The Quest for Life Leads Underground: Exploring Modern-Day Subsurface Habitability & Extant Life on Mars

A White Paper Submitted to the ESA Call for Voyage 2050

Contact Scientist

Dr. Stamenković Vlada

Jet Propulsion Laboratory, California Institute of Technology 4800 Oak Grove Drive, M/S:183-301 Pasadena, CA 91109, USA Tel: +1 626-390-7631 Email: Vlada.Stamenkovic@jpl.nasa.gov

Members of the Proposing Team

- 1. Pietro Baglioni, ESTEC, ESA, Noordwijk, The Netherlands,
- 2. Christopher Ballentine, University of Oxford, Oxford, UK,
- 3. Luther Beegle, Jet Propulsion Laboratory, Pasadena, CA, United States,
- 4. Doris Breuer, German Aerospace Center DLR Berlin, Berlin, Germany,
- 5. Charles Cockell, University of Edinburgh, Edinburgh, Scotland, UK,
- 6. Véronique Dehant, Royal Observatory of Belgium, Brussels, Belgium,
- 7. Charles Edwards, Jet Propulsion Laboratory, Pasadena, CA, United States,
- 8. Raphael Garcia, ISAE, Toulouse, France,
- 9. Matthias Grott, German Aerospace Center DLR Berlin, Berlin, Germany,
- 10. Axel Hagermann, University of Stirling, Scotland, UK,
- **11. Fumio Inagaki,** Institute for Marine-Earth Exploration and Engineering, Agency for Marine-Earth Science and Technology, Yokohama, Japan,
- **12. Taichi Kawamura**, Université de Paris, Institut de physique du globe de Paris, Paris, France,
- 13. Nina Lanza, Los Alamos National Laboratory, Los Alamos, NM, United States,
- 14. Robert E Grimm, Southwest Research Institute Boulder, Boulder, CO, United States,
- **15. Philippe Lognonné**, Université de Paris, Institut de physique du globe de Paris, Paris, France,
- **16. Bénédicte Ménez**, Université de Paris, Institut de physique du globe de Paris, Paris, France,
- 17. Joseph Michalski, University of Hong Kong, Hong Kong,
- 18. Michael Mischna, Jet Propulsion Laboratory, Pasadena, CA, United States,
- 19. John F Mustard, Brown University, Providence, RI, United States,
- 20. Victoria J Orphan, California Institute of Technology, Pasadena, CA, United States,
- 21. Magdalena R Osburn, Northwestern University, Evanston, IL, United States,
- 22. Ana-Catalina Plesa, German Aerospace Center DLR Berlin, Berlin, Germany,
- 23. Karyn L Rogers, Rensselaer Polytechnic Institute, Troy, NY, United States,
- 24. Barbara Sherwood Lollar, University of Toronto, ON, Canada,
- 25. Tilman Spohn, International Space Science Institute, Bern, Switzerland,
- **26. Fabien Stalport**, Laboratoire Interuniversitaire des Systèmes Atmosphériques, Université Paris Créteil, France,
- 27. Vlada Stamenković, Jet Propulsion Laboratory, Pasadena, CA, United States,
- 28. Jorge Vago, ESTEC, ESA, Noordwijk, The Netherlands,
- 29. Frances Westall, Université de Orléans, Orléans, France,
- 30. Kris Zacny, Honeybee Robotics, Pasadena, CA, United States.

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1 Science Leading Us Underground

1.1 Questions

The ExoMars rover, planned to land in 2021 on the Martian surface, will begin the journey to explore the <u>shallow (<2 m) Martian subsurface</u> and seek for signs <u>of ancient and extinct life</u>. As we describe below in greater detail, the most likely regions on modern Mars to find liquid water are at depths of kilometers. At these depths on Mars, environments might exist where microbes could still be alive. We propose that the next frontier for planetary exploration that should spearhead the Voyage 2050 is the Martian subsurface with the quest for modern-day habitable environments and extant life.

Three broad questions are directing the trajectory of this journey:

- I. Is there liquid water in the modern-day Martian subsurface? How much is there? What is its chemistry?
- II. Are there large enough redox gradients and sufficient nutrients to support modernday subsurface life on Mars?
- III. Is there extant life in the Martian subsurface today? If so, where is it and how much biomass and productivity are there?

Such exploration, will, as we shall see later, ultimately also help address the following questions that are not directly related to modern-day habitability and extant life:

- IV. Was there life on Mars early on that is now extinct?
- V. What kind of & how much resources are in the Martian subsurface?
- VI. How did the water inventory and climate change across time?

1.2 Science Goals & Expected Significance

Mars's surface is today in many ways inhospitable to life, for two main reasons:

- 1. Liquid water environments are generally deep: Liquid water and most brines are only metastable on the Martian surface [1]. The conditions needed to keep water liquid are, for the majority of the planet, generally rather at depths of several kilometers in the subsurface [2] [3]. Only salts such as perchlorates or soils with very low thermal conductivity can shift this depth, locally, closer to the surface [1] but the availability of such salts is debated [4] [5].
- 2. Organics are being destroyed on the surface: Organics are being bombarded by oxidizing radicals and harsh radiation on the surface to a yet to be determined depth.

