radiogenic (formation) age from noble gases evolved from the drilled Sheepbed mudstone samples. Farley et al. (2014) showed that the sampled rocks were exposed ~ 80 million years ago, based on cosmic-ray-produced ^{3}He, ^{21}Ne, and ^{36}Ar. The geologic context suggests that wind-driven erosion is the cause of the relatively recent exposure. SAM also measured ^{40}Ar, which decaying ^{40}K produces with a time constant of 1.3 Ga. The bulk K abundance from the APXS measurement of this mudstone completed the information needed to make an age determination of ~ 4.2 Ga. In EM1, this type of experiment could provide critical information on how Mt. Sharp's layers formed.

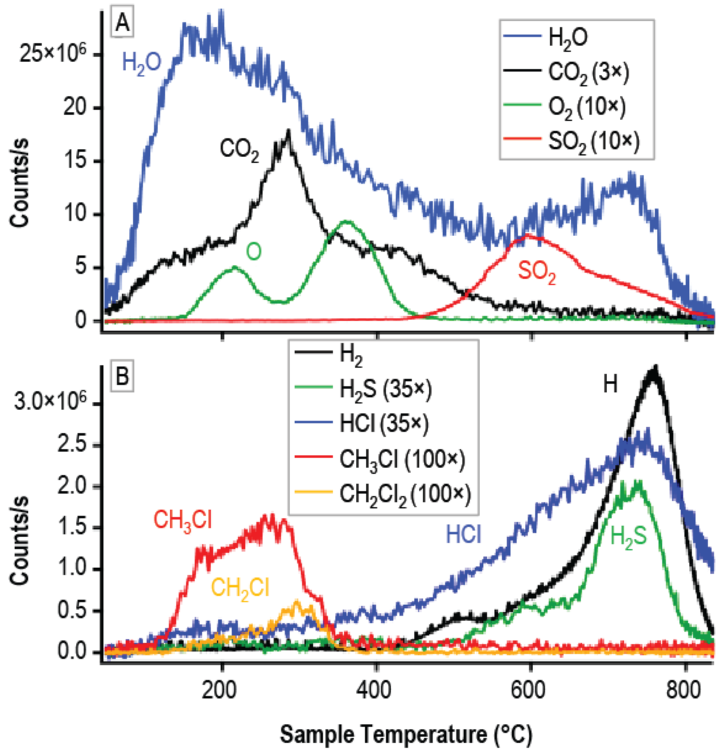

Figure 1-4. *Major (top) and less abundant (bottom) species released from one of the Yellowknife Bay samples. Evident is the high temperature water evolution and presence of oxidized and reduced S compounds. The O_2 peak coincident with the rise and fall of the CO_2 with temperature is suggestive of the combustion of organic compounds (Ming et al. 2014).*

1.3.3 Potential for Preservation of Organic Compounds

The RAD instrument quantified the present-day surface radiation environment at Gale Crater (Hassler et al. 2014), constraining the preservation window for any organic matter in the top few meters of the subsurface. Radiation penetrates this shallow zone, creating a cascade of atomic and subatomic particles that ionize molecules and atoms in their path. Surface radiation observations provide an anchor point for predictive models, with implications for microbial survival times of possible extant or past life, as well as for the preservation of potential organic molecules in ancient strata (Hassler et al. 2014, Farley et al. 2014). Using amino acid degradation rates observed by Kminek and Bada (2006), RAD results imply a ~ 1000-fold decrease in 100 atomic mass unit molecules at 4–5 cm depth in ~ 650 million years, almost half the time modeled by Pavlov et al. (2012).

In light of the surface exposure age of ~ 80 million years, this suggests that preservation of organics accumulated in the primary environment is possible, although the signal would be substantially reduced. Most significantly, for EM1 and future Mars exploration, this series of findings serves as a proof of concept in the search for preserved organic materials and biosignatures on Mars: *geologic mapping can identify places where rocks that record ancient environments have been protected and only recently exposed by ongoing geologic processes.*

1.4 Other Significant Mineralogical and Geochemical Results

The breadth of spectroscopic and analytical capabilities offered by Curiosity's payload have provided a number of additional mineralogical and geochemical results relevant to prime mission science objectives, but not directly related to habitability. These are discussed in detail in Appendix C, along with a comprehensive table of historical accomplishments from the prime mission.

1.5 Insights from Atmospheric Sampling

Atmospheric sampling by the SAM suite has refined knowledge of bulk composition, provided evidence for early atmospheric loss, and set an upper limit on methane.

The SAM quadrupole mass spectrometer (QMS) and tunable laser spectrometer (TLS) have analyzed samples of Mars air throughout Curiosity's mission, starting with the first month following the rover's landing. Both the abundance of volatiles and isotopic ratios of key constituents are measured, providing previously unavailable data critical to atmospheric and climate evolution models, hence the habitability of Mars. Air samples were collected mostly a few hours after sunset; however, some daytime ingestions were performed. Seasons covered were spring, summer, and autumn. We carried out searches for methane using the inter-band cascade laser of the TLS on nine different occasions, widely separated in time. Results from the first six runs have been published, while analyses of the last three are in progress at the time of this proposal submission.

1.5.1 Low Upper Limit on Methane

Six separate sets of measurements from spring to late summer at Gale Crater showed no evidence of methane (Webster et al. 2013a). The current 1.3 ppbv upper limit measured by SAM TLS is far below anything reported in the past. However, the search for methane by Curiosity is continuing, considering its significance to Martian habitability, as well as results from previous observations that reported plumes of methane, localized sources, global averages of 15 ppbv, a maximum of tens of ppbv, and seasonal variability.

1.5.2 Early Loss of Mars's Atmosphere: Noble Gas Isotopes

The SAM QMS has carried out multiple high-precision measurements of the atmosphere's composition to determine the abundance and seasonal variation of principal components, including CO_2, ^{40}Ar, N_2, CO, and O_2. The first of such measurements made in early spring showed that, while there is broad agreement between the SAM data and those obtained by Viking's gas chromatograph/mass spectrometer (GCMS) in 1976, there are also significant differences. SAM measures a volume-mixing ratio (VMR) of radiogenic argon that is 20% greater than Viking, while N_2 is 30% lower (Mahaffy et al. 2013), resulting in a value of $^{40}Ar/N_2 = 1.02$, which is 70% greater than the Viking result (Mahaffy et al. 2013). The throughput of gas enabled by SAM's high-capacity turbomolecular pumping system, as well as the repeated analyses, are likely giving a more accurate view of gas abundances than previous *in situ* measurements.

