



Report of the iMOST Study

Sept. 11, 2018

International MSR Objectives and Samples Team (iMOST)

D. W. Beaty, M. M. Grady, H. Y. McSween, E. Sefton-Nash (co-chairs), B. L. Carrier (documentarian), F. Altieri, Y. Amelin, E. Ammannito, M. Anand, L. G. Benning, J. L. Bishop, L. E. Borg, D. Boucher, J. R. Brucato, H. Busemann, K. A. Campbell, A. D. Czaja, V. Debaille, D. J. Des Marais, M. Dixon, B. L. Ehlmann, J. D. Farmer, D. C. Fernandez-Remolar, J. Filiberto, J. Fogarty, D. P. Glavin, Y. S. Goreva, L. J. Hallis, A. D. Harrington, E. M. Hausrath, C. D. K. Herd, B. Horgan, M. Humayun, T. Kleine, J. Kleinhenz, R. Mackelprang, N. Mangold, L. E. Mayhew, J. T. McCoy, F. M. McCubbin, S. M. McLennan, D. E. Moser, F. Moynier, J. F. Mustard, P. B. Niles, G. G. Ori, F. Raulin, P. Rettberg, M. A. Rucker, N. Schmitz, S. P. Schwenzer, M. A. Sephton, R. Shaheen, Z. D. Sharp, D. L. Shuster, S. Siljeström, C. L. Smith, J. A. Spry, A. Steele, T. D. Swindle, I. L. ten Kate, N. J. Tosca, T. Usui, M. J. Van Kranendonk, M. Wadhwa, B. P. Weiss, S. C. Werner, F. Westall, R. M. Wheeler, J. Zipfel, M. P. Zorzano

Notes

- *This document is the PPT representation of a large text-formatted report (“The Potential Science and Engineering Value of the Samples that Could be Delivered to Earth by Mars Sample Return”). In case of discrepancies, the text report should be interpreted as superior.*
- *This study was sponsored by the International Mars Exploration Working Group (IMEWG).*



Introduction to This Study

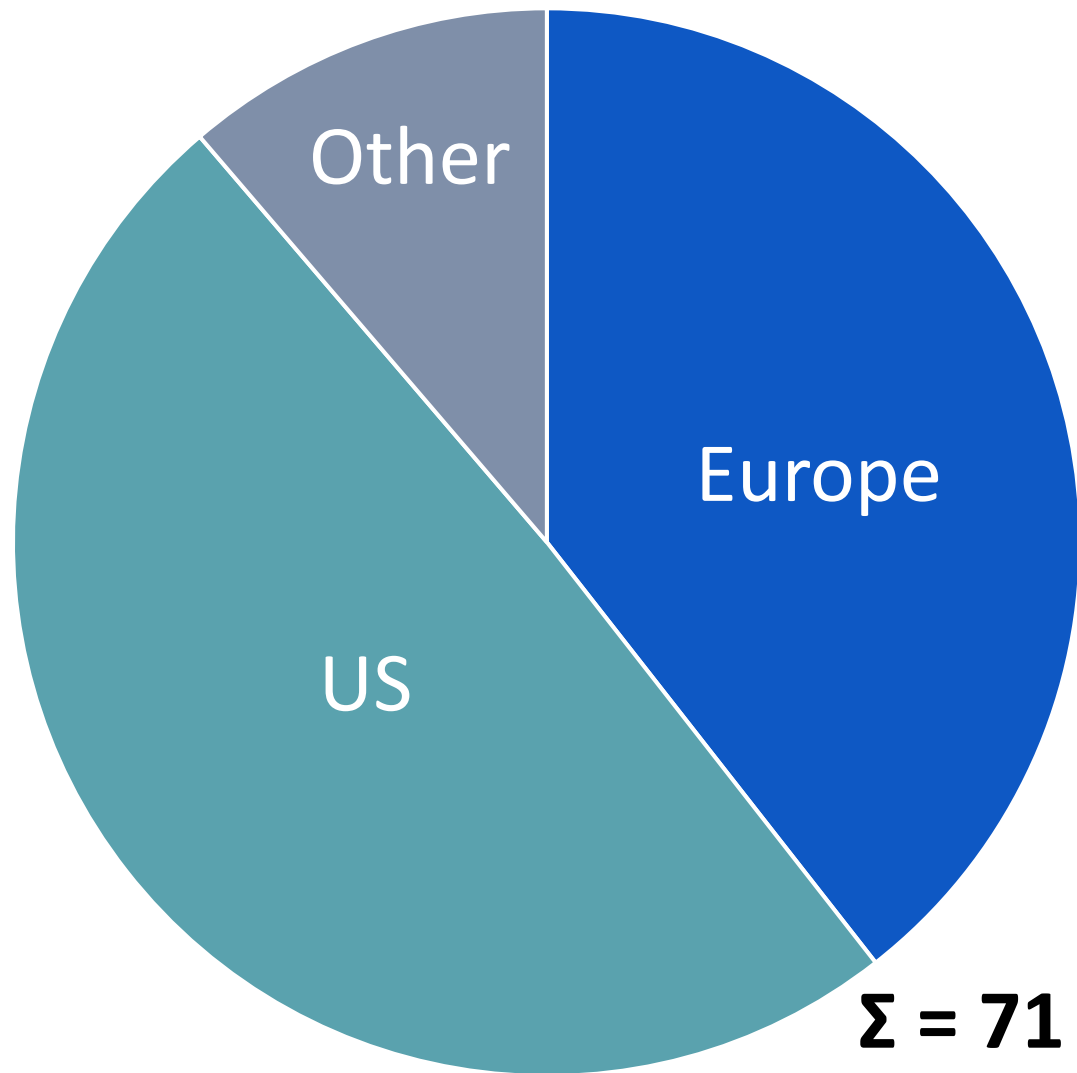
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- The iMOST study was chartered in November, 2017 by the International Mars Exploration Working Group (IMEWG) to assess the **expected value of the samples** to be collected by the M-2020 rover. Included is a request to:
 - **Update the proposed scientific objectives** of Mars Sample Return (MSR)
 - Map out the **kinds of samples** that would be desired/required to achieve each of the objectives, and the implied **measurements** on the returned samples
- Guided by the science community's already established priorities for Mars science
- The existence of the M-2020 sample-caching rover, and the interest of key space agencies in completing the transportation missions of MSR, makes the forward planning scenarios **much more specific and tangible**.