These two points illustrate a trade-off between depth, modern-day habitability, and signatures of life: although it is still debated to which extent, it is possible that the first few meters could be too harmful for modern life to exist, freshwater at kilometers depth might offer high water activity needed by life, and brines could offer locally shallower liquid water but with a lower water activity.

We propose to include for Voyage 2050 payload/mission concepts that seek to explore the trade-offs between depth, modern-day habitability, and signatures of extant life on Mars with two goals & four objectives as described on the next page:

Goal 1: Quantify the trades for <u>modern-day subsurface habitability with depth</u> by determining

- A. Liquid water: the state of liquid water in the Martian subsurface,
- B. Energy & nutrients: subsurface geochemistry and changes with depth.
- C. Stability: the stability of biomolecules and changes with depth.
- Goal 2: Search for signs of extant subsurface life by determining
 - D. Biomarkers and signatures of metabolic activity and changes with depth.

These topics are directly relevant not only to modern habitability and the potential for extant life, but also to an emerging understanding of Mars's dynamic climate, hydrosphere, atmosphere, geologic & geophysical history and ancient (and possibly extinct) life. Building on previous missions and the next generation subsurface explorers such as the ExoMars rover, planned to launch in 2020, we have the contextual knowledge to develop strategic targets and objectives, thus advancing the search for signs of life on Mars by extending our exploration from 2D to 3D (surface + subsurface) and going from searching for signs of extinct life to seeking signatures of extant life.

1.3 Motivation

Access to the Martian subsurface offers an unprecedented opportunity to search for the "holy grail" of astrobiology—evidence of possibly still habitable subsurface environments and maybe even extant life—a journey started by the Viking landers more than four decades ago. Analyzed samples would also deliver the puzzle pieces needed to help complete our understanding of how the Martian climate, carbonates, chemical deposits and volatile inventories changed over time and may have impacted, or may have been impacted by, life. The proposed concepts might also hold the key for understanding the chances for ancient (and possibly extinct) subsurface life.

Evidence from orbiters and rovers suggests a once "warmer and wetter" Mars and recent results from the MAVEN mission demonstrated that a significant fraction of the Martian atmosphere was lost early in the planet's history [e.g., [6] [7] [8] amongst many others]. As its atmosphere thinned, the flux of harmful radiation reaching the Martian surface would have increased and the surface temperatures would have cooled well below the freezing point of water. Consequently, the cryosphere would have thickened and stable groundwater would have moved to greater depths below the surface. Therefore, if Mars ever had life (regardless whether it emerged on or below the surface), then it should have followed the permafrost/groundwater interface to progressively greater depths where stable liquid water can exist. There, shielded from seasonal and diurnal temperature effects as well as from harmful effects of ionizing radiation, it could have been sustained by hydrothermal activity, radiolysis, and rock/water reactions. Hence, the subsurface represents the longest-lived habitable environment on Mars. Therefore, in comparison to the surface, our chances of finding signs of extinct life are much greater in deep, protected, self-sustaining subsurface habitats that putative organisms might have inhabited, e.g., [9].

If extant life exists on Mars today, then the most likely place to find evidence of it is at depths of a few hundred meters to many kilometers, where groundwater could persist despite today's low geothermal gradients [10]. Moreover, while the preservation of molecular biosignatures on Mars is debated, the consensus is that detection at depths greater than a few meters is favored because of the shielding from harmful radiation, [11] [12] [13].

Additionally, accessing information in the Marian subsurface (geochemical, geophysical, and astrobiological) to obtain subsurface profiles of the D/H, ¹⁸O/¹⁶O, carbonate content, organics, pH, volatiles, redox conditions, porosity, permeability, temperature, and stratigraphy—unaffected by atmospheric processes or solar/cosmic radiation—will enable us to much better constrain the

environment for life over geological timescales, i.e., the time-dependent variation of water loss, climate, volcanism, and tectonic processes.

Therefore, the exploration of the full potential of extinct or extant life on Mars and its environmental context over the last few billion years requires sounding and also accessing the deep subsurface, and the collection of samples. Starting a few meters below the surface but ideally reaching towards greater depths of ~100 m—in order to be deep enough to be able to extrapolate habitability characteristics to even greater depths of many hundreds of meters and kilometers, where extant life could still be today.



Figure 1: Three aspects that enable Mars subsurface exploration today: 1) Technological advancements in drilling & sounding—driven by miniaturization, automation, increased computational speed, sensor-driven adaptation, and in situ analysis have significantly reduced power, size, and mass footprints and created new tools for subsurface exploration [14] [15] [16] [17] [18], 2) New scientific achievements, from mapping of aqueous minerals, active gullies, recurring slope Lineae, ice and water deposits (showing water-equivalent hydrogen as background color and ice-exposing new impacts) allow us to know better where and how to drill, [19] [20] [21] [22]; this scientific progress will be improved by ExoMars TGO and the ExoMars rover, which will help to localize potentially biologically relevant zones of interest such as methane seeps, and 3) commercial, international, and human opportunities create a powerful paradigm shift and out-of-the-box opportunities for the search for life on Mars—connecting ESA even more to the commercial and international world of space exploration.