The new value of the $^{40}Ar/N_2$ ratio suggests a more vigorous outgassing of ^{40}Ar from the interior of Mars than previously recognized. Moreover, the $^{40}Ar/^{14}N$ ratio is frequently used to assess the degree of mixing between the atmospheric and mantle gas components in shocked glass of Mars meteorites. The SAM QMS measures the $^{14}N/^{15}N$ separately using an enrichment technique (Wong et al. 2013). The non-radiogenic argon isotope ratio ($^{36}Ar/^{38}Ar$) (Figure 1-5) places a strong constraint on models of atmospheric loss since approximately 4 Ga ago in the post-hydrodynamic loss phase (Atreya et al. 2013). Nitrogen isotopes give supporting evidence, but might suffer from effects of reservoirs of nitrogen compounds in the crust (Wong et al. 2013).

1.5.3 Atmospheric Loss and Seasonal Variability: CO_2 and H_2O Isotopes

The SAM TLS measurements of the $^{13}C/^{12}C$ and $^{18}O/^{16}O$ in CO_2 (Webster et al. 2013a; Mahaffy et al. 2013) greatly refined the precision from the Viking measurements and superseded values from the limited data set from the Phoenix lander. These isotope ratios are consistent with the D/H (Webster et al. 2013a) and noble gas measurements, all of which point toward significant atmospheric loss (Atreya et al. 2013).

The SAM QMS data so far have shown a clear correlation between CO_2 VMR and surface pressure. They also show, for the first time, seasonal changes in the VMRs of ^{40}Ar and N_2 in the equatorial region (Atreya et al. 2013). ^{40}Ar and N_2 are found to track each other. Previous observations have shown that atmospheric CO_2 undergoes massive condensation over the poles in the winter, followed by sublimation in the summer, leading to a dramatic increase in the relative abundance of noncondensable volatiles over the poles in the winter and reversal in the summer. This annual cycle of volatile migration could be tracked in ^{40}Ar in the Mars Odyssey (ODY) data, but those data did not indicate any seasonal changes in ^{40}Ar in the equatorial region. Mars Exploration Rover (MER) APXS data, on the other hand, seem to imply a seasonal change in ^{40}Ar count rates, but lack of calibration prevents it from obtaining a direct result on the variability of argon abundance. It is important to continue monitoring the seasonal variability trend in all atmospheric volatiles throughout EM1.

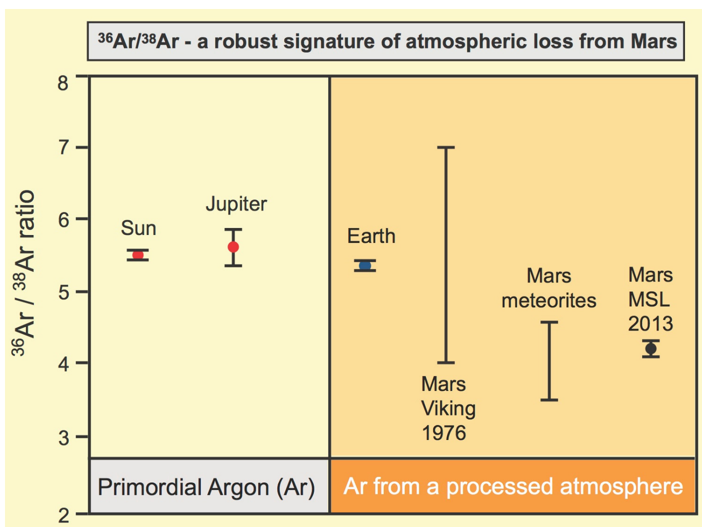

Figure 1-5. *Comparison of the $^{36}Ar/^{38}Ar$ ratio measured in the Martian atmosphere by Curiosity's SAM-QMS in 2013 with the Viking GCMS result in 1976, Mars meteorites, Earth, Jupiter, and the Sun. The low value of Mars is a clear signature of atmospheric loss (Atreya et al. 2013).*

1.6 Meteorology and Climate

A dedicated meteorological package (Rover Environmental Monitoring Station (REMS)) and additional contributions from imaging of opacity, clouds, and aeolian processes (Mastcam and Navcam); column water abundance (ChemCam); subsurface hydrogen sounding (Dynamic Albedo of Neutrons (DAN)), and atmospheric composition (SAM), each capable of sampling seasonally and over the diurnal cycle, result in a data set unprecedented in coverage and breadth. The REMS package (surface pressure, relative humidity, air and ground temperature, UV fluxes, and wind speed and direction) has operated nearly continuously since sol 10, providing ~500 minutes of 1-Hz meteorological data each sol.

These observations (along with support imaging) reveal the seasonal evolution of the diurnal cycle, day-to-day variability, and specific phenomena linked to particular times and/or locations.

Measurements of winds by REMS (Figure 1-6a) constrain a wide range of processes relevant to weather, climate, and geology, such as surface fluxes of heat and moisture, dust lifting and transport, and sand transport and abrasion. The team has begun to exploit the combination of wind measurements with imaging at scales from loose surface fines to the active dunes at the foot of Mt. Sharp. While observed bedforms appear controlled by present-day winds, many abrasional features are not, suggesting different paleocirculations. The diurnal cycle of ground temperatures (Figure 1-6c) is strongly controlled by the degree of lithification of surface materials, but also may show the influence of other factors such as subsurface layering (Hamilton et al. 2014).

