Science Returns Expected from MACIE: Mars Astrobiological Caves and Internal Habitability Explorer (a New Frontiers Mission Concept).

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Introduction: Caves represent one of the best localities for finding evidence of life beyond Earth. These features offer subsurface access without the costs of a deep drilling payload [1] and and are ideal locations for potential human habitation. Mars has more than a thousand cave-like features [2], which formed from volcanic processes (e.g. lava tubes), tectonic processes (e.g. atypical pit crater chains), or both. Together, these features represent substantial void space in the subsurface. Numerical heat and mass-transfer modeling of the martian surface indicates equatorial martian caves may not only be shielded from cosmic radiation, but also host favorable conditions to maintain stable water-ice deposits [3]. Both factors would enhance the habitability and astrobiological potential of martian caves relative to surface environments. Therefore, these features represent ideal astrobiological targets on Mars.

Objectives and Relevance: We assessed the potential science returns for a New Frontiers (NF) Mars lava tube (cave) exploration mission. The Mars Astrobiological Caves and Internal habitability Explorer (MACIE), named after Macie Roberts NASA's first human computer [4], would address a key recommendation of the 2019 National Academies' Astrobiology Strategy, "NASA's programs and missions should reflect a dedicated focus on research and exploration of subsurface habitability in light of recent advances... [in our understanding of] the history and nature of subsurface fluids on Mars..." [5].

MACIE's Science Goals would address all four goals of the Mars Exploration Program, including (1) Determine whether life ever existed on Mars; (2) Characterize the climate of Mars; (3) Characterize the Geology of Mars; and (4) Prepare for human exploration [6]. MACIE also addresses Strategic Objective 1.1 by "Searching for Life Elsewhere" and Objective 2.2 by "leveraging scientific expertise for human exploration of the Solar System" [7]. If the MACIE did not detect evidence of past or present life, it would still provide significant habitability and geology science returns, and enable us to develop criteria for accessing lava tubes for future use as human astronaut shelters or bases.

Science Goals: MACIE's primary science goal would be to (1) Assess the astrobiological potential of the subsurface by determining the presence of extant/past life and life-related indicators. MACIE's other goals, including (2) Assessing habitability of the subsurface, and (3) Determining the geologic history would support interpretation of astrobiological data.

Instrumentation: A number of heritage instruments could be used to satisfy Objectives 1-3 as shown in the STM (**Table 1**). Payload selection will be driven in part by spacecraft architecture; however, the payload would emphasize instrumentation associated with assessing the astrobiological potential of Mars' subsurface. A possible strawman payload would include cameras for stereo imaging, a DUV/Vis Raman spectrograph and/or a mass spectrometer, a temperature (T) and relative humidity (T/RH) probe, and a Gamma ray or neutron spectrometer.

