Report of the iMOST Study

April 25, 2018

International MSR Objectives and Samples Team (iMOST)

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

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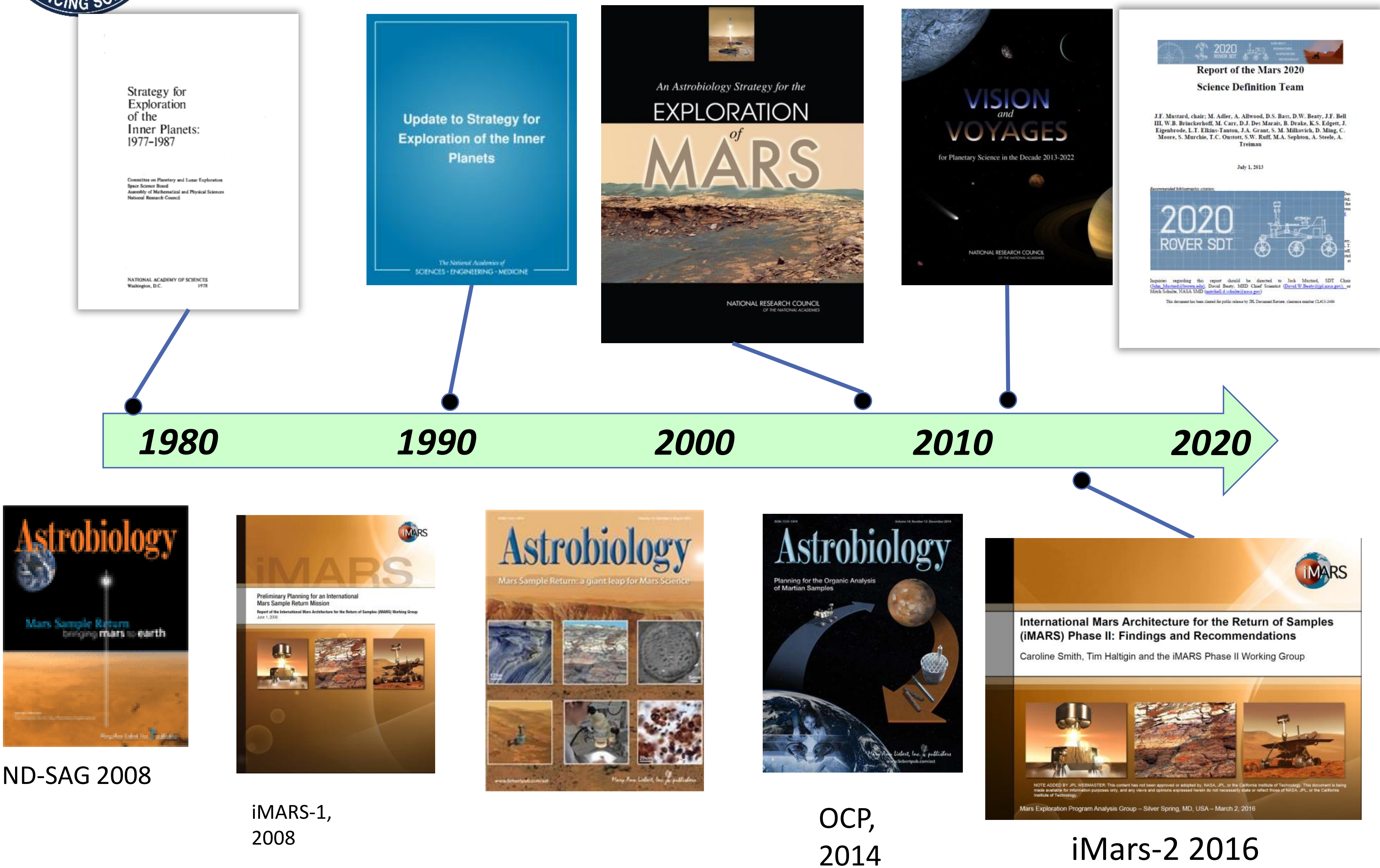
Introduction to the 2018 iMOST Study

Dave Beaty & Monica Grady

Introduction to This Study

- 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 MSR
  - Map out the kinds of samples that would be desired/required to achieve each of the objectives, and the measurements on the returned samples implied.
- Guidance 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.

History of Scientific Support for MSR



What Has Changed Recently?

- The expected value of the samples needs to be updated in light of the following:
  - Progress in the study of **Mars meteorites** (the number has increased from 55 in 2011 to >100 today).
  - **New mission results** from Mars.
    - Curiosity rover. Now approaching 6 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.

Structure of the iMOST Analysis

INPUTS

ASSUME:
- Well-designed sample suites
- Sample context established
- High-quality samples collected/delivered

DEPENDENCY #1:
Final landing site selection (being managed by NASA)

DEPENDENCY #2:
What kinds of samples will be available to be collected?

Within these dependencies/ assumptions we can map out:

- The scientific/ engineering objectives expected to be achieved using returned sample analysis.
- The sample-related investigation pathways to achieve each objective
- The samples required/ desired to complete those investigations
- The measurements that would need to be made on those samples.

OUTPUTS

- **How valuable are the retrieval missions?**
- **Strategies to optimize the sample collection**
- **Support planning for activities after receipt.**

Assume: Sample Context Well Documented

Regional, Planetary Context

Local Context

Detailed Analytic Data

INTEGRATE

Most Complete Science answers

Assume: Samples are High Quality

- Sample quality attributes established using M-2020 RSSB and several precursors, 2014-17.
- All factors translated into requirements, and have been adopted by M-2020 and discussed by MSR advance planning teams.

Sample Quality Parameter	Recommended Requirement
Biologic Contamination	<1 viable terrestrial organism per tube, <10 total terrestrial organisms 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

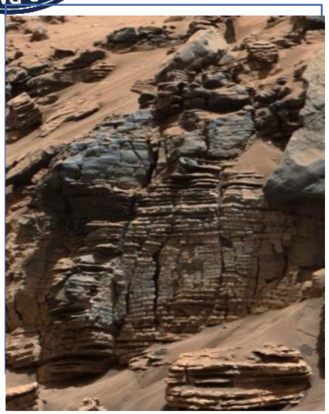
Source: RSSB (2018)

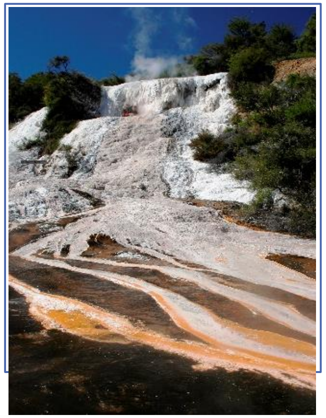
Objectives Proposed for Mars Sample Return

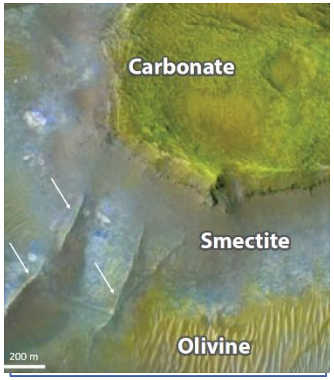
	Objective
1	*Geological environment(s)*
2	*Life*
3	*Geochronology*
4	*Volatiles*
5	*Planetary-scale geology*
6	*Environmental hazards*
7	*ISRU*

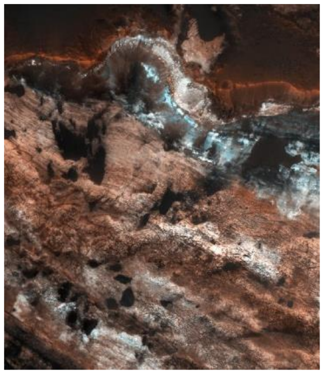
Sub-Objective
Sedimentary System
Hydrothermal
Deep subsurface groundwater
Subaerial
Igneous terrane
Carbon chemistry
Biosignatures--ancient
Biosignatures--modern

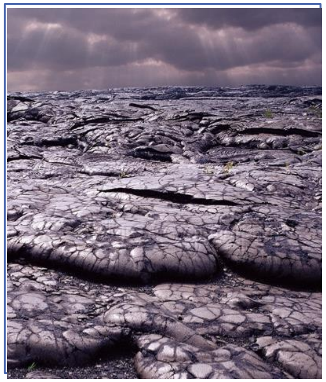
Geologic Environments of Primary Interest











A martian sedimentary system

A paleo-hydrotherm. system

Deep subsurface system

Subaerial W/R interaction

An igneous system

- Understanding these geologic environments is both an end and a means
  - We need to know how martian geologic processes in these environments worked in order to understand Mars as a system
  - We need this information in order to carry out the themed objectives of astrobiology, geochronology, volatile studies, and planetary geology/geophysics.

Geologic Environments: Sedimentary Systems

Presented by: Nicolas Mangold

on behalf of the iMOST Team

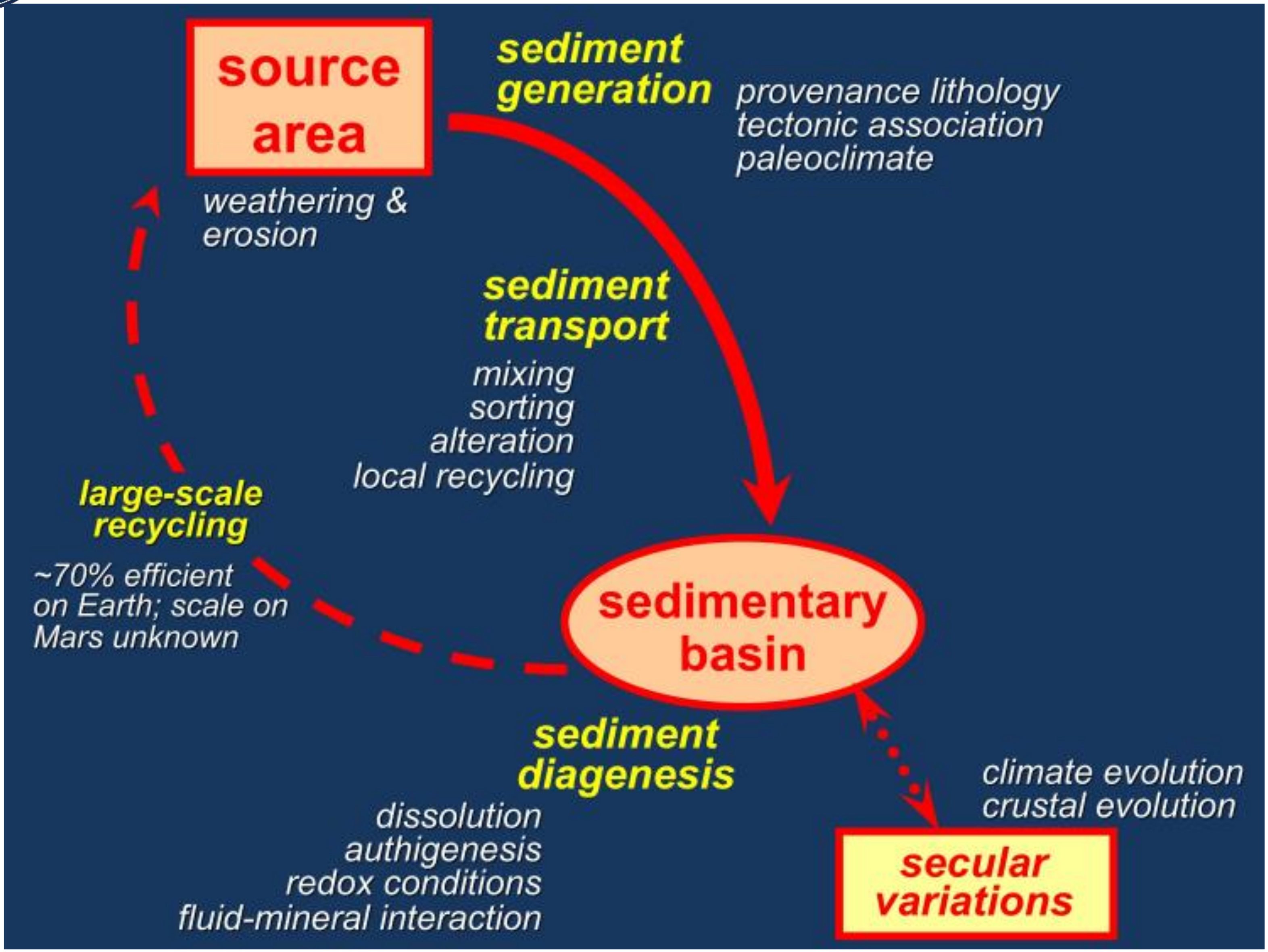
	Objective
1	*Geological environment(s)*
2	*Life*
3	*Geochronology*
4	*Volatiles*
5	*Planetary-scale geology*
6	*Environmental hazards*
7	*ISRU*

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

Introduction

- 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…)
- 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

Source-to-Sink Paradigm for Sedimentary Systems



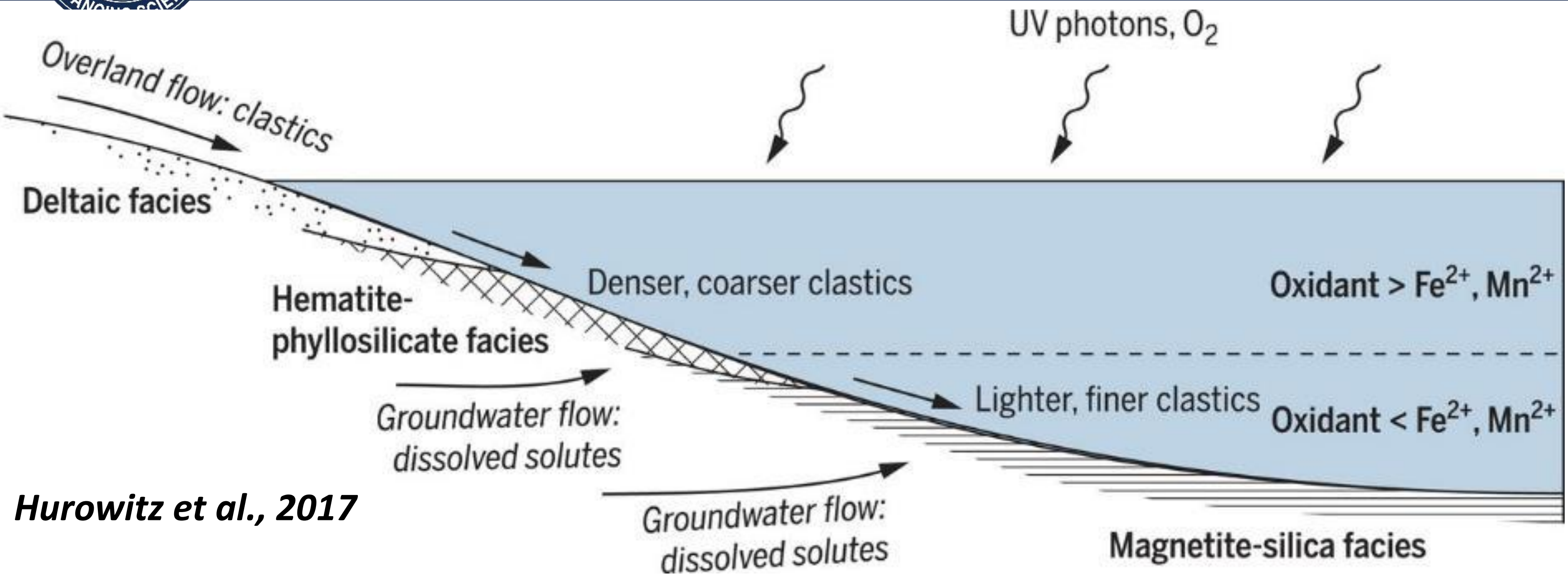
Critical Open Questions

1. What was the history, including timing, quantity, and chemistry, of widespread surface water on Mars?
2. How did the process of sediment diagenesis on Mars work?
3. How was sediment generated on Mars?
4. What was the character of the provenance region for the sediment that accumulated in a martian depo-center?
5. What was the nature of water-related sediment transport regimes?
6. What was the nature of martian aeolian processes?
7. Do martian sedimentary rocks record the evidence of ancient martian life?

Questions → Investigation Strategies

Sedimentary System	Understand the essential attributes of a martian sedimentary system.
Invest. 1.1A	Investigate physical and chemical sedimentary processes in standing or ponded water to better understand sustained, widespread liquid surface water on Mars, including the examination of evaporites resulting from such processes.
Invest. 1.1B	Investigate sediment diagenesis, including the processes of cementation, dissolution, authigenesis, recrystallization, oxidation/reduction, and fluid-mineral interaction.
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

Gale Crater Lacustrine Model

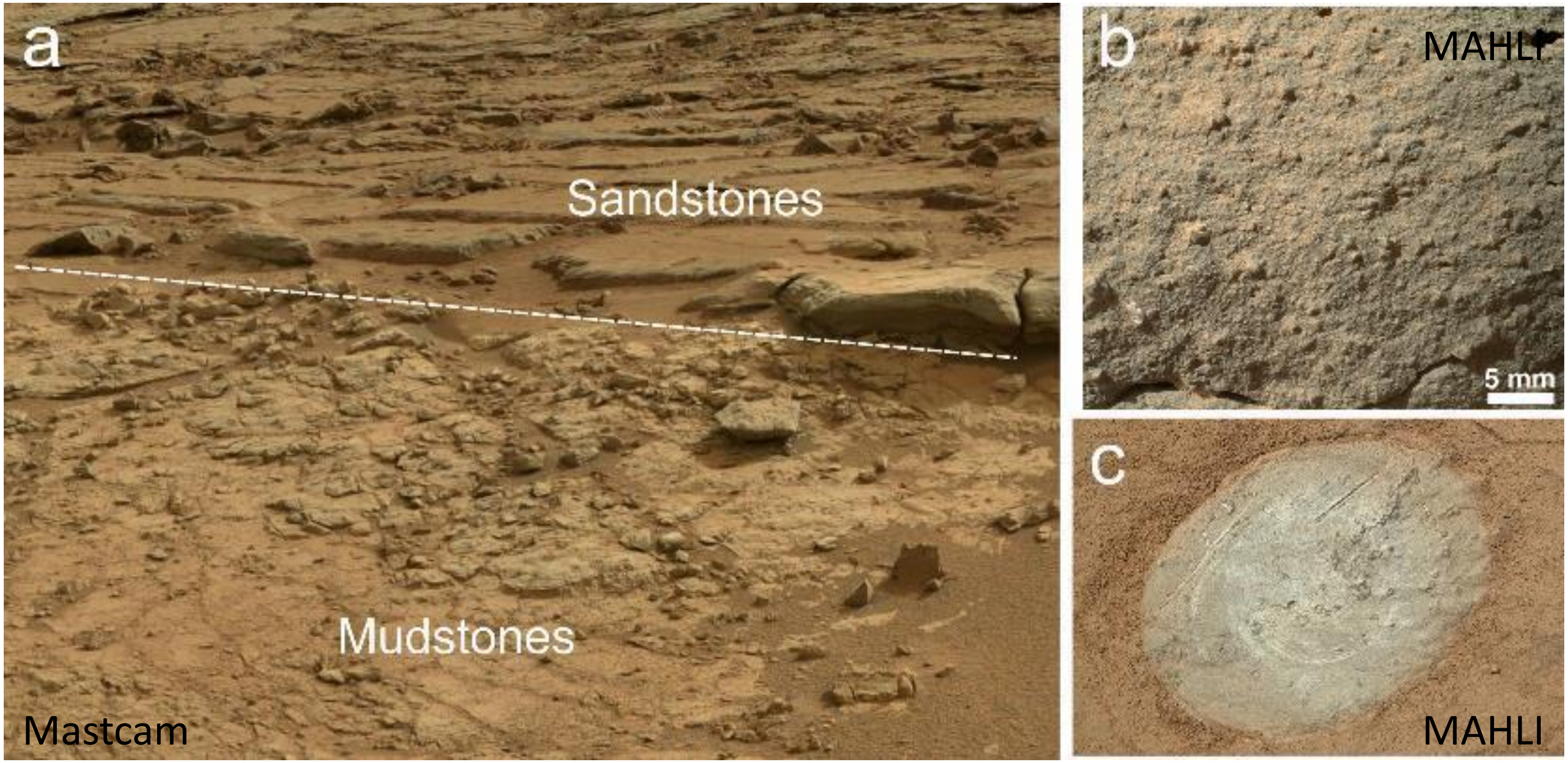


Hurowitz et al., 2017

- Redox stratified lake model for Murray Formation preserved in Gale crater, showing physical and chemical processes
- Model based on combined geology, stratigraphy, sedimentology, geochemistry and mineralogy
- Such a depositional environment is habitable and possesses the energy sources to support chemoautotrophic life
- **Further model tests and details require sample studies**

Sampling fluvio-lacustrine sedimentary rocks

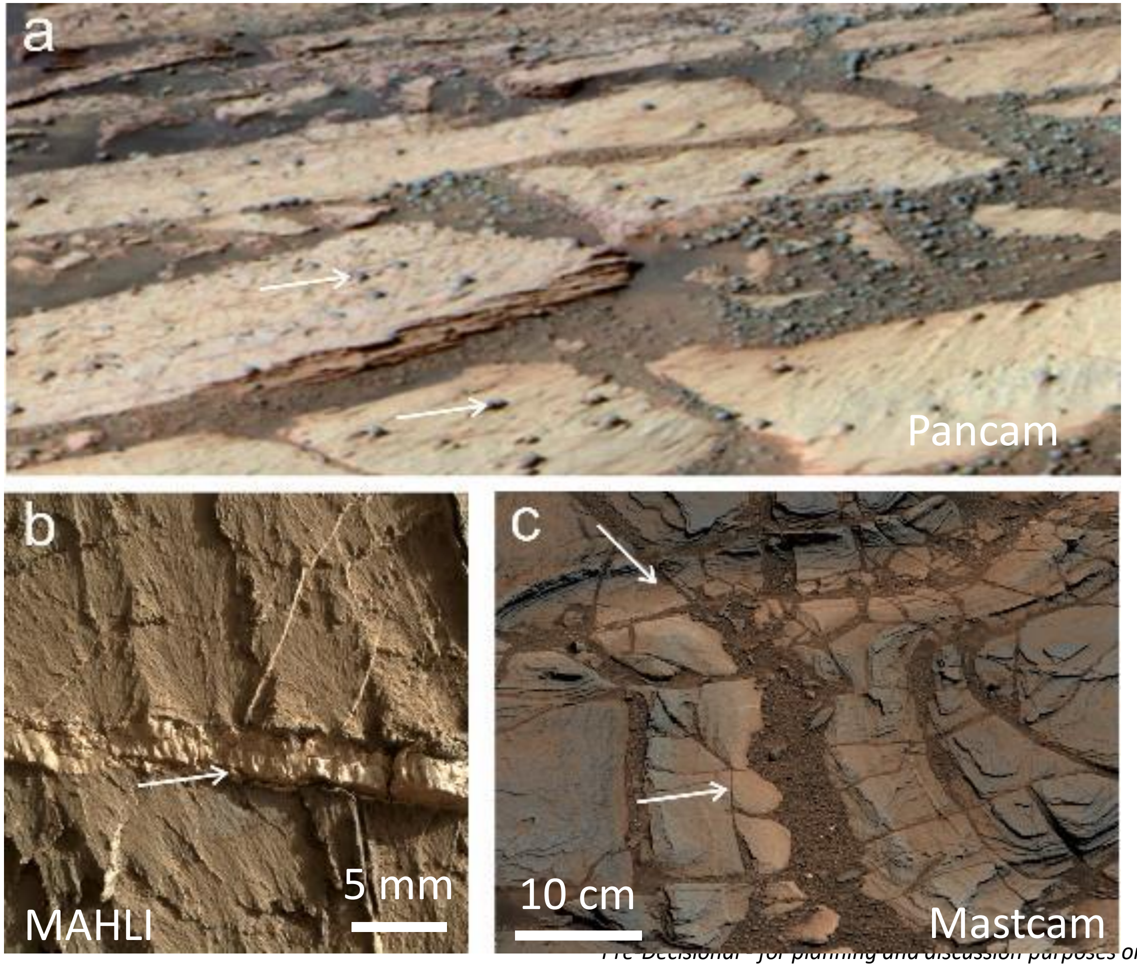
- Lacustrine deposits in a quiet environment favorable to organic preservation
- **Sampling a suite of sediment types would enable analysis of processes such as: sorting effects, cementation, input of detrital rocks, etc.**



(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.