We now have the capability to explore the deep Martian subsurface (~ 100 m), specifically due to (a) recent technological advances, (b) an improved understanding of the local variability of Martian subsurface environments, and (c) increasing commercial, international, and human opportunities on Mars (see Figure 1):

- a) Technological advancements in miniaturization, automation, data processing, sensor-driven adaptation, fault protection and recovery, and instrumentation for chemical characterization of soluble, gaseous, and solid compounds can make *in situ* deep subsurface exploration and wide high resolution subsurface sounding for volatiles down to a few km of depth feasible,
- b) Latest scientific results on the 3D diversity of Martian surface and, increasingly, subsurface environments facilitate more rigorous landing site selection and the correlation of local results within a global context, and,
- c) Emerging commercial, international, and human opportunities on Mars enable out-of-the box approaches: commercial collaboration opportunities through, e.g., SpaceX, Blue Origin, Firefly, Relativity Space, etc. could provide frequent and more affordable flights to Mars; growing international interest in Mars exploration by the Emirates, India, China, and Japan in the early 2020s can broaden international collaborations beyond ESA, Roskosmos and NASA.

1.4 On the Shoulders of Giants: ExoMars 2020, InSight, MSL, Mars 2020 & MSR

1.4.1 ExoMars Rover 2020

The ExoMars 2020 rover plans to access samples at a depth of \sim 1-2 m within the shallow Martian subsurface in order to search for signs of extinct life. This is a major milestone in Mars subsurface exploration but it is just the first step. We need to go to greater depths of \sim 10 m in order to make sure that ionizing radiation and oxidants are low enough for extant life and in order to start seeing large enough geochemical gradients beneath the oxidizing surface veil (Section 2.1.4.1). This requirement leads us to be able to drill to at least 10 m. Ultimately, our extended goal of drilling is \sim 100 m and would enable completely novel insights on large-scale depth gradients that the ExoMars rover will not be able to address. This would be the key step in order to start constraining the subsurface habitability of modern Mars.

1.4.2 InSight

We will address later the issues with the HP³ mole and why such a system is completely different from drills that we try to apply. From a science perspective, the InSight mission is addressing different questions and spatial scales focusing on mantle processes and planet structure. In contrast, we are proposing to study the shallow crust with a focus on habitability and life.

1.4.3 MSL Curiosity & Mars 2020

MSL demonstrated our ability to use a complex instrument payload to perform a full habitability assessment of a ~3.5 Ga paleolake environment in Gale Crater [23] [21]. Beyond the scientific discoveries, we have developed our operations and sample delivery concepts. We can build upon the lessons learned from both MSL and Mars 2020 in order to extend exploration into the subsurface and towards extant life. Our focus on delineating depth-dependent redox gradients, the preservation of potential biosignatures (or abiotic organic carbon history) with depth, and the implications for habitability and extant life are critical and natural extension of the Curiosity and Mars 2020 missions.

1.4.4 Alignment with Mars Sample Return

ESA and NASA are exploring the possibility of a joint Mars Sample Return Mission (MSR). Getting first constraints on the state of liquid water and other volatiles, in addition to salts, nutrients, and potential energy sources with depth—as we propose to do here— would provide complementary, and spatially deeper, context for the planned Mars Sample Return mission [24].

1.5 Specific Technologies & Enabling Scientific Developments

Deeper subsurface mission concepts can capitalize on recent technological efforts aimed at advancing miniaturization, automation, data processing, sensor-driven adaptation, and fault protection and recovery technology. Such progress allows adaptive and automated deep drilling in various soils and simultaneous *in situ* analysis.



Figure 2: For example, the WATSON drill with integrated Mars2020 Sherlock instrument could be used to penetrate to 100s m. We would want to also infuse heritage from the ExoMars rover drill into this design.

The technologies for terrestrial subsurface sample characterization and extraction are already developed for harsh environments (low/high temperature and the high shocks that the equipment could be subjected to during launch, landing, and drilling operation). Continual advancements in drilling, completion, and rig technology from the oil, gas and water service industries have enabled significant progress to be made in addressing the specific issues of Martian subsurface characterization (via seismic, electromagnetic sounding and ground-penetrating radar, in addition to other techniques), remote drilling, and borehole stability. Also, significant progress has been made in clean drilling and avoiding/detecting contamination in drill cores of ancient rocks on

Earth. Additional enhancements in life-compatible drilling technologies might be expected to follow from the International Continental Scientific Drilling Program (ICDP)'s growing interest in life-inspired drilling. Next generation drills, like WATSON [18] currently deployed in terrestrial cryoenvironments could be deployed from a Lander or even Curiosity size rover and penetrate the subsurface to approx. 100s m to 1 km depth (see Figure 2).

Next to this game-changing technological progress, our expanded understanding of the Martian surficial and sub-surficial variability will facilitate mission planning, specifically site selection by providing better *a priori* subsurface information (see Figure 1).

More details on relevant technology will be provided in our description of potential concepts in Section 2 starting on the next page.

2 Preliminary Concepts

In the following, we will describe preliminary mission concepts that would be able to address the questions mentioned in Section 1.1. We will first start with a baseline mission concept (see Figure 3) that would require an M- to L-Class mission. We will then discuss how this baseline mission concept can be extended or reduced to fit within a smaller framework.

2.1 An M- to L-Class Scenario Depending on Payload

In this section, we will first present our **notional** science traceability matrix, STM, (Figure 4) that lays out the infusion path from mission goals and defines the objectives and investigations. We present the current state of knowledge for our objectives and describe the investigations necessary to improve that knowledge.