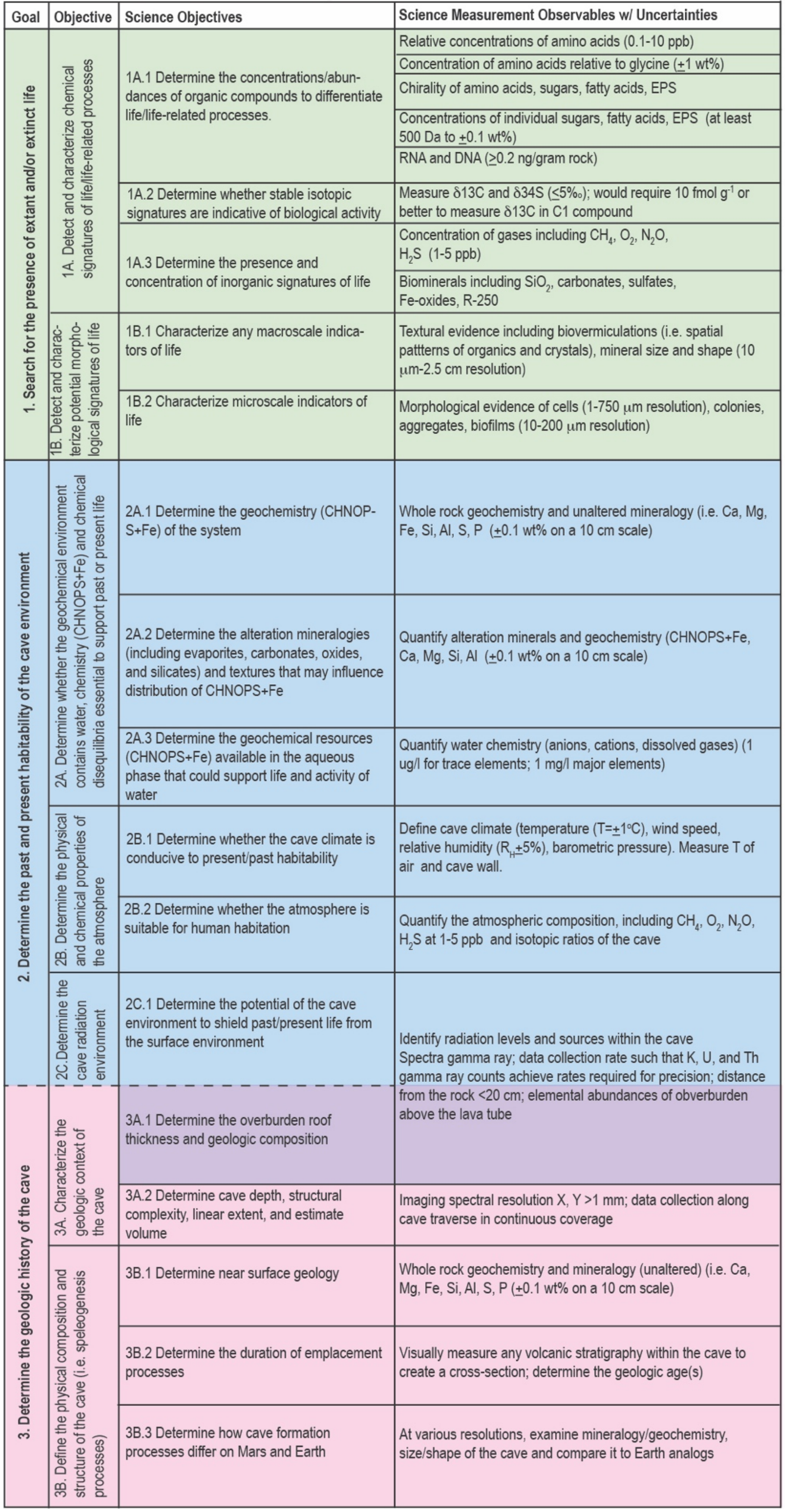
Goal 1 Astrobiology: Both Raman and Mass Spectrometry can be used to address Objective 1A (**Table 1**). However, a mass spectrometer would be required to quantify isotopic ratios (Obj 1A.2) and gas concentrations (Obj 1A.3). A microscope would be required to characterize morphological signatures of life Obj 1.B.

Goal 2 Habitability: Objective 2A and part of 2B could be addressed either by mass spectrometry or Raman. Quantifying atmospheric gases would require a mass spectrometer (Obj 2B.2). Cave climate would require an T/RH probe similar to Mars Science Laboratory's Remote Environmental Monitoring Station and Obj. 2C and 3B.1 would require a Gamma ray or neutron spectrometer.

Goal 3 Geology: Cameras required for robotic traverse of the cave can also provide data on the depth, structure, and extent of the cave. In particular stereophotogrammetry may provide a low mass alternative to LiDAR and address Obj 3A.2 and 3B.2. Raman or mass spectrometry can provide insight into Objective 3B.1 and 3B.3.

Spacecraft Architectures: There are three main robotic architectures that could support a NF Mars' Caves Mission, mainly a rock climbing robot (LEMUR; TRL 6) [8], a two-wheeled axial robot (i.e. similar to MoonDiver) [9], and unmanned aerial systems (SwRI drone; TRL 9 for Earth applications; TRL 4/5 for space). In all cases, the robotic architecture will consist of a surficial