Curiosity's location within a deep basin has allowed it to capture unique phenomena in thermally driven pressure tides, aerosols, and boundary layer processes not accessible to previous missions. REMS finds that convective vortices are active mid-day at Gale, but suppression of the boundary layer within the crater likely keeps them from entraining dust and becoming dust devils (Haberle et al. 2014). The amplitude of the daily pressure tide is found to be much larger than at any previous site, largely due to the hydrostatic adjustment flow required to maintain hydrostatic balance. "Evening oscillations" in pressure (Figure 1-6b) are linked to gravity waves triggered as strong downslope flows develop after sunset. REMS relative humidity data (Figure 1-6d) show the atmosphere remains unsaturated even when temperatures are coolest just before dawn. DAN finds that the regolith 10–20 cm below the

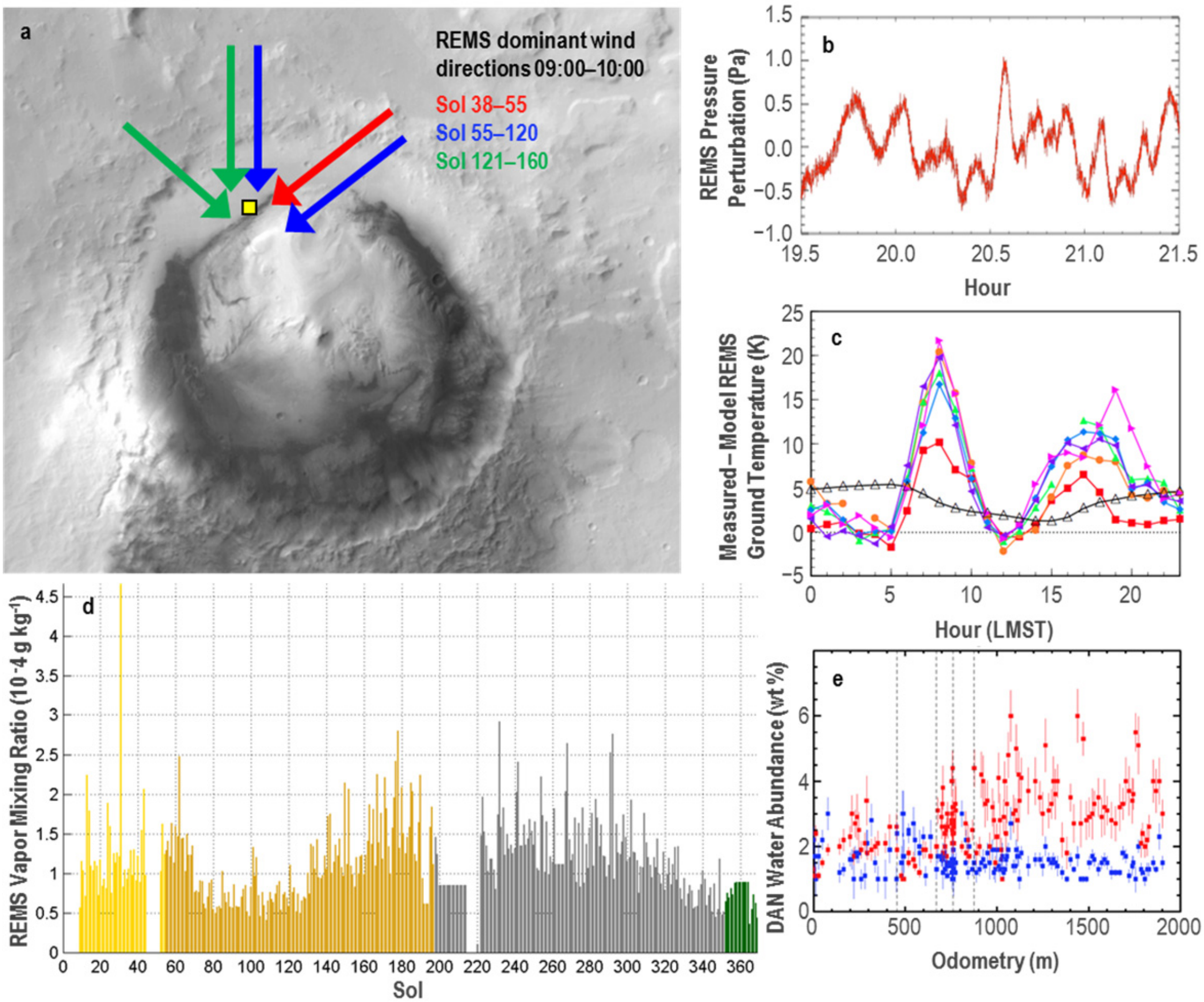

Figure 1-6. *(a) REMS dominant wind directions from 09:00–10:00 for three periods. (b) Typical evening (19:30–21:30) REMS pressure perturbation (to a quadratic fit to a smooth pressure curve, in Pa) showing the "evening oscillation" (Haberle et al. 2013b). (c) Difference between measured (REMS) and modeled diurnal ground temperature cycle (in K) used to infer likelihood of subsurface layering (Hamilton et al. 2014). (d) Evolution of vapor pressure (in 10^{-4} g/kg) derived from REMS relative humidities over the first ~ 360 sols. (e) Evolution of top and bottom layer water content (wt %) inferred from DAN active data assuming two-layer model of subsurface water.*

surface retains more water due to its relative isolation from the diurnal thermal wave (Figure 1-6e).

1.7 Mars's Radiation Environment

During the cruise to Mars, the RAD instrument obtained ~ 7 months of unprecedented measurements of the radiation environment inside the shielding of the MSL spacecraft, providing insight into the radiation hazards for astronauts during cruise on future crewed missions to Mars (Zeitlin et al. 2013). These results show that the radiation dose equivalent is dominated by galactic cosmic rays (GCR) with roughly 5% of the observed total dose due to solar energetic particles (SEP), even though five SEP events were observed. Actual astronaut exposures will depend on the habitat shielding and the rate of large SEP events. Measurements of the radiation environment on the Martian surface are important not only for validating radiation transport models and preparing for future human exploration, but also for understanding the limits to preserving organic molecules and providing constraints to estimates of microbial survival times (§1.3). RAD observations of total dose and dose equivalent rates (Hassler et al. 2014) are turning out to be highly variable, with total dose rate anticorrelated with atmospheric pressure, but neutron dose rate positively correlated with pressure. From a human exploration point of view, the RAD surface measurements, together with the RAD cruise measurements, provide representative observations corresponding to all three phases (outbound interplanetary journey, Mars surface stay, and return journey) of a human Mars mission at this time in the current solar cycle (i.e., solar maximum of a weak cycle).