International Participation, iMOST Study

International MSR Objectives & Samples Team



Countries Represented	
Australia	Netherlands
Belgium	Norway
Canada	Spain
France	Sweden
Germany	Switzerland
Italy	UK
Japan	US
New Zealand	



Science of MSR : What Has Changed?

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- The expected value of the samples needs to be updated in light of the following:
 - Progress in the study of **Mars meteorites** (the number and diversity has increased from 55 in 2011 to >100 today)
 - **New mission results:** from Mars.
 - Curiosity & MER rovers. Now approaching 26 combined years of ops; key results in habitability/preservation potential)
 - Mars orbiters: MRO, MEx, ODY
 - **Astrobiology:** Significant improvements in our understanding of the potential for the preservation of the signs of life in the geologic record, and how to translate that to specific times/places on Mars
 - **Planning for Human Exploration:** Improved understanding of the ways returned sample studies would reduce the risk of a future human mission
 - **Instrument Developments:** Better ability to handle and analyze very small samples
 - **Sample Quality Attributes:** now known



Assume: Samples will be High Quality

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- **Sample quality attributes established** using M-2020 RSSB and several precursors (2014-17), PP and Advance Planning.
- All factors translated into **requirements**, and have been adopted by M-2020 and have flowed into MSR Advance Planning teams.

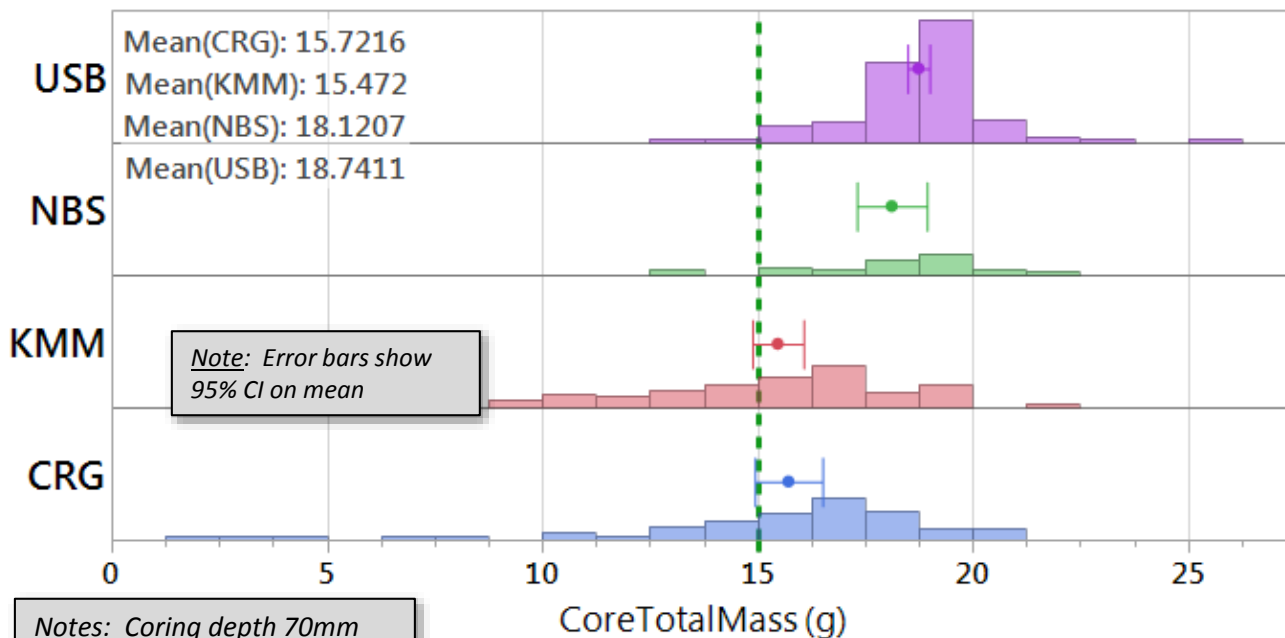


Sample Quality Parameter	Recommended Requirement
Biologic Contamination	<1 viable terrestrial organism per tube
Organic Contamination	Tier 1 compounds <1 ppb Tier 2 compounds <10 ppb TOC <40 ppb
Inorganic Contamination	Group A <1% Group B <0.1% Pb <2 ng/g
Magnetics	Exposure to <0.5 mT Shock pressure <0.1GPa Orientation to half-cone uncertainty of <5°
Fracturing	Size distribution in a single core of <20% by mass in pieces ≤2 mm, and >70% by mass in pieces with largest dimension >10 mm
Internal Movement	Minimize by preloading tubes compatible with X-ray CT imaging of core before removal
Temperature	<60 °C required, <40 °C desired
Cross-Contamination	<150 mg per samples tube
Sealing	<1% water, translated to He leak rate for 20 years
Radiation	<100 krad over 20 years



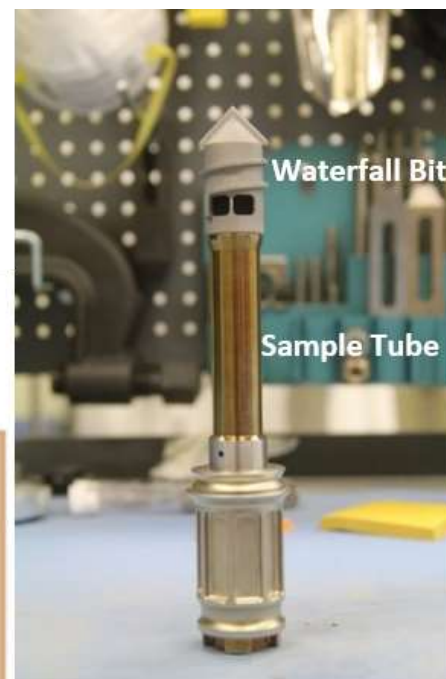
Expected Sample Mass

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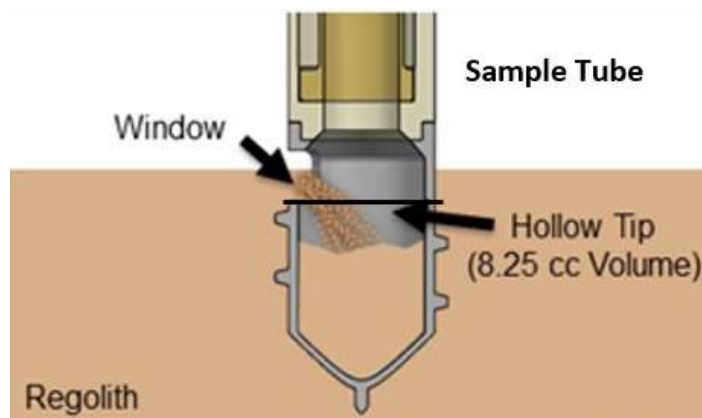
REGOLITH