Table 1: MACIE Science Traceability Matrix



Goal	Objective	Science Objectives	Science Measurement Observables w/ Uncertainties
1. Search for the presence of extant and/or extinct life	1A. Detect and characterize chemical signatures of life/life-related processes	1A.1 Determine the concentrations/abundances of organic compounds to differentiate life/life-related processes.	Relative concentrations of amino acids (0.1-10 ppb)
			Concentration of amino acids relative to glycine (±1 wt%)
			Chirality of amino acids, sugars, fatty acids, EPS
			Concentrations of individual sugars, fatty acids, EPS (at least 500 Da to ±0.1 wt%)
			RNA and DNA (≥0.2 ng/gram rock)
		1A.2 Determine whether stable isotopic signatures are indicative of biological activity	Measure δ13C and δ34S (≤5‰); would require 10 fmol g^{-1} or better to measure δ13C in C1 compound
		1A.3 Determine the presence and concentration of inorganic signatures of life	Concentration of gases including CH_4, O_2, N_2O, H_2S (1-5 ppb)
			Biominerals including SiO_2, carbonates, sulfates, Fe-oxides, R-250
	1B. Detect and characterize potential morphological signatures of life	1B.1 Characterize any macroscale indicators of life	Textural evidence including biovermiculations (i.e. spatial pattterns of organics and crystals), mineral size and shape (10 µm-2.5 cm resolution)
		1B.2 Characterize microscale indicators of life	Morphological evidence of cells (1-750 µm resolution), colonies, aggregates, biofilms (10-200 µm resolution)
2. Determine the past and present habitability of the cave environment	2A. Determine whether the geochemical environment contains water, chemistry (CHNOPS+Fe) and chemical disequilibria essential to support past or present life	2A.1 Determine the geochemistry (CHNOPS+Fe) of the system	Whole rock geochemistry and unaltered mineralogy (i.e. Ca, Mg, Fe, Si, Al, S, P (±0.1 wt% on a 10 cm scale)
		2A.2 Determine the alteration mineralogies (including evaporites, carbonates, oxides, and silicates) and textures that may influence distribution of CHNOPS+Fe	Quantify alteration minerals and geochemistry (CHNOPS+Fe, Ca, Mg, Si, Al (±0.1 wt% on a 10 cm scale)
		2A.3 Determine the geochemical resources (CHNOPS+Fe) available in the aqueous phase that could support life and activity of water	Quantify water chemistry (anions, cations, dissolved gases) (1 ug/l for trace elements; 1 mg/l major elements)
	2B. Determine the physical and chemical properties of the atmosphere	2B.1 Determine whether the cave climate is conducive to present/past habitability	Define cave climate (temperature (T=±1°C), wind speed, relative humidity (R_H±5%), barometric pressure). Measure T of air and cave wall.
		2B.2 Determine whether the atmosphere is suitable for human habitation	Quantify the atmospheric composition, including CH_4, O_2, N_2O, H_2S at 1-5 ppb and isotopic ratios of the cave
	2C. Determine the cave radiation environment	2C.1 Determine the potential of the cave environment to shield past/present life from the surface environment	Identify radiation levels and sources within the cave Spectra gamma ray; data collection rate such that K, U, and Th gamma ray counts achieve rates required for precision; distance from the rock <20 cm; elemental abundances of obverburden above the lava tube
3. Determine the geologic history of the cave	3A. Characterize the geologic context of the cave	3A.1 Determine the overburden roof thickness and geologic composition	
		3A.2 Determine cave depth, structural complexity, linear extent, and estimate volume	Imaging spectral resolution X, Y >1 mm; data collection along cave traverse in continuous coverage
	3B. Define the physical composition and structure of the cave (i.e. speleogenesis processes)	3B.1 Determine near surface geology	Whole rock geochemistry and mineralogy (unaltered) (i.e. Ca, Mg, Fe, Si, Al, S, P (±0.1 wt% on a 10 cm scale)
		3B.2 Determine the duration of emplacement processes	Visually measure any volcanic stratigraphy within the cave to create a cross-section; determine the geologic age(s)
		3B.3 Determine how cave formation processes differ on Mars and Earth	At various resolutions, examine mineralogy/geochemistry, size/shape of the cave and compare it to Earth analogs

lander for communication, and a mobile unit for communication, and a mobile unit for exploration. Communication repeaters may also be used in the lava tube to enable deep exploration.

Planetary Protection: A lava tube cave mission would access an area designated as a "special region" [10] and require compliance with Planetary Protection Category IVc, which addresses special regions [11]. Accordingly, the mission would ensure a total bioburden level of <1.5x10^{-4} spores.

Discussion: Advancement of several spacecraft architectures for use in lava tube cave exploration make the search for life in Mars subsurface feasible within the next decade. We recommend exploration of Mars' subsurface via cave access points for inclusion on the NF list for the upcoming Decadal Survey and recommend that a mission concept study be performed to determine the best payload(s) that could determine whether life existed in Mars' subsurface with different robotic architecture options.

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