Figure 3: This figure illustrates the driving mission Concept in a Nutshell. The description is for a complete M to L class mission, which can be downscaled to smaller mission concept by focusing on A, B, or just C.

			NOTIONAL SCIENCE TRACABILITY MATR	X	
u			GOALS INFUSION		
ioissiM IsoĐ	<u> </u>	ern-day Subsurface Habitabilityj: C Towards Extant Subsurface Life <mark>)</mark> : Qu	uanury the modern-day habitability of the Martian subsurface with antify any biosignatures in the subsurface and how they change wit	a rocus on water, ener h depth as well as trace	gy, and nutrients and their change with depth. e gases, their change with depth and time.
				ā.	
Goa	Objectives	Investigations	Measurement Requirements	Instrument Classes	Model Instruments
	A. <u>Habitability </u> Evaluate at the	A1. Determine the existence of local liquid groundwater and characterize its size.	<u>M1.</u> Measure the amount of adsorbed water as a function of depth, the depth to the water table and the thickness of the water table. Detect aquifers of thickness greater than 10 m down to a depth of 5 km.	Liquid water sounder.	Primary Choice: Transient Electromagnetic Sounder (TEM), Alternatives but less capable: Ground Penetrating Radar, High- frequency Seismometer.
	cvictorco of licuid	A2. Determine the composition of	M2. Measure the electric conductivity of groundwater with a sensitivity of	Electrical Conductivity	Transient Electromagnetic Sounder (TEM).
	provindwater on	local liquid groundwater.	0.01 S/m.	Sounder.	
	modern-day Mars		<u>M3</u> . Measure the temperature of the surrounding rock as a function of depth with a sensitivity of at least 0.01 K.	Thermal Sensor.	Thermometer.
	and characterize it.	A3. Determine the water storage	M4. Measure the porosity change with depth at each meter capable to	Porosity Sensor.	Micro In Situ Tomography, Desiral Miscorcond (c. a. MATCON on Marco 2020 or considented
		A4. Determine the local geologic	<u>with the subsurface of the subsurface with a</u>	Ground Penetrating	ground-based radar.
1		subsurface habitability.	resourced of a fin down to good in act a median in equency and write. MG. Map the geologic surface context.	Surface Context Imager	Camera with multispectral filter spanning visible and IR range (e.g., ChemCam on MLS, SuperCam on Mars 2020, Mastcam type or equivalent).
t le		A5. Determine the local thermal state of the subsurface.	(N3). Measure the temperature of the surrounding rock as a function of depth.	Thermal Sensor.	Thermometer.
99			M7. Measure the temperature change of the drill as a function of depth.	Thermal Conductivity Sensor.	Thermal Needle or Thermal Properties Sensor.
	B. <u>Habitability II</u> Determine the chemical, &	B1. Determine the chemical composition of the subsurface with depth in relation to energy & nutrients.	MB. Measure the chemical composition of soil with depth—in particular focusing on the abundance of CHNOPS and redox partners (e.g., the amounts of reducers and oxidizers with depth).	Vibrational Spectrometer.	 UV/Fluorescence Raman Spectrometer (maybe paired with LBS). 4-channel Tunable Laser Spectrometer (e.g., TLS or equivalent). Maybe additionally also Wet Chemistry Laboratory (Phoenix).
	mineralogical state of the subsurface and its change with depth at the landing site.	B2. Determine how the redox state and hydration of minerals changes with depth.	$\frac{M9}{M^2}$ Measure the minerology with depth with a particular focus on fugacity, Fe^2+/Fe^3+ hydration state, and oxidation state of Mn.	Mineralogical analysis tool box.	Spectrometer such as MicrOmega on the ExoMars rover or equivalent, optical microscope (e.g., WATSON on Mars 2020 or equivalent).
	C. <u>Habitability III</u> Determine how ionizing radiation	C1. Determine the amounts of oxidizers with depth.	(M8). Measure the chemical composition of soil with depth— in particular the abundance of oxidizers such H_2O_2 , ClO_{*} ClO_3 .	Vibrational Spectrometer.	 UV/Fluorescence Raman Spectrometer (e.g., SHERLOC on Mars 2020 or equivalent). Maybe additionally also Wet Chemistry Laboratory (Phoenix).
	changes with depth.	C2. Determine the amount of ionizing radiation and its change with depth.	<u>M10</u> . Measure the dosage of ionizing radiation with depth (still to be better defined but possibilities are alpha, beta, neutron particles, free ions, and gamma and X-rays).	Radiometer. Neutron spectrometer.	Radiometer (e.g., as on MSL or equivalent).
	D. Towards Extant Life Determine the existence of biosignatures and their change with depth at the landing site as well as	D1. Determine and characterize organic indicators of life and metabolic activity changing with depth.	<u>M11</u> . Measure the presence, identities, and relative abundances of organics, amino acids and their chirality, lipids, biomolecules, and metabolic byproducts (and their chirality) at compound concentrations as low as 1 picomole in a 1 g sample of soil. <u>M12</u> . Measure the stable isotope composition of multiple compounds of carbon ^{(13e}) ²¹² (for organic compound concentrations as 1 picomole in at sample of soil with a relative standard deviation of fless than 5%.	 Organic Compositional Analyzer, Vibrational Spectrometer. 	 Gas Chromatograph Mass Spectrometer with chirality and stable isotope analyzers (e.g., QMS and GC from SAM on MSL or equivalent), UV/Fluorescence Raman Spectrometer (e.g., SHERLOC on Mars 2020 or equivalent).
2 leo	changes in trace gases with depth and in time.	D2. Detect and characterize inorganic indicators and microstructures of life changing with depth.	<u>M13</u> . Measure to hundreds of parts per thousand by mass biominerals such as carbonate or magnetite structures, or enrichments in SiO ₂ and iron sulfides and search for cells or other nano-or microstructures indicative of life.	 Microscope, Vibrational Spectrometer. 	 Optical Microscope (e.g., WATSON on Mars 2020). UV/Fluorescence Raman Spectrometer (e.g., SHERLOC on Mars 2020).
9		D3. Determine the abundance of local trace gases with depth and their change in time.	M14 . Measure the atmospheric abundance and temporal change of methane, water, oxygen, sulfur dioxide and ammonia on the surface and in the borehole with depth. Take measurements during day and night in the following channels $CH_{\rm eff}$ 3.27 µm, CO_{2} and H_{2} @ 3.78 µm, O_{2} @ 0.76 µm following channels $rS_{\rm eff}$ @ 7.42 µm and $NH_{\rm eff}$ @ 9.92 µm with a spectral resolution of 10 Å. Methane sensitivity must be greater than 0.1 ppbv.	IR spectrometer.	 4-channel Tunable Laser Spectrometer (e.g., TLS or equivalent), Spatial Heterodyne Spectrometer on surface. 2-channel Tunable Laser Spectrometer in borehole (e.g., mini-TLS or equivalent).
			<u>M15</u> . Measure the pressure, temperature, radiation and wind at the surface to provide additional constraints for the local atmospheric trace gas analysis.	MET station.	Phoenix or MSL type MET stations.