- *Can collect 8 cm³ of regolith material*
- *Using ρ of 1.15 g/cm³, ~9.5 gm of sample*



ROCK

- *Average sample mass in tests is 16.5g*
- *90% of samples are $\geq 13.4g$*
- *Rock cores $< 5g$ are considered engineering failures*





Objectives



Objectives Proposed for Mars Sample Return

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Objective	Shorthand	Full Statement of Objective
1	<i>Geological environment(s)</i>	Interpret the primary geologic processes and history that formed the martian geologic record, with an emphasis on the role of water.
2	<i>Life</i>	Assess and interpret the potential biological history of Mars, including assaying returned samples for the evidence of life.
3	<i>Geochronology</i>	Determine the evolutionary timeline of Mars.
4	<i>Volatiles</i>	Constrain the inventory of martian volatiles as a function of geologic time and determine the ways in which these volatiles have interacted with Mars as a geologic system.
5	<i>Planetary-scale geology</i>	Reconstruct the history of Mars as a planet, elucidating those processes that have affected the origin and modification of the crust, mantle and core.
6	<i>Environmental hazards</i>	Understand and quantify the potential martian environmental hazards to future human exploration and the terrestrial biosphere.
7	<i>ISRU</i>	Evaluate the type and distribution of in situ resources to support potential future Mars Exploration.



Objectives Proposed for Mars Sample Return

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Proposed Sample-Related Objectives from the 2018 iMOST Study

Objective		Sub-Objective	
1	<i>Geological environment(s)</i>		<i>Sedimentary System</i>
2	<i>Life</i>		<i>Hydrothermal</i>
3	<i>Geochronology</i>		<i>Deep subsurface groundwater</i>
4	<i>Volatiles</i>		<i>Subaerial</i>
5	<i>Planetary-scale geology</i>		<i>Igneous terrane</i>
6	<i>Environmental hazards</i>		<i>Carbon chemistry</i>
7	<i>ISRU</i>		<i>Biosignatures--ancient</i>
			<i>Biosignatures--modern</i>



Structure of the Information

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Introduction & Current State of Knowledge

KEY OPEN QUESTIONS: SUB-OBJECTIVE 1.1	
What was the character, diversity, geological history and age of the provenance region for the sediment that accumulated in any given martian depositional basin?	
How was sediment generated on Mars and has that changed over geological time?	
What was the history, including timing, quantity, and chemistry, of widespread surface and near-surface water on Mars and how is the sediments?	
What was the nature of water-related	
How did the many possible processes	
What is the nature of martian aeolian	
Do martian sedimentary rocks record the chemistry?	

Investigation Strategies (IS) for Objective 1 Sub-Objective 1.1		
1	Geological environment(s)	Interpret the primary geologic processes that formed and modified the pre-Amazonian martian geologic record.
1.1	Sedimentary System	Understand the essential attributes of a martian sedimentary system.
IS 1.1A	Investigate physical and chemical sedimentary processes in standing or ponded water to understand more completely the occurrence of sustained, widespread liquid surface water on Mars, including the examination of evaporites resulting from such processes.	
IS 1.1B	Investigate sediment diagenesis, including the processes of cementation, dissolution, authigenesis, recrystallization, oxidation/reduction, and fluid-mineral interaction.	
IS 1.1C	Investigate the mechanisms by which sediment is/was generated on Mars, by understanding the weathering and erosional processes.	
IS 1.1D	Investigate the provenance, lithology, tectonic associations, and sedimentary structures of the rocks.	
IS 1.1E	Investigate the nature of sedimentary basins, including whether they are tectonically controlled and timescales of sedimentation.	
IS 1.1F	Characterize the physical processes and climate history of the sedimentary system.	

Key Open Questions & Why Returned Sample Studies are Needed

Investigation Strategies

Samples identified to advance Investigation Strategy 1.1C:

- Rocks of any type that show a range of weathering styles and weathering intensity, including weathering rinds, if present.
- Sedimentary rocks with a variety of grain compositions.
- Modern regolith, especially if locally derived.

Measurements identified to advance Investigation Strategy 1.1C:

- Determine the minerals formed by the weathering process over a range of distinct parent lithologies.
- Determine the mineralogical relationship to the parent lithology.
- Determine the provenance of the rocks (and associated minerals that can be used to trace provenance).

UNDERSTAND A MARTIAN SEDIMENTARY SYSTEM

Why is this objective critical?

A key input into interpreting the history of water on Mars; search for life.

What are the most important samples?

One or more suites of sedimentary rocks representative of the stratigraphic section, different lithification intensity and style, and coarse-grained rocks with grain diversity.