Diversity in diagenetic processes

- Diagenetic features indicate various fluid episodes and conditions (pH, Eh, T°) linked to changes in surface or subsurface environment
- **Sample studies needed to understand strong implications of diagenetic conditions to preservation of exobiological material**

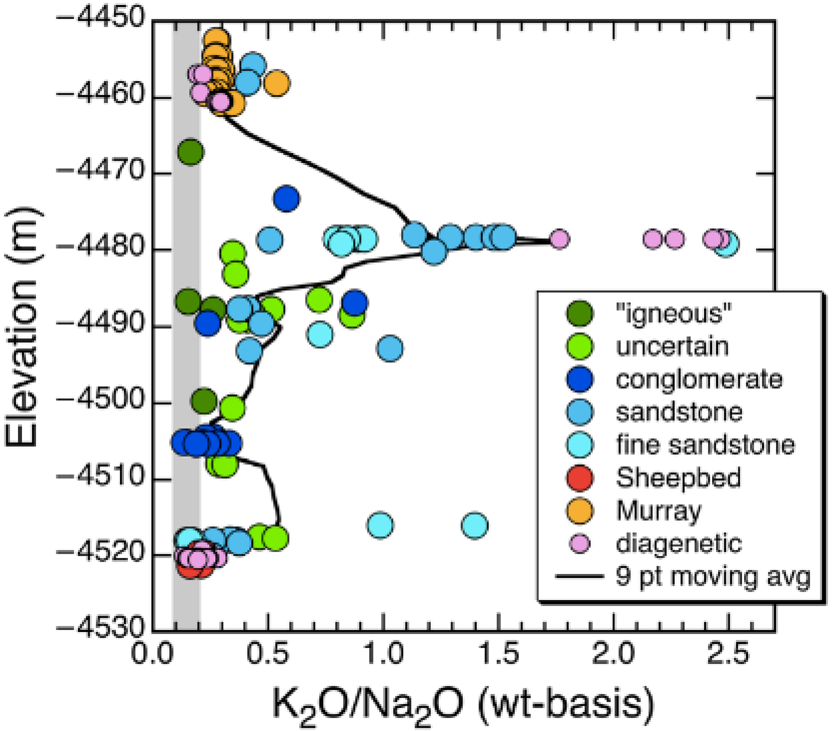


Hematite-rich concretions at Meridiani Planum (Opportunity rover, PanCam)

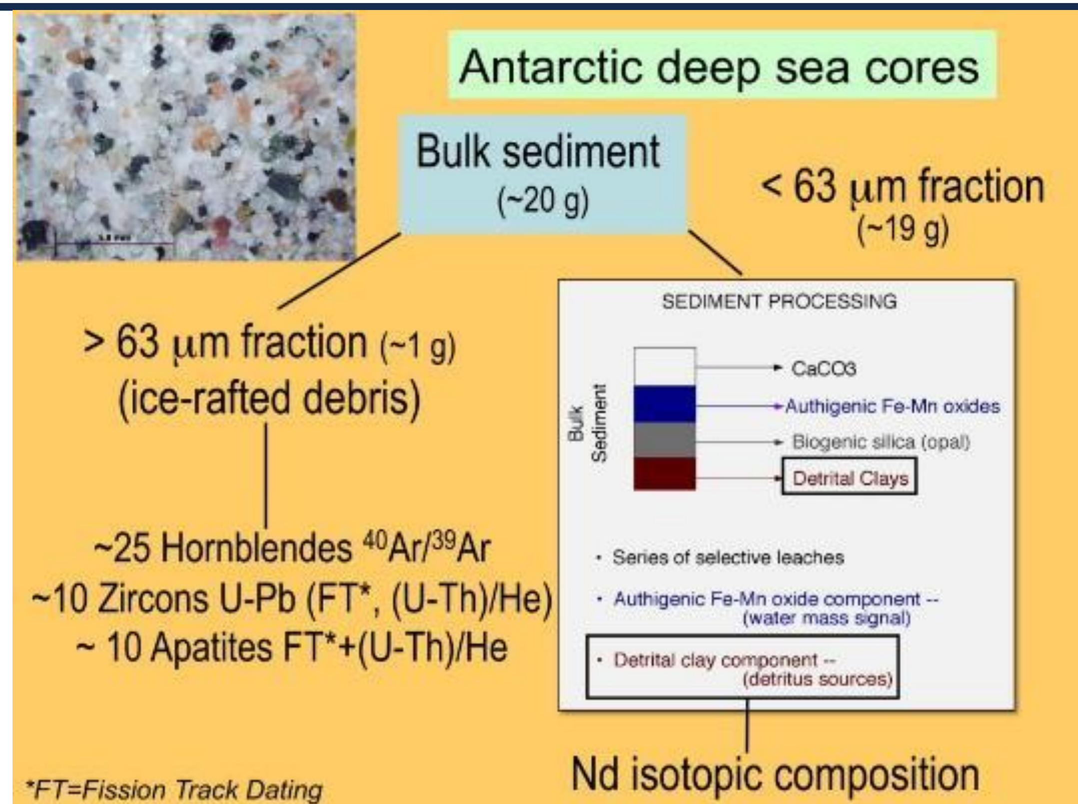
Sulfate-rich veins (left) and silica-rich halo (right) at Gale Crater (Curiosity rover, MAHLI and Mastcam)

Sedimentary Provenance Analysis

International MSR Objectives & Samples Team



Siebach et al., 2017

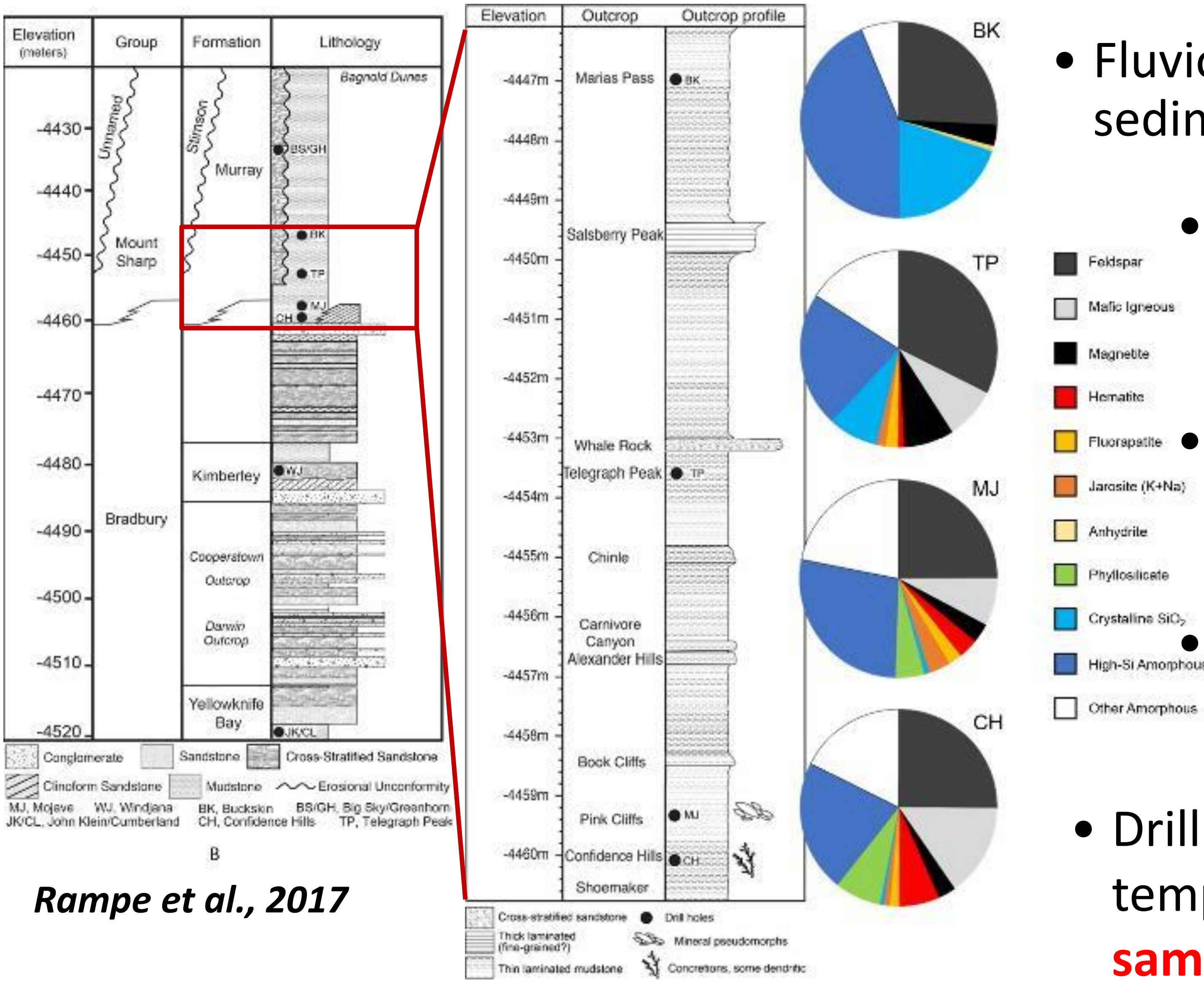


courtesy S. Hemming & E. Pierce (LDEO)

- Chemostratigraphy of Gale crater Bradbury Gp identified distinctive K-rich provenance signal

- **Sample studies: Modern provenance analyses often carried out on a “grain-by-grain” basis using multiple petrographic / geochemical / isotopic approaches**

Gale Crater Stratigraphy and Sampling

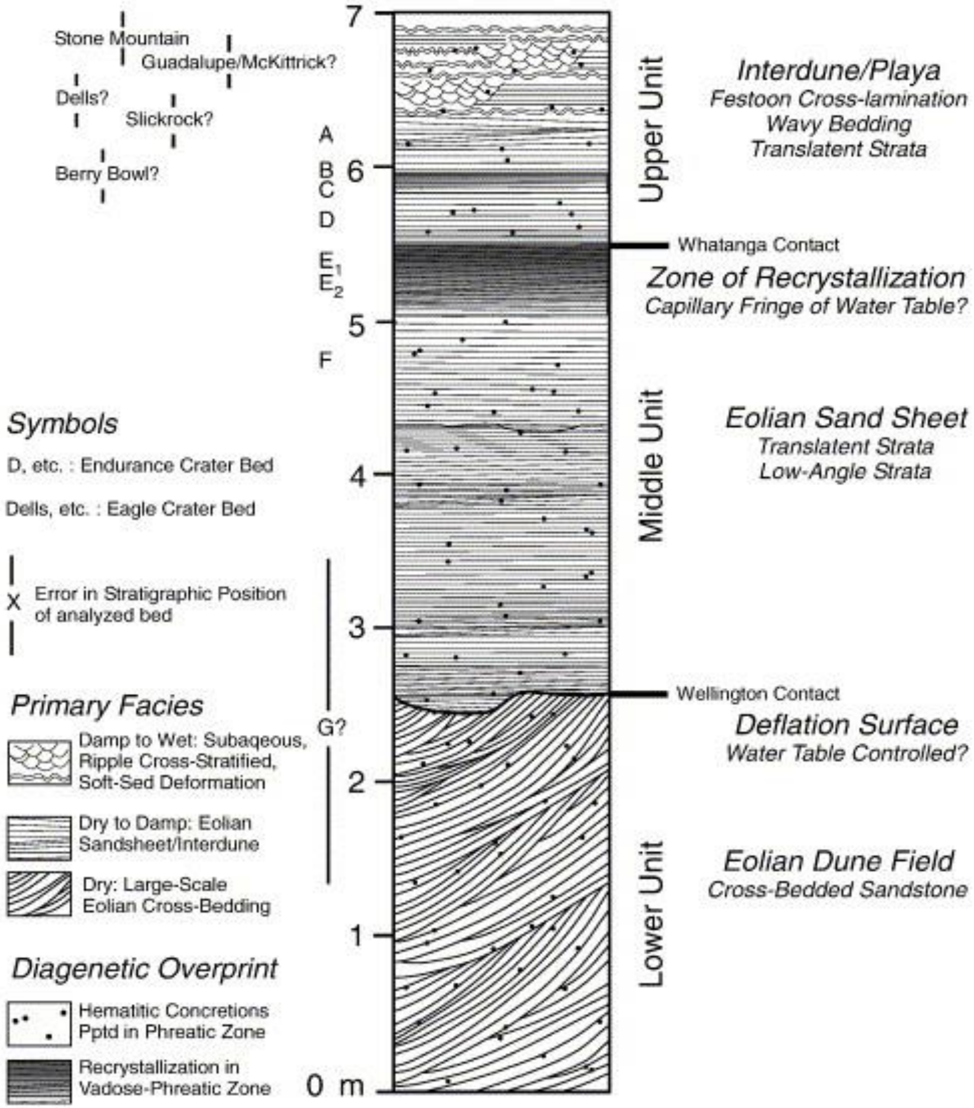


Rampe et al., 2017

- Fluvio-lacustrine sedimentary sequence
- Systematic redox variation in mineralogy
- Variable chemical weathering (climate) history
- Diagenetic overprint
- Drill sites provide template for **potential sampling strategy**

Pre-Decisional - for planning and discussion purposes only.

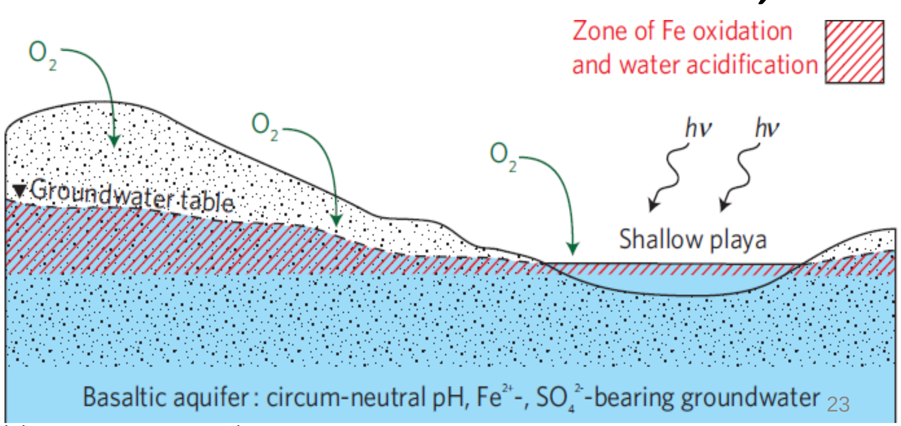
Meridiani Stratigraphy and Sampling



Grotzinger et al., 2005

- Aeolian sedimentary sequence with groundwater mediated evaporative diagenesis
- Groundwater redox processes reflected in iron mineralogy
- RAT sites provide template for **potential sampling strategy**

Hurowitz et al., 2010



Why Returned Sample Studies are Important

- 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/problems require further measurements that simply cannot be made at Martian surface – e.g.:
  - synchrotron studies to evaluate ubiquitous sedimentary amorphous components
  - micrometer-scale, multiple stable and radiogenic isotope analyses to evaluate diagenetic aqueous fluid flow histories
  - multiple radiogenic isotope techniques to obtain reliable age dates
  - complex organic geochemistry analyses to evaluate ’life question’

Samples and measurements

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

Geologic Environments: Hydrothermal Systems

Presented by: Kathy Campbell

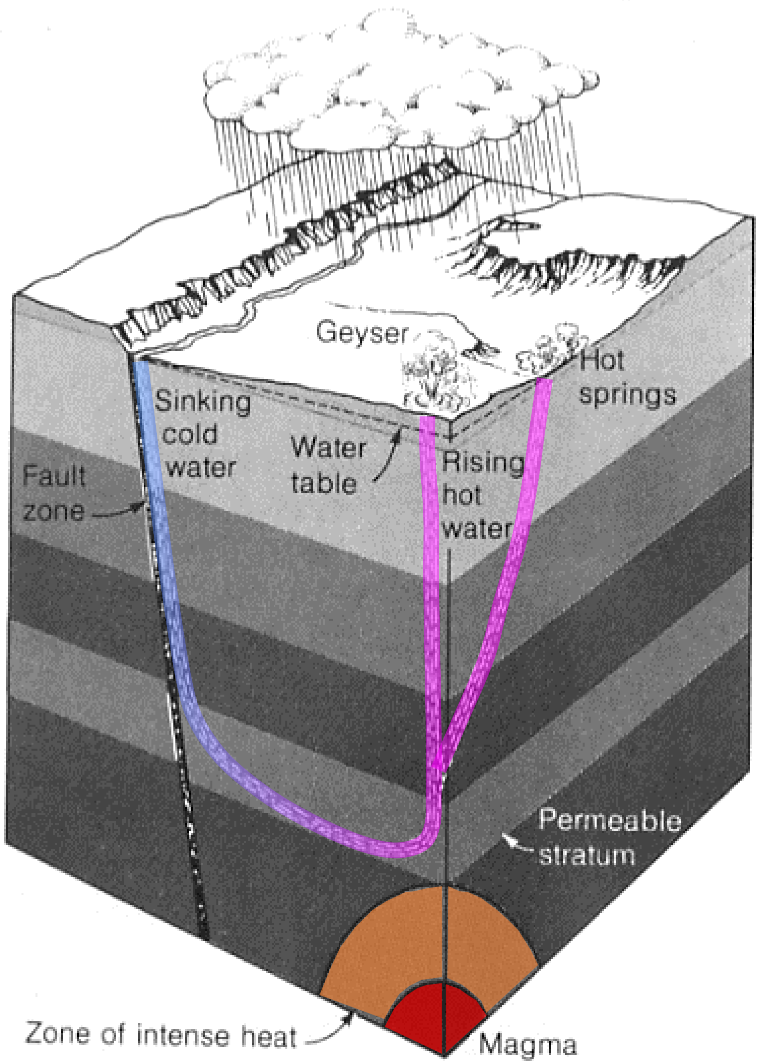
on behalf of the iMOST Team

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

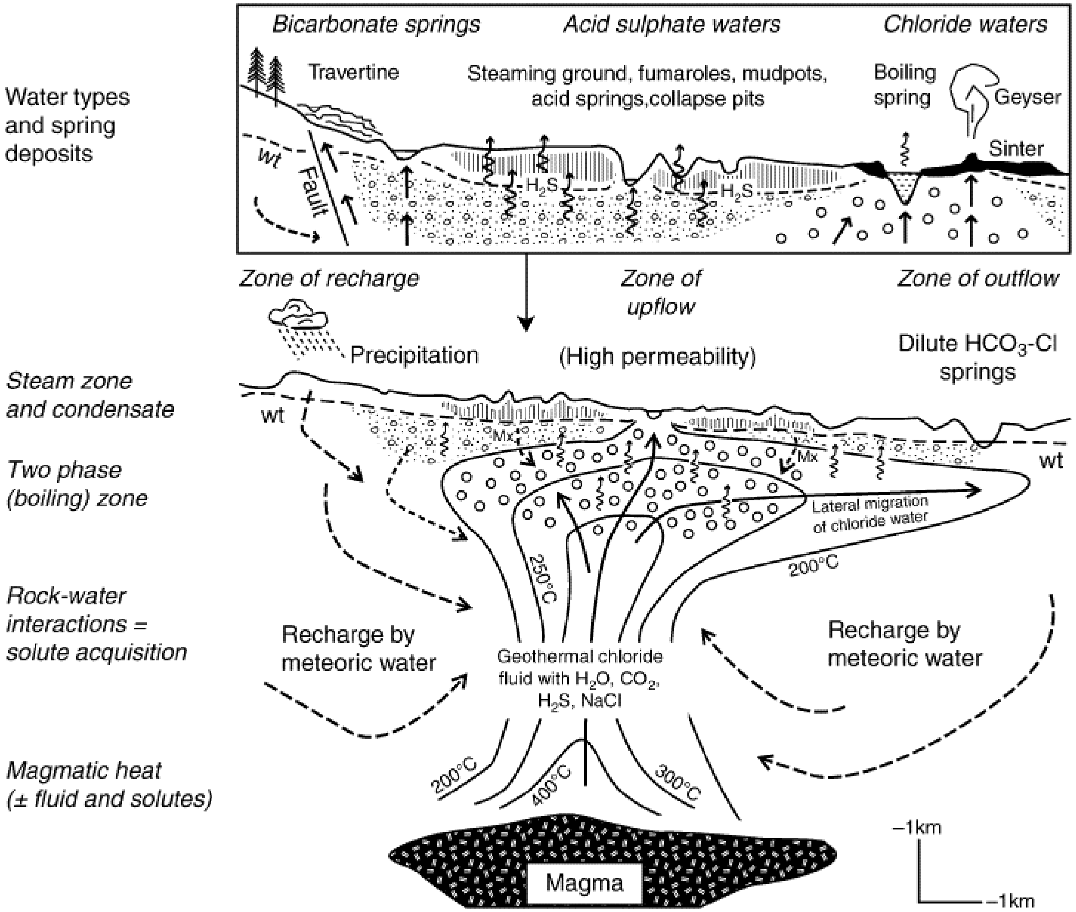
Sub-Objective
Sedimentary System
Hydrothermal
Deep subsurface groundwater
Subaerial
Igneous terrane
Carbon chemistry
Biosignatures--ancient
Biosignatures--modern

Introduction

- Hydrothermal systems combine heat from magmatic or impact-generated molten rock with magmatic gases and atmospherically-derived crustal water
- Rocks produced from or processed by hydrothermal systems preserve a record of the interactions of atmospheric, hydrologic, and lithospheric cycles, as well as possible biologic activity
- Long predicted for Mars, extinct hydrothermal systems are now recognized both from orbiter and rover-based observations



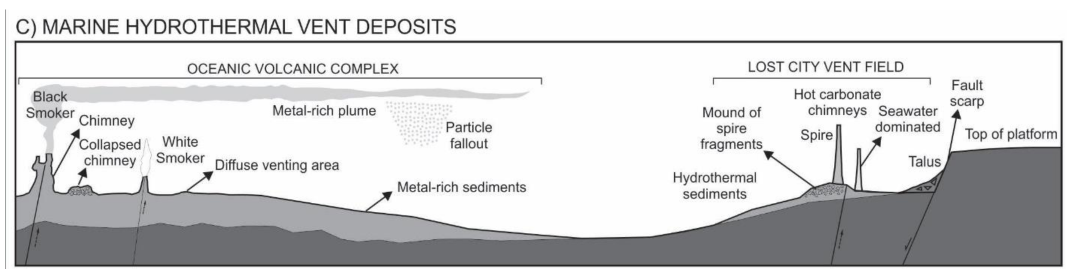
Terrestrial shallow hydrothermal facies



Continental shallow hydrothermal sedimentary facies, fluids

– Renaut and Jones, 2011 (Encycl. Geobio.); Ruff & Farmer, 2016 (Nature Commun.)

Marine shallow hydrothermal sedimentary facies, fluids *– Van Dover, 2000 (Princeton Univ. Press); Kelley et al., 2001 (Nature)*



Critical Open Questions

- What is the spatiotemporal distribution of hydrothermal deposits – volcanic and impact related – throughout Mars' evolution?
- How have hydrothermal processes affected Mars' climatic, hydrologic, and lithospheric domains? How are they linked?
- Would martian hydrothermal processes and products be expected to be similar to or different from those on Earth?
- Do hydrothermal systems on Mars reflect lower average temperatures than Earth?
- Have these differences influenced assessments of habitability and preservation potential?
- What do hydrothermal systems tell us about the interior (e.g. oxidation state) and exterior (e.g. atmospheric volatiles) conditions of Mars?
- Do hydrothermal systems provide information about the abiotic and/or biotic routes of formation of organic compounds on Mars?

Questions → Investigation Strategies

Hydrothermal	Understand an ancient martian hydrothermal system through study of its mineralization products
Invest. 1.2A	Identify hydrothermal facies that reflect primary differences in deposit formation temperature, due to cooling and degassing of fluid discharge along a gradient with respect to proximity to the vent source.
Invest. 1.2B	Reconstruct the character of the fluids of the paleo-hydrothermal system. Determine the primary environmental and geochemical parameters at the time the system was active.
Invest. 1.2C	Reconstruct how the depositional system changed over time, and as a function of position within the system.
Invest. 1.2D	Determine the age of the hydrothermal system, and the duration and rate of water flow.
Invest. 1.2E	Investigate the possibility of post-depositional modification/fluids, and interpret those processes.

Manifestations of Hydrothermal Systems

- Alteration of Existing Rocks -

Surface rocks are altered by acidic steam from fumaroles leaving a leached residue and/or mineral sublimates.

Subsurface rocks are altered by hydrothermal fluids moving in permeable zones and then exposed by erosion and/or uplift.

Both can leave a record of distinctive mineral assemblages, deposits, textures – windows on geochronology, fluid-crust-climate history, PBS

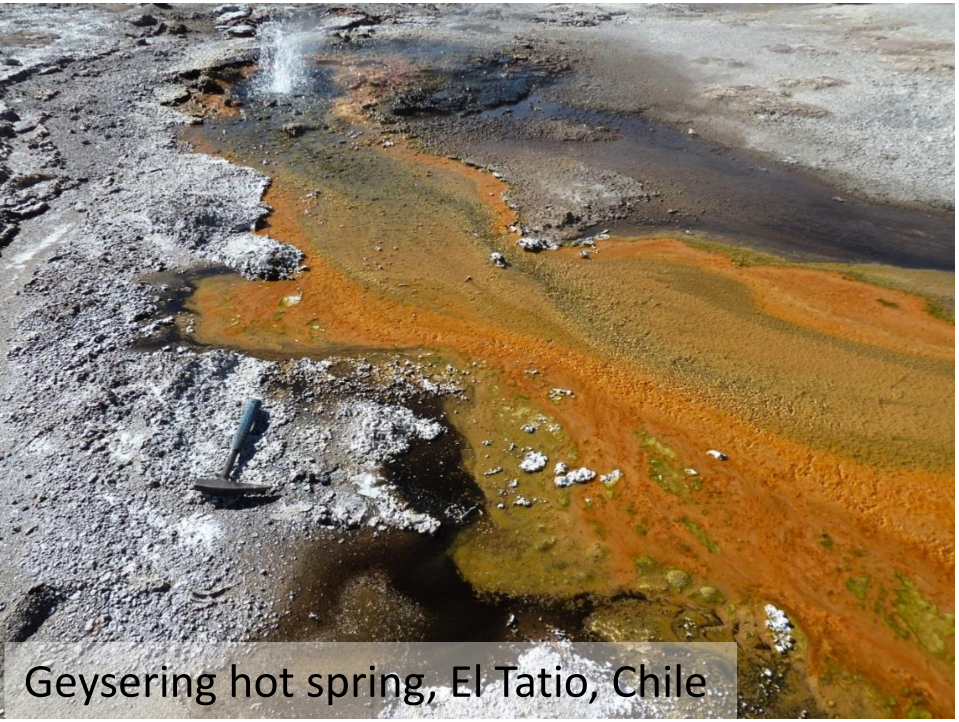
Manifestations of Hydrothermal Systems

- Production of New Rocks -

Hot springs and geysers produce mounds and terraces of chemical sedimentary deposits known as sinter (opaline silica) or travertine (carbonate). Distinctive rock textures and shapes are produced in these settings. All these features can be preserved in the geologic record.

Manifestations of Hydrothermal Systems

- Habitats for Microbes -



Geysering hot spring, El Tatio, Chile

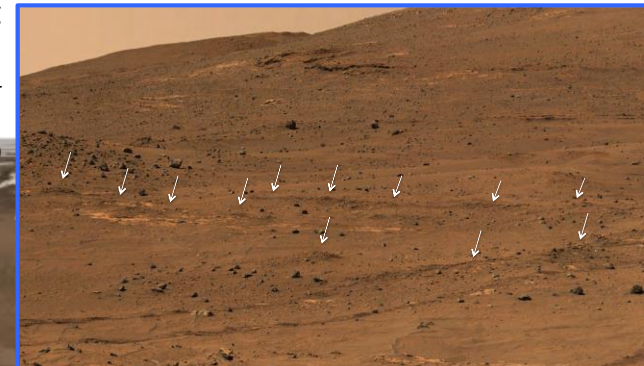
Fumaroles, Roosevelt Springs, Nevada

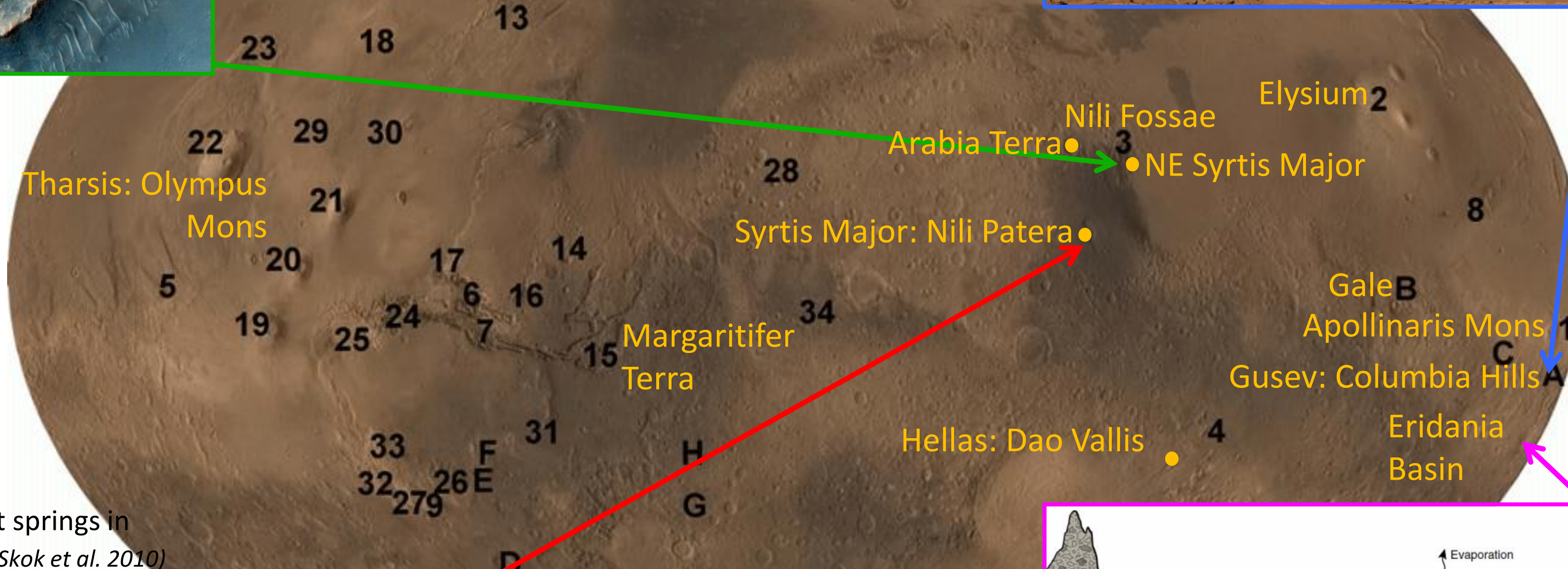
Hydrothermal settings provide varied thermal and chemical environments conducive to a range of microorganisms. Precipitation of minerals from hydrothermal fluids can entomb microbes and preserve fossil and organic evidence in the rock record.