Figure 4: <u>Notional</u> Science Traceability Matrix. Some identical measurements are needed for more than one objective; if so, they are shown in brackets, e.g., (M8) and (M3) for A5 and C1. See text for explanations on the chosen sensitivities and how measurements are used to complete the investigations.

2.1.1 Science Traceability: From Goals & Objectives to Investigations

Our proposed mission goals are to:

- 1. Quantify the modern-day Martian subsurface habitability
- 2. And search for evidence of extant life.

In this proposal, we focus on the primary science goals related to modern habitability and life. Secondary mission goals are related to extinct life, climate history, polar sciences, resources and human exploration, but are not discussed here in great detail. We refer for now to a community paper, [25], that discusses the broad impact of Mars subsurface exploration on planetary sciences.

We postulate that subsurface habitability has three requirements: (A) liquid water, (B) energy and nutrient sources, and (C) molecular and cellular stability (Figure 3, Figure 4).

Whether liquid water exists today on Mars is explored with the first objective. The second objective focuses on the availability of nutrients and energy gradients that drive metabolic activity by determining the geochemical and mineralogical state of the subsurface. The third objective investigates molecular and cellular stability, by studying how deep ionizing radiation and oxidants penetrate into the Martian subsurface. This leads directly into the last, fourth objective (**D**), which tackles the second mission concept goal to search for signs of extant subsurface life—by looking at biomarkers and signs of metabolic activity.

2.1.2 Objective A: Habitability I—Subsurface Water

2.1.2.1 Current knowledge

The post-Noachian hydrogeology of Mars is controlled by the cryosphere, the outermost portion of the interior that is below freezing. [2] and [3] calculated the cryosphere thickness—below which saturated groundwater could exist-using average heat flow estimates of 15 and 30 mW/m². Recent models that consider both temporal and the full 3D spatial variations in heat flow suggest an average heat low of $25 \pm 2 \text{ mW/m}^2$ with a lateral distribution that leads to a cryosphere depth of 2-4 km in the tropics and 11-20 km at the poles (Figure 5 & Figure 6e). The original simplistic hypothesis of an interconnected global water table at uniform depth (cf. [2]) has been advanced by lessons from the Earth that demonstrate how geologic setting and fracture distributions determine subsurface water patterns. This illustrates how geologic setting could help determine landing sites for the Voyage 2050. Portions of the subsurface may be sufficiently pressurized, needing say a magmatic intrusion, to intermittently reach breakout (e.g., Athabasca Valles: [26], potential landing sites, Section 2.1.6). Groundwater may be in contact with the base of the cryosphere (confined aquifer) or an intervening unsaturated zone may exist (unconfined aquifer). Seasonal narrow, dark features on the present-day Martian surface called Recurring Slope Lineae (RSL) [27] are quantitatively consistent with liquid water discharge [28] but their formation is still debated [22], as slope characteristics seem to suggest dry, granular flows [29]—which would be in agreement with liquid water being generally only stable at much greater depths, see Figure 5. Based on geological evidence, ancient Mars up to the late Hesperian (~3 Ga) possessed a 0.5-1 km-thick global equivalent layer (GEL) of H₂O [6], which may be locked today as ground ice and liquid water in the planet's upper crust [2]. If indeed the post-Noachian crustal H₂O inventory was ~100s meters GEL or more, then modest water loss since then would suggest that groundwater

likely exists globally on Mars today [30]. This is further supported by the measured deuterium-tohydrogen ratio (D/H), which indicates that the total water loss since the Hesperian has only been about 60 m (interquartile range 30-120: [30]). Importantly, the heat flux estimates for modern Mars from [31] strongly support the idea that liquid groundwater still exists abundantly in the deep Martian subsurface.