Samples and Measurements

Summary



EXAMPLE:

1.1 Understand a Martian Sedimentary System

Objective	
1	<i>Geological environment(s)</i>
2	<i>Life</i>
3	<i>Geochronology</i>
4	<i>Volatiles</i>
5	<i>Planetary-scale geology</i>
6	<i>Environmental hazards</i>
7	<i>ISRU</i>

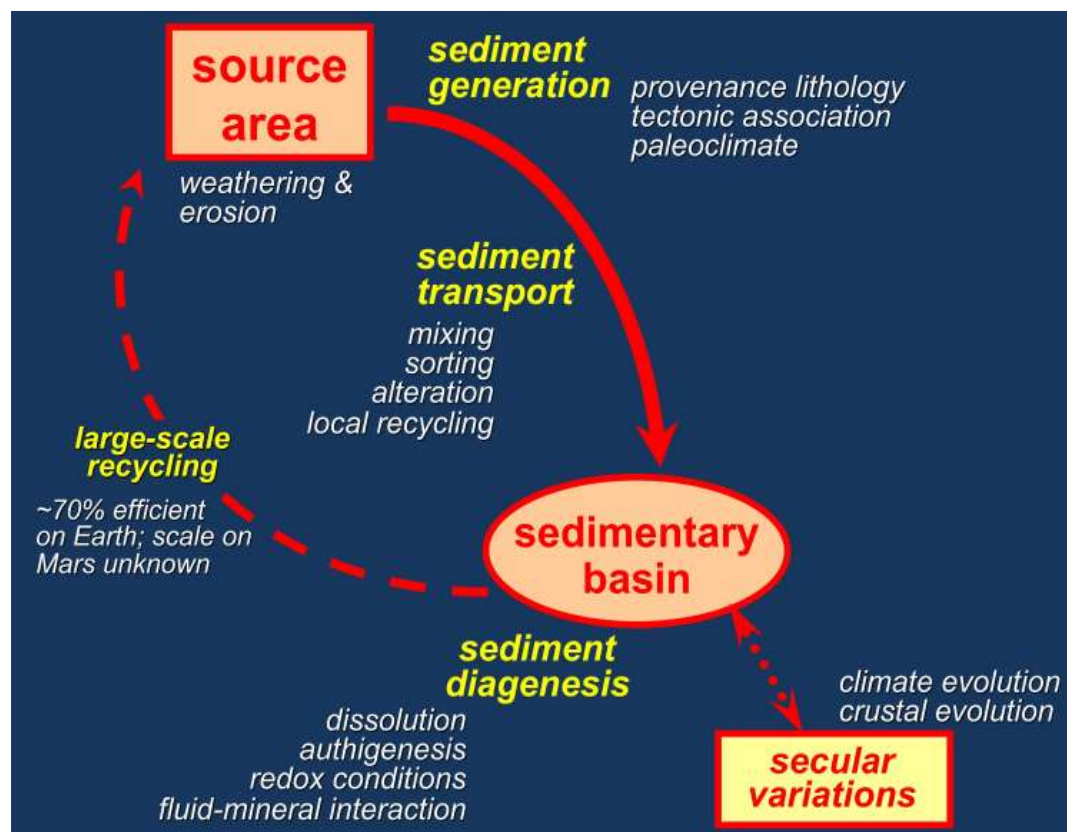
Sub-Objective
<i>Sedimentary System</i>
<i>Hydrothermal</i>
<i>Deep subsurface groundwater</i>
<i>Subaerial</i>
<i>Igneous terrane</i>
<i>Carbon chemistry</i>
<i>Biosignatures--ancient</i>
<i>Biosignatures--modern</i>



Introduction

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- Sedimentary rocks preserve the most continuous record of the geological history of planetary surfaces, including any history of life
- Sedimentary history is best understood in terms of “source-to-sink” processes that track sedimentary rocks:
 - from their ultimate origins (provenance)
 - through formation of sedimentary components (particulate & dissolved)
 - transport (particulate & dissolved) and deposition (clastic & chemical)
 - post-depositional changes (lithification, diagenesis, recycling...)





Introduction/Critical Open Questions

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- Despite the fact that Mars missions have tracked these processes, many critical questions require more thorough analyses than is possible using orbiting and landed spacecraft
- Return to Earth of carefully selected sedimentary sample suites would be required to move substantially forward on these questions

Critical Open Questions

- What was the history of surface water on Mars?
e.g., including timing, quantity, and chemistry
- What were the characteristics of the provenance region(s)?
- How did the process of sediment diagenesis on Mars work?
- Do sedimentary rocks record the evidence of ancient life?



Questions → Investigation Strategies

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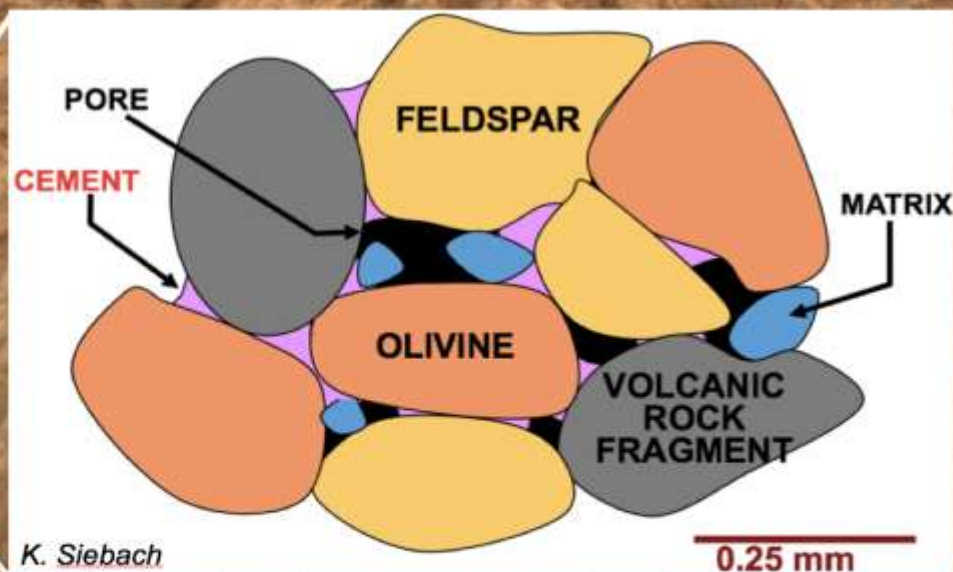
<i>Sedimentary System</i>	Understand the essential attributes of a martian sedimentary system
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Invest. 1.1C	Investigate the mechanisms by which sediment is/was generated on Mars, by understanding the weathering and erosional processes .
Invest. 1.1D	Investigate the provenance of the sediment in the sedimentary system, including variation in lithology, tectonic association, and paleoclimate.
Invest. 1.1E	Investigate the nature of subaqueous (or subglacial) transport regimes that cut channels and valleys, including whether they were persistent or episodic, the size of discharge, and the climatic conditions and timescales of formation.
Invest. 1.1F	Characterize the physical properties of aeolian materials to understand aspects of the surface processes and climate history.