Candidate Volcanic Hydrothermal Sites on Mars

A range of possible hydrothermally-produced minerals in NE Syrtis Major *(Mustard et al. 2007; Ehlmann & Mustard, 2012; Bramble et al. 2017)*

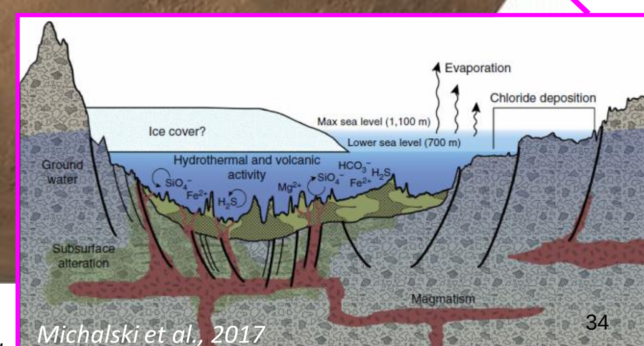
Possible hot spring sinter deposits in the Columbia Hills *(Squyres et al., 2008; Ruff & Farmer, 2016)*





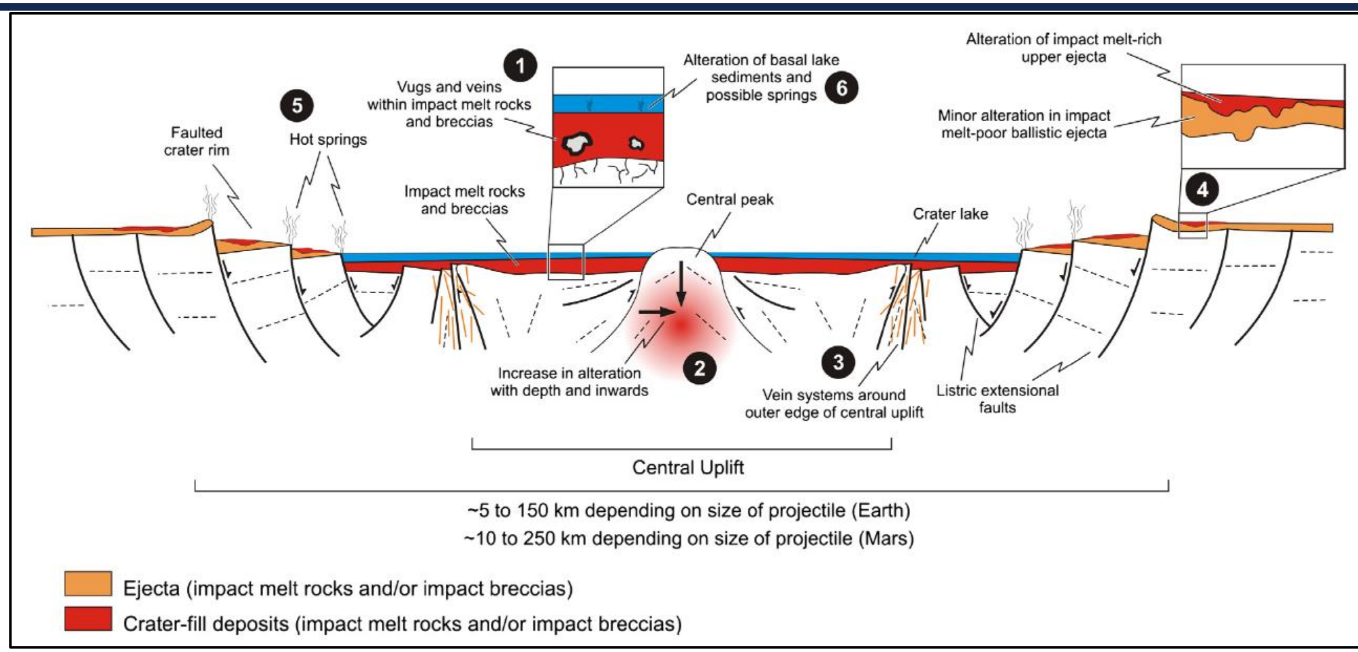
Possible hot springs in Nili Patera *(Skok et al. 2010)*

Possible hydrothermal seafloor volcanic sedimentary setting in Eridania Basin

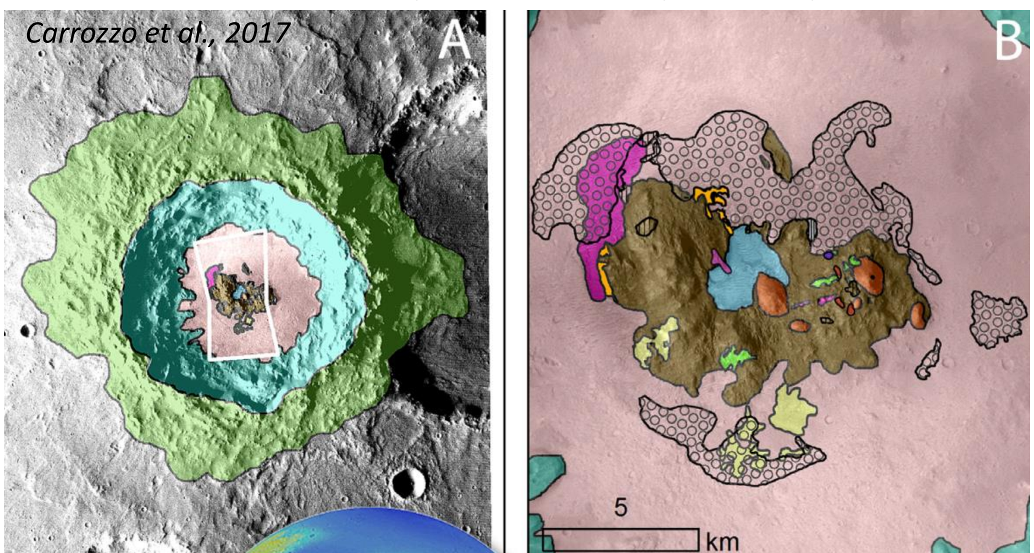


Candidate Impact-related Hydrothermal Sites on Mars

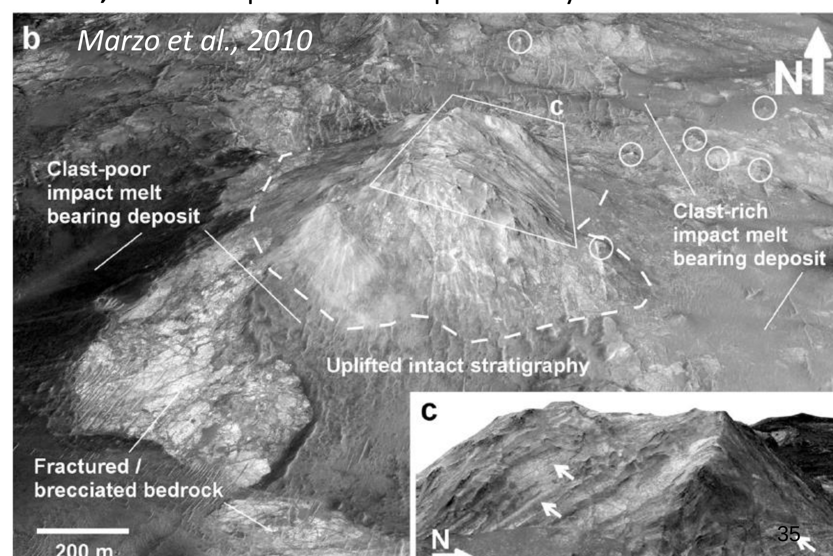
Schematic of impact crater with locations of potential hydrothermal activity
(Osinski et al., 2013)



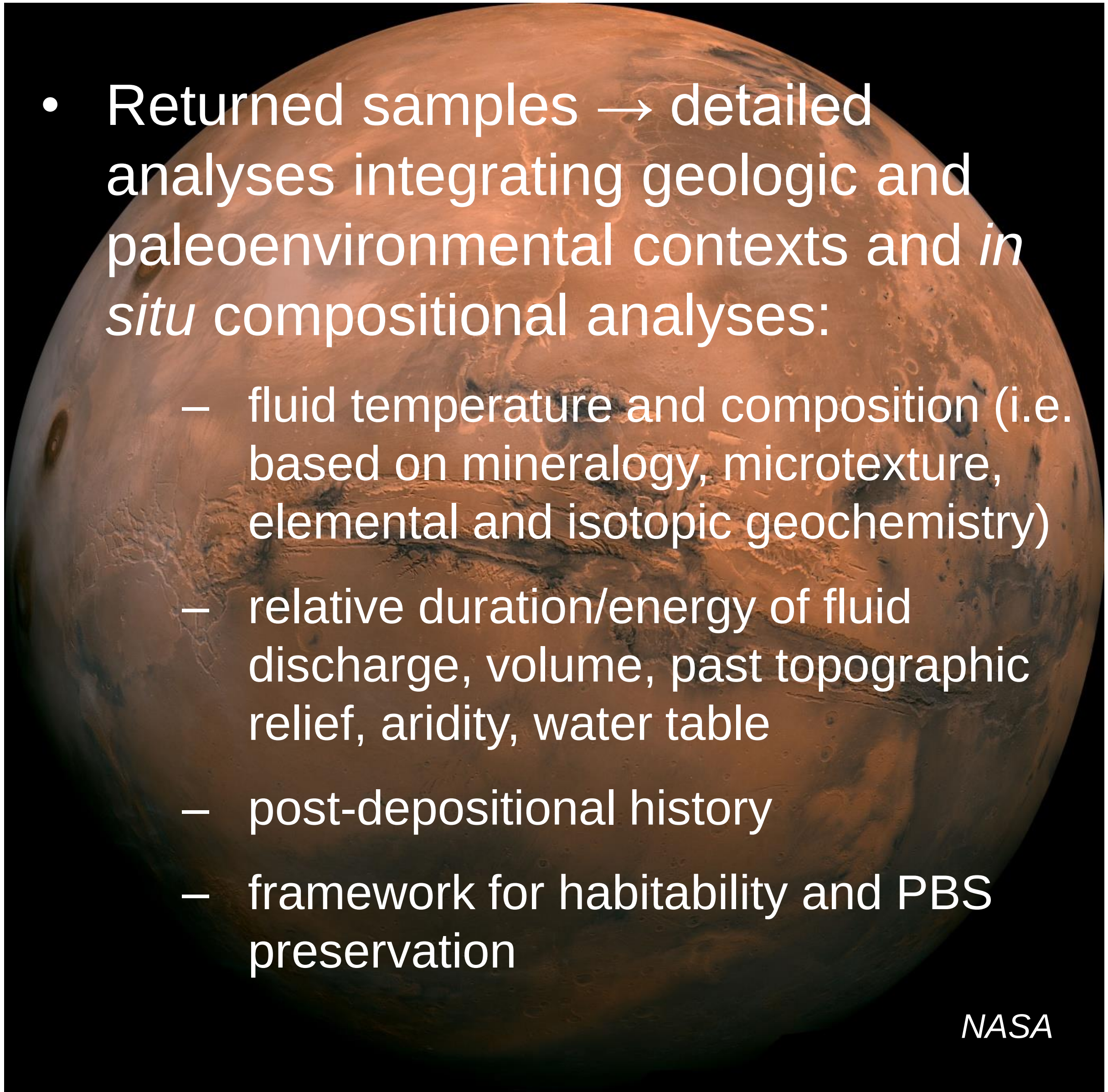
Auki Crater, Mars – Possible hydrothermal activity in central peak



Toro Crater, Mars – Impact melt and possible hydrothermal mounds



Why Returned Sample Studies are Important



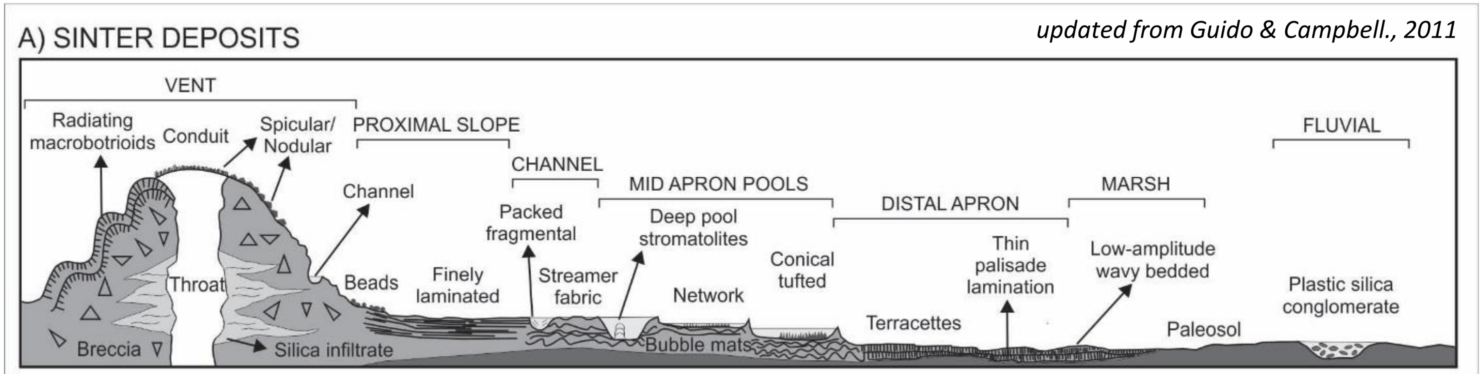
- Returned samples → detailed analyses integrating geologic and paleoenvironmental contexts and *in situ* compositional analyses:
  - fluid temperature and composition (i.e. based on mineralogy, microtexture, elemental and isotopic geochemistry)
  - relative duration/energy of fluid discharge, volume, past topographic relief, aridity, water table
  - post-depositional history
  - framework for habitability and PBS preservation

NASA

Samples and measurements

Summary of samples required/desired to achieve proposed objectives:

- A suite of hydrothermal samples and/or altered host rocks representing –
  - decreasing paleo-temperature with distance (e.g., proximal to distal) from the hydrothermal vent



  - the range of chemistry and mineralogy within hydrothermal system
  - the range of rocks fitting hypothesized age model of the system
  - interbedding, cross-cutting and/or overgrowth relationships from different stratal positions within the hydrothermal system
  - rocks and minerals, especially clays, that potentially show evidence of late-stage diagenetic processes such as hydrothermal alteration, superimposed on the hydrothermal system

Introduction to Proposed Objective 2

- Three sub-objectives defined.
  - Carbon chemistry is a component of both ancient and modern life detection, but it is so much more.
  - The strategies for ancient life detection are rather different than the strategies for modern life detection, so these are described separately.
- It is assumed that all of the samples collected as part of Objective 1 are of interest for these three sub-objectives.

		Shorthand	Full Statement of Objective
Objective 2		***Life***	Assess and interpret the biological potential of Mars
Complete ALL of the following sub-objectives.			
	Sub-obj. 2.1	***Carbon chemistry***	Assess and characterize carbon, including possible organic and pre-biotic chemistry.
	Sub-obj. 2.2	***Biosignatures--ancient***	Assay for the presence of biosignatures of past life at sites that hosted habitable environments and could have preserved any biosignatures.
	Sub-obj. 2.3	***Biosignatures--modern***	Assess the possibility that any life forms detected are still alive, or were recently alive.

Evaluate Martian Organic Carbon

Presented by: Sandra Siljeström

on behalf of the iMOST Team

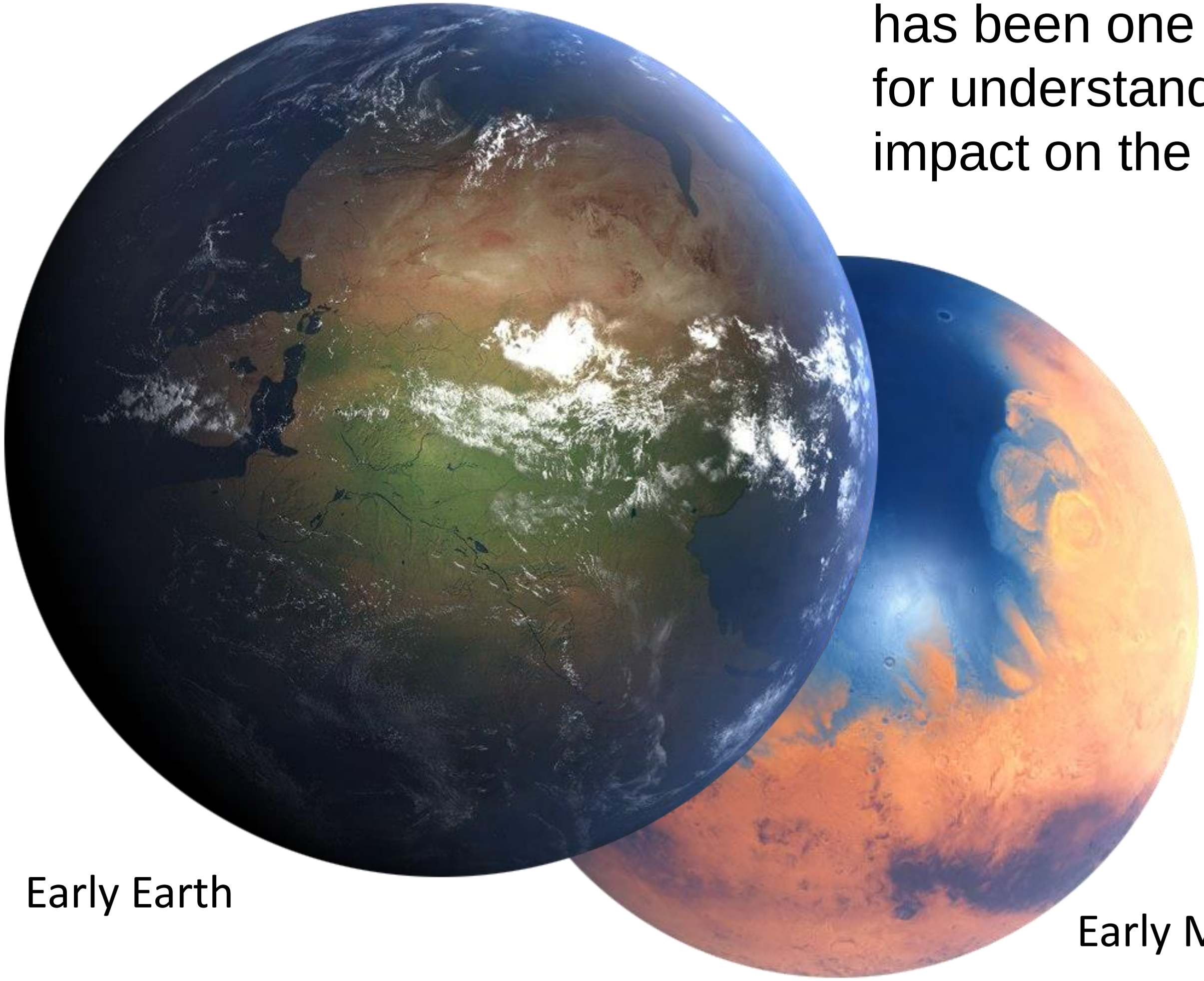
Objective	
1	*Geological environment(s)*
2	*Life*
3	*Geochronology*
4	*Volatiles*
5	*Planetary-scale geology*
6	*Environmental hazards*
7	*ISRU*

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

Introduction

- The study of organic carbon molecules on Earth, and carbon cycling in general, has been one of our most powerful tools for understanding ancient life and its impact on the environment.

- Because of the similarity between early Earth and early Mars, this approach holds great promise for Mars.

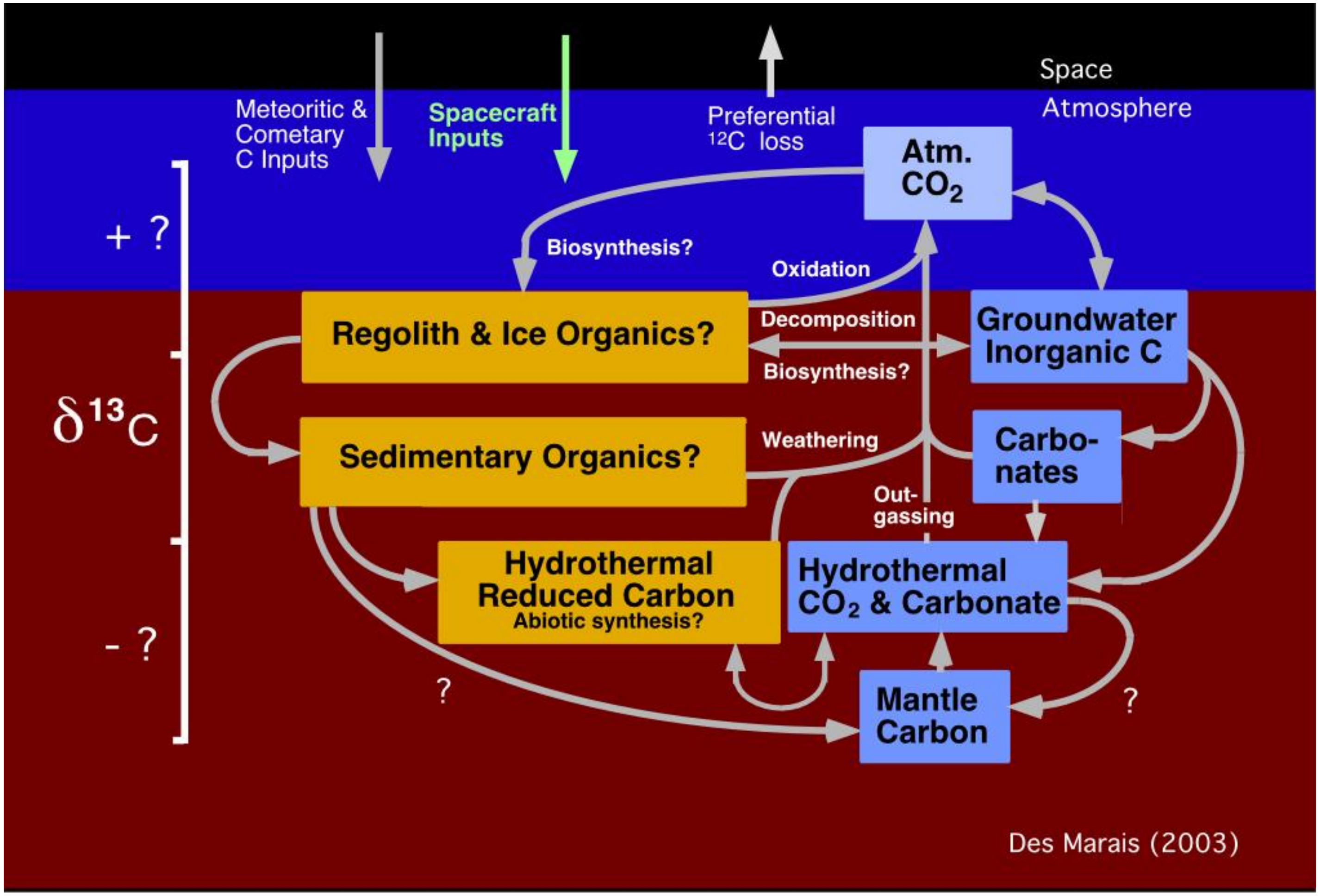


Early Earth

Early Mars

Mars (Bio)geochemical Carbon Cycle

- Carbon chemistry is more than just biosignatures. What reservoirs and fluxes of mass between reservoirs happened on Mars? We need to know the full picture to interpret possible superimposed biological signal.



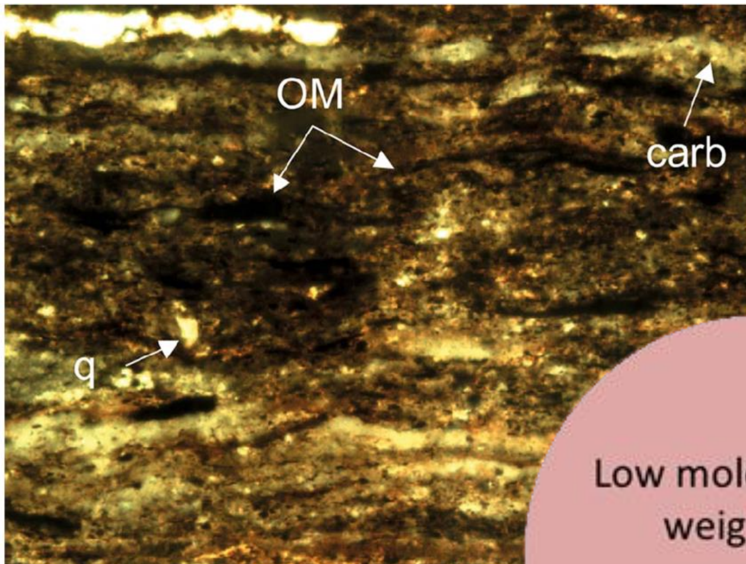
Critical Open Questions

- What is the full suite of indigenous martian carbon phases and organic molecules-recorded in its geologic record?
- What is the “inorganic baseline”? How does “baseline” relate to the carbon and organic phases present?
- How do the suite of carbon phases and organic molecules differ between different reservoirs on Mars?
- Is there evidence for prebiotic carbon chemistry?
- Are there organic molecules that indicate extinct or extant martian life?
- What processes on Mars degrade organic molecules? What are the rates and effects? What processes protect against the destruction?