Figure 5: A standard run for the depth of the cryosphere/liquid water table interface (calculated based on simulated heat flow data from [31] [32]), depending on surface temperature and on local heat flux. For simplicity, we assume only a latitude-dependent surface temperature model and did not include any salts, which would shift the water table to shallower depths. We

highlight regions around $\pm 30^{\circ}$ latitude, which are common landing constraints with potential depths to pure liquid water of 2-4 kilometers. Large potential depths of groundwater beyond $\pm 60^{\circ}$ demonstrate that the polar regions are not ideal for liquid groundwater exploration.

The detection of liquid water in the Martian subsurface by the orbiting radar MARSIS on Mars Express [33] and SHARAD on the Mars Reconnaissance Orbiter [34] was likely limited to an average depth of ~100-200 m except for "regions with favorable subsurface conditions" with ice or volcanic ash. Moreover, detections would be limited to continuous liquid water bodies with horizontal extent greater than ~1-10s kilometers, see [35] and [36]. Regions with such favorable subsurface conditions are the poles, but due to low surface temperatures they are also the regions where liquid water is expected to be deepest (Figure 5). Nonetheless, MARSIS data were recently used to establish the possibility of perchlorate-containing liquid water, 20 km wide, at a depth of 1.5 km close to the South Pole [37]. The data also allow for alternative interpretations and the reported penetration depth is beyond some predictions for the maximum penetration depth (see [35], [36]), making this claim speculative (Figure 6e). The large subsurface signal attenuation encountered by MARSIS and SHARAD indicates subsurface properties more intermediate between the Earth and the Moon, which may be attributed to higher-than-initially-expected levels of absorbed water, drier than the Earth but wetter than the Moon (see [38], [39], [30]). Ultimately, the encountered signal attenuation might support the possible presence of deeper liquid water in the Martian subsurface that is beyond the detection ability of the existing orbiting radar.

2.1.2.2 Advancement of current knowledge with proposed investigations

The presence and distribution of groundwater on Mars are open questions that we propose to answer with the here presented mission concepts. The proposed investigations would determine the amount of adsorbed subsurface water as a function of depth, the depth to and thickness of the putative groundwater table (A1), and constrain the chemistry of the subsurface water (A2). This may be achieved by using a transient electromagnetic sounder (TEM), which measures the electrical conductivity of the subsurface and inverts those data into profiles of water abundance (Section 2.2.1). The electrical conductivity will help us to narrow down the presence of salts in the groundwater by relating the measured electrical conductivity with potential salt mixtures. A TEM sensitivity of 0.01 S/m will allow us to distinguish better the isolation time of the water, which is

thought to increase from 0.01 S/m over 0.1 S/m to 1 S/m for increases in isolation time of 100 million, 1 billion to billions of years [38], [40], [41]. Measurements on the thermal state of the subsurface $(A5 \rightarrow M3, M7)$ will help us to further constrain the composition of the groundwater due to information on the presence of freezing-point reducing salts. Measuring the porosity change with depth (Figure 6g) will allow us to extrapolate porosity to greater depths to estimate the crustal water storage capacity (A3). Porosity decreases with depth, the change from surface porosity to its value at 10 m is expected to be only 0.3%, but at 100 m this change is expected to be much greater around ~ 5% and, hence, easier to detect [9]. We propose to set a porosity detection limit to 0.3% in order to be able to detect the predicted change at 10 m. Beyond the baseline concept, GPR (A4, M5) and seismometers, similar to SEIS on InSight, would help to even better constrain subsurface layering. *Approaches utilizing a combination of TEM, GPR, and seismometers should be explored in greater depth to maximize science return.*

2.1.3 Objective B: Habitability II—Energy and Nutrients with Depth

2.1.3.1 Current knowledge

Rovers like Curiosity have sampled limited parts of the Martian subsurface down to a depth of approximately six centimeters. The Phoenix lander sampled one regolith sample from 18 cm using a scoop. Although we have barely scratched the Martian surface. we see already indications for diverse subsurface environments reflected in the many subsurface sample colors underlying a homogeneous red surface layer (Figure 6a). Images from Curiosity (Figure 6a) suggest that the oxic to anoxic transition



Figure 6: Science with depth framework showing how science return is affected by the depth of exploration. [37]², [83]¹.

is closer to the surface than previously postulated, but we have no constraints on how redox gradients change with depth beyond those few inches, and whether they suffice to fuel life possibly at much greater depth. The ExoMars rover will start to stretch this geochemical exploration into a depth of 1-2 meters in 2021. Discoveries from Curiosity and Mars Express of spatial and temporal variability in methane detections in the Mars near-surface (with peaks reaching for short times ~7 ppbv) suggest that the right geochemical environments for rock-water reactions and subsequent H_2 and CH_4 formation could exist at much greater depth.