Sedimentary Provenance Analysis

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- Modern sedimentary analyses rely on “**grain by grain**” studies, using the most sophisticated analytical methods, to fully understand provenance and sedimentary history
- Physically disaggregate sediment and/or use modern beam methods (e.g., SIMS, LA-ICP-MS, μ XRF, etc.)



Volcanic Frags (Provenance)

- source lithologies
- nature / history of mantle sources
- source ages

Feldspar (Provenance)

- source lithologies
- age / age history of source

Olivine/Pyrox. (Provenance)

- source lithologies
- T/P history of sources

Matrix (Provenance & Diagenesis)

- source lithologies
- fluid chemistry / fluid interactions
- clay mineral origins and diagenesis

Cements (Diagenesis)

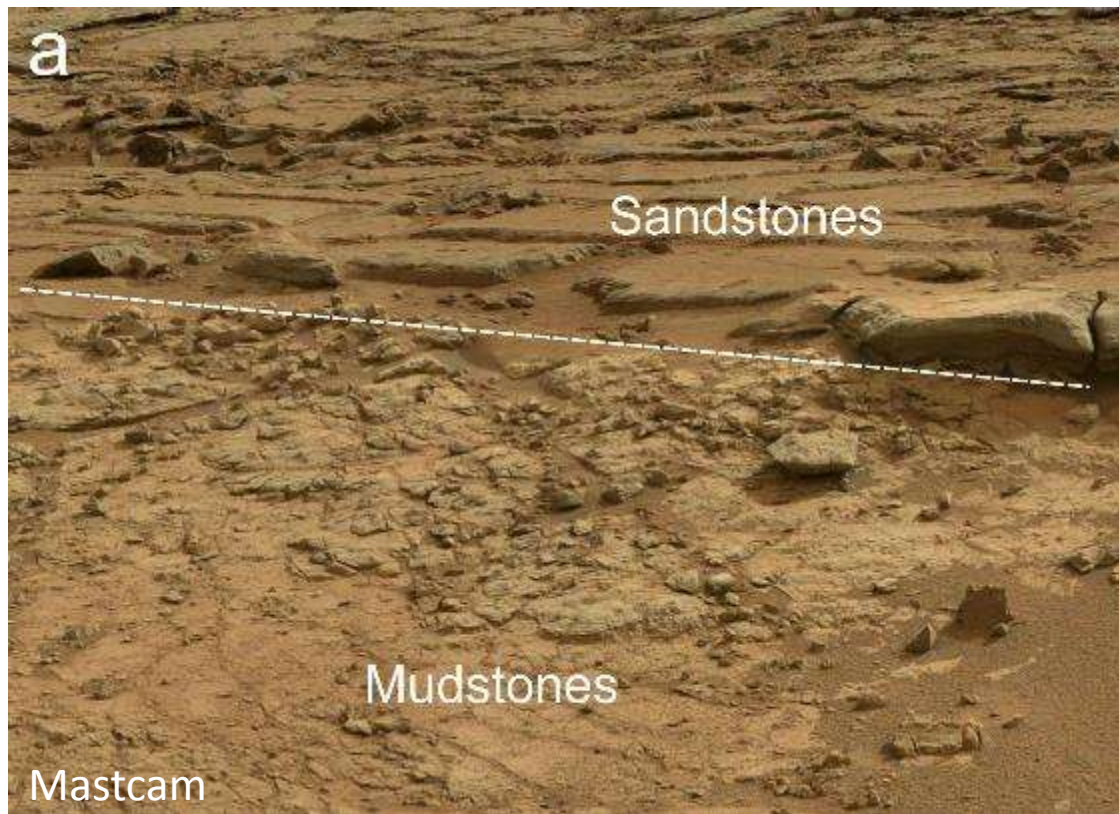
- cement “stratigraphy”
- fluid chemistry (e.g., pH, Eh)
- fluid sources / fluid histories



Sampling Fluvio-Lacustrine Sedimentary Rocks

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- Lacustrine deposits in a quiet environment favorable to organic preservation
- Sampling a **suite of sediment types** would enable analysis of processes such as: sorting effects, cementation, input of detrital rocks, etc.



- (a) Contact between lacustrine mudstones (bottom) and fluvial sandstones at Yellowknife Bay, Gale crater.
- (b) Close-up on the sandstones showing cemented coarse grained deposits.
- (c) Close-up on a brushed area of mudstones only displaying local concretions.
- Pre-Decisional - for planning and discussion purposes only.



Why Returned Sample Studies are Important

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- Orbital and In Situ data provide **critical geological context** for samples
- In Situ missions have demonstrated that sophisticated measurements can be obtained : e.g., quantitative mineralogy, major/trace element geochemistry, GC-MS / TLS analyses

BUT such measurements inevitably require **'follow on' analyses**

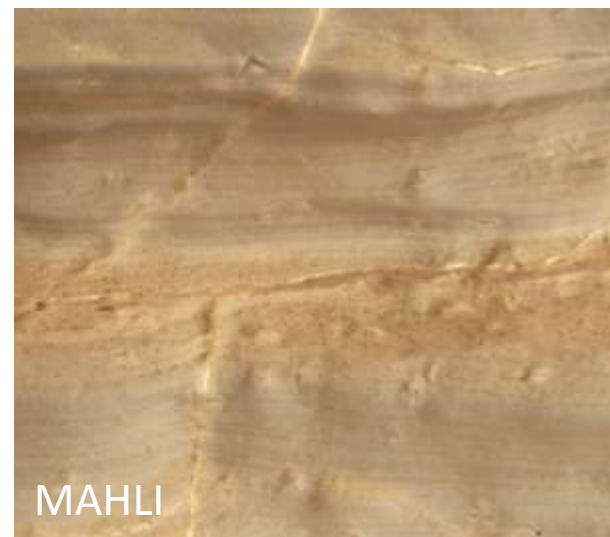
- Many key questions require further measurements that cannot be made on Mars – e.g.:
 - multiple radiogenic isotope techniques to obtain **reliable age dates**
 - synchrotron studies to evaluate sedimentary **amorphous components**
 - complex **organic geochemistry** analyses to evaluate 'life question'



MAHLI



MAHLI



MAHLI



Samples and Measurements

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Summary of measurements required/desired for returned samples:

- Textural analyses (e.g., grain size / shape)
- Quantitative mineralogy and μm -scale mineral chemistry
- Major and trace elemental geochemistry
- Stable isotope geochemistry
- High resolution (micron-scale) petrographic analyses
- Geochronology using multiple isotope systems on both whole rocks and individual minerals

Summary of samples required/desired to achieve objectives:

- Suite of sedimentary rocks representative of selected depositional setting
- Suite of sedimentary rocks showing range of lithification and diagenetics
- Rocks showing range of weathering intensity/style, incl. modern regolith
- Sedimentary rocks with a variety of grain compositions, including relatively coarse-grained (multi-lithological) clastic sedimentary rocks.
- Samples of modern and ancient (lithified) aeolian sediment and sedimentary rocks



Conclusions

- **Geologic processes generate heterogeneous products.**
- **Using sample studies to interpret geologic history/processes typically requires a sample suite that spans the range of variation, not single samples.**

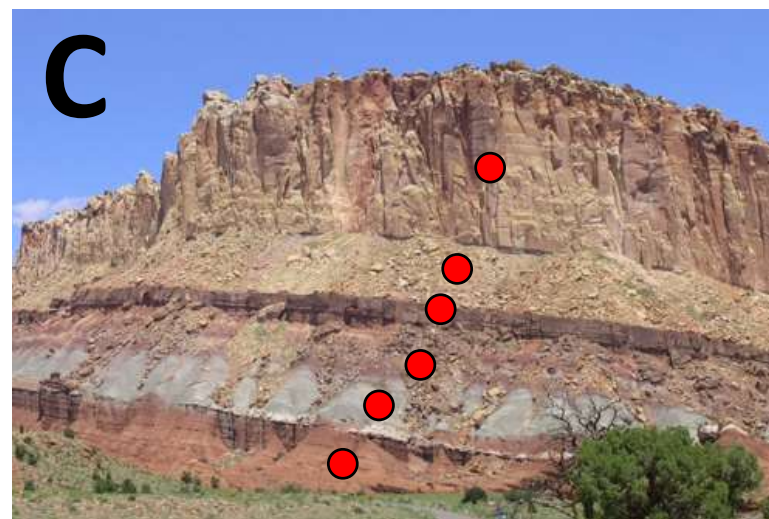
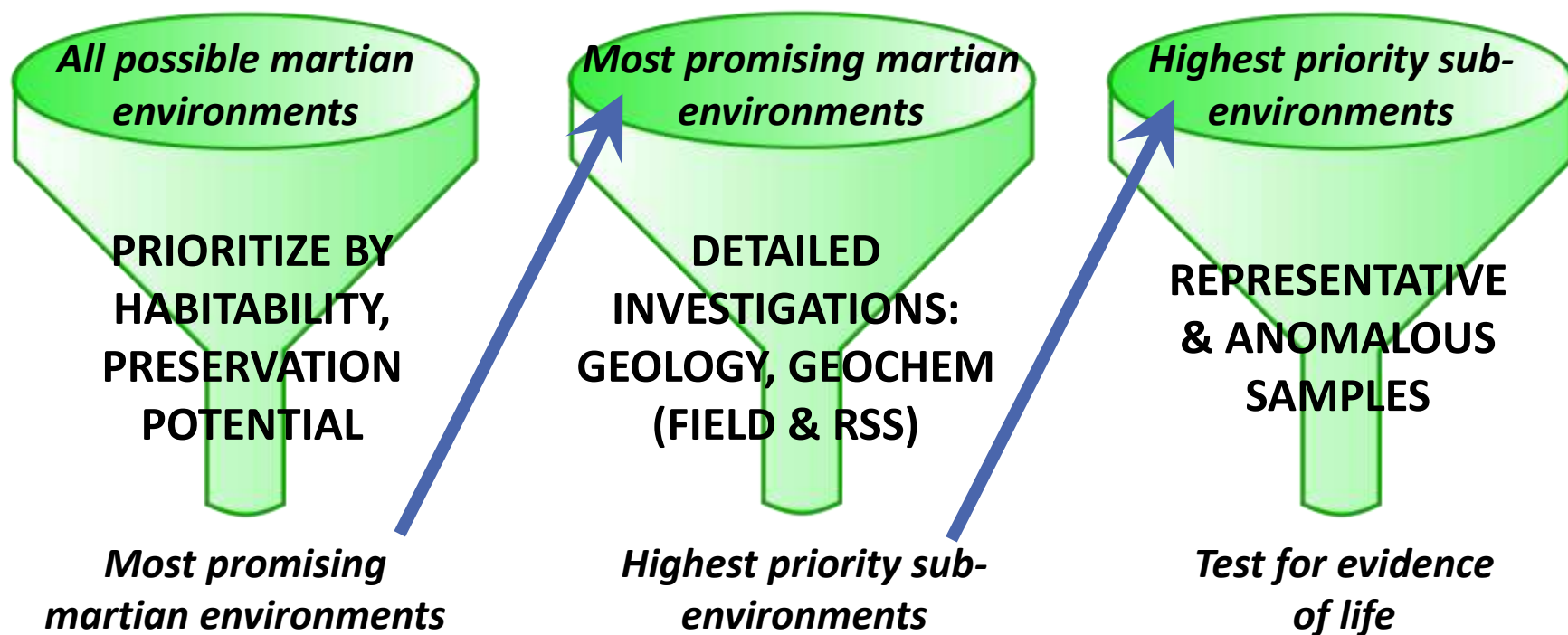


Figure caption. A primary value of suites is that they allow for study of the similarities/differences between samples. A) A suite of rocks showing some of the geologic variation in Wisconsin. B) Sample suite showing variations in sedimentary rocks on Earth. C) An example of stratified sedimentary rocks (on Earth), and the possible design of a scientifically useful sample suite.



MSR Needs to Narrow the Search Space for Life



Key Message: Since we do not know exactly how evidence of martian life might be preserved in the geologic record, we need to sample a location with as much variety as possible, and it needs to be sampled carefully and systematically.