2 Science Objectives for the Mission to Mt. Sharp

The science of EM1, in a nutshell:

- *The diverse layers of sedimentary rock exposed in the foothills of Mt. Sharp will guide our understanding of what environmental factors may have enhanced the habitability of Mars as a young planet and, within those environments, what factors may lead to preservation of organic carbon.*
- *The four major layers targeted in EM1 have likely recorded a very broad range of environmental conditions, and therefore promise variation in habitability and potential for organic preservation. However, these ideas derive from incomplete orbiter data and Earth-based experience;* in situ *analyses and sampling are required to test them.*
- *By studying each of the four layers (and potentially others), MSL will observe transitions between habitable and uninhabitable environments, see the spectrum of conditions that favor or preclude organic preservation, and seek to link those to the environmental history of Gale Crater, as a sample of the planet's early history.*

At the start of EM1, we anticipate being close to Murray Buttes—an entry point to the rocks of greatest interest at the base of Mt. Sharp (Figure 2-1). Curiosity will continue its exploration at the foothills of Mt. Sharp, where orbiter data predict vast tracts of layered hydrated phyllosilicate and sulfate-bearing strata to occur, along with hematitic rocks, and other rocks of unknown composition and nonlayered texture. Although we have already discovered hydrated phyllosilicate and sulfate minerals, the Mission to Mt. Sharp will allow us to test the hypothesis that such mineral suites may characterize different kinds of habitable environments, as well as study transitions and break points between combinations of habitable and uninhabitable environments.

Curiosity and her science team are now experienced in identifying and assessing habitable environments (Grotzinger et al. 2009; 2012; 2014a; 2014b). However, we are only beginning to sense what is required to understand distribution of organic carbon on Mars. As noted in the 2012 Decadal Survey, characterizing carbon cycling and prebiotic chemistry is a necessary objective in determining whether life arose on Mars. In addition, a search for organic carbon will aid our understanding of how organic compounds are preserved in rocks, which could provide guidance to narrow down where and how to find fossil biological materials. We will make the search for organic carbon a focus of our exploration campaign at Mt. Sharp, as expressed in the first of two new science objectives for EM1 (Tables 1-1 (9), 2-1). This is a very important step forward for Mars scientific exploration, as we expect that the geochemical/environmental factors controlling preservation have only modest overlap with those that regulate habitability (Summons et al. 2011). Just as liquid water is a necessary but insufficient criterion for habitability, past habitability is a necessary but insufficient criterion for modern discovery of traces of ancient life. We will search for the subset of habitable environments that preserve complex organic molecules.

A major factor in selecting the Gale Crater landing site was the hypothesis that the varying textures and mineralogy of Mt. Sharp's lower rock layers recorded the most important transitions in Mars's planetary and climatic evolution (Milliken et al. 2010). Given the strong influence of the environment on habitability and potential for preservation of organics, our second new objective for EM1 is to characterize these major environmental transitions (Tables 1-1 (10), 2-1). Curiosity also will continue to address the existing science objectives that trace to the Decadal Survey goals of the potential for life on Mars, understanding the nature and evolution of the geological processes that have created and modified the Martian crust over time, the present atmosphere and climate, and the ancient climate. *Through a dedicated search for habitable environments and organic carbon, the Mission to Mt. Sharp will explore what geological settings and environmental conditions are conducive to preservation.*

Table 2-1. *Science traceability matrix (STM) for all options.*

2012 Decadal Goals & Obj.		MSL EM1 Science Objectives (# from Table 1-1)	Associated Measurement and Relevant Instruments	Mission Constraints
Determine if Life Ever Arose on Mars	Assess the past and present habitability of Mars Assess whether life is or was present on Mars in its geochemical context Characterize carbon cycling and prebiotic chemistry	(2) Determine the mineralogy and chemical composition of surface and near-surface materials (including C, H, N, O, P, S) (3) Determine energy sources that could be used to sustain biological processes (4) Characterize organic compounds and potential biomarkers in representative regolith, rocks, and ices (6) Identify potential bio-signatures (chemical, textural, isotopic) in rocks and regolith	**Mastcam, MAHLI, MARDI:** geology and geomorphology at micrometer to landscape scales **SAM:** chemical and isotopic composition of rocks/fines; identification and abundance of carbon compounds **CheMin:** mineralogy of rocks/fines **APXS and ChemCam:** elemental chemistry of rocks/regolith **RAD, DAN, and REMS:** characterization of surface UV and high-energy radiation; rate of radiation-induced modification of regolith	Access to multiple* geologic units on Mt. Sharp and surrounding plains Remote sensing, *in situ* study, and sampling of environments with high potential for habitability, e.g., clays and sulfates At least two samples of each unit
		(9) Identify and quantitatively assess that subset of habitable environments that also is capable of preserving organic compounds (10) Explore and characterize major environmental transitions recorded in the geology of the foothills of Mt. Sharp and adjacent plains	**SAM:** determination of surface exposure age **Mastcam, ChemCam, MAHLI, APXS, CheMin, SAM:** geologic history; chemistry and mineralogy; refined models for primary facies distributions and diagenesis	
		(7) Characterize the broad spectrum of surface radiation, including galactic cosmic radiation, solar particle events, and secondary neutrons	**RAD, DAN, and REMS:** characterization of surface UV and high-energy radiation; rate of radiation-induced modification of regolith	Continuous diurnal and seasonal monitoring
Understand the Processes and History of Climate	Characterize Mars's atmosphere, present climate, and climate processes under both current and different orbital configurations Characterize Mars's ancient climate and climate processes	(5) Determine stable isotopic and noble gas composition of the present-day atmosphere and of ancient H_2O and CO_2 preserved in hydrated minerals	**SAM:** abundance and isotopic composition of CO_2, H_2O, CH_4, D/H, and noble gases in atmospheric samples and in gases evolved from hydrated minerals	Multi-seasonal atmospheric sampling Sampling of multiple* geologic units
		(8) Characterize the local environment, including basic meteorology, the state and cycling of water and CO_2, and the near-surface distribution of hydrogen	**REMS:** systematic measurements of pressure, winds, ground and air temperature, relative humidity, and UV flux **Mastcam:** atmospheric opacity **Mastcam and MAHLI:** relic and modern aeolian processes **DAN and ChemCam:** near-surface hydrogen; column water and ozone in atmosphere	Continuous diurnal and seasonal monitoring
Determine the Evolution of the Surface and Interior	Determine the nature and evolution of the geologic processes that have created and modified the Martian crust over time	(1) Characterize geological features, contributing to deciphering geological history and the processes that have modified rocks and regolith, including the role of water	**Mastcam, MAHLI, MARDI:** geology and geomorphology at micrometer to landscape scales **SAM, CheMin, APXS, ChemCam, and DAN:** assessment of rocks/regolith; determination of alteration products and history **SAM, CheMin:** chemical, isotopic, and mineralogical composition of rocks/fines, including aqueous and diagenetic components	Access to multiple* geologic units identified from orbit Remote science, *in situ* study, and sampling