Although multiple abiotic processes could provide an energy source for extant life in the Martian subsurface, H_2 production is likely a key energy source and primary electron donor produced through anaerobic groundwater reacting with Fe-rich basalts at depths where liquid water exists, see [42] and Figure 6f. Fe oxidation coupled to nitrate reduction can regenerate Fe³⁺ for subsequent biological reduction. H_2 along with H_2O_2 and O_2 is also generated through radiolysis of groundwater and ices, or it could also be delivered from diffusion or intrusion of atmospheric gases (Figure 6d). Abiotic oxidation of endemic sulfides to sulfate can provide additional electron

acceptors for chemotrophic metabolisms, e.g., [43]. The higher porosity at a given depth on Mars resulting from lower gravity (see [44], [45], [46]) suggests that the H₂ flux in the Martian subsurface via radiolytic H₂ production may be greater than on Earth. This is also supported by the larger Fe/Mg ratio found in Martian rocks, that facilitates H₂ production [42]. Methane observed with Curiosity and Mars Express could be a relic of such deeper processes, where H₂ is ultimately converted into CH₄ via Sabatier-type reactions (Figure 6b) [47].

2.1.3.2 Advancement of current knowledge with proposed investigations

The proposed investigations would allow us to finally determine the geochemical (B1) and mineralogical (B2) properties of the Martian subsurface at depths beyond inches, going towards 10 m (baseline) and ultimately 100 m (extension). The baseline depth of 10 m will allow us to exceed the maximum depth where oxidants and ionizing radiation are modeled to affect life (Section 2.1.4) and to start being deep enough to observe associated changes in geochemistry with depth beyond this near-surface region. Obtaining geochemical and mineralogical samples to greater depths of ~100 m would allow us to finally observe large-scale geochemical gradients with the potential to extrapolate these gradients to greater depths where liquid water could be stable. Of particular focus will be the characterization of chemical redox gradients, oxygen fugacity, and the oxidation state of Fe and Mn in soil (M8, can contain volatiles/ices) and minerals (M9). The Fe-Mn pair provides good constraints on redox conditions and water availability with depth, as Fe and Mn need very different concentrations of oxidizing agents and liquid water to become oxidized.

2.1.4 Objective C: Habitability III—Stability with Depth 2.1.4.1 Current knowledge

Oxidative and ionizing radiation conditions on the surface of Mars play a role in degradation of macromolecular organic carbon. Chemical oxidants such as perchlorate and its reactive decomposition species (see [48], [49]) would likely drive oxidative damage. The highly ionizing radiation environment on the Martian surface will also play a role in biosignature degradation. Not only is the resulting photo-Fenton chemistry extremely destructive to living organisms [50], it also degrades ex situ organic molecules. The ionizing radiation dose at the Martian surface is estimated to be 0.54 - 0.85 Gy/year, [51]. Empirical studies have suggested that the preservation of >500 amu functionalized organic molecules within the top \sim 5 cm of the surface would be reduced 1000 times within 300 million years of exposure to surface radiation conditions, [13]. As a result of enhanced surface degradation, exposure age is a primary concern. Despite relatively young exposure within Gale Crater (78 \pm 30 Ma; [52]), and significantly slower weathering on Mars compared to terrestrial rates, the combination of ionizing radiation and oxidative damage will degrade all molecular biomarkers at the surface. Model-dependent estimates on the penetration depth of ionizing radiation and oxidants, mixing in the subsurface, and the destructive effects on biomolecules, spores, and living cells suggest that depths up to ~7.5 m could be harmful to life (see, e.g., [51], [13], [11], [12]). The SAM instrument onboard Curiosity detected organic carbon, particularly in the Murray and Sheepbed mudstones of Gale Crater, e.g., [53], [54], with an average of 11.15 ± 6.86 ppm with high temperature release consistent with the presence of thiophenes, aromatics, aliphatics, and thiols, showing that organic molecules within mostly clays may be further protected from degradation (see [20], [55]). Preservation might be also enhanced by the presence of reduced sulfur species through sulfurization, reduction, and cross-linking of reactive functional groups, or by providing an alternative oxidative sink (see [55] and refs therein).

Nonetheless, we do not have *in situ* data that could test those hypotheses. This suggests that the subsubsurface harbors a more extensive record and remains the most promising target for characterizing the molecular diversity and complexity required for biosignature definition, and is hence a natural and essential extension of the Curiosity and future Mars 2020 and ExoMars missions.

2.1.4.2 Advancement of current knowledge with proposed investigations

The proposed mission concepts would test existing hypotheses on the availability of oxidizers (C1) and ionizing radiation (C2) as a function of depth. The measurements needed to complete the investigation C1 are already part of B1 (e.g., the measurement M8). For C2, we would still need to define the ideal set of instruments needed to measure how ionizing radiation changes with depth. By accessing samples to at least ~10 m, we necessarily include the worst-case predictions of the depth where cells could still be damaged and enable the measurement of geochemical gradients with depth beyond this likely heavily altered near-surface region (e.g., [51], [13], [11], [12] and refs therein). These objectives are tightly linked to the availability of organics with depth (contained in Objective D1) and connect to the search for evidence of extant subsurface life.