Questions → Investigation Strategies

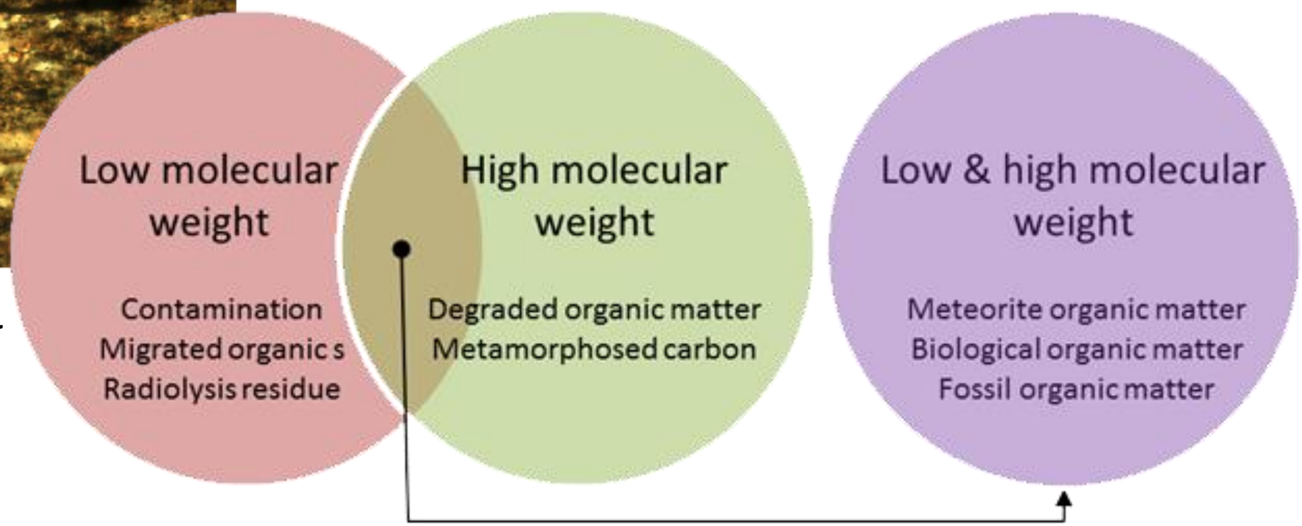
Carbon chemistry	Assess and characterize carbon, including possible organic and pre-biotic chemistry
Invest. 2.1A	Develop as complete an inventory as possible of the organic molecules present in the samples, as well as any oxidized carbon compounds.
Invest. 2.1B	Determine isotopic fractionation between organic matter and carbon-bearing minerals such as carbonates.
Invest. 2.1C	Establish the indigeneity of any detected analytes
Invest. 2.1D	Establish whether chemical relationships potentially indicate biological processes
Invest. 2.1E	Identify any aspects of the environment potentially conducive to the existence and preservation of prebiotic chemistry and amenable to detection

Non-Life vs Life Associations



Pacton et al. (2009) *Facies, 55, 401-419.*

The association of organic matter with sedimentary features is characteristic of microbial habitats



The association of molecular weight fractions of organic matter can reveal the source

Sephton et al. (2014) *Geophysical Research Letters, 41, 7453-7460.*

Non Life vs Life Chemistry

Meteorite molecules

- Complete isomeric diversity
- Generally racemic
- Decrease in abundance with carbon number
- Unusual or unique forms
- ^{13}C enrichment
- Stepwise synthesis

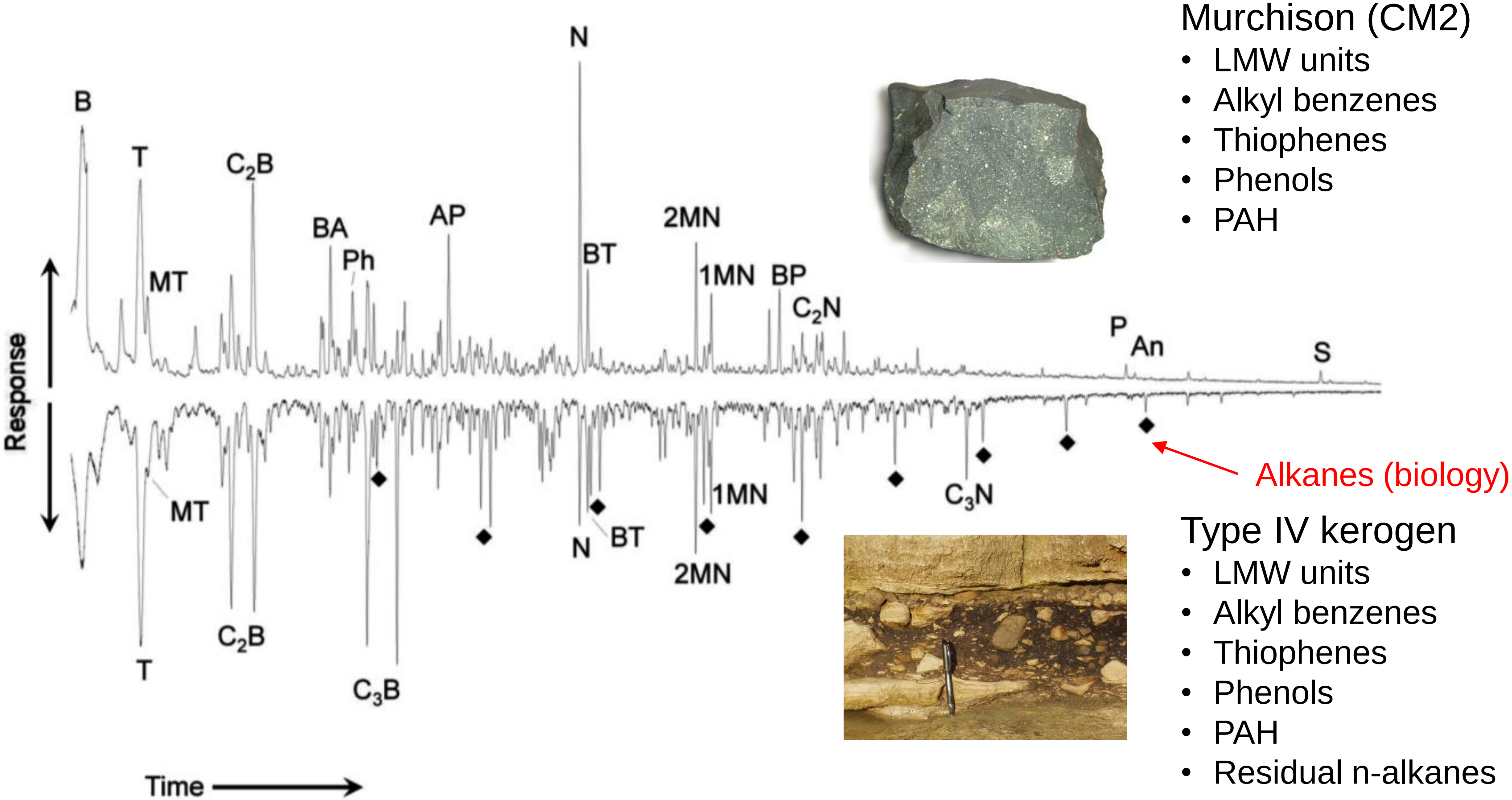
Life molecules

- Specific isomers
- Homochirality
- Abundance related to biological function
- Common forms
- ^{13}C depletion
- Biosynthesis

We can distinguish between non-biological and biological organic matter, but only when enough primary information is preserved

Sephton and Botta (2005) *International Journal of Astrobiology*, 4, 269–276.

Preservation and Organic Signals



Murchison (CM2)

- LMW units
- Alkyl benzenes
- Thiophenes
- Phenols
- PAH

Type IV kerogen

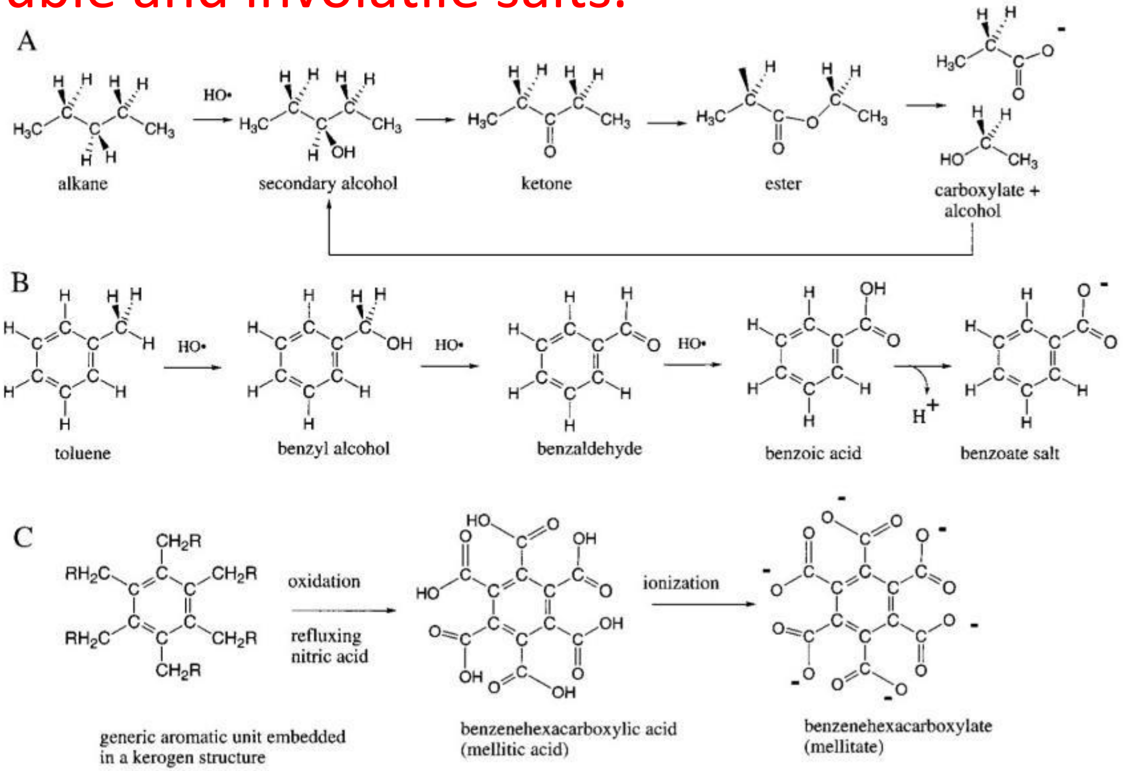
- LMW units
- Alkyl benzenes
- Thiophenes
- Phenols
- PAH
- Residual n-alkanes

Good preservation is highly desirable but even degraded organic signals (e.g. Type IV kerogen) indicate provenance

Matthewman et al. (2013) *Astrobiology 13, 324-33.*

Martian Organic Degradation (1 of 5)

Oxidation: Mars has an oxidising surface that degrades organic matter to insoluble and involatile salts.



- No organic molecules detected by Viking GC-MS
- 2.4 x 10^8 g carbon comes to Mars each year via meteorites

- Oxidative degradation
  - Units lost, residues produced
- Benner et al. 2000 PNAS 97, 2425-2430
  - A) pentane, B) toluene, C) Kerogen

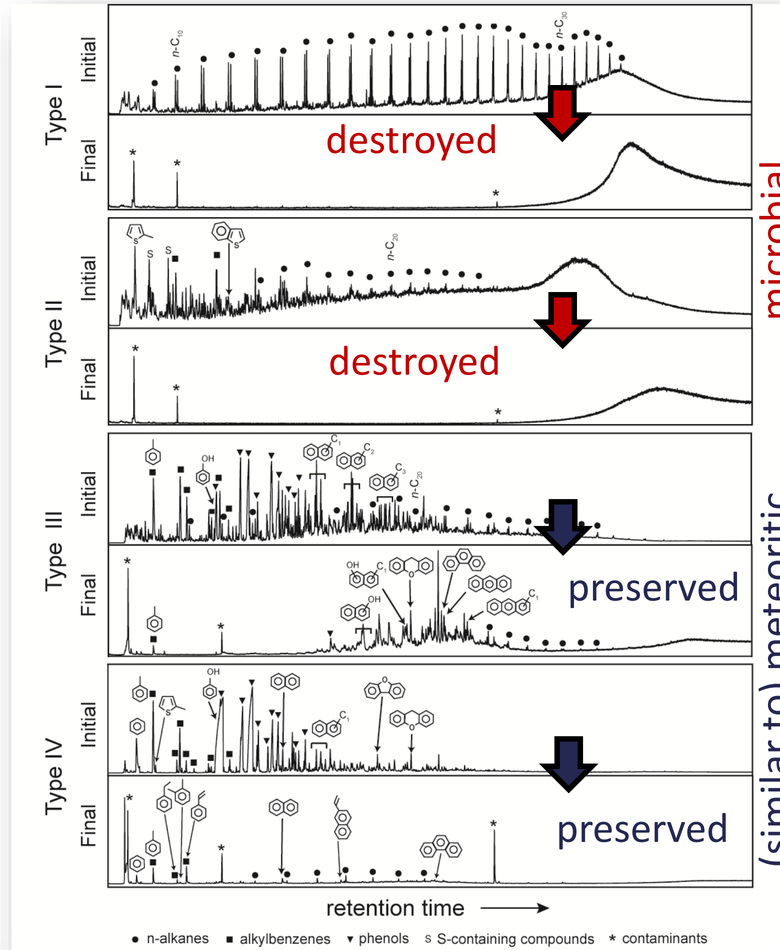
Martian Organic Degradation (2 of 5)

- Radiolysis
  - Due lack of magnetic field and thin atmosphere on Mars, UV, solar and cosmic radiation is much higher on Mars than Earth.
  - Radiation promotes destruction of organic molecules.
  - Effects are the strongest at the surface of Mars. Therefore, more likely to find intact organic molecules below surface, especially a few meters down.

Martian Organic Degradation (3 of 5)

Impact excavation: introduces preservation bias

- Impact ejected biomarkers
  - Deep rocks avoid oxidation
  - Microbial organic matter is hydrocarbon chain rich
  - Meteorite organic matter is hydrocarbon ring rich
  - Rings survive but chains are destroyed



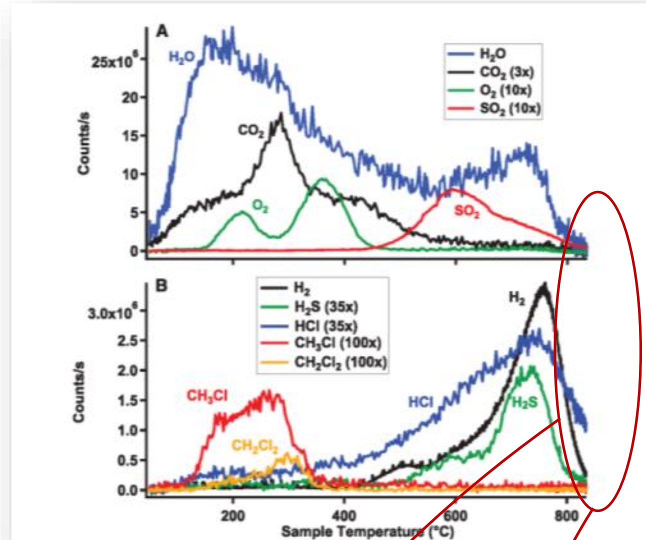
Montgomery et al. (2016) Scientific Reports, 6, 30947.

Martian Organic Degradation (5 of 5)

Salt-Induced Degradation

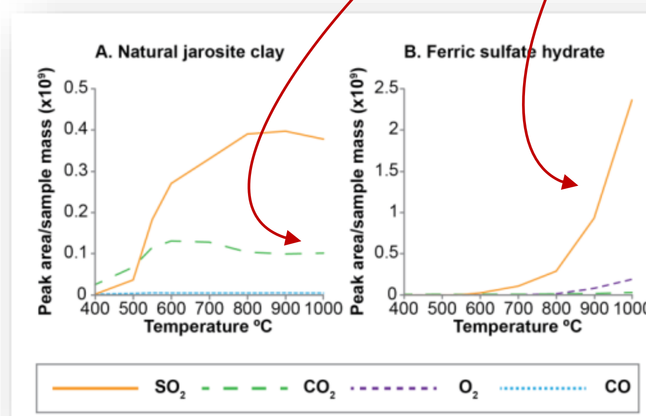
RSL indicate salt presence and mobilisation

< 800 °C perchlorates



Ming et al.2014, Science, 343,1245267

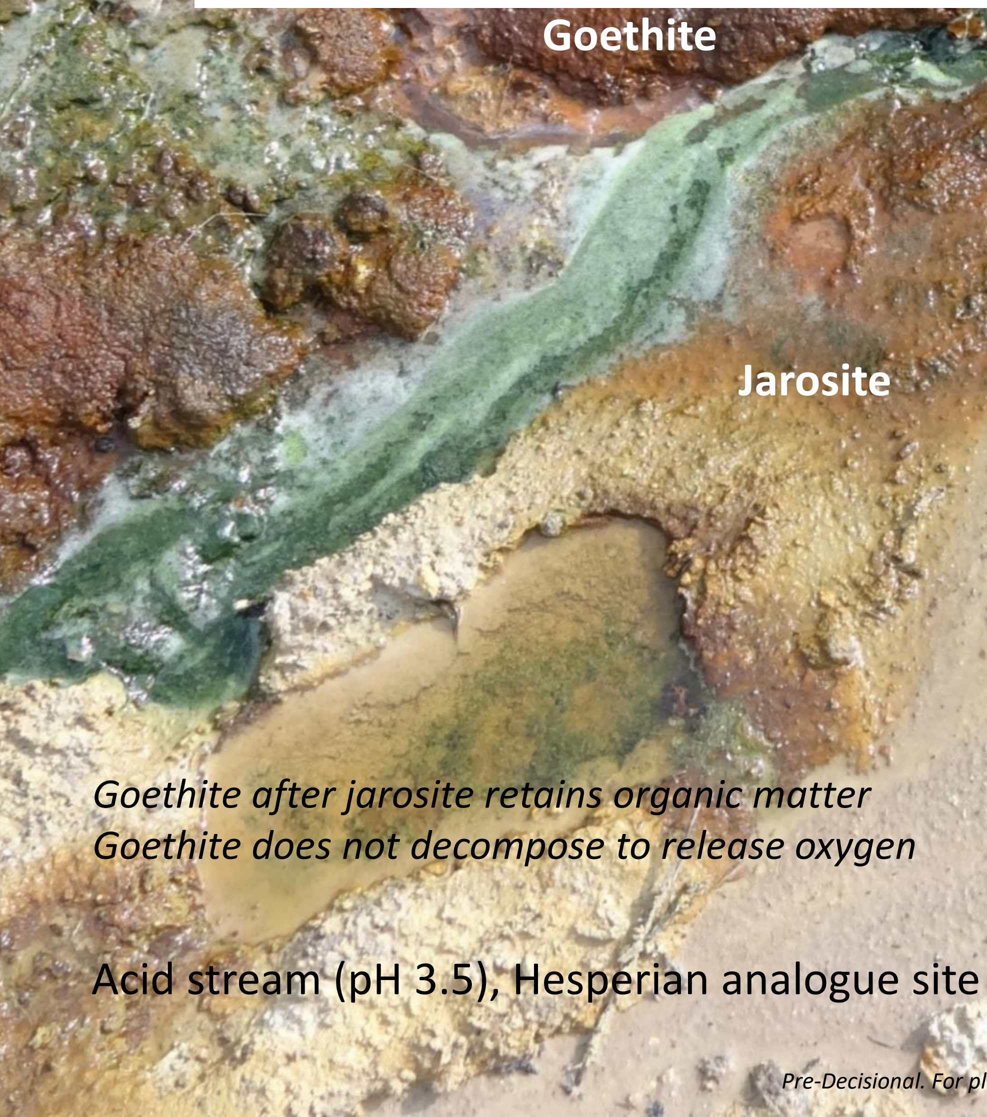
> 800 °C sulfates

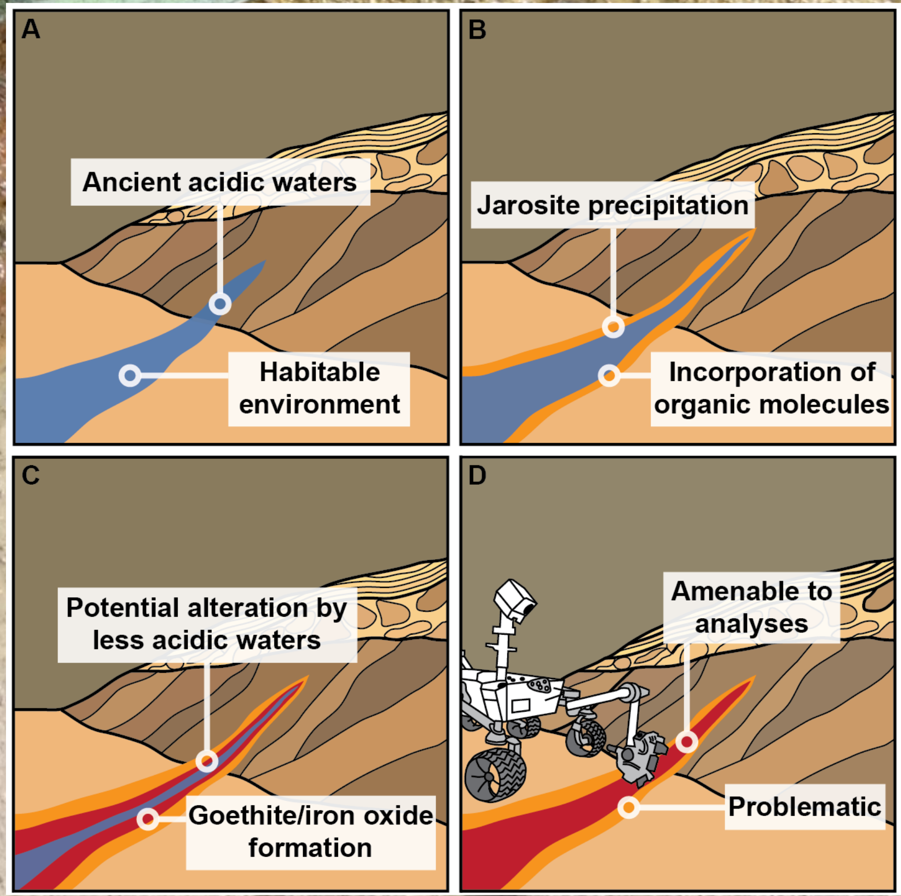


Lewis et al. 2015, Astrobiology, 15, 247-58

Martian Organic Degradation (4 of 4)

The preservation effect of certain Fe minerals





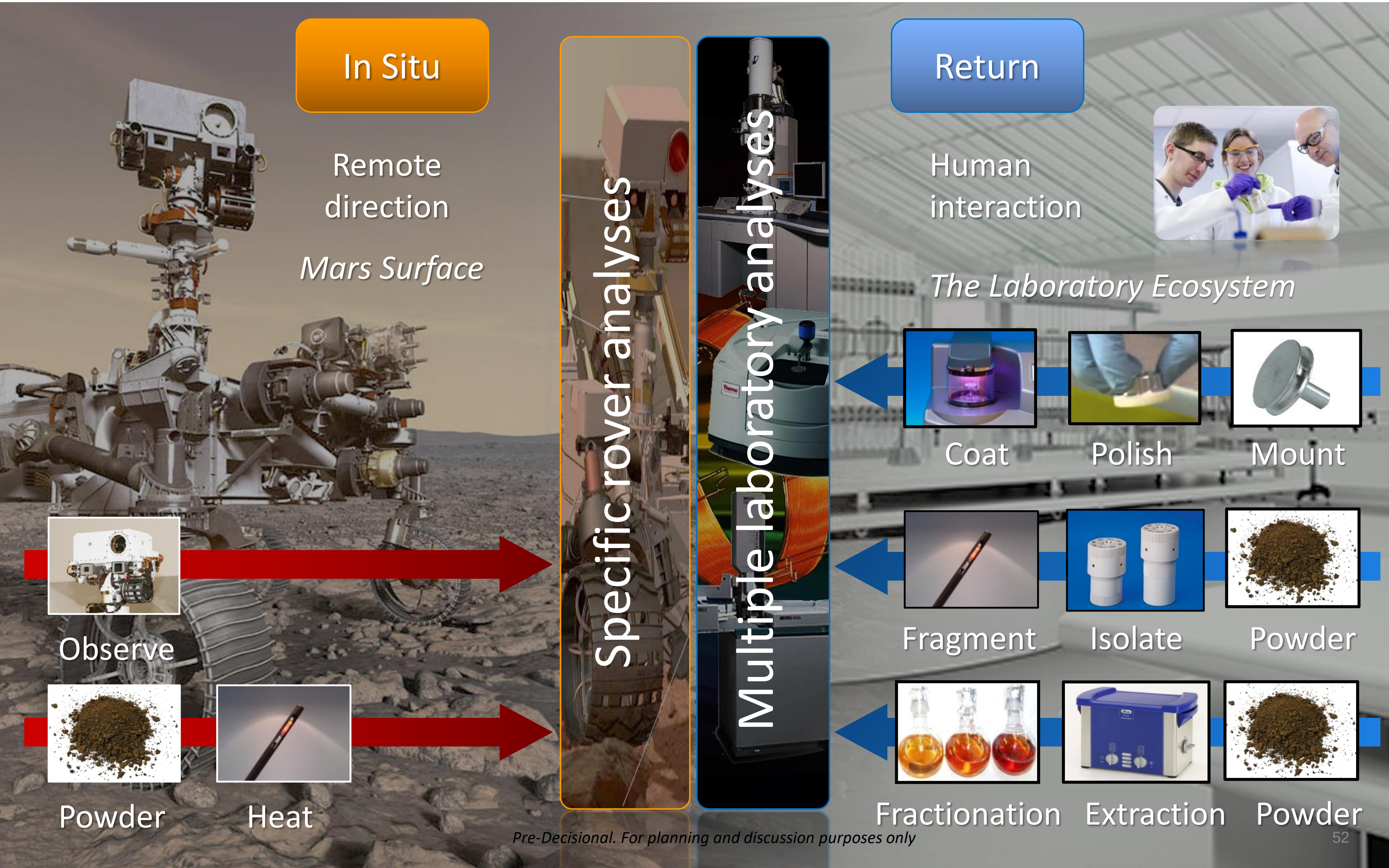
Goethite after jarosite retains organic matter
Goethite does not decompose to release oxygen

Acid stream (pH 3.5), Hesperian analogue site

Lewis et al. 2018 Astrobiology, in press

Why Returned Sample Studies are Important

International MSR Objectives & Samples Team



Seeking the Signs of Life: Biosignatures

Presented by: David Des Marais

on behalf of the iMOST Team

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

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

Biosignature - Definition

A biosignature is an object, substance and/or pattern whose origin specifically requires a biological agent.

The usefulness of a biosignature is determined not only by the probability that life produced it, but also by the improbability that nonbiological processes produced it.

Biosignature types: Objects Substances Patterns

Basic Concept of Life and Biosignatures

Life is a self-sustaining system,

capable of Darwinian evolution,

that utilizes free energy

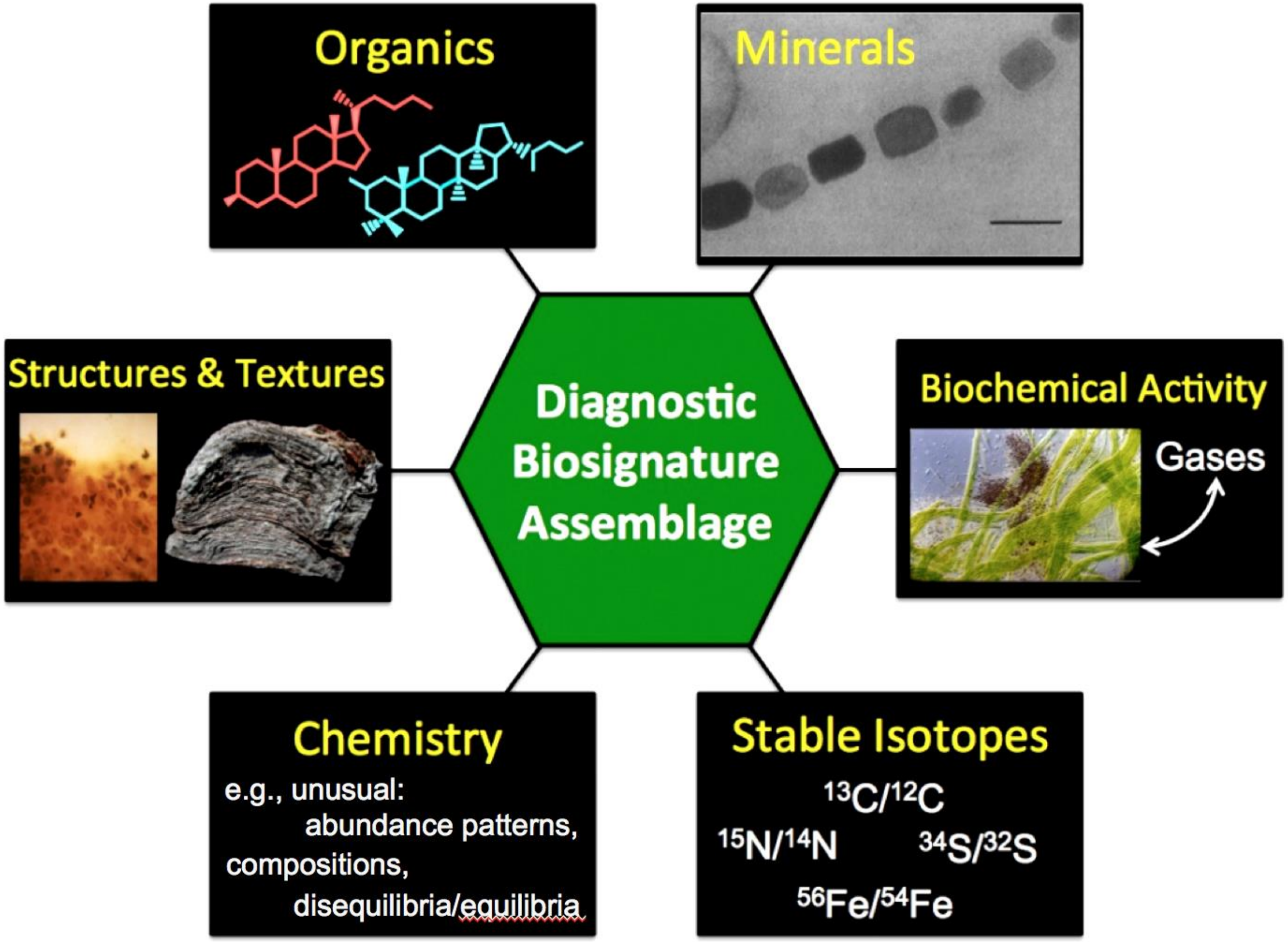
to sustain and propagate

an automaton, a metabolic network,

and functionally-related larger structures

Biosignature types: Objects Substances Patterns

Biosignature Categories



Coordinated analyses of several categories of potential biosignatures can greatly strengthen our interpretations of their origins and significance

Questions ⟶ Investigation Strategies

Critical Open Question: Are there detectable biosignatures in any of the returned samples

Biosignatures--ancient	Assay for the presence of biosignatures of past life at sites that hosted habitable environments and could have preserved any biosignatures.
Invest. 2.2A *	Characterize aspects of the environment that are conducive to the preservation or degradation of biosignatures.
Invest. 2.2B	Determine the presence and nature of any organic potential biosignatures.
Invest. 2.2C	Characterize any patterns of stable isotopic abundances that might indicate biological processes.
Invest. 2.2D	Identify any minerals that might indicate biological processes
Invest. 2.2E	Identify any morphological evidence of life
Invest. 2.2F	Identify any chemical evidence of life

*Regarding 2.2A , also see Investigation 2.1 - Mars and Organic Degradation

2.2A – Preservation and Degradation

'PRESERVERS:'
Silica
Carbonates
Phyllosilicates
Evaporites
Low T & P

'DEGRADERS:'
Oxidation
Radiation
High T & P

Preservation favored by:

*Relatively rapid sequestration in rocks silica, carbonates, shales, evaporites, etc.