**The number of geologic units accessed depends on the mission option selected. The Science Floor (Descope) option accesses two units, the Guideline option accesses three units, and the Optimal Science (Overguide) option accesses four units.*

Finally, the type of habitable environments discovered at Yellowknife Bay, and those that might be present at Mt. Sharp, have broader implications for Mars beyond Gale Crater. They suggest that other post-Noachian fluvial-deltaic sedimentary sequences on Mars might also have preserved habitable environments. This therefore increases the overall prospects for missions oriented toward sample return and potential *in situ* biomarker/life detection. We are beginning to learn how to explore, deliberately, for materials that are known to be difficult to preserve even on Earth. Building this understanding is the central focus of EM1.

2.1 Beyond Habitability: Taphonomy and the Search for Organic Carbon

In EM1, the MSL mission will evolve from a mission seeking to understand the habitability of ancient Mars, to a mission focused on developing predictive models for the preservation of Martian organic matter.

The first few billion years of the planet's geologic history shows surface environments considerably different from those today. As described in §1, Curiosity was designed and built to explore for these materials and thus potentially delineate one or more habitable environments at the Gale Crater landing site. The habitable environment discovered at Yellowknife Bay provides one example.

The diverse assemblage of rocks at the base of Mt. Sharp offers opportunities to study different types of habitable environments. For example, they may differ in geologic age, perhaps having formed hundreds of millions of years before the rocks at Yellowknife Bay, assuming they stratigraphically underlie the Yellowknife Bay formation (Note: the other ordering also is possible, which we will test at and around Mt. Sharp). Understanding which of the rock units at Mt. Sharp may most likely harbor organic compounds is a critical aspect of EM1. Just because the environment may have been habitable does not mean it also preserved organic carbon, even if it was there to begin with.

Scientists studying the reasons for destruction of organic matter in ancient rocks address this challenge through the discipline of "taphonomy," which seeks to understand the process of preservation of materials of potential biologic interest (Summons et al. 2011). On Mars, a first step would involve detection of complex organic molecules, and either an abiotic or biotic origin would suffice; the point is that organic molecules are reduced and the planet is generally regarded as oxidizing, and so the preservation of any kind of complex organic compounds requires special conditions. For success on Mars, several processes must be optimized (Grotzinger 2014a): Primary enrichment of organics must first occur; their destruction should be minimized during the conversion of sediment to rock; and exposure of sampled rocks to ionizing radiation should be limited. The third is a unique challenge at Mars, since Earth's thick atmosphere and magnetic field greatly reduce incoming radiation. Curiosity can directly measure both the modern dose of ionizing cosmic radiation (Hassler et al. 2014), as well as the accumulated dose for the interval of time that ancient rocks have been exposed at the surface of Mars (Farley et al. 2014).

Sediments that were buried and lithified beneath the radiation penetration depth, along with organic molecules, would eventually be exhumed by erosion and exposed at the surface. During exhumation, organics would become subject to radiation damage as they entered the upper few meters below the rock/atmosphere interface. The timescale of erosion and exhumation, and thus the duration that any parcel of rock is subjected to ionizing radiation, can be determined by measuring cosmogenically produced noble gas isotopes that accumulate in the rock. ^{36}Ar is produced by the capture of cosmogenic neutrons by Cl, whereas ^{3}He and ^{21}Ne are produced by spallation reactions on the major rock-forming elements. Farley et al. (2014) showed that the sampled rocks at Yellowknife Bay were exposed relatively recently, on the order of ~ 80 million years ago, suggesting that preservation of any organics that accumulated in the primary environment was possible, although the signal might have been substantially reduced.

Wind-induced erosion of rocks in Yellowknife Bay appears to have been the mechanism responsible for erosion and exhumation of the ancient lakebed sampled by Curiosity. The geomorphic expression of this process is a series of rocky scarps that retreated in the downwind direction. Understanding this process leads to the prediction that *rocks closest to the scarps were most recently exhumed and thus most likely to preserve organics, all other factors being equal*. The foothills of Mt. Sharp reveal numerous scarps and larger buttes, all of which seem to have formed by wind-induced erosion. In this manner, the MSL mission appears to be on the cusp of evolving from a mission initially seeking to understand the habitability of ancient Mars (and doing it successfully), to one focused on developing predictive models for the preservation of Martian organic matter. This is not just important for the continued success of MSL, but also for the proposed Mars 2020 mission, which would seek to find promising materials for possible return to Earth. We intend to apply this developing exploration paradigm in searching for organics at Mt. Sharp.

2.2 Specific Targets for Exploration

Interpretations of orbital imagery and spectra provide a framework for exploring Mt. Sharp. While uncertain, the data predict a range of potential for habitability and preservation of organic materials.

Murray Buttes, near the EM1 starting point, represents the transition from rocks that comprise the crater plains, to those that define the base of Mt. Sharp (Figure 2-1), which exhibit changes in a lithologic succession of strata (Milliken et al. 2010) consistent with transitions in aqueous and climatic conditions proposed to be global in scale. The succession exhibits a net transition in mineralogy from hematite/clay mineral → clay mineral/sulfate → sulfate/oxide assemblages and is separated from overlying anhydrous strata by an erosional unconformity. Superposition and crater counts suggest that the hydrated strata lie along the Noachian-Hesperian boundary, whereas overlying apparently anhydrous strata, resting above the unconformity, may be considerably younger. The observed stratigraphic trends are consistent with the rocks at Gale Crater, recording a global transition from a climate favorable to clay mineral formation to one more favorable to forming sulfates and other salts. Rocks juxtaposed by the unconformity might represent the transition from a wetter Mars to a drier Mars.

Given lower Mt. Sharp's unique attributes, we have identified four primary targets of opportunity to be explored by Curiosity in EM1, in ascending stratigraphic order: (1) the paintbrush unit, (2) the hematite ridge, (3) the clay-bearing trough, and (4) the mixed sulfate-clay unit. Each might represent a different ancient habitable environment or a different taphonomic setting for preserving organics, if any were initially deposited. To explore them all requires an elevation gain of several hundred meters and a drive distance of ~ 8 km, a distance similar to that achieved in the prime mission (§3.3.7.1).