Mars Sample Return

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SCIENCE



- Civilization-scale science
- Samples: the gift that keeps on giving
- Definitive scientific results
- Only way to advance critical sectors of planetary science & astrobiology

ENGINEERING



- Unique technical challenges drive unprecedented innovation
- Advances will benefit future robotic and human missions.
- Crucible for engineering as a discipline.

PREPARATION



- Prepare for humans to Mars
- Inform planetary protection policy evolution to enable future missions

INSPIRATION



- Inspire and train the next generation
- Magnet for international cooperation

We have the opportunity and motivation to carry out MSR on an international basis

Pre-Decisional - For planning and discussion purposes only



What Makes Laboratory Samples so Valuable?

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Four powerful technical advantages:

Access to sophisticated sample prep.



Coat Polish Mount



Fragment Isolate Powder



Fractionation Extraction Powder
Organic prep. pathways

- *Reduces detection limits (by orders of magnitude)*
- *Improves precision*
- *Greater accuracy*
- *Required for many instruments*

Discovery-responsive investigation pathways

- *Answers to early questions change choice/ design of later experiments*



Thin section

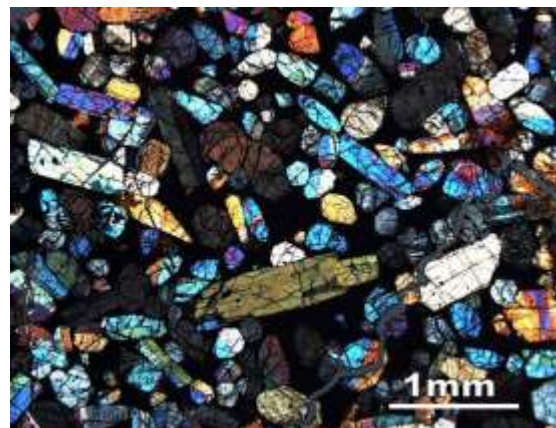
Multiple, diverse, and large instruments that cannot be miniaturized.

- *Opportunity to make confirming measurements using multiple methods*
- *“Gift that keeps on giving” – analysis by future instruments*
- *“Extraordinary claims require extraordinary evidence”*



SEM

Greatly improves spatial focus/resolution



- *For evaluating microbial life, microscopic scale is crucial*
- *Access to small grains crucial*

Mars meteorite



The iMOST Text Report

International MSR Objectives & Samples Team

The Potential Science and Engineering Value of Samples Delivered to Earth by Mars Sample Return

International MSR Objectives and Samples Team (iMOST)

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Final Report

August 14, 2018

Recommended bibliographic citation:

iMOST (2018). The Potential Science and Engineering Value of Samples Delivered to Earth by Mars Sample Return, (co-chairs D. W. Beaty, M. M. Grady, H. Y. McSween, E. Sefton-Nash; documentarian B. L. Carrier; plus 66 co-authors), 186 p. white paper. Posted August, 2018 by MEPAG at <https://mepag.jpl.nasa.gov/reports.cfm>.

This report requested by the International Mars Exploration Working Group (IMEWG).

Questions or requests for follow-up information should be sent to David Beaty (dwb@beaty@jpl.nasa.gov, 918-354-7968), Monica Grady (monica.grady@open.ac.uk), Hap McSween (McSween@utk.edu), Elliot Sefton-Nash (esefton@cosmos.esa.int), or Brandi Carrier (Brandi.L.Carrier@jpl.nasa.gov)

Pre-Decisional – For Planning and Discussion Purposes Only

- MSR has multiple technical dimensions
 - 71 co-authors
 - Presentation and community feedback at 4 recent science conferences
 - 31 reviewers
- Report posted on the MEPAG web site
- Further publication strategy is as-yet TBD.



Proposed Next Steps—Science Perspective (1 of 2)

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Fly the M-2020 sample caching rover, select/acquire compelling samples

- Landing site selection (3rd landing site workshop will be held the week of Oct. 15, 2018; JPL area)
- Need good set of sample scientists to join Project as Participating Scientists (Michael Meyer to discuss on Friday)
- Design logical, effective sample suites; establish recoverable sample cache(s)

Design/fly retrieval missions

- Prioritize samples collected by M-2020 for potential retrieval, so that logic of the suites is not lost. Carefully choose the best 31.
- Collect atmospheric sample(s)
- The retrieval missions would have at least some instruments of interest to science (cameras, T, etc.). We hope scientists are allowed to participate.



Proposed Next Steps—Science Perspective (2 of 2)

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Planning related to what would happen after the samples are returned

- Planning for Sample Receiving and Curation Facilitie(s), and the activities that would take place in each.
- How the tubes would be opened, samples extracted (incl. headspace gas).
- Planning on whether and how a subset of the collection should be sterilized, so as to get some samples to external labs (SCFs).
- Curation planning (atmosphere, T, metals, contamination control, etc.)
 - If there are multiple facilities, should they store the samples under the same or different conditions?
- Planning for any specialty sample analysis instruments—e.g. that significantly reduce the sample mass needed or sample contamination?
- Planning for science funding mechanisms (international), and sample allocation processes.
- Sample Management Plan (e.g. the sequencing of samples/analyses—which measurements can make use of left-over material from a previous measurement?).
- Other?



BACKUP

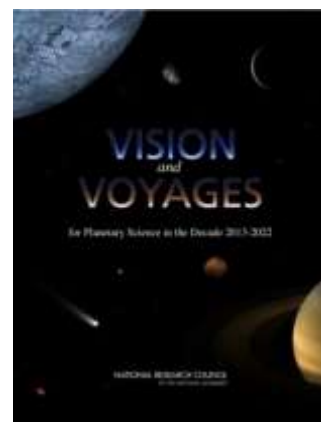
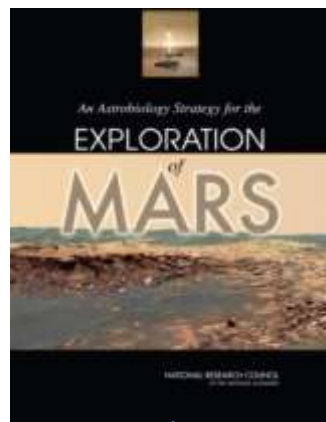