*Reducing conditions

*Low temperatures and pressures after burial

Degradation promoted by:

*Oxidation of reduced compounds (e.g., organics)

*Radiation (e.g., radioactivity, cosmic radiation)

*Metamorphism (elevated temperature/pressure)

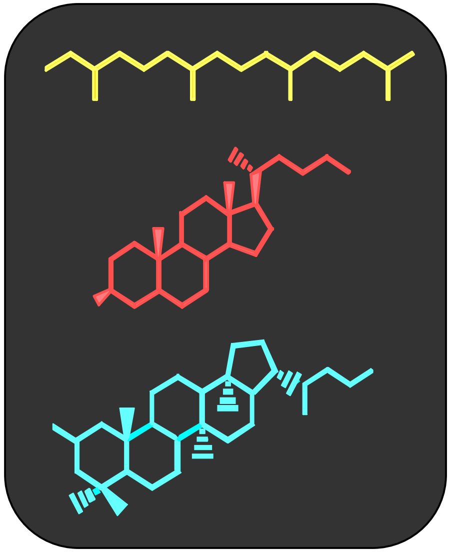
Proposed Measurements

*Identify any phases (e.g., silica, carbonates, phosphates, phyllosilicates, evaporite minerals) that enhance preservation.

*Identify evidence for post-depositional diagenetic alteration of sedimentary or hydrothermal deposits.

*Measure cosmogenic nuclides to determine surface exposure ages and erosion rates.

2.2B – Organic Biosignatures



Attributes

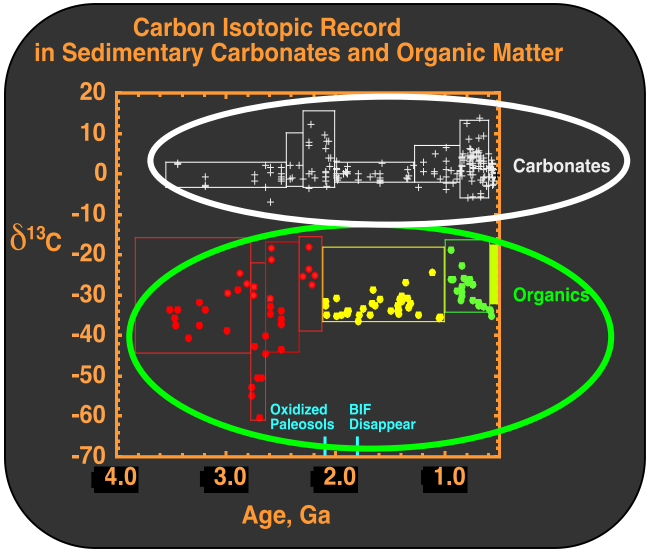
These reflect the biosynthetic pathways and biological functions of organic biosignatures. Diagnostic attributes include the following:

*Structures of individual molecules
*Relative abundances of molecules
*Molecular weight distributions
*Abundances of species containing C,H,N,O,P,S

Proposed Measurements

*Organic macromolecules and smaller molecules - molecular structures, abundances and molecular weight distributions
*Relative abundances of species containing N, O, P and S
*Spatial relationships between organic matter and minerals
*Relationships between organics and history of host rock

2.2C – Stable Isotope Abundance Biosignatures



Abundance patterns reflect environments, enzymes and metabolic pathways of biota.

Attributes include patterns:

*Within organic molecules

and also between:

*Individual organic molecules

*Classes of organic compounds

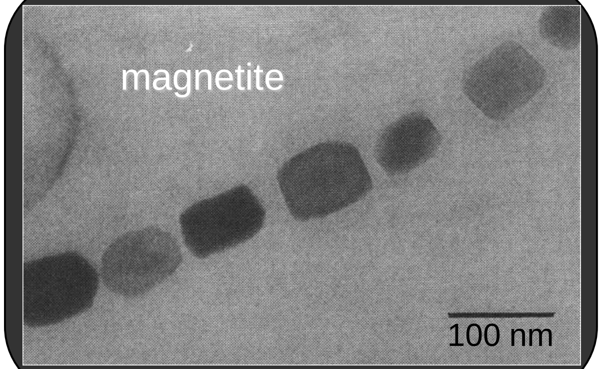
*Oxidized vs reduced compounds that contain C, N, S, and redox metals

Proposed Measurements

*Isotopic compositions of bulk organic matter and also patterns of isotopic abundances between organic compounds and within individual compounds

*Patterns of stable isotopic compositions of minerals and other inorganic phases.

2.2D – Mineral Biosignatures



Attributes

*Biochemical processes may be responsible, directly or indirectly, for most of Earth's known mineral species.

*Some carbon-bearing minerals probably occur exclusively due to biological activity.

Proposed Measurements

*Detect minerals that, on Earth, are compositionally and morphologically associated with biological activity or catalytic activity (e.g., carbonates, sulfur minerals, phosphates, phyllosilicates, transition metal oxides, etc.)

*Map spatial relationships between minerals in formerly habitable environments.

*Document relationships between potentially biogenic minerals and the histories of their host rocks.

2.2E – Morphological Biosignatures

Attributes

Morphologies include the following:
*Body fossils (cells, cell clusters, etc.)
*Biofilms (e.g., flexible organic sheets)
*Bioherms (e.g., stromatolites, other microbialites)
*Biofabrics (e.g., various microbially-induced sedimentary structures)
*Trace fossils (e.g., molds, burrows, pits, etc.)

Proposed Measurements

*Microscopic (even submicron) potential body fossils
*Microscale to macroscale rock or mineral fabrics and structures
*Mounds or columnar structures as potential bioherms
*Molds, casts with associated geochemical features
*Associated evidence of organics and/or metabolic activity

2.2F – Chemical Biosignatures

EXAMPLES
'unusual':
abundance patterns
compositions
disequilibria/equilibria

Attributes – some examples:

*Abundance patterns of metals used by biota
*Elevated concentrations of organic matter
*Abundance patterns of elements involved in redox reactions (e.g., S, N, transition metals)
*Redox boundaries in rocks (redox 'fronts')

Proposed Measurements

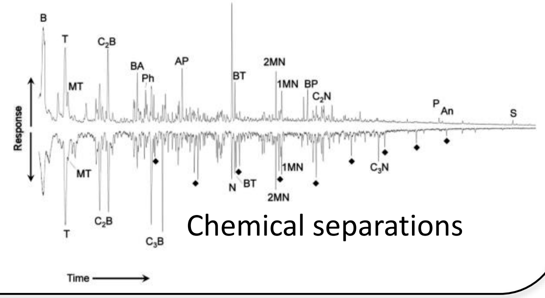
*Elemental abundance patterns
*Abundance patterns of minerals and other phases and of their elemental and chemical compositions
*Crystallographic structures and major- and minor-elemental abundances of individual phases
*Zones enriched in minerals formed by leaching or by *in situ* transformations

Why Returned Sample Studies are Important

Returned samples

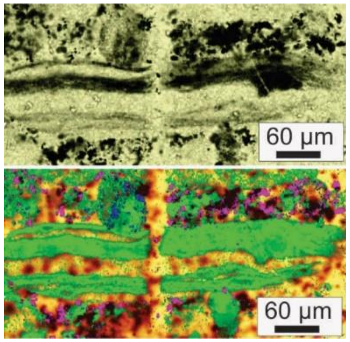
Observation-guided sample preparation, e.g.:

Petrographic thin sections

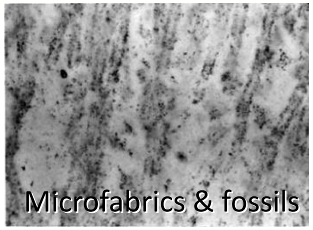


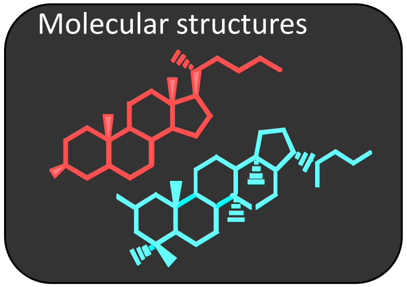
Chemical separations

Laboratory consortia exchange samples to interrogate potential biosignatures

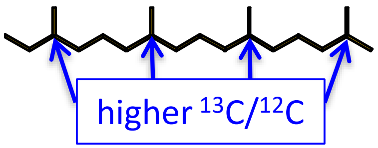


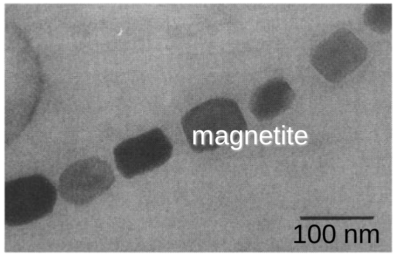
Chemical patterns





Isotopic patterns





Biomineral structures and trace element contents

The Geochronology of Mars

Presented by: Thorsten Kleine

on behalf of the iMOST Team

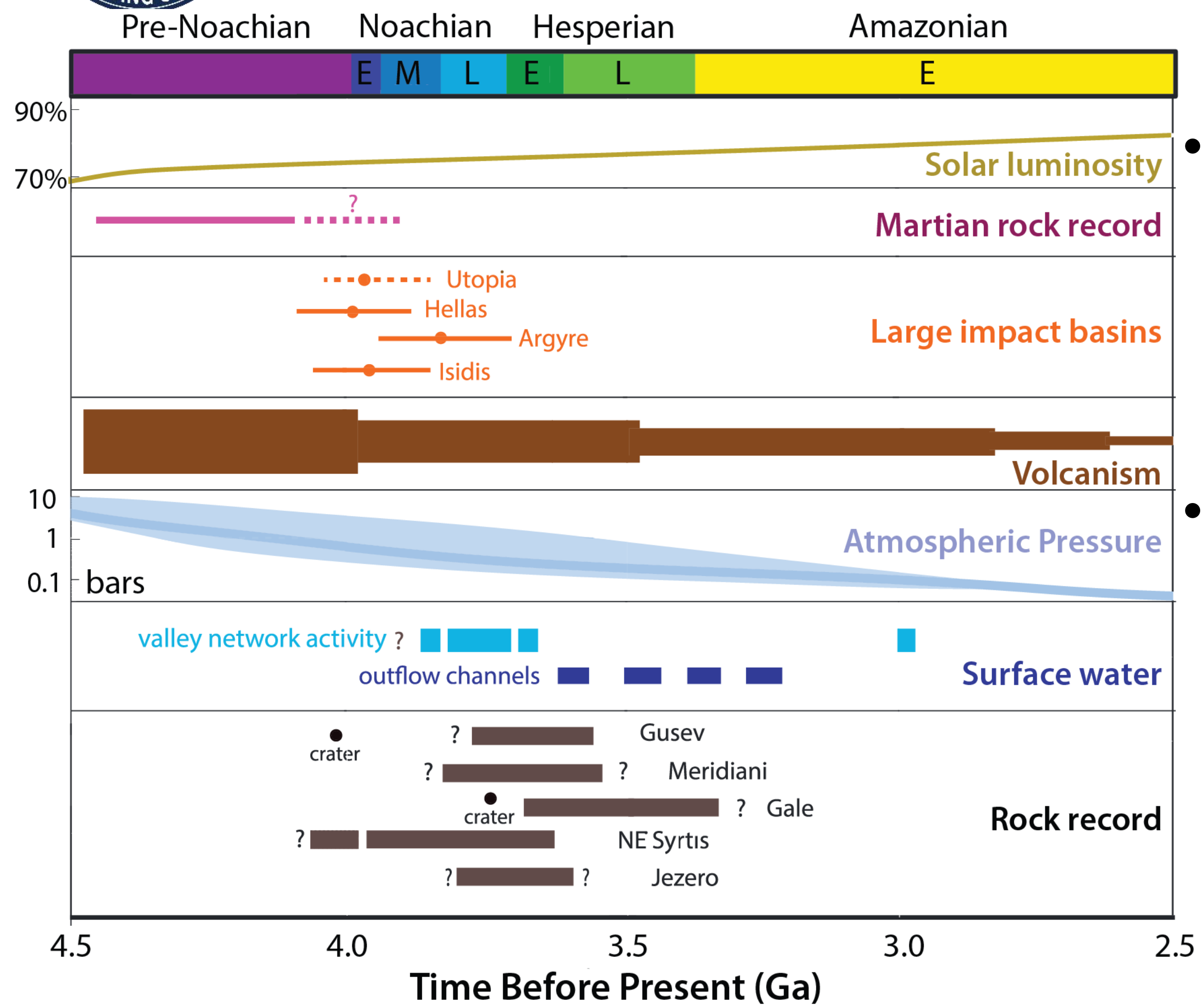
Objective	
1	*Geological environment(s)*
2	*Life*
3	*Geochronology*
4	*Volatiles*
5	*Planetary-scale geology*
6	*Environmental hazards*
7	*ISRU*

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

Introduction

- A key input into understanding the origin and evolution of the solar system is to determine what was happening on different objects at the same time. Quantitative comparison of the timelines of Earth and Mars is especially important.
  - Earth's early geologic record was not preserved, so studying Mars is the only way to understand what was happening in our neighborhood at that time.
  - Life on Earth got started during that missing time interval.
  - We need to understand the evolution of Mars as a system.
- This proposed objective seeks to provide radioisotope-based timing for major evolutionary events on Mars. This includes the timing of magmatic, tectonic, magnetic, fluvial, and impact events and the timing of formation of major deposits of secondary minerals and geomorphologic features.

Schematic Evolution of Mars



Weiss et al. (2018) after Ehlmann et al. (2016)

- <u>Relative</u> timing of the major factors associated with martian geologic history.
- <u>Quantitative</u> timescale is inferred, and could be in error by at least 0.5 Ga.

Critical Open Questions

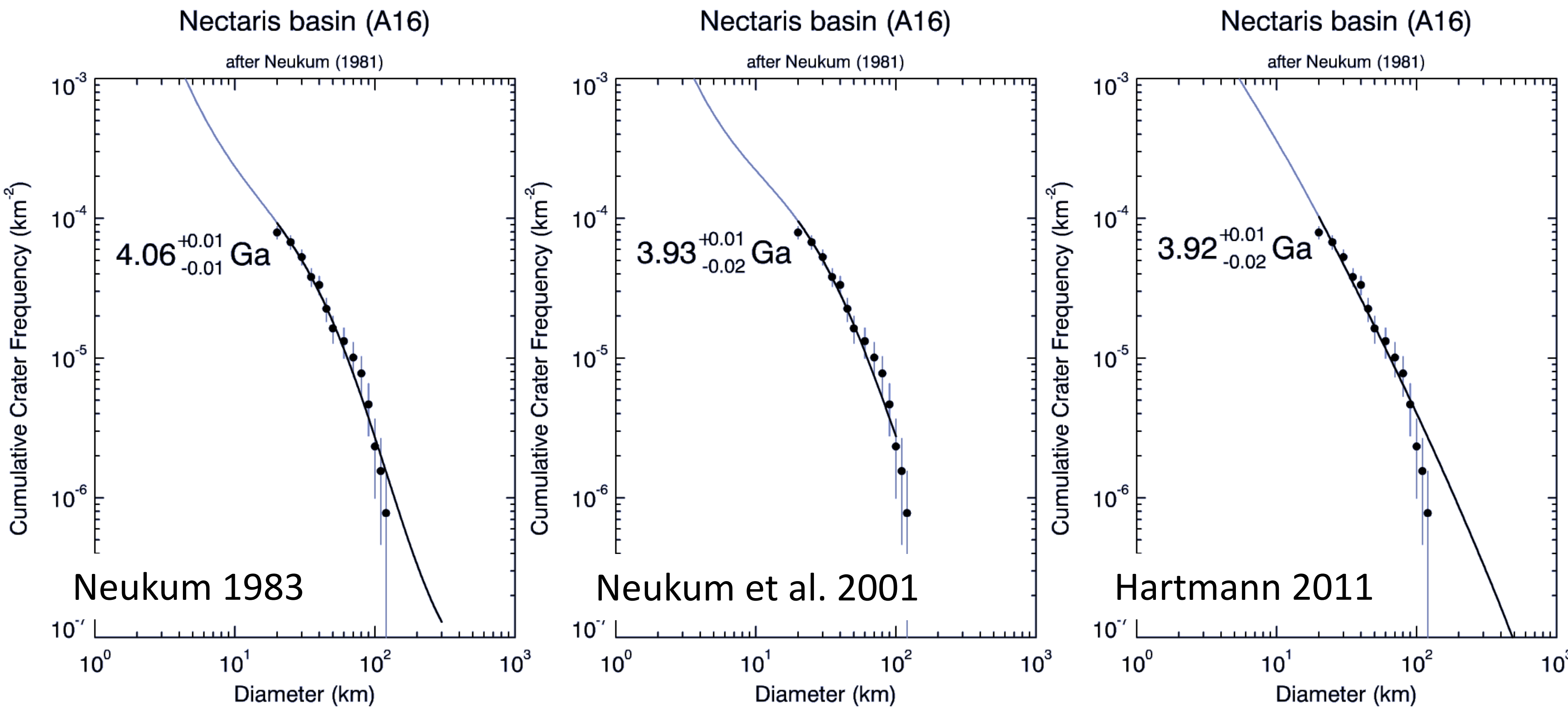
- What is the absolute history of Martian cratering?
- Did Mars experience a late heavy bombardment and, if so, when?
- What was the history of Martian mantle convection and magnetic field generation is there a causal link with ancient climate change?
- What was the timing and history of surface and subsurface aqueous activity, and other major geologic processes?
- What was the timing of accretion and what was the composition of the accreting materials?
- What was the history of surface exposure, uplift, exhumation and burial?

Questions → Investigation Strategies

Geochronology	Determine the evolutionary timeline of Mars, including calibrating the crater chronology time scale.
Invest. 3A	Calibrate the cratering chronology method by determining the radioisotope age for the formation of one or more geologic surfaces which has a well-defined cratering density.
Invest. 3B	Assess the existence of a late heavy bombardment on Mars, for comparison to the impact bombardment history of the Moon.
Invest. 3C	Constrain the thermal and magnetic histories of Mars and their relationship to global tectonics and heat loss
Invest. 3D	Determine the age of the martian hydrosphere, possible transitions in climatic conditions supporting habitability
Invest. 3E	Improve our understanding of the timing, nucleosynthetic isotope anomalies, noble gas compositions and distributions, and stable isotopic variations involved in the accretion and early differentiation of Mars.
Invest. 3F	Determine the history of surface exposure, including the timing and rates of crustal uplift/erosion and burial on Mars.

Mars Geochronology is Based on the Moon

A16: Nectaris Basin Age determined with various SFDs



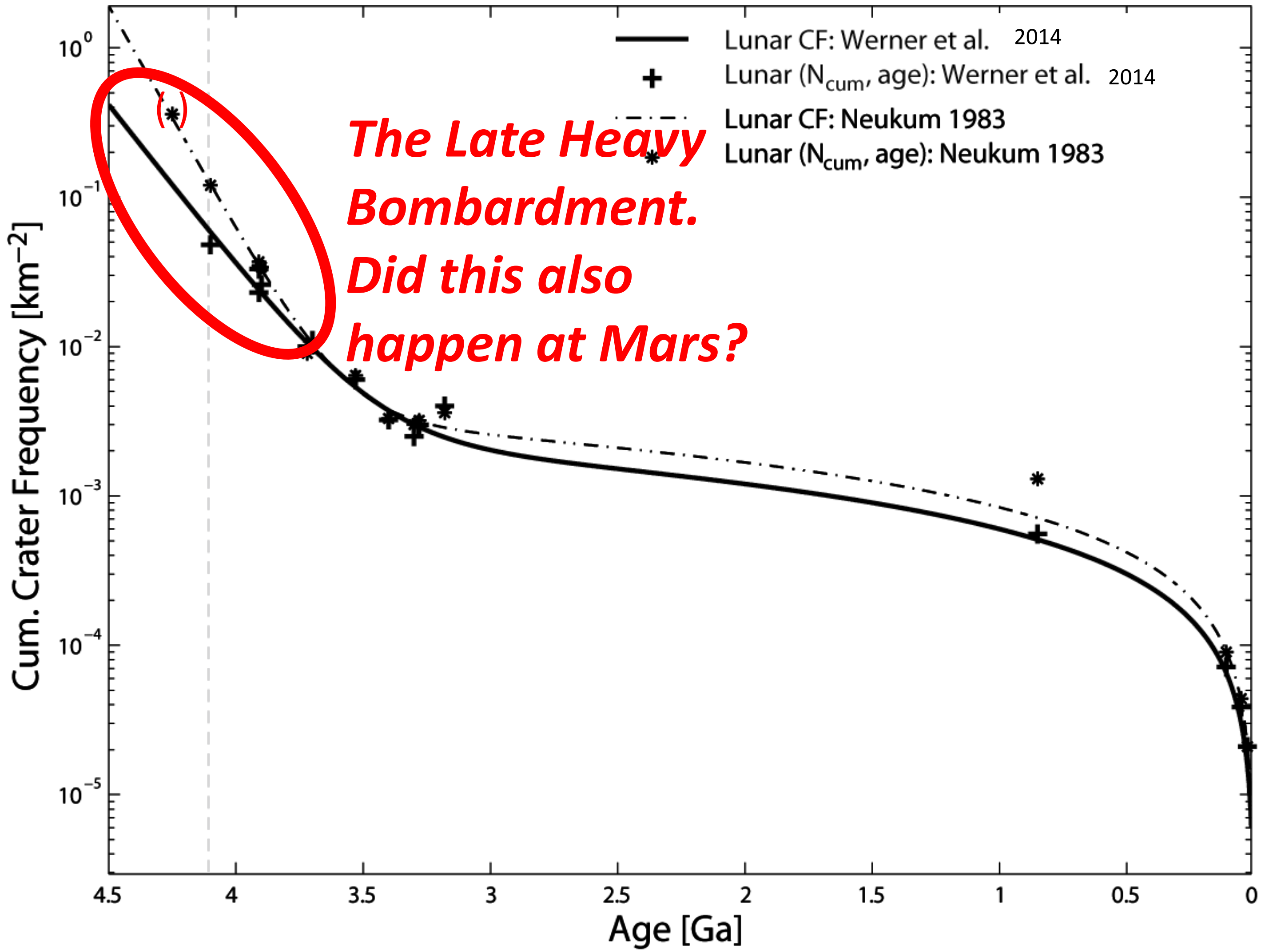
Calibration value: 4.1 Ga

Werner & Ivanov (2015) ToG2nd

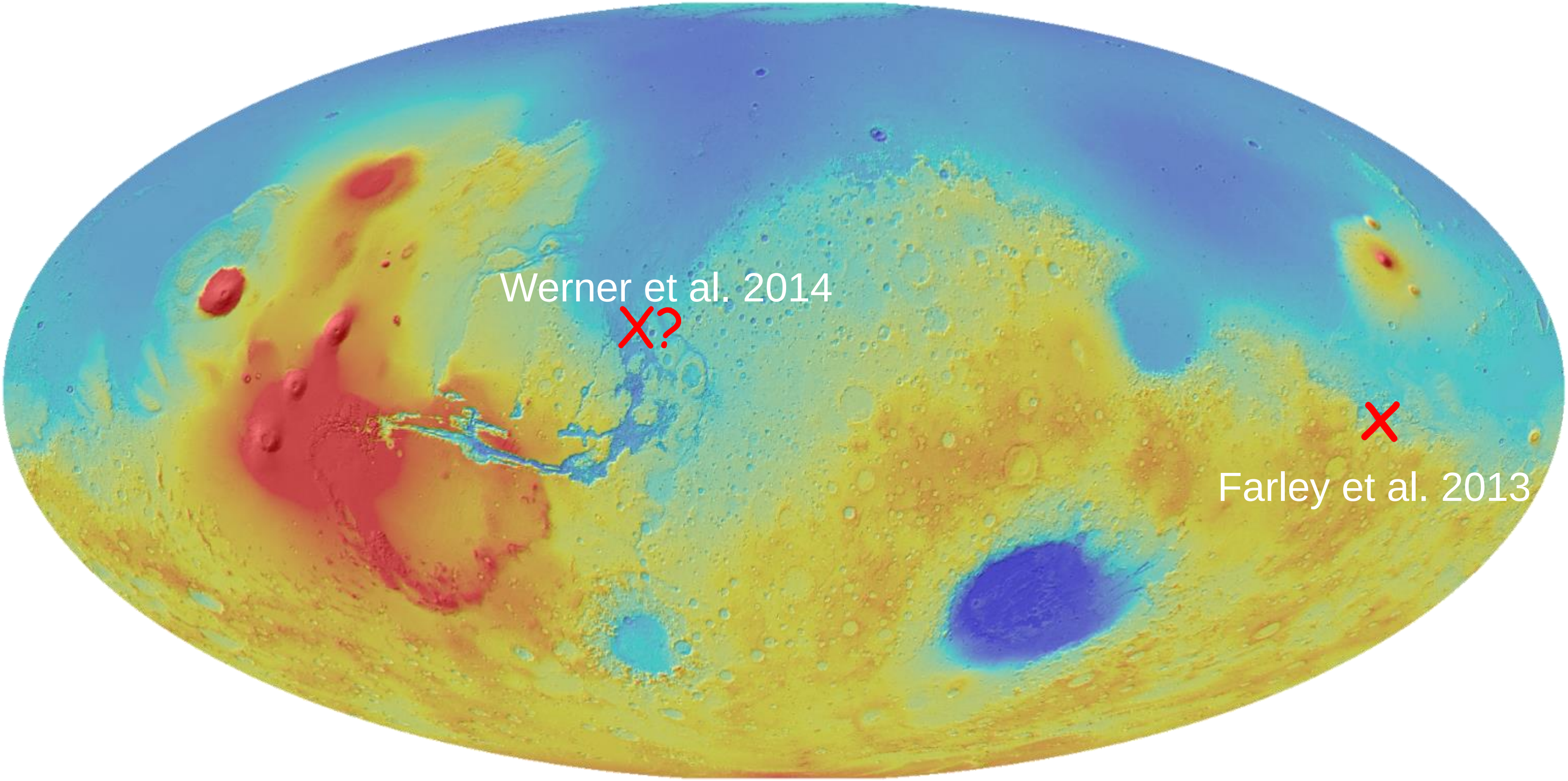
We Are Missing Quantitative Data for Mars

Werner et al. 2014

New Lunar Time Scale Proposed



Mars *in situ* calibration

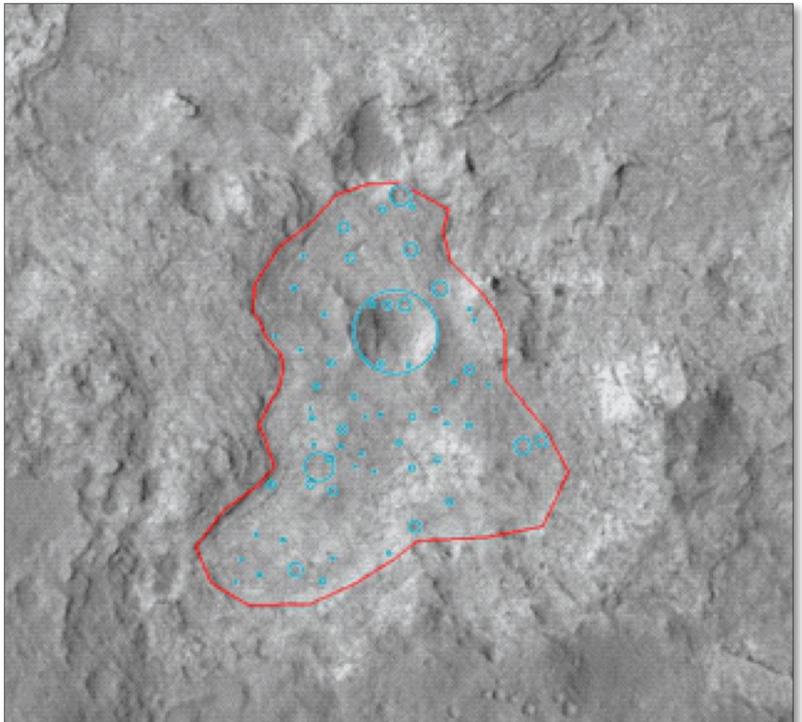


Radiometric ages have only been established for one or possibly two known locations on the Martian surface

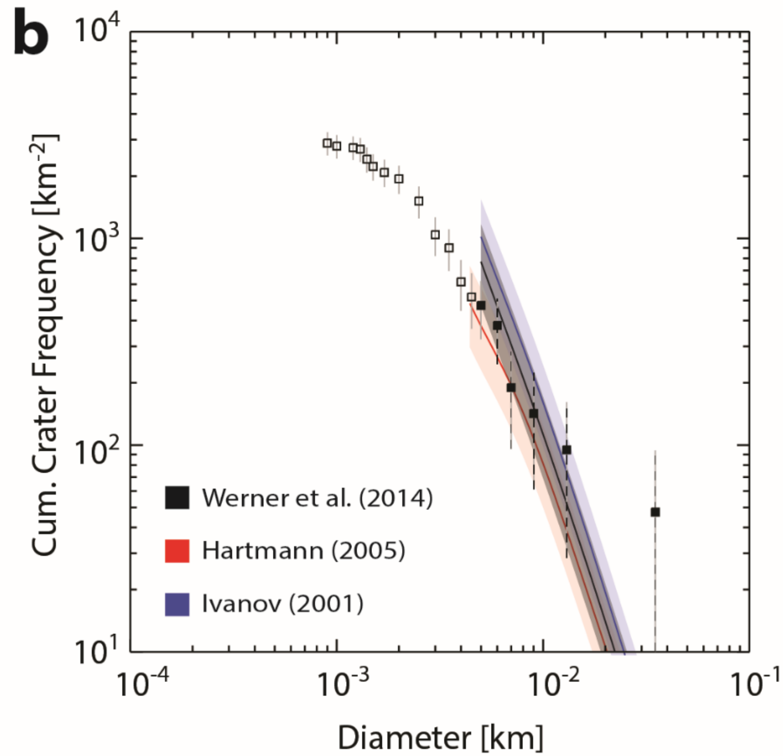
The Martian Surface (in one place) has not been exposed for very long

Surface Exposure Ages in Gale Crater: 78 ± 30 Ma

Best fit ages **79.8 ± 28 Ma** **125 ± 44 Ma** **55 ± 20 Ma**



Werner (2017, LPSC)



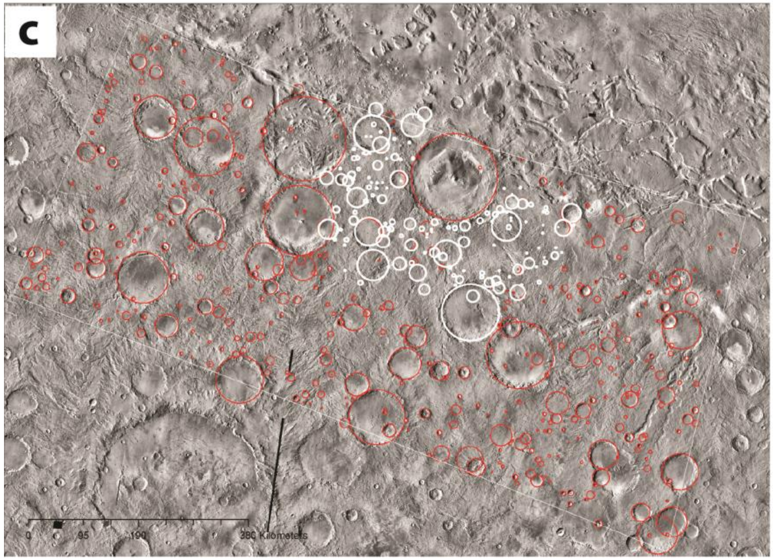
Farley et al. (2013)

This result is potentially very significant to interpreting martian organic geochemistry. We need more data of this type.

K-Ar age: 4.21 ± 0.35 Ga

Farley et al. (2013) :

mixture of detrital (from the crater rim) and authigenic components

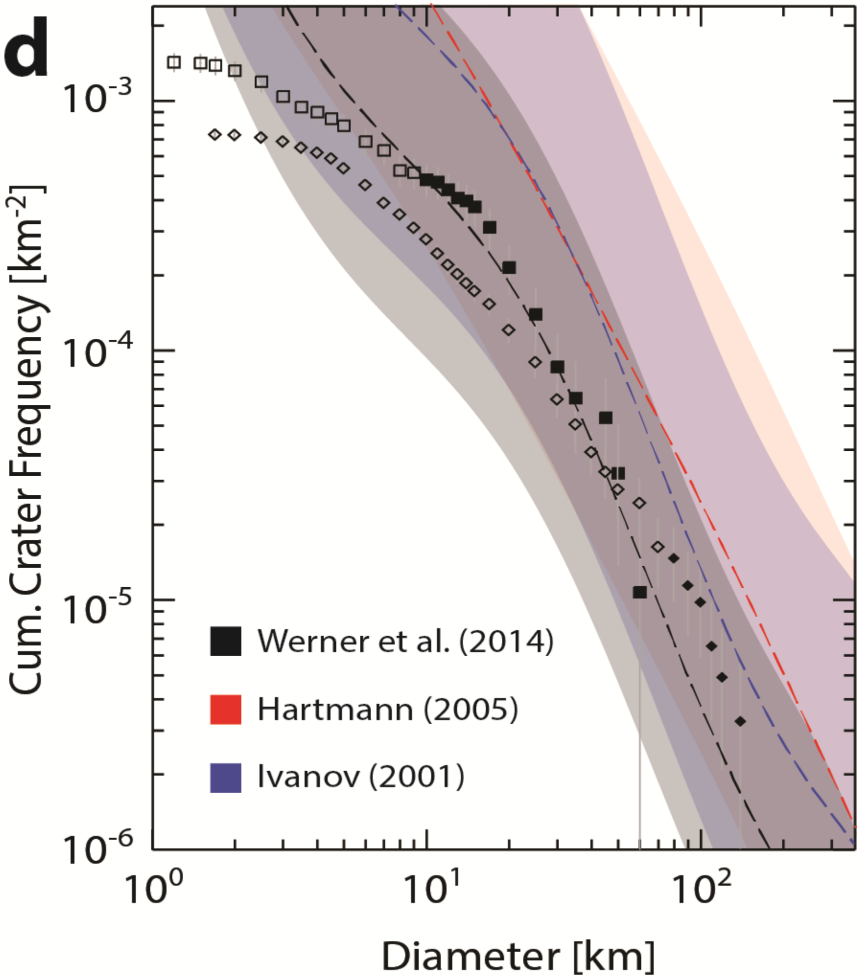


Best fit ages

4.24 ± 0.03 Ga

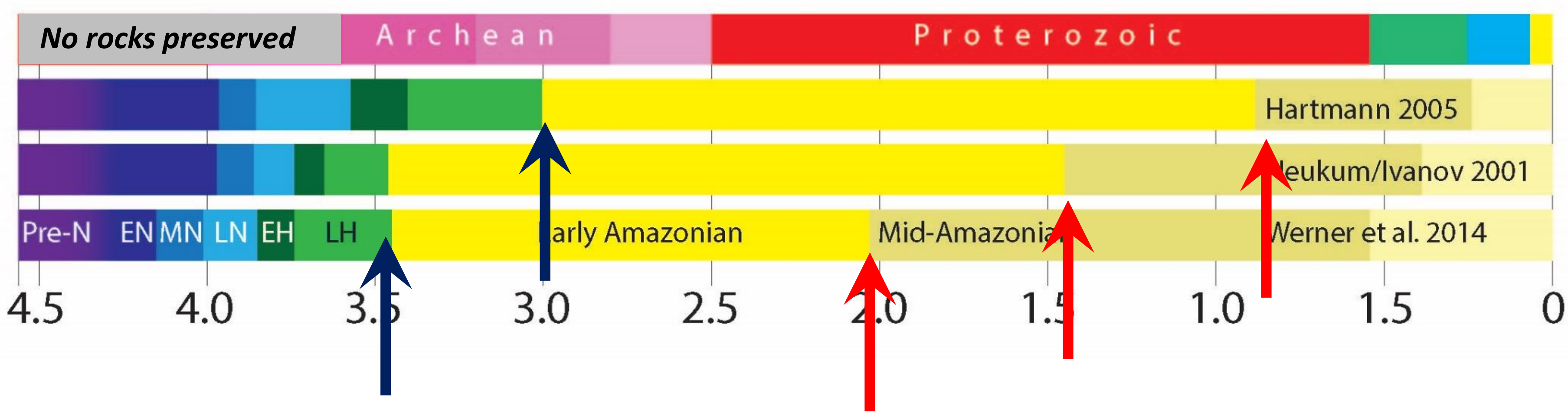
4.01 ± 0.02 Ga

4.03 ± 0.02 Ga



Werner (2017, LPSC)

Comparison of Mars and Earth Timelines



- For Mars, note the huge discrepancies between the interpretations of different workers.
- What is the right answer?
- What was happening in the Earth-Mars neighborhood between 4.5-3.5 Ga?

Determine the age of the martian hydrosphere

- I have recommended deleting three slides. Can we add one instead relating to Investigation 3D?

The accretion and early differentiation of Mars

- I have recommended deleting three slides. Can we add one instead relating to Investigation 3E?

Why Returned Sample Studies are Important

- Returned samples would provide the first unambiguous link between known Martian surfaces and geologic materials with well-determined radiometric ages.
- Returned samples from stratigraphy would constrain geologic processes through time.
- Returned samples would enable high-precision and high accuracy dates.

Mechanics

- It is possible to measure the isotopes in any sample. However, whether the data can be interpreted depends on how much is known about the sample, and on the character of the sample prep. This REQUIRES interactions with humans on Earth.

Hand-picking a high-purity mineral separate

Samples and Measurements

- 3A: ^{40}Ar-^{39}Ar dating of impact melt associated with large basin-forming impacts could constrain the crater chronology.
- 3B: U-Pb dating of zircons in breccias could constrain the heavy bombardment prior to pre-3.8 Ga.
- 3C: ^{40}Ar-^{39}Ar dating of oriented igneous samples would constrain the lifetime of the dynamo and test for plate tectonics and true polar wander.
- 3D: Li isotope in concert with U-Pb measurements of zircon could constrain aqueous weathering in the rock cycle
- 3E: Measurements of nucleosynthetic isotope anomalies could constrain the accretion history of Mars.
- 3F: Erosion rates and exposure histories could be obtained by cosmogenic nuclide (^{3}He, ^{21}Ne, ^{10}Be, ^{26}Al, ^{36}Cl) dating of surface rocks.

The Actions and Effects of Martian Volatiles

Presented by: Timothy Swindle

on behalf of the iMOST Team

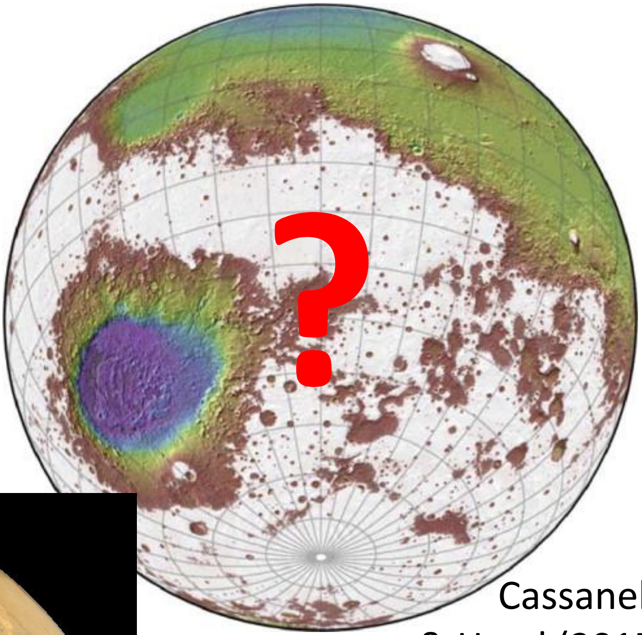
	Objective
1	*Geological environment(s)*
2	*Life*
3	*Geochronology*
4	*Volatiles*
5	*Planetary-scale geology*
6	*Environmental hazards*
7	*ISRU*

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

Introduction

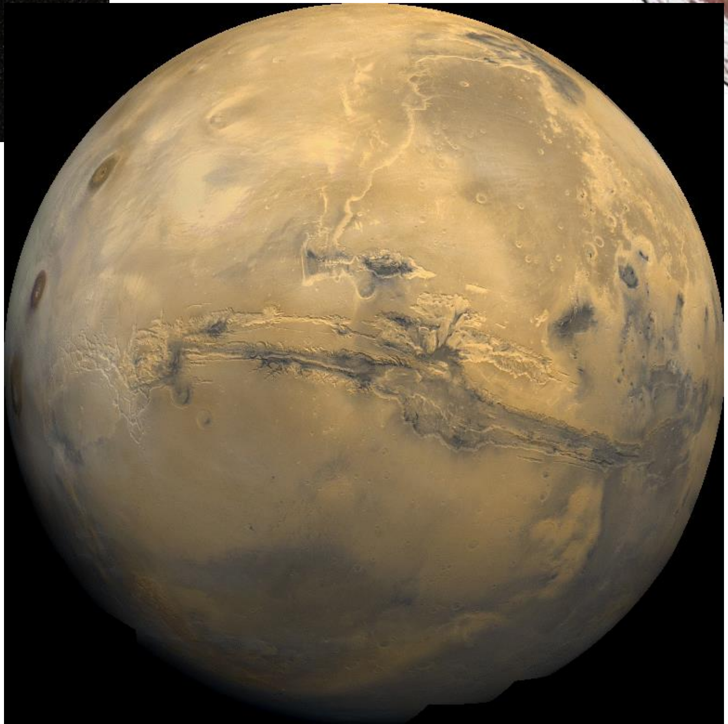
NASA/GSFC

How rich in volatiles was Mars in the past? How did it get from that state to what it is today?



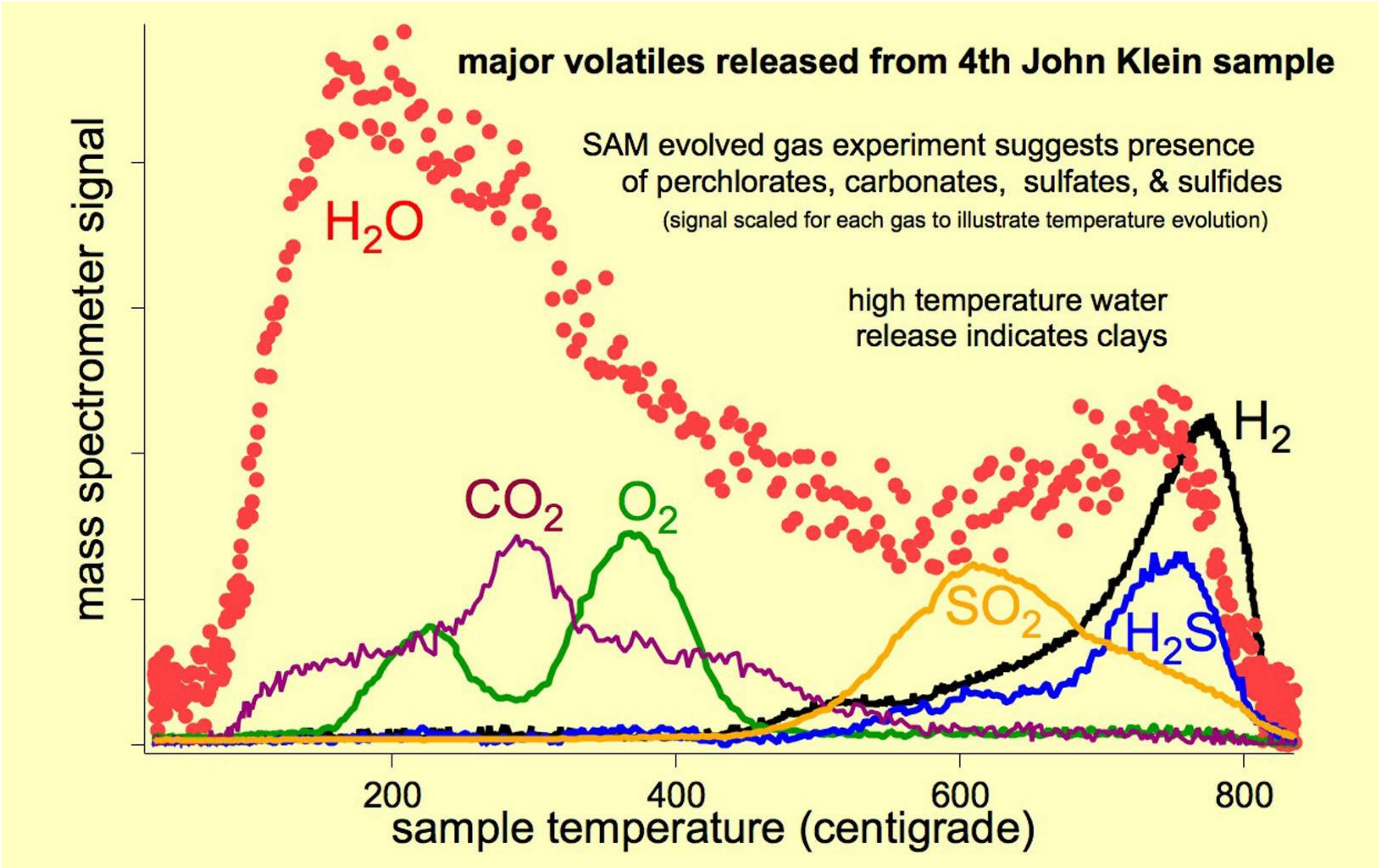
Cassanelli & Head (2015) Icarus 253: 243-255

Volatiles have played a key role in the evolution of Mars' atmosphere, hydrosphere and geosphere



Viking 1 Orbiter, NASA

Volatile signatures can be found in rocks

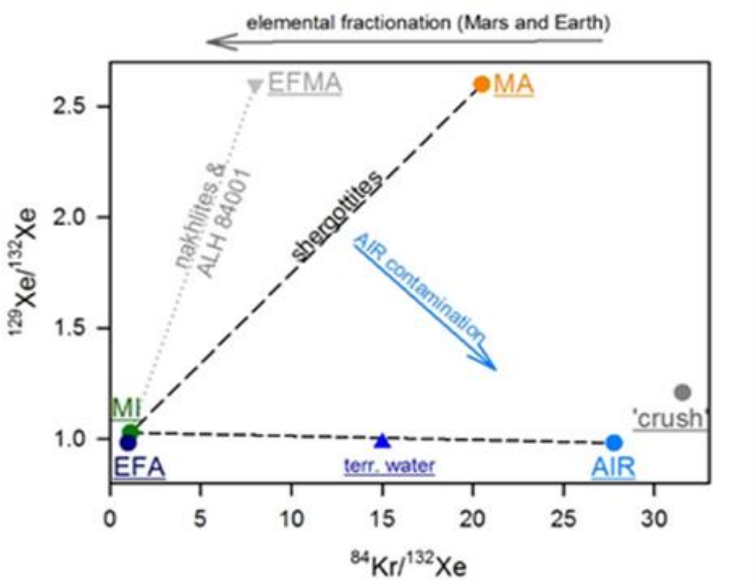


NASA/JPL-Caltech

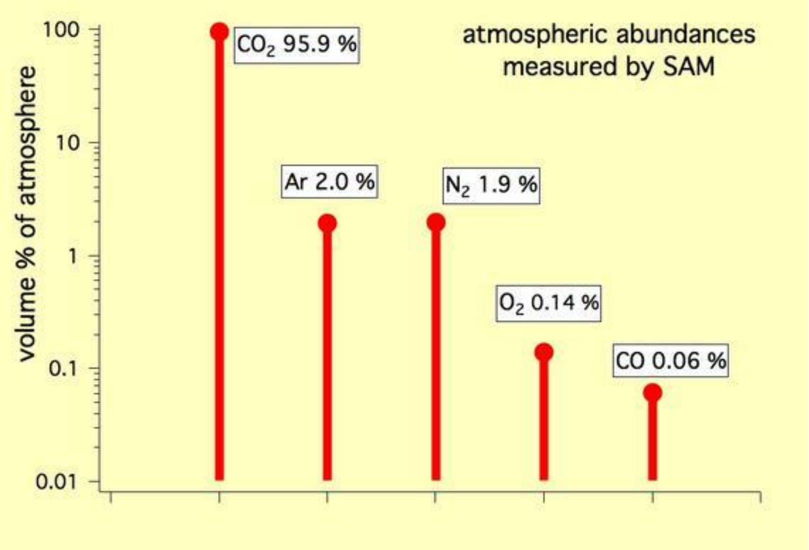
Curiosity measurements of volatiles in sample of mudstone

Sample of current atmosphere needed

- Baseline for models of the past
- Viking, Curiosity have measured some constituents well, but questions remain
  - Example: Uncertainty in Kr/Xe ratio measured in situ is nearly entire width of figure at right (based on meteorites)



Endmembers commonly used in Martian meteorite heavy noble gas research. MI, EFMA, MA and "crush" are all Martian components (the others are terrestrial)



Critical Open Questions

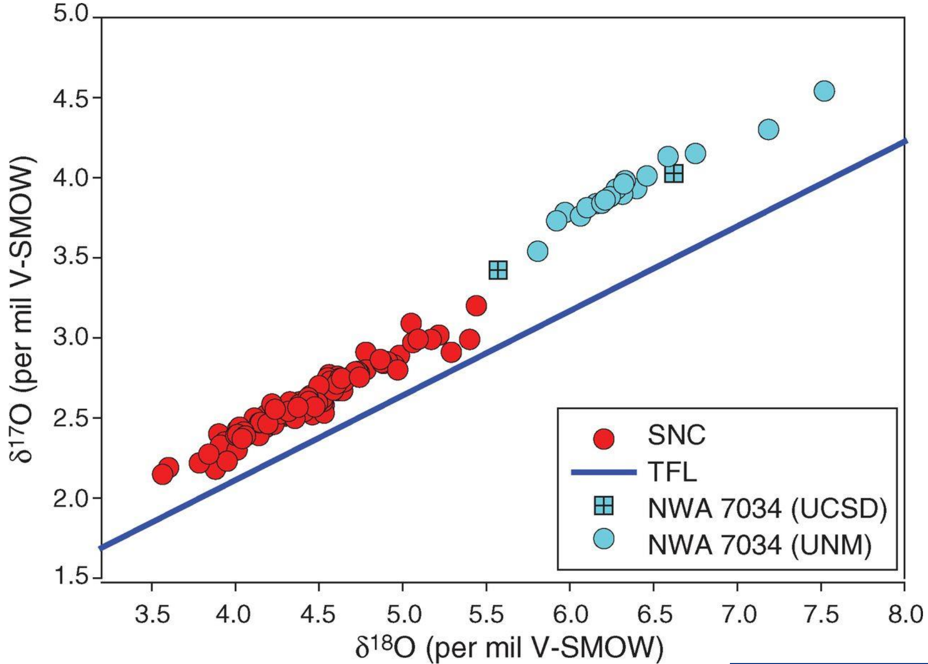
- Where did the volatiles on Mars come from?
- How do the martian crust and atmosphere interact and exchange material over time?
- How has the martian interior contributed to the volatile composition of the surface and atmosphere?
- How has Mars' atmospheric composition evolved over geologic time?
- How does Mars atmosphere vary over seasonal, and other, time scales?

Questions → Investigation Strategies

Volatiles	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
Invest. 4A	Determine the original source(s) of the planet's volatiles, and the initial isotopic compositions of the constituent gases in the atmosphere.
Invest. 4B	Understand crustal-atmospheric interactions and feedbacks, especially for C, O, S, N, Cl, and H, in order to interpret present and past geochemical cycling on Mars.
Invest. 4C	Quantify the history of the composition of the atmosphere, and the history of contributions from the interior (e.g. H, C, Cl, N, O, noble gases and radiogenic products).
Invest. 4D	Assess temporal (seasonal) variations in the composition of the present-day atmosphere to determine dynamic compositional evolution and effects of the exposure of the atmosphere to high UV irradiance.

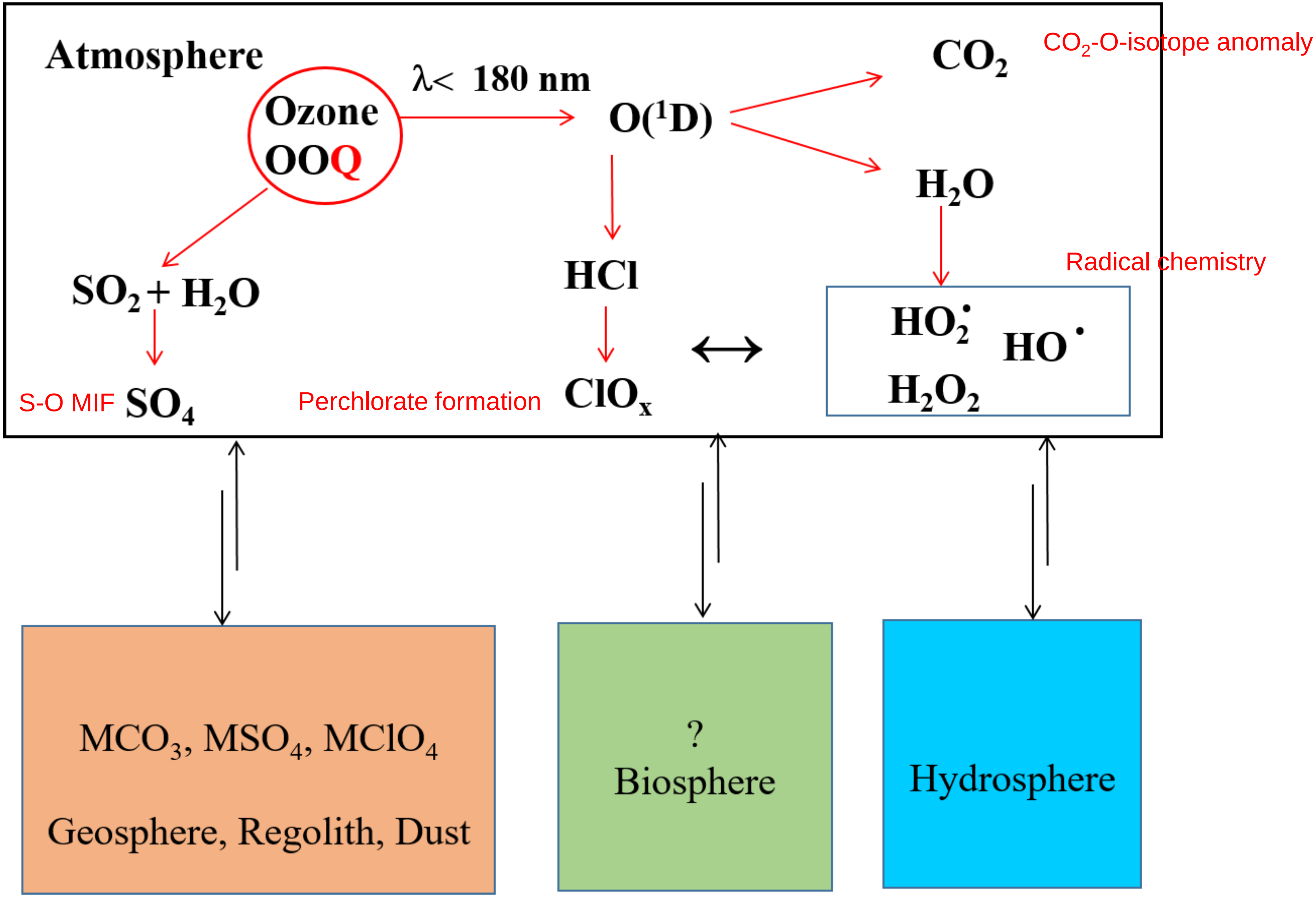
Where did the volatiles come from?

- Constraints
  - Oxygen isotopes
    - Distinct from terrestrial, other reservoirs
    - Some Mars meteorites distinct from one another
  - Cl in apatite
    - In unaltered Noachian samples, tracer for original volatiles
  - Noble gas signature
    - Similar to Earth, but with distinct differences



Oxygen isotope plot for Martian meteorite NWA 7034 and other Martian meteorites (SNC) compared to the terrestrial fractionation line (Agee et al. Science 2013;339:780-785)

How do the crust and atmosphere interact?



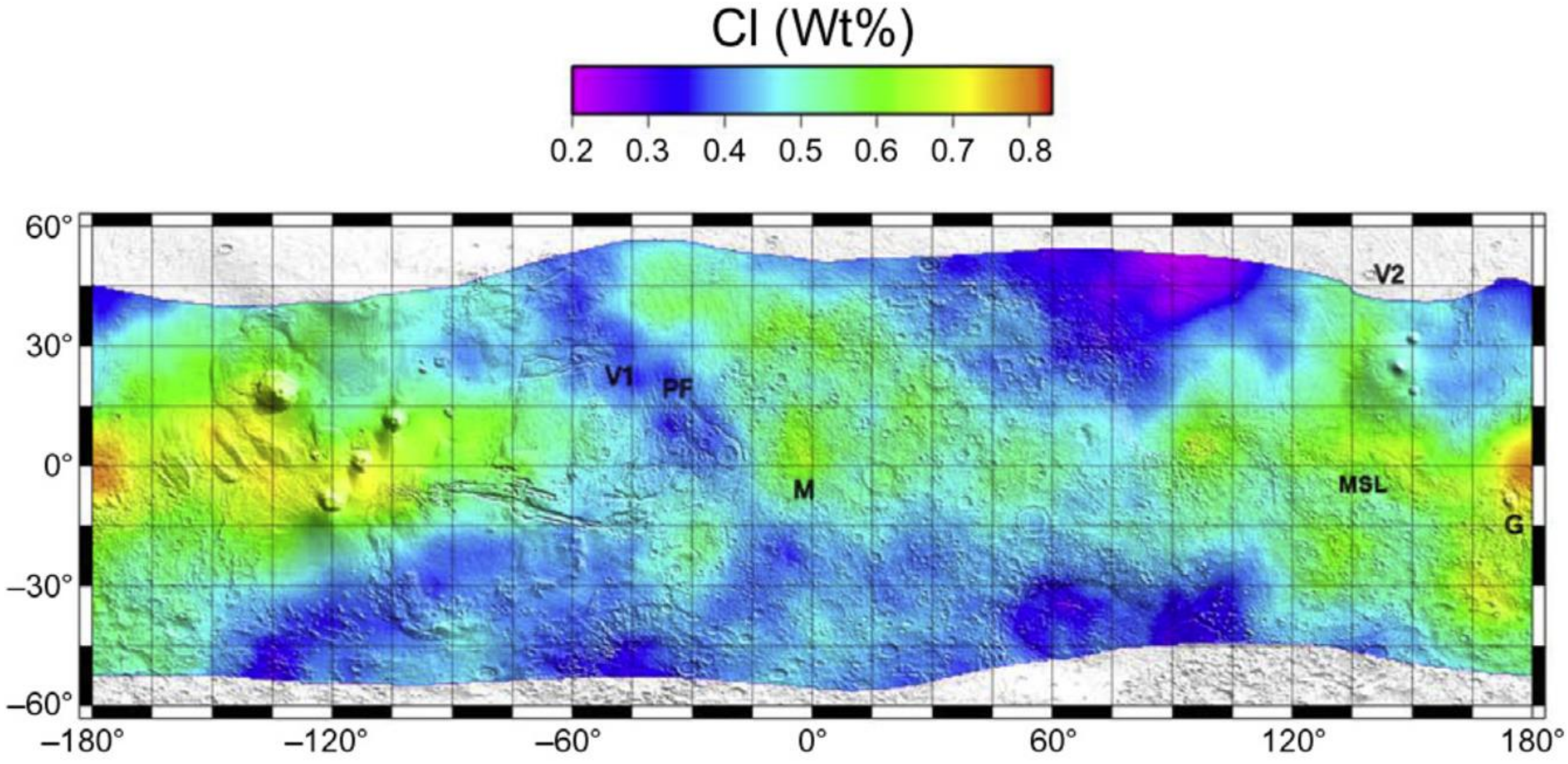
Shaheen et al., PNAS 2010, 2015

How has atmosphere composition evolved?

- MAVEN has provided information on atmospheric loss
- Primary source presumably degassing
  - Either volcanic or impact related
- Measuring paleoatmospheric would be ideal, but difficult to find
  - Even on Earth
- More likely to be able to measure volatiles in key minerals
  - Apatite, amphibole, even nominally anhydrous minerals

Has the interior contributed volatiles?

- Example (below): Cl abundances (from Filiberto, 2018, in press) are highest near volcanic vents, suggesting ongoing outgassing of Cl from the interior
- Volatiles in key Noachian-aged minerals desired

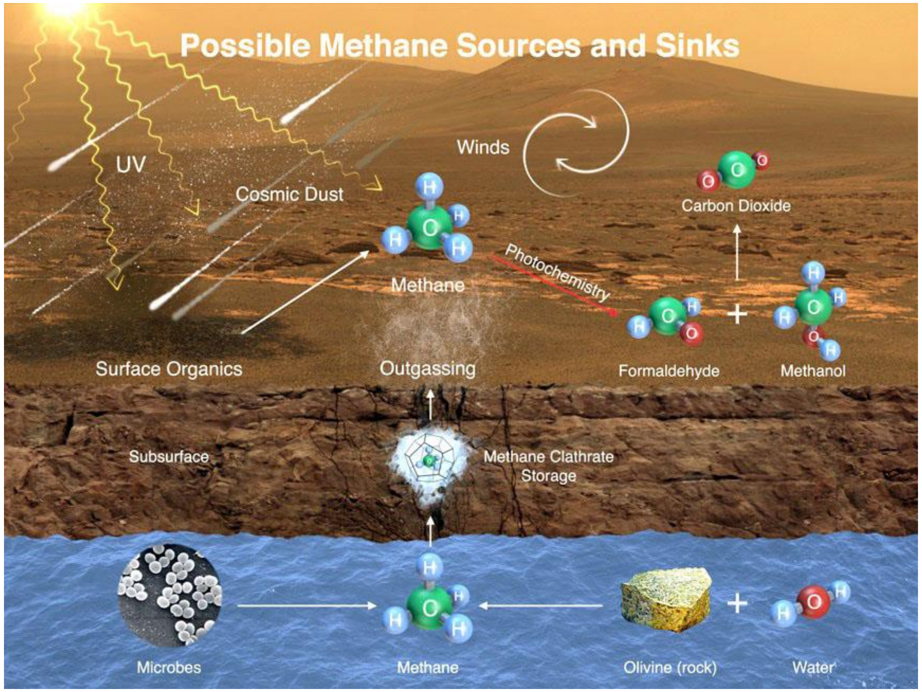


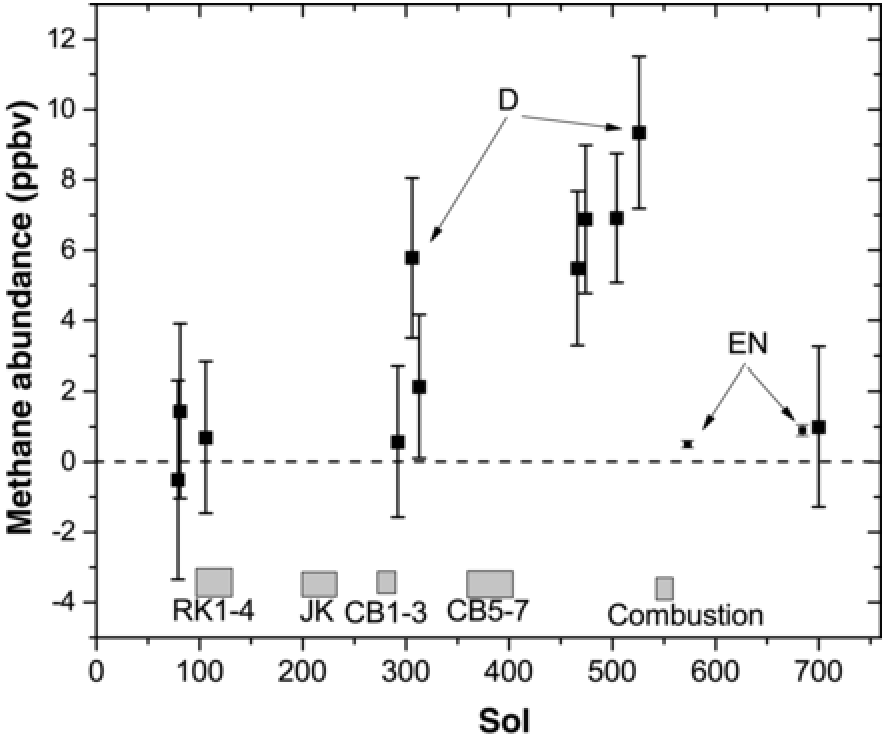
Does the atmosphere vary with time?

- Many atmospheric components vary seasonally
  - CO_2, Ar, N_2, O_2, H_2O, H_2O_2, CO known to vary
  - Methane varies for reasons not understood
  - Heavy noble gases might vary
- Observed processes vary seasonally, due to volatiles, though details aren't always understood
  - Polar caps
  - Dust storms
  - Recurring Slope Lineae

Methane

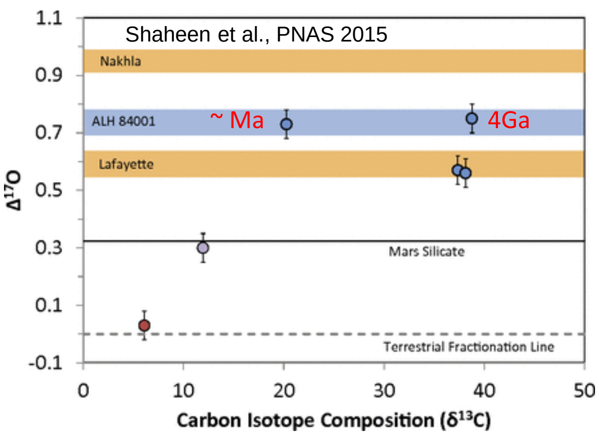
Not in equilibrium with atmosphere, indicates active source(s)
Intriguing and unexplained variability, indicates active sink(s)
Difficult measurement in situ

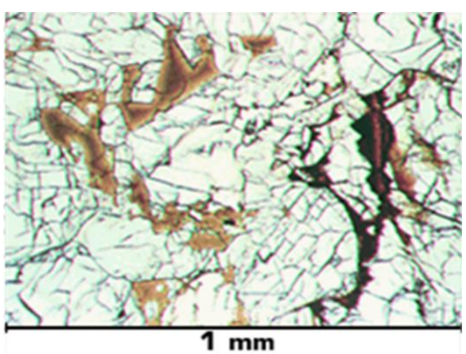




Left, Possible methane sources and sinks, from https://www.nasa.gov/jpl/msl/pia19088; right, TSL-SAM measurements showing detection and variability at Gale Crater, from Webster et al. Science 2015;347:415-417

Why Returned Sample Studies are Important





[Allan Treiman, Lunar and Planetary Institute.]

- Despite Herculean efforts, Curiosity's SAM suite (left) can not measure trace isotopes e.g. ^{17}O in atmospheric CO_2 and carbonates. Oxygen isotope anomaly is produced in the atmosphere with excited oxygen atoms and preserved in carbonates. Two different generations of carbonates in ALH84001 showed similar O-isotope anomaly thus preserving oxidation history of the atmosphere ~4Ga and at the time of ejection of meteorites.

- A high precision O-triple isotope analysis of atmospheric CO_2 samples will allow us to estimate the crust-atmosphere interactions and constraint the oxidation state of the atmosphere as shown in slide 87.

- Multiple S and O- isotope analysis and concomitant isotope anomalies of atmospheric gases and regoliths with state of the art high precision analytical techniques will allow us to understand the UV driven atmospheric chemistry, free radical generation and potential of conservation of any biosignature in subsurface ice-dust mixtures.

- Laboratory techniques make it possible to identify and analyze volatile-rich alteration materials (such as those in the Lafayette meteorite at left) at a scale inaccessible to landers or rovers

Samples and Proposed Measurements

<table>
<tr><th>Samples</th><th>Measurements</th></tr>
<tr><td rowspan="3">Two to four atmospheric samples from different seasons</td><td>Noble gas elemental, isotopic abundances</td></tr>
<tr><td>H, O isotopes of water vapor</td></tr>
<tr><td>Seasonal variability of composition</td></tr>
<tr><td>Rocks, regolith, particularly if age is known, with volatile-bearing minerals (hydrous silicates, carbonates, sulfates, nitrates, chlorides)</td><td rowspan="3">H, C, N, O, S, and/or Cl abundances, isotopic compositions</td></tr>
<tr><td>Trapped fluid inclusions, vesicles</td></tr>
<tr><td>Dust, dune material</td></tr>
<tr><td>Impact melt</td><td>Trapped atmospheric gas</td></tr>
<tr><td>Unaltered Noachian rock with apatite</td><td>OH, Cl, F composition, Cl isotopes</td></tr>
</table>

Lightning Talks

Geologic Environments: Deep Subsurface Groundwater

Presented by: Jack Mustard

on behalf of the iMOST Team

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

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

PROPOSED OBJECTIVE 1.3

Understand the rocks and minerals representative of an ancient deep subsurface groundwater environment

Geologic Environments: Subaerial Environments

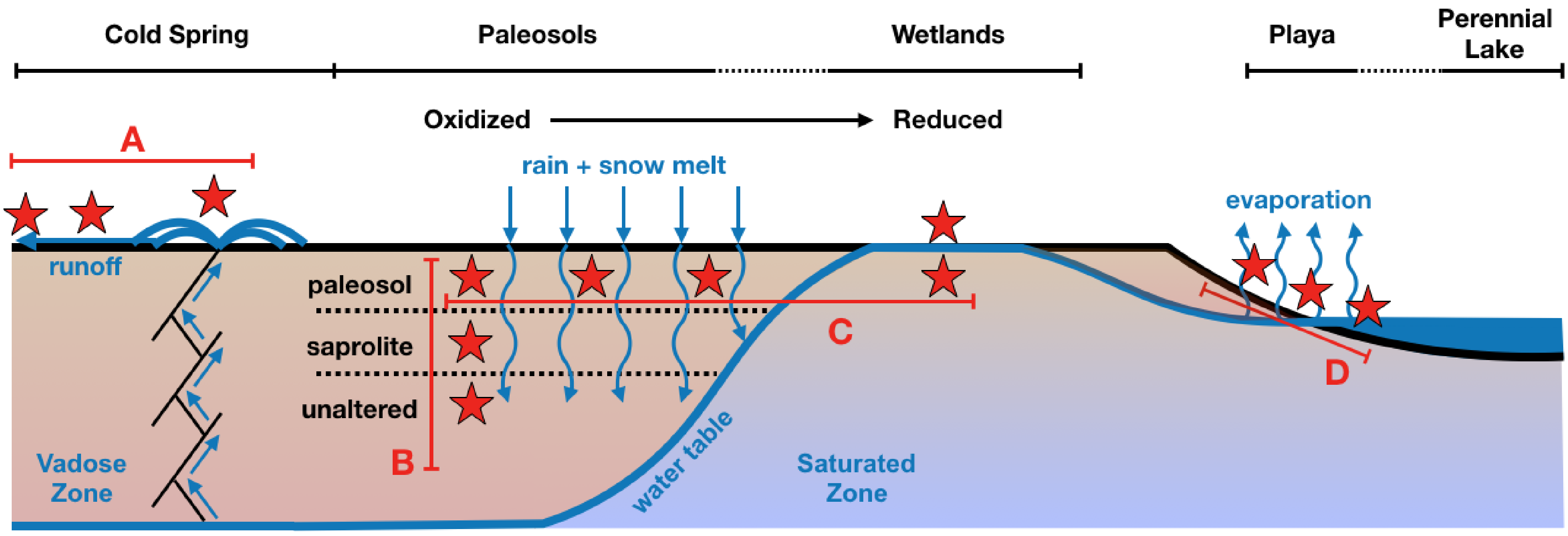
Presented by: Janice Bishop

on behalf of the iMOST Team

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

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

Subaerial Environments



A: spring precipitates at increasing distance from spring source along fluvial channels.

B: paleosol horizons at increasing depths from paleosurface, from altered to unweathered parent material.

C: paleosols at variable redox states, including reduced wetland deposits.

D: playa evaporites at increasing distance inward from highest lake level.

Geologic Environments: Igneous Terrane

Presented by: Ben Weiss (tentative)

on behalf of the iMOST Team

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

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

The attributes of a martian igneous system

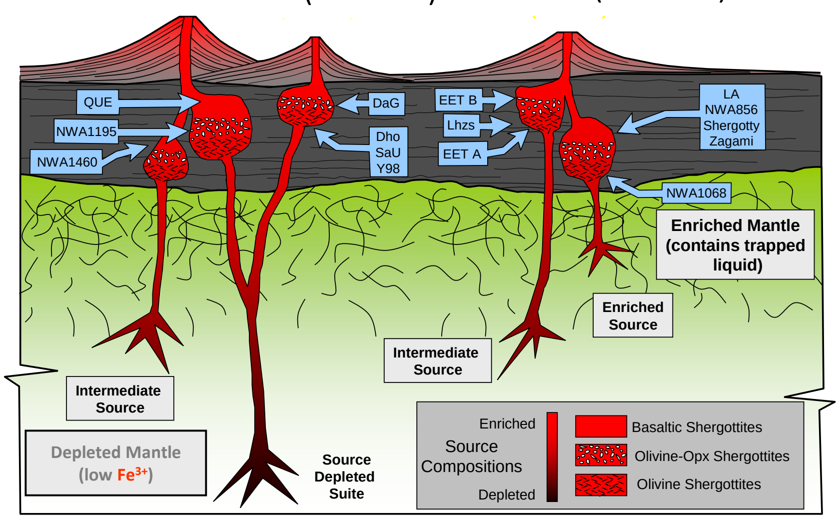
Igneous rocks constitute probes of a planet's interior, and are uniquely amenable to geochronology.

Is the mantle of Mars as viewed from the shergottite meteorites applicable to all of Mars?

Old shergottites (~340 Ma)

Old shergottites (>474 Ma)

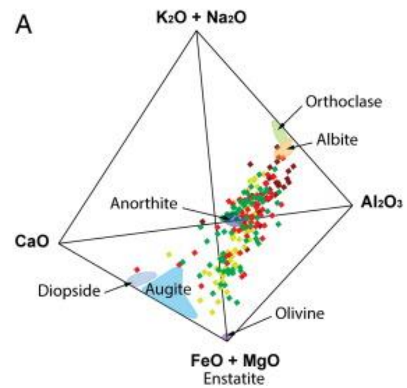
Young shergottites (~175 Ma)

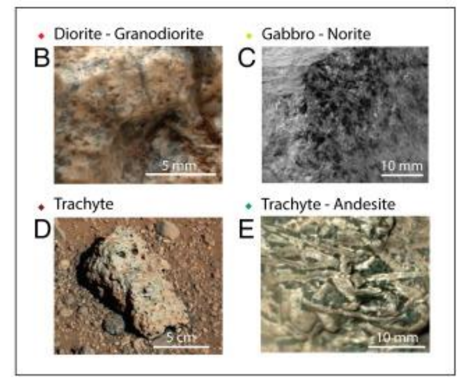


After Symes et al. (2008)

What did the mantle of Mars look like > 3.5 Ga? Was metasomatism involved?

What is the diversity of igneous rock compositions? Have they changed over time?





Sautter et al. (2016, Lithos); the 4 main types of igneous rocks found around Bradbury landing site (Gale Crater)

<u>The martian meteorites represent a biased sample set</u>

It is recommended that MSR must selectively sample <u>diverse</u> igneous rocks that are <u>distinct</u> from the meteorites, obtained either *in situ* (in outcrop) or *ex situ* (in boulders).

Summary of why sample studies are important for this objective

- For *any* igneous rock collected on Mars, laboratory studies would provide insights into:
  - Physical properties of magmas
  - Compositions of mantle sources
  - Conditions of magmagenesis
  - Timing, style and duration of igneous activity

- For an igneous rock collected *in situ* (from outcrop), laboratory studies would provide:
  - Insights into all of the above, plus
  - Geochronology, yielding an absolute age on timing of emplacement and crystallization relative to other rocks (e.g., sedimentary)

Extant Life

Presented by: Rachel Mackelprang

on behalf of the iMOST Team

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

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

Life-discovery assays would have to be conducted on Earth

Instruments and protocols are large and complex and many are necessary

Glovebox train
Thales Alenia Space
Italy

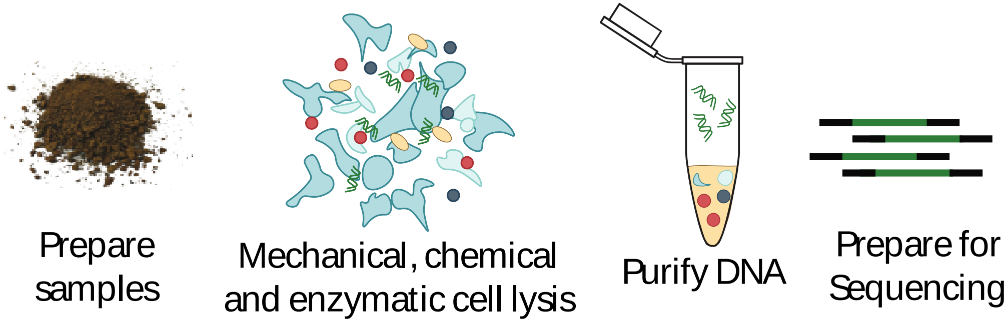
NanoSIMS

DNA Sequencer

Examples of instruments and processing strategies

Samples require special handling

- Soil and mineral samples are difficult, requiring optimization
- Processing is a multi-step process requiring human attention
- Low biomass samples require extra precision



Example: DNA extraction and sequencing

Pathway of investigation is discovery-dependent

We don't know:

What form life might take
Whether it would be alive upon return to Earth
Its ability to grow and metabolize on Earth
Whether it is related to life on Earth

The answers to these questions will dictate downstream experiments

Planetary-Scale Geology

Presented by: Ben Weiss (tentative)

on behalf of the iMOST Team

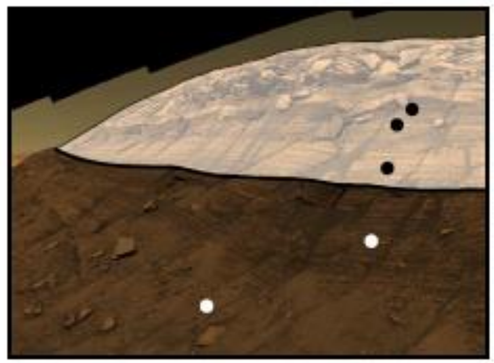
	Objective
1	*Geological environment(s)*
2	*Life*
3	*Geochronology*
4	*Volatiles*
5	*Planetary-scale geology*
6	*Environmental hazards*
7	*ISRU*

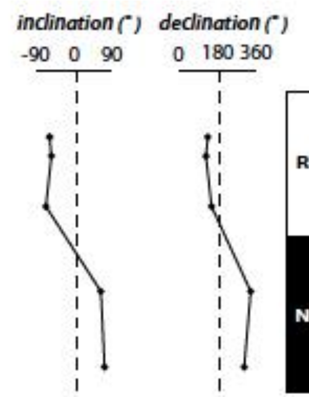
Sub-Objective
Sedimentary System
Hydrothermal
Deep subsurface groundwater
Subaerial
Igneous terrane
Carbon chemistry
Biosignatures--ancient
Biosignatures--modern

Reconstruct the history of Mars as a planet

This proposed objective seeks to place quantitative limits on the processes that have shaped Mars' crust and underlying structure. Such processes include, but are not confined to, ***differentiation*** *(including formation of the* ***original crust*** *of Mars),* ***core segregation*** *and state of the* ***dynamo****, and impact* ***cratering****.*

Imagine a martian mantle xenolith! (Creative Commons)





Oriented samples are necessary for some paleomagnetic investigations.

<u>Most important samples</u>*: a suite of igneous rocks as diverse in composition and texture as possible; oriented igneous or sedimentary rocks; ancient rocks; and impactites.*

Melt-bearing breccia (aka suevite) from the Mistastin Lake impact structure, Canada; courtesy G. Osinski

Reconstruct the history of Mars as a planet

- We note that a megabreccia with Noachian/pre-Noachian decameter-scale clasts could provide access to all rock types needed for this objective.

Hazards to Potential Human Exploration

Presented by: Andrea Harrington

on behalf of the iMOST Team

	Objective
1	*Geological environment(s)*
2	*Life*
3	*Geochronology*
4	*Volatiles*
5	*Planetary-scale geology*
6	*Environmental hazards*
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Sub-Objective
Sedimentary System
Hydrothermal
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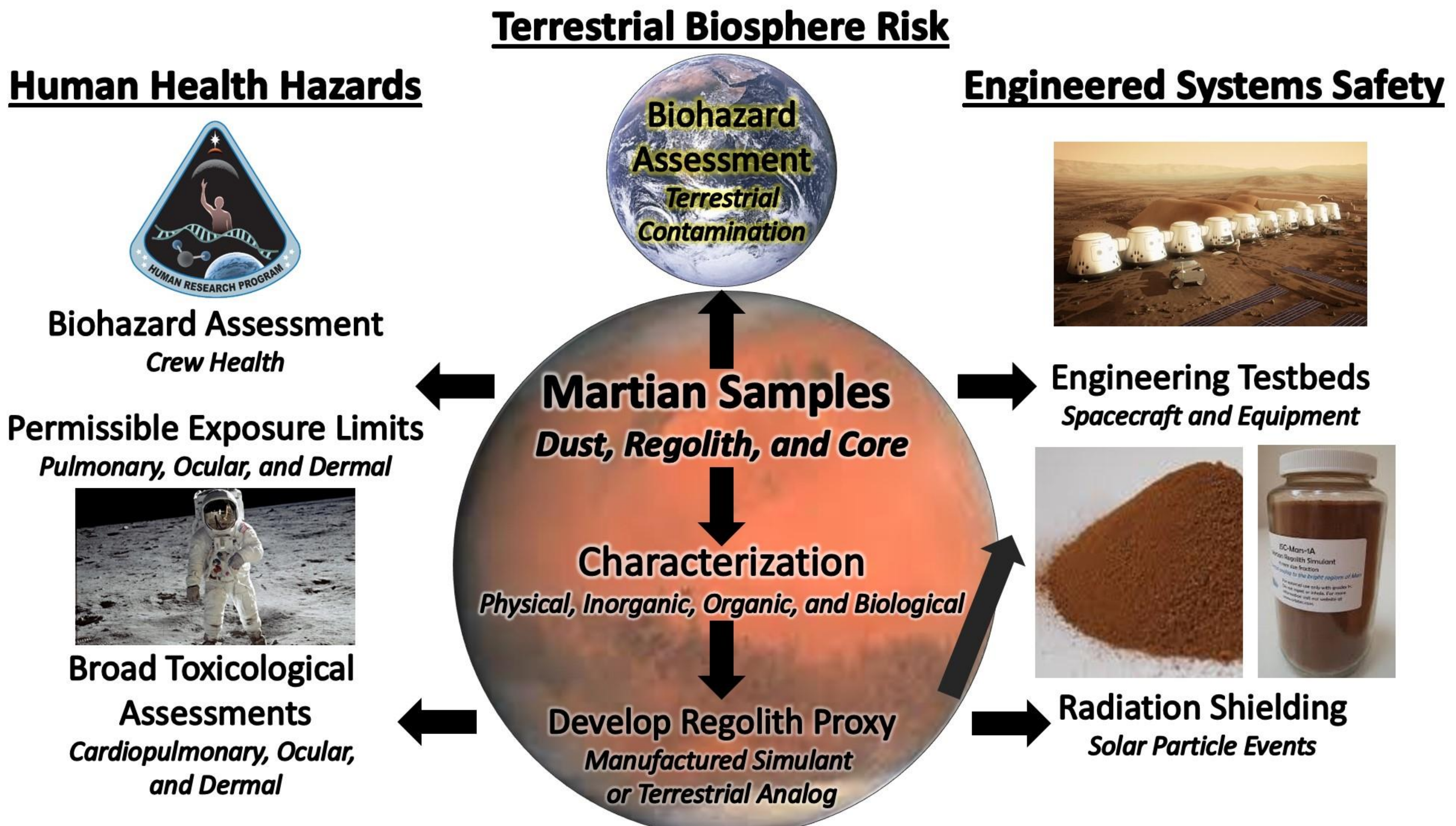
Biosignatures--ancient
Biosignatures--modern

Hazards of Future Martian Exploration

- Three primary gaps in our knowledge about potential environmental hazards that could be addressed via the analysis of returned martian samples.



In Situ Resource Utilization

Presented by: Brandi Carrier (tentative)

on behalf of the iMOST Team

Objective	
1	*Geological environment(s)*
2	*Life*
3	*Geochronology*
4	*Volatiles*
5	*Planetary-scale geology*
6	*Environmental hazards*
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Sub-Objective
Sedimentary System
Hydrothermal
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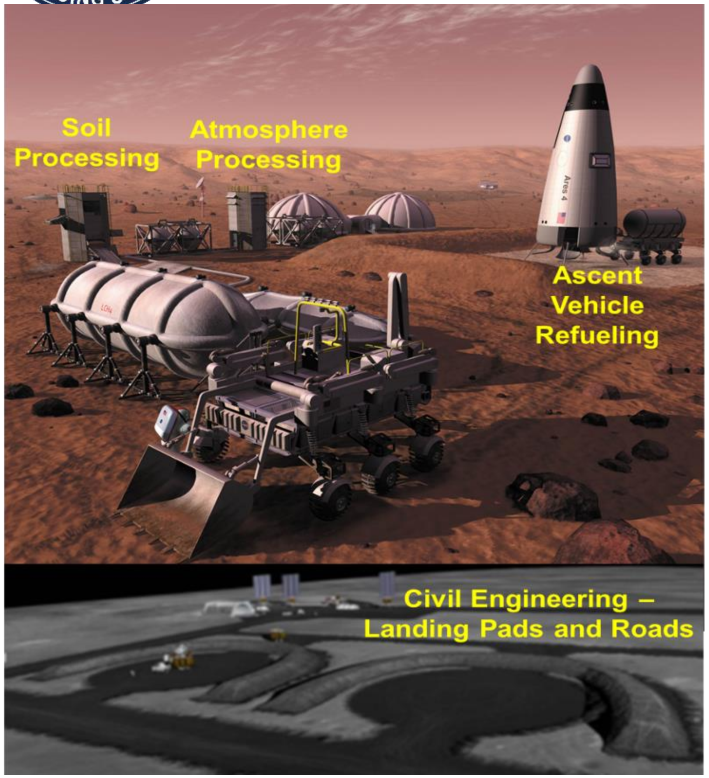
In Situ Resource Utilization (ISRU)



Artist's Concept

Potential Benefits of ISRU

- Reduces mission and crew risk
- Decreases mission cost
- Increases payload capacity
- Increases surface access
- Extends mission

Mars Surface Resource Examples

- Water: hydrated minerals or Ice
  - Propellant Production, Life support, Agriculture, Radiation Shielding, Thermal management
- Regolith & extracted minerals
  - Fertilizer, agriculture substrate, Absorbents
  - Construction material, Additive manufacturing feedstock

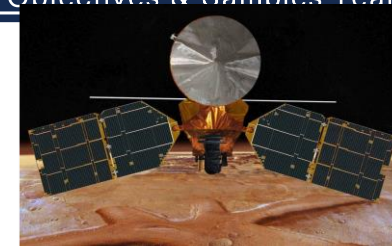
Open Questions: Goals of potential sample return

- What is concentration, mineralogical basis and variation of water in mars surface materials
- What the physical and thermophysical properties of the surface materials
- What is the potential of granular surface material for use in agriculture
- If discovered in significant quantities, can we predict significant deposits of metal commodities?

Conclusions: Why Mars Sample Return?

Dave Beaty & Monica Grady

Why is Sample Return Required?



- 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

- The return of samples from Mars would allow us to achieve a broad range of high-end scientific objectives not possible in situ
- Specific formulations of the MSR objective set are proposed
  - 7 objectives (5 planetary science, 2 humans-to-Mars)

Opposite approaches for Mars Exploration

We need BOTH!

Large amounts of sample but limited instruments

Small amounts of sample but unlimited instruments

Sample Return

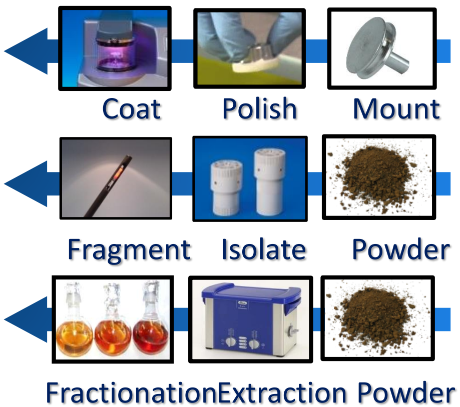
- Finite number and types of analyses using prescribed protocols.
- Important preliminary organic characterization steps.

- Unlimited number of analyses with complete flexibility.
- Comprehensive organic characterization.

What Makes MSR so Valuable?

Sample return would have four powerful technical advantages:

Access to sophisticated sample prep.



Organic investigation pathways

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

Access to multiple, diverse, and large instruments that cannot be miniaturized.

- *opportunity to make confirming measurements using multiple methods*
- *Instruments not yet invented*
- *"extraordinary claims require extraordinary evidence"*

SEM

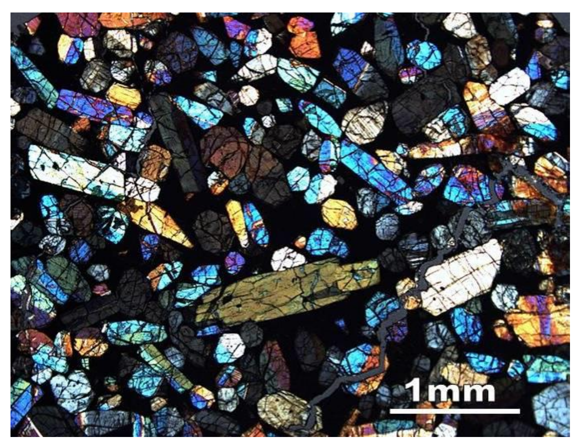
Discovery-responsive investigation pathways

- *Early results change choice/ design of later experiments*

Oolitic limestone
Cretaceous

thin section

Greatly improves the spatial focus/resolution



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

Mars meteorite

Proposed Next Steps (1 of 2)

Planning for science during retrieval

- The retrieval missions would have instruments of interest to science (cameras, T, etc.). How will this be optimized?

Planning related to what would happen after the samples are returned

- Planning for the SRF (and the activities that would take place in the SRF),
- Planning on whether and how a subset of the collection should be sterilized so as to get the samples out early to certain kinds of high-end labs (an input into requirements definition for the SRF).
- Planning for how the sample tubes would be opened, samples extracted.
- Curation planning (atmosphere, T, metals, contamination control, etc.)
  - If there were two facilities, should they store the samples under the same or different conditions?
- Planning for any specialty sample analysis instruments needed to optimize the science return from MSR—for example, instruments that significantly reduce the sample mass needs or sample contamination.
- Planning for the sample allocation processes (a follow-up to iMARS Phase II).

Proposed Next Steps (2 of 2)

- Sample Management Plan, which would cover how samples would be optimized (e.g. the sequencing of analyses—which measurements can make use of left-over material from a previous measurement?).
- Other?

Who would sponsor different elements of this planning?

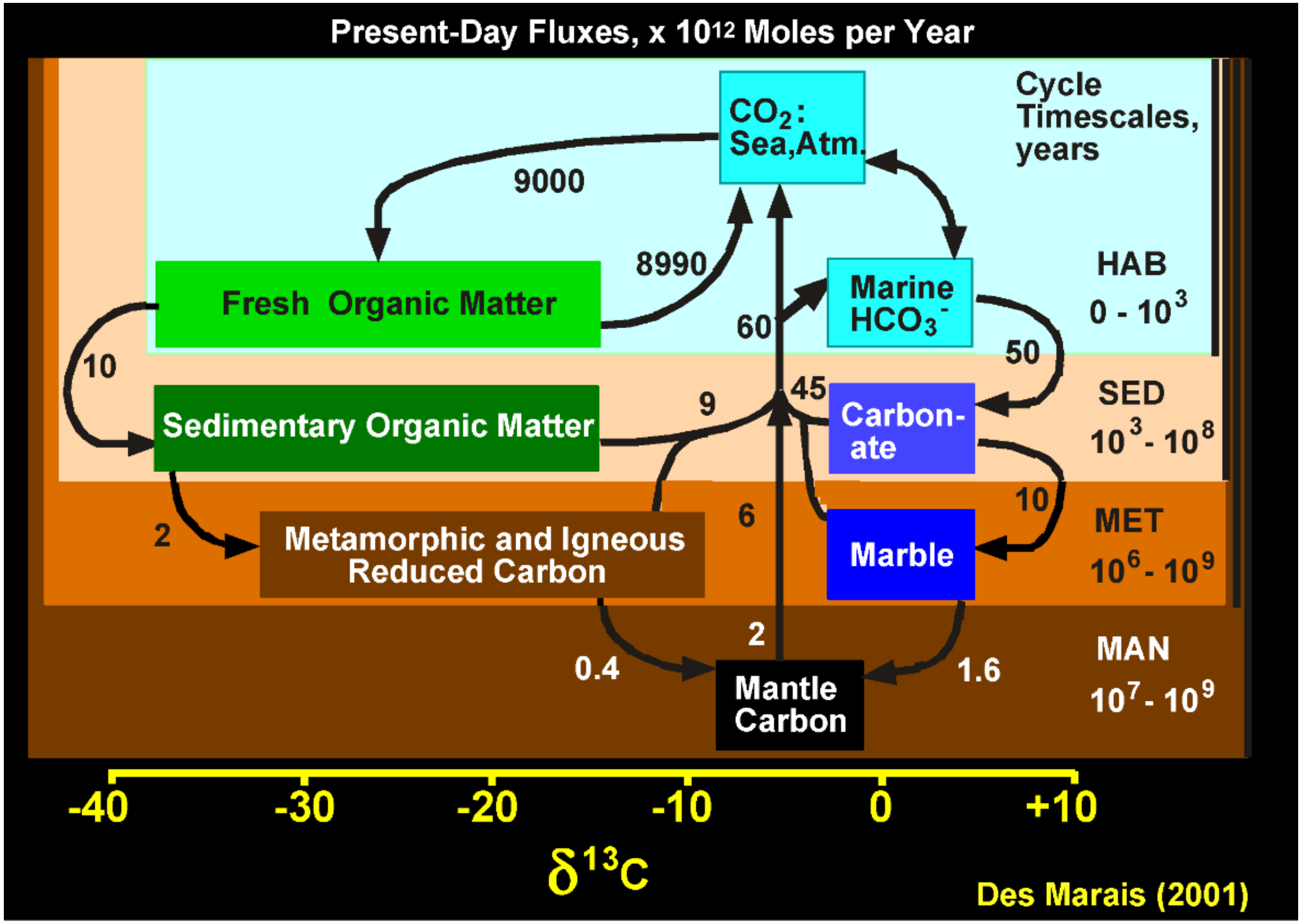
- The agency partners in an international MSR coalition? Joint Science Definition Team?
- IMEWG?
- MEPAG (by means of a science analysis group)? CAPTEM?
- JSC? EuroCares?
- Advisory panels (e.g. U.S. National Academy of Sciences)?
- Some prior work would need to be redone. Certain critical components, like mechanisms for funding scientists, could not be properly assessed until now.

Why MSR NOW?

BACKUP

Earth Biogeochemical Carbon Cycle

The Earth provides a comparator for a fully active biogeochemical carbon cycle.



Proposed Sample-Related Objectives of MSR

		Proposed Objective	
		Shorthand	Full Statement of Objective
Objective 1		***Geological environment(s)***	Interpret in detail the primary geologic processes that formed and modified the pre-Amazonian geologic record.
	Sub-Obj. 1.1	***Sedimentary System***	Understand the essential attributes of a martian sedimentary system,
	Sub-Obj. 1.2	***Hydrothermal***	Understand an ancient martian hydrothermal system through study of its mineralization products
	Sub-Obj. 1.3	***Deep subsurface groundwater***	Understand the rocks and minerals representative of an ancient deep sub-surface groundwater environment
	Sub-Obj. 1.4	***Subaerial***	Understand ancient water/rock/atmosphere interactions at the martian surface and how they have changed with time
	Sub-Obj. 1.5	***Igneous terrane***	Understand the essential attributes of a martian igneous system
Objective 2		***Life***	Assess and interpret the biological potential of Mars
	Sub-obj. 2.1	***Carbon chemistry***	Assess and characterize carbon, including possible organic and pre-biotic chemistry.
	Sub-obj. 2.2	***Biosignatures--ancient***	Assay for the presence of biosignatures of past life at sites that hosted habitable environments and could have preserved any biosignatures.
	Sub-obj. 2.3	***Biosignatures--modern***	Assess the possibility that any life forms detected are still alive, or were recently alive.
Objective 3		***Geochronology***	Determine the evolutionary timeline of Mars, including calibrating the crater chronology time scale.
Objective 4		***Volatiles***	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.
Objective 5		***Planetary-scale geology***	Reconstruct the history of Mars as a planet, elucidating those processes that have affected the origin and modification of the crust, mantle and core
Objective 6		***Environmental hazards***	Understand and quantify the potential martian environmental hazards to future human exploration
Objective 7		***ISRU***	Evaluate the type and distribution of in-situ resources to support potential future Mars Exploration

Introduction to Proposed Objective 1

"Workshop on Biosignature Preservation and Detection in Mars Analog Environments", May 16–18, 2016

Key Outcome:

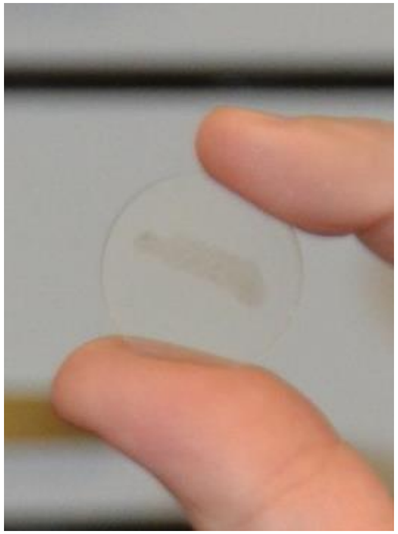
- Reached consensus that in the Earth's geologic record, four paleo-environments known to exist on Mars have the greatest potential for biosignature preservation:
  - Deep subsurface, Water-lain sedimentary, Sub-aerial, Hydrothermal
  - Samples from these environments are of special interest to MSR

Workshop documented by Hays et al. (2017)

Sophisticated Sample Preparation

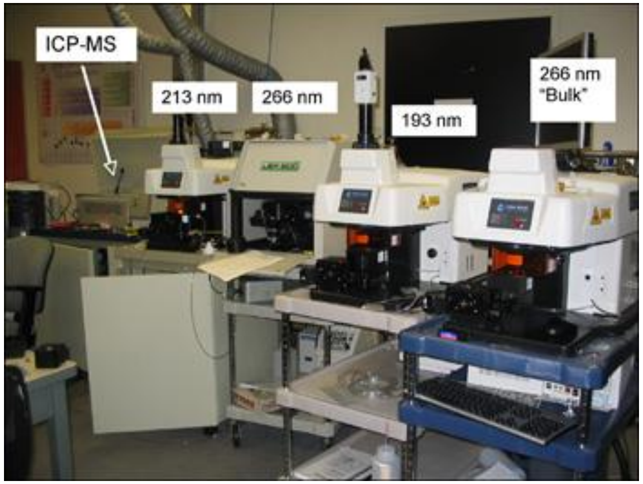
Four well-known examples of critical sample preparation methods

Preparing a high-purity mineral separate by hand-picking the grains, one at a time



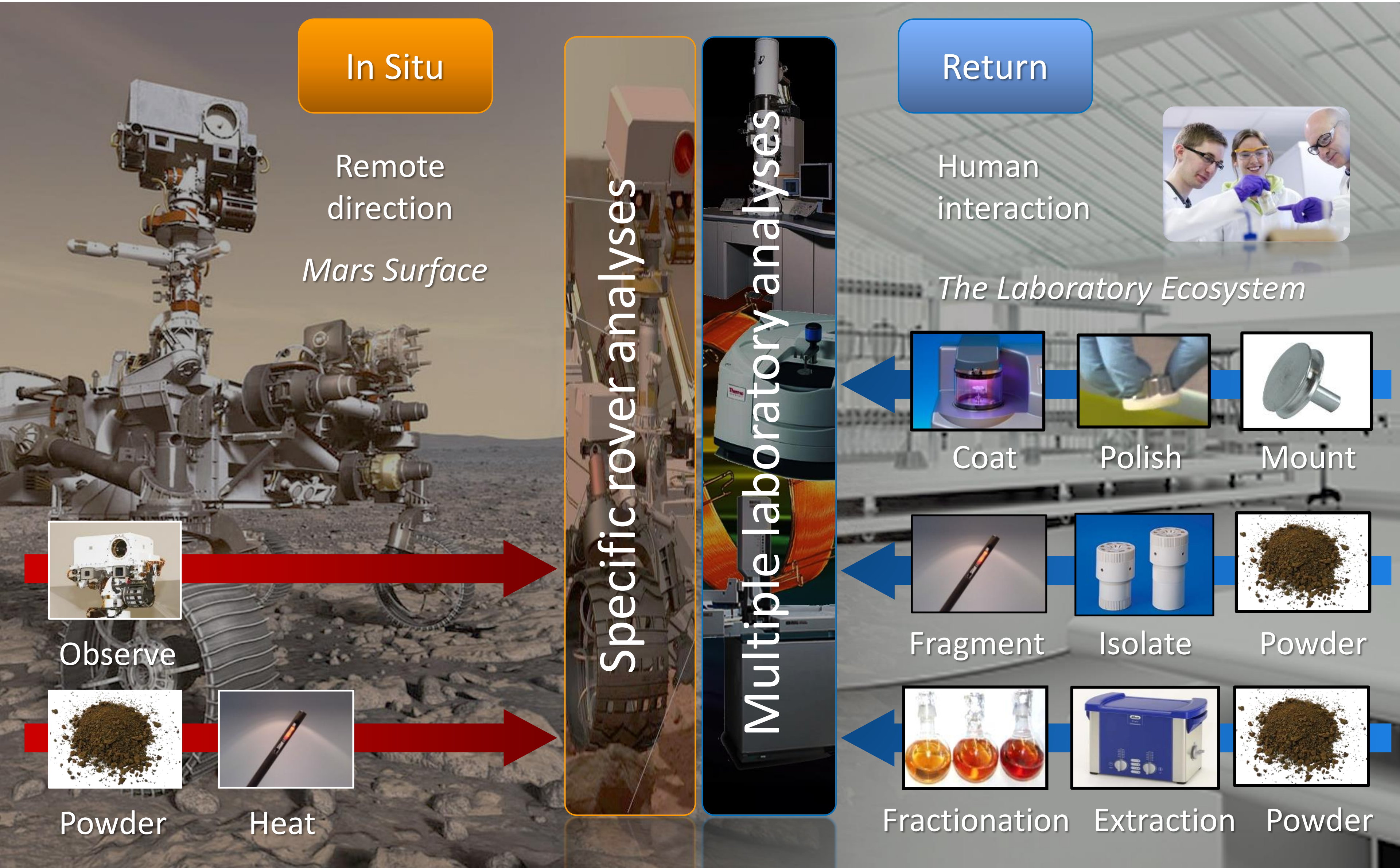
A polished thin section, consisting of a slice of rock, of precise thickness, glued to a glass slide

Access to diverse and large instruments




SEM

Discovery-responsive investigation pathways



WHY MSR IS REQUIRED FOR DIFFERENT OBJECTIVES

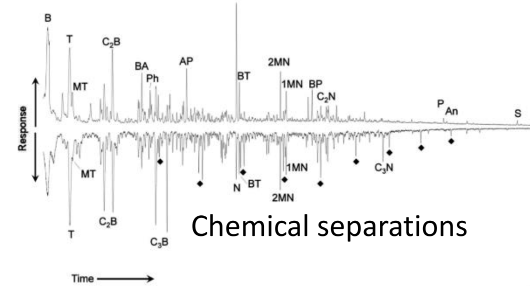
Why is Sample Return Required?

International MSR Objectives & Samples Team

Returned samples

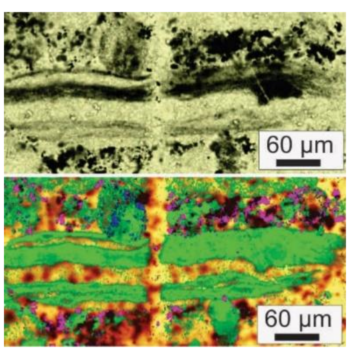
Observation-guided sample preparation, e.g.:

Petrographic thin sections

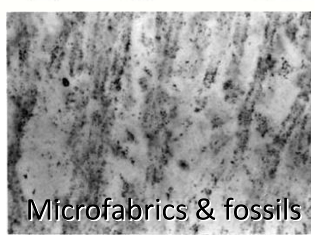


Chemical separations

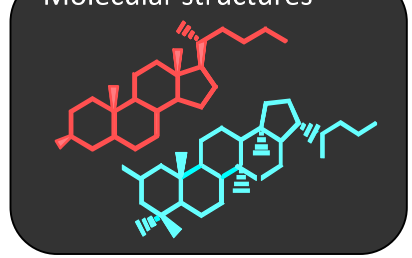
Laboratory consortia exchange samples to interrogate potential biosignatures



Chemical patterns

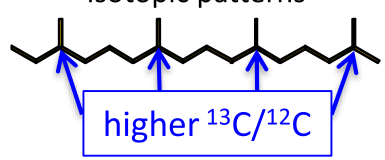


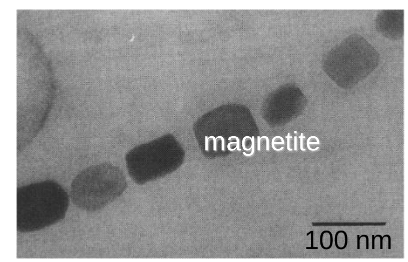
Microfabrics & fossils



Molecular structures

Isotopic patterns





Biomineral structures and trace element contents

Why Returned Sample Studies are Rrquired

Essential sample preparation and handling would require Earth-based facilities, e.g. :

- Observation-guided sample preparation and dissection to explore microscale spatial relationships between fabrics, minerals and any organic matter.
- A single prepared sample often must be shared between multiple state-of-the-art analytical instruments.

Confirming definitive biosignatures requires state-of-art analyses :

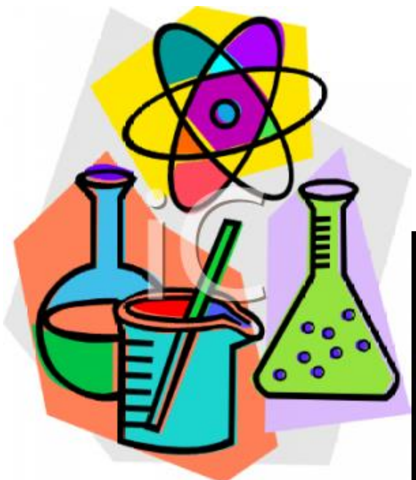
- Preservation and degradation – assessing taphonomy of microscale features
- Organic molecular structures, relative abundances, diastereoisomeric and structural isomer preferences, chirality – down to subnanomole abundances
- Stable isotopic abundance patterns within molecules and between molecules, compound classes and minerals – down to nanomole abundances
- Mineral diversity and trace element contents – down to submicrogram abundances
- Rock fabrics (and biological?) structures – from submicron to centimeter scales
- Inorganic chemistry –microscale compositional and spatial patterns
- Application of multiple analytical methods to a key individual sample

Scientific Objectives Achievable with MSR

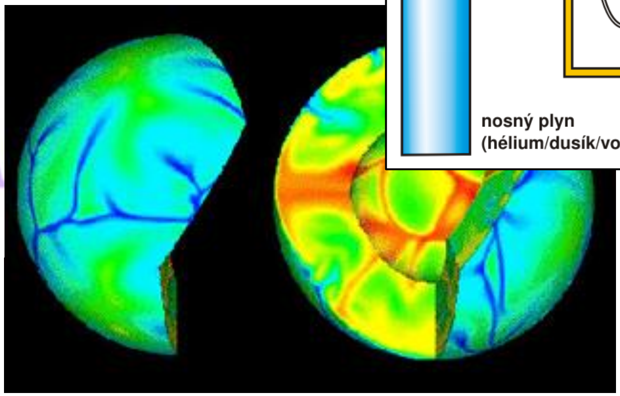
Natural Resources

Understand local geology

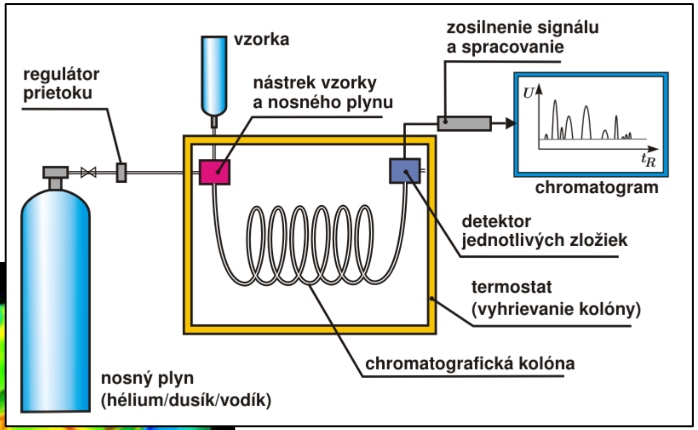
Interpret biological potential



Hazards



Planetary evolution



History of volatiles

Geochronology