A well-defined network of incised valleys transects these strata, providing a number of potential ascent routes that appear navigable based on orbital imagery and topography (Grotzinger et al. 2012). In one case, a fan-like feature is present that backfills the incised valley (Anderson and Bell 2010). Stratigraphically, this fan appears to downlap across the contacts marking the hematite/clay and clay/sulfate units. This feature would therefore be younger than those rocks, and indeed younger than the main phase of erosion of Mt. Sharp, which exposed those strata. If aqueous in origin, it may well indicate a much younger phase of water activity on Mars, and possibly habitability as well. Examination of this feature would help establish the mechanism(s) by which Mt. Sharp was formed and sculpted.

2.2.1 Paintbrush Unit: the Enigmatic Base of Mt. Sharp

The paintbrush unit derives its name from its distinctive texture, as seen from orbit in High Resolution Imaging Science Experiment (HiRISE) image data. It is over 100 m thick and lacks any evidence of the simple layering that is so ubiquitous in other rock formations of Mt. Sharp, Yellowknife Bay, and the plains in between. The unit has higher thermal inertia values compared to overlying stratigraphic units, and sparse detections of hematite, sulfate, and possibly other minerals (Figure 2-1a–c). Locally, there are suggestions of steeply to even vertically dipping, folded strata (Figure 2-1b). This complexity results in a patchy texture, with streaks reminiscent of paintbrush strokes at various trends. Based on this limited information, it is possible that these rocks form a completely different rock package from what overlies them; possibly, it represents an older sequence of stratified rocks that has been complexly deformed, possibly by impact events along an unconformity surface, before being overlain by undeformed strata. Alternatively, it may represent something like slump-folded fine-grained rocks, such as mudstones. It seems unlikely to be crater central peak or peak ring material because it is off-axis and at an elevation higher than what might be predicted. However, each of these hypotheses is testable with Curiosity.

Sampling the paintbrush unit would allow us to assess the peculiar nature of lowermost Mt. Sharp. After landing, our team's mapping effort (Grotzinger et al. 2014b) identified this unit as something distinctive that had not been widely discussed before landing site selection. As described above, it is massive to possibly fractured, or features strongly deformed bedding. The origin of this unit is uncertain, but it conceivably represents much older bedrock, and possibly an unconformable surface beneath the overlying hematite unit. Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) data (see Figure 2-2) suggest that hematite, silica, and/or clay minerals may be present in these rocks; however, these signals are not as strong as in overlying units.

2.2.2 Hematite Unit: an End Member for Habitability and Preservation?

A hematite ridge-forming unit (Fraeman et al. 2013) apparently overlies the paintbrush unit. CRISM data show the location of red crystalline hematite within a geomorphic ridge that extends laterally ~ 6.5 km (Figure 2-2c). Iron oxide minerals are most concentrated at the top of the ridge, which makes a very specific target. Ridge-forming strata are finely layered and contrast strongly with underlying massive and paintbrush-textured rocks (Figure 2-1c). Clay minerals stratigraphically overlie the hematite-bearing strata. Emplacement of the hematite is hypothesized to result either from exposure of anoxic Fe^{2+}-rich groundwater to an oxidizing environment, leading to precipitation of hematite or its precursors, or from in-place weathering of precursor silicate materials under oxidizing conditions. These hypotheses and implications for habitability will be testable with Curiosity.

Fraeman et al (2013) hypothesize a redox gradient stabilized in a groundwater system, which might have supported microbial metabolism. Today the rocks have been eroded, revealing this redox front as the erosionally resistant hematite ridge. The hematite is not strongly associated with sulfates as was the case at Meridiani (McLennan et al. 2005) and so it is possible that this represents a different kind of aqueous environment, with different habitability potential (Knoll and Grotzinger 2006). In terms of taphonomy, iron oxide is generally not ideal for preservation of organics, and hematite in particular is especially problematic (Sumner 2004). Nevertheless, this unit may form an important end member for Mars as we learn to decode the recipe for what kinds of habitable environments may also preserve organics. Therefore, we propose to sample and study it with Curiosity's full payload.

2.2.3 Clay Mineral-bearing Unit (Clay Unit): Promising, but Unexplored

The "clay unit" refers to clay mineral-bearing strata that occur as thin, recessive beds (Figure 2-1d), without reference to grain size. Clay mineral signatures are most consistent with Fe smectite (nontronite; Milliken et al., 2010) and are confined to a stratigraphic interval ~ 20–30 m thick (Figure 2-1c). Whether or not these clay minerals are authigenic, as at Yellowknife bay, or detrital and derived from older rocks is uncertain. Curiosity will need to explore the clay unit to resolve this question. However, using the same approach applied to the Sheepbed mudstone, we hope to make this distinction. In either case, clay minerals do offer the prospect for greater preservation potential of any organics that might have accumulated along with the sediments (Summons et al. 2011).