History of Scientific Support for MSR

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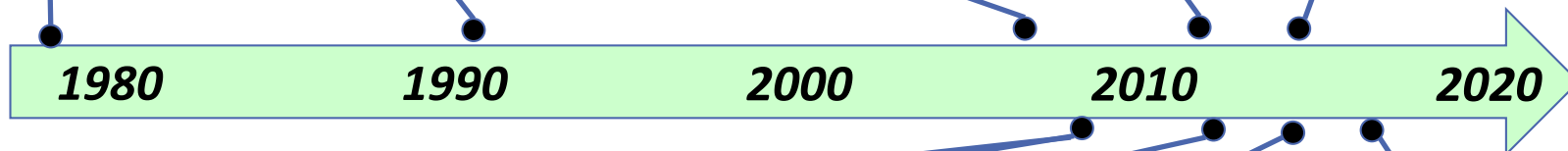
Inner Planets, 1977



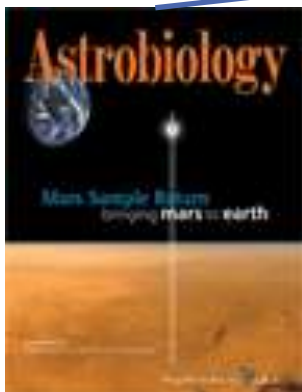
Dec. Sur., 2011



M-2020 SDT, 2013



ND-SAG 2008



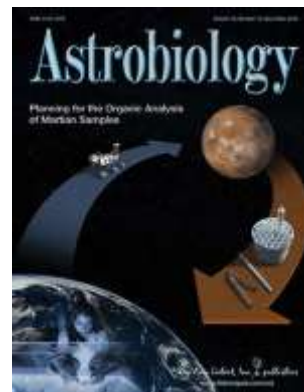
iMARS-1 2008



E2E-iSAG 2011



OCP 2014



iMARS-2 2016





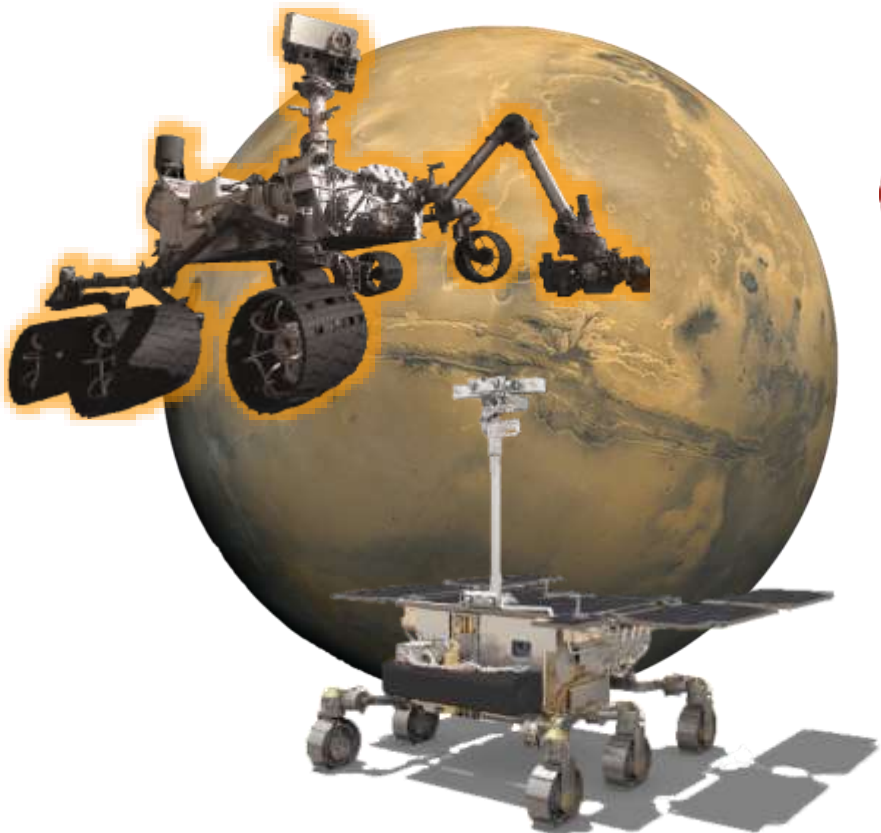
Opposite Approaches for Mars Exploration

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We need BOTH!

*Large amounts of sample but
limited instruments*

*Small amounts of sample but
unlimited instruments*



Sample Return



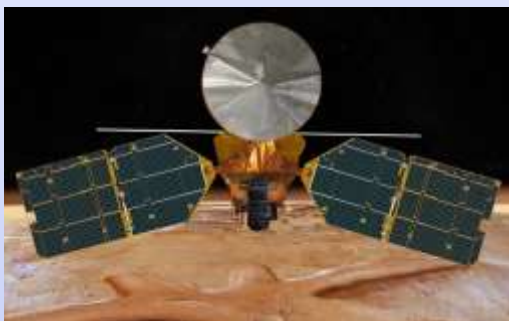
- Finite number and types of analyses using prescribed protocols.
- Unlimited number of analyses with complete flexibility.
- Important preliminary organic characterization steps.
- Comprehensive organic characterization.



Why MSR *now*?

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STRATEGIC PLANNING



- *Highest priority of Planetary Science Decadal Survey (2012)*
- *Strategic advantage to use Mars Reconnaissance Orbiter (MRO) to support MSR mission before MRO end of life*
- *Critical technology (M2020, MAV, PP containment) is understood and ready*
- *Advancements will benefit other future missions*

SCIENCE



- *Can move the science from characterizing the environment to explaining what was/is happening at Mars today/into the future*
- *Opportunity to acquire pristine samples before human explorers potentially introduce ambiguity into Mars astrobiology investigations*

HUMAN EXPLORATION



- *Data can inform future human mission hardware concepts early in the design process, before it becomes too expensive or difficult to change*



Why Mars Sample Return?

International MSR Objectives & Samples Team

- Exploration of Mars to date, from orbit and from the surface, has given us incredibly **valuable insights** into many aspects of Mars.
- These insights have allowed us to pose **new, far more detailed, questions** that could not have been asked before.



Taking the next step

- A certain set of scientific objectives can **only be achieved** with samples in a laboratory.
- For Mars, we are at the point where the scientific logic implies this **should be done next**.
- Results are expected to be **profound** (“civilization-scale” science)