2.1.5 Objective D: Bio- & Metabolic Signatures of Extant Subsurface Life 2.1.5.1 Current knowledge

Subsurface life on Earth is present to depths of 4-5 km in the continental crust and 2.5 km in subseafloor sediments comprising $\sim 10^{30}$ cells or at least 10% of the surface biosphere, [56] [57]. A significant portion of this subsurface biomass is independent of surface photosynthetic CO₂ fixation, instead obtaining energy from chemosynthetic reactions analogous to those predicted to occur in the Martian subsurface (e.g., radiolysis, serpentinization, and abiotic organic synthesis of organic compounds). On Earth, subsurface chemolithoautotrophic microbial communities gain energy from reduced metals in soil substrates (see [58] and refs therein). Reduced S, Fe, N and Mn

provide substrates for exergonic redox based metabolisms. Similarly, we expect that H_2 and CH₄ formation on Mars (Section 2.1.3.1) should subsurface operate in environments containing liquid water and potentially driving metabolic activity independent from the surface. As a byproduct of radiolysis. kev subsurface electron acceptors such as sulfate have been shown to be liberated from sulfide minerals common in



Figure 7: Divergence of Earth and Mars. It is possible that even ancient life primarily inhabited the Martian subsurface, and that life might still be underground. Image provided by Haley Sapers (Caltech/JPL/USC).

crystalline rocks (see [59], [60]) and provide mechanisms to supply both the requisite electron

donor and electron acceptor to drive subsurface metabolism. Therefore, the potential for extant life in the modern Mars subsurface exists, providing that liquid water and suitable redox gradients exist at those depths.

Moreover, the Martian subsurface could have been the largest and longest-lived habitable environment on Mars, a hypothesis for which the arguments are illustrated in Figure 7: due to a potential significant loss of atmosphere by \sim 3.7 Ga ([61], [62], [19], [7], [63], [64], [65]) the surface was likely largely inhospitable due to ionizing radiation and the instability of surface water by \sim 3.5 Ga. There is evidence of intermittent surface water throughout the first 1.5 Ga of Mars history [66] *but with a more spatially and temporally extensive subsurface presence* (see [3], [10], [67]). The earliest, reliable evidence for life on Earth appears around \sim 3.6 Ga [68]. During this time, there is evidence of widespread surficial terrestrial oceans [69]. The dominant surficial biomass on Earth, however, is arguably due to the evolution of oxygenic photosynthesis at \sim 2.5 Ga. This singular evolutionary event was a consequence of over 2 billion years of evolution on a stable and habitable surface, unlike conditions on Mars. It can be argued that due to the lack of continued habitable conditions on the surface of Mars, a surface biosphere might have never evolved. Rather early chemosynthetic metabolisms independent of organic photosynthate, common on the early Earth, likely dominated in the relative refugia or place of emergence in the subsurface of Mars—supporting the call to finally go deep in the search for signs of life on Mars.

2.1.5.2 Advancement of current knowledge with proposed investigations

We propose a 3-fold strategy for searching for signs of extant life in the Martian subsurface, which is inevitably linked to a detailed analysis of Martian subsurface habitability, and also tightly related to the search for signs of extinct life. We propose to focus on organic (D1) and inorganic (D2) indicators of life, by focusing on the relative abundances of amino acids, lipids, biomolecules, metabolic byproducts, isotopic signatures in multiple organic compounds, and biominerals and microstructures. The change in depth of these biosignatures, especially in relation to variations in mineral hydration states, will help us explore whether we see indications of a deeper biosphere. Adding to the observations as well sampling of trace gases or volatile metabolic byproducts (D3) and studying their variability not just with depth but also in time will provide further constraints for evaluating the likelihood of observing the first evidence of extant subsurface life.

2.1.6 From Local Measurements to Global Predictions

One of the challenges will be to select appropriate landing sites to acquire the first *in situ* data and to explore how local measurements can inform us about global properties. Preliminary insights are: **(I) In relation to liquid water**: The minimum depth to groundwater on Mars is given by the thickness of the cryosphere (e.g., [3]) which is based on a common assumption of a global, interconnected water table. However, the water table may be deeper, shallower or absent, depending on the 3-D architecture of the upper crust. Radar sounding has revealed precious few sites that can be interpreted as a modern (or ancient) water table (e.g., [37] for modern; [70] for ancient). Low latitudes are favored for a thin cryosphere, but mid-latitudes may better preserve ground ice that blocks groundwater evaporation. Groundwater in a globally leveled aquifer would be closest to the surface at the lowest elevations (e.g., [9], [2]), though some outflow channels like Kasei and Athabasca Valles originated at higher elevations. Our ability to select an optimum site for a first landed sounding will also improve with modeling as illustrated in Figure 5: here we show preliminary results for the depth at which liquid water could exist. In equatorial regions, depths of 2-4 km for liquid water are predicted. These calculations in combination with mapping geomorphic features associated with water will factor into the landing site analysis. However,

systematic, rigorous and quantitative characterization of the subsurface, whether liquid water is or is not detected, would allow us to put constraints to the likelihood of subsurface water on modern Mars, similar to InSight's SEIS instrument approach to better constrain seismological models of Mars with both detections and non-detections. In particular, choosing specifically a landing site at the lowest elevation possible would allow us to test the hypothesis whether there is an interconnected groundwater table on Mars or not. Right now, we have no data at all to be able test such a hypothesis, our mission concepts would change this. **(II) In relation to ongoing modern-day water-rock reactions**: the ongoing debate related to methane observations near Gale crater with MSL and Mars Express poses Gale crater itself as an interesting region to explore the subsurface, as methane could be coming from deeper water-