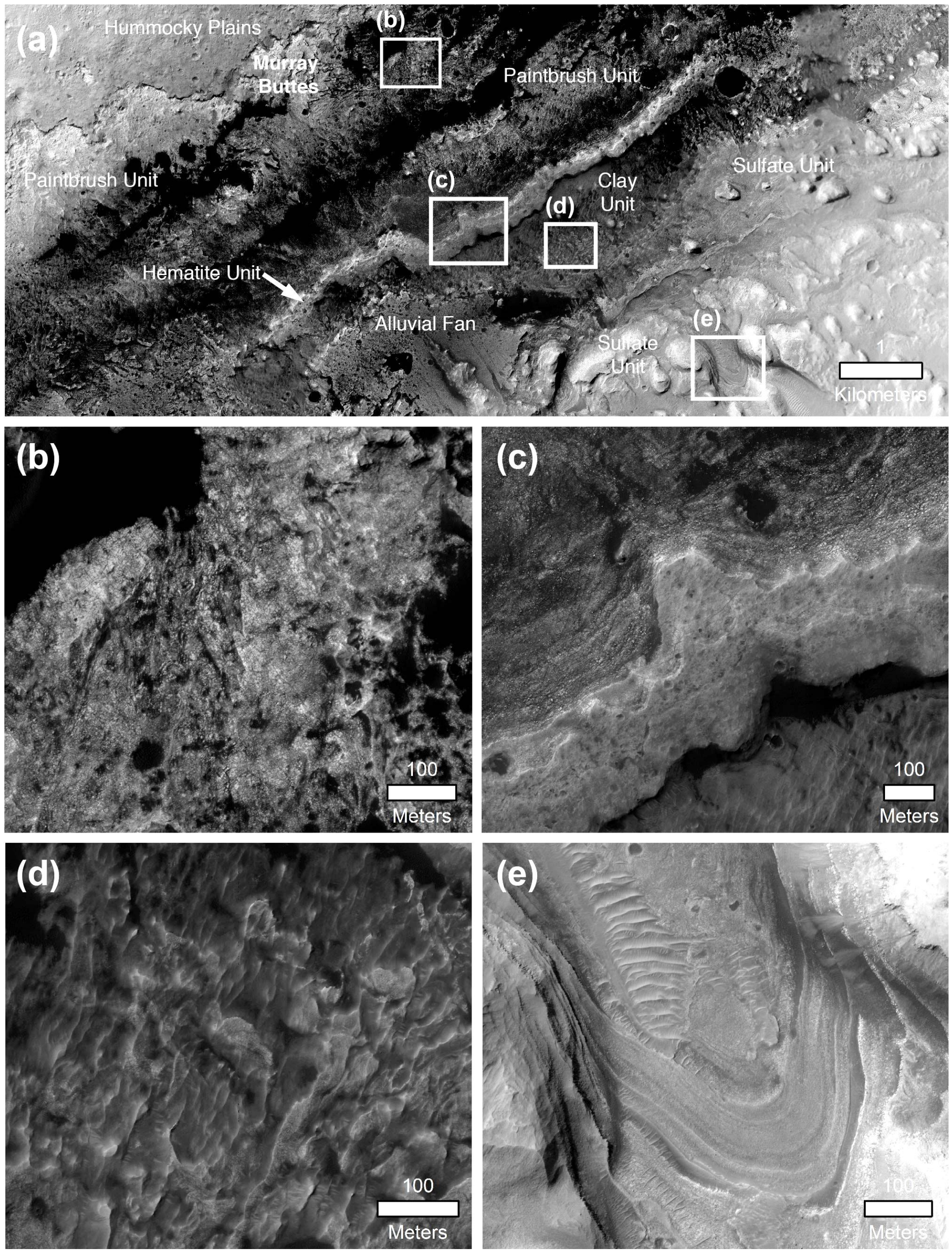

__Figure 2-1.__ Morphogeology of the foothills of Mt. Sharp. Curiosity will enter the region near Murray Buttes and then traverse and sample the paintbrush unit (a, b), the hematite unit (ridge; a, c), the clay unit (a, d), and sulfate unit (a, e).

Clay minerals are generally regarded as favorable exploration targets for habitability and preservation of organics. In terms of habitability, at Yellowknife Bay, they indicate relatively neutral pH, which opens the range of possibilities for potential microbial metabolisms. Beyond that, it would be difficult to predict more from orbit since we have insufficient data to constrain paleowater salinity and determine what redox gradients might have existed in the sediments. Clay minerals also suggest increased potential for a taphonomic window into unusual conditions for preservation of organics. It is noteworthy that the clay unit is quite thin, and a relatively rare occurrence on Mt. Sharp. This occurrence of clay minerals at Gale Crater has a very different context from that at Yellowknife Bay, where smectite clays were associated with calcium sulfates and magnetite rather than hematite and magnesium sulfates. Consequently, we strongly advocate sampling the clay unit in Curiosity's search for habitable environments and preservation of organics.

2.2.4 Sulfate (and Mixed Clay-Sulfate) Unit: A Major Change in Environment

Sampling across the clay-sulfate transition is an extraordinary opportunity to test models of taphonomy and environmental history.

The stratigraphic interval bearing magnesium sulfates is the thickest of the entire succession, extending upward for over 400 m. These rocks are more thickly bedded (Figure 2-1e) than the clay mineral-bearing strata and are laterally continuous over at least several tens of kilometers. The spectra for strata in the lower part of the unit indicate the presence of both clay minerals and sulfate, though whether these rocks are sulfate cemented clay minerals or alternating thin beds of clay minerals and sulfate cannot be determined at the spatial resolution of CRISM (Milliken et al. 2010). Spectra of both mono and polyhydrated sulfates are observed and the lack of strong ferrous absorptions in the former suggest it is likely the Mg variety kieserite ($MgSO_4 \cdot 1H_2O$; Figure 2-2c). Similarly, spectra of the polyhydrated sulfates are inconsistent with Ca varieties and lack strong Fe absorptions, suggesting they are likely Mg sulfates. We have also observed crystalline ferric oxide (hematite) in some of the sulfate layers (Figure 2-1d).

Reaching this unit would require a complete traverse through the most important aqueously formed and altered units, as well as transitions between those units. With regard to taphonomy, transitions are important, as environmental gradients are usually steepest when preserved in rocks, as are geochemical energy gradients that might have regulated microbial metabolism. Therefore, detailed sampling across such a transition is an extraordinary opportunity never before attempted on Mars.

2.3 Atmospheric and Environmental Monitoring During EM1

EM1 will extend the temporal and geographic coverage of Curiosity's environmental monitoring (REMS, RAD, DAN, and ChemCam passive spectroscopy). Multiple years of data are necessary to understand the extent of interannual variability and the impact of irregular events such as major dust storms (not yet observed by Curiosity) and solar energetic particle events. As the rover approaches Mt. Sharp and begins to climb, meteorological sensors will access new circulations and slope flow phenomena, providing insight into how aeolian processes may have affected the formation and evolution of Mt. Sharp itself.

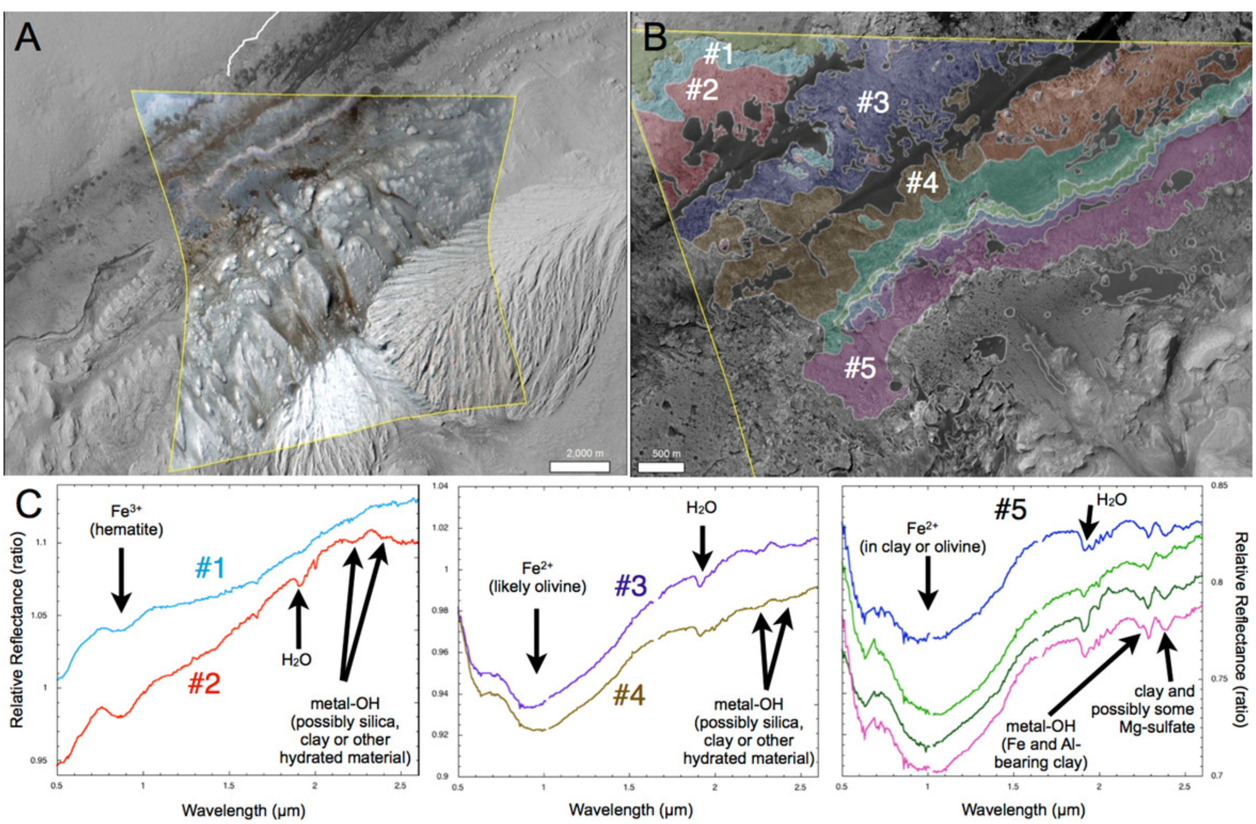

Figure 2-2. *Spectral geology of Mt. Sharp. (a) Location of CRISM hyperspectral image across foothills of Mt. Sharp. (b) Close-up of northwestern corner of CRISM image, showing location of key mineral detections, #1, #2 suggest presence of hematite, silica and/or clay minerals in paintbrush unit; #3, #4, suggest presence of olivine and possibly silica or clay minerals in the paintbrush unit. #5 indicates presence of clay minerals in the clay unit, as well as suggestions of Mg-sulfates. Data not shown here indicates clay unit (mixed with some sulfates) is overlain by sulfate unit (mixed with some clay minerals).*

There are many opportunities to build on Curiosity's unprecedented compositional studies of Mars's atmosphere, some of which involve instrument capabilities not exercised in the prime mission. Considering the importance of methane as a potential sign of past or current microbial life on Mars, we propose to continue monitoring methane throughout EM1 to look for temporal, seasonal, sporadic, or local changes in methane abundance at Gale Crater. Moreover, methane pre-enrichment by QMS is essential for measuring trace amounts of methane and to constrain the production loss and release mechanisms of any methane on Mars. In the event of detections at a level of 10 ppbv or greater, the pre-enrichment experiment may also allow a measurement of carbon isotopes ($^{13}C/^{12}C$) in methane (Mahaffy et al. 2012), which would help discriminate between biological and geologic production of methane on Mars (Atreya et al. 2007), especially when combined with other relevant SAM and MSL observations.

Although the SAM measurements of CO_2 isotopes are robust, they cover a limited time period. The D/H isotope ratio has an uncertainty of ± 20% because only a single direct atmospheric measurement has been made to date. Furthermore, the CO_2 and H_2O cycles on Mars are complex because of exchange of atmospheric component with surface and interior reservoirs and escape from the top of the atmosphere. These could lead to variability in CO_2 and H_2O isotope abundances over the short term including diurnal and seasonal changes, and over longer time spans. To fully understand these processes and construct a convincing scenario of Mars climate evolution, it is essential to develop a comprehensive database of the CO_2 and H_2O isotopes in the atmosphere together with those in evolved gas from solid samples throughout EM1. In order to capture this concept more comprehensively in the mission's requirements, we have revised existing science objective #5 to include the isotopic analyses of evolved gases in solid samples (Table 1-1).

In order to understand volatile evolution and atmosphere-interior coupling, it is desirable to continue monitoring nitrogen and radiogenic argon isotopes throughout EM1. To understand loss of atmosphere in the hydrodynamic loss phase prior to 4 Ga ago, however, it is essential to measure the isotopes of xenon, as any fractionation in this heavy gas would have occurred only in that phase, not after. Measuring xenon and its isotopes requires a special enrichment method (Mahaffy et al. 2012) not yet implemented on Mars during SAM operations. A complete scenario of the loss of atmosphere from Mars from its early geologic history requires measurements of xenon isotope, combined with isotopes of another heavy noble gas, krypton, as well as the $^{36}Ar/^{38}Ar$ ratio and the stable isotopes of C, N, and O. Even though the precision heavy noble gas measurements are challenging to implement *in situ*, their significance for understanding the Mars's climate history is profound, so it will be important to repeat these measurements periodically for robustness throughout EM1. Finally, combining the atmospheric isotope data taken by Curiosity from the surface of Mars with the isotope data to be collected by the Mars Atmosphere and Volatile Evolution (MAVEN) mission in the upper atmosphere will provide unprecedented insight into the processes of diffusion of volatiles through the atmosphere and their escape from the top of the Martian atmosphere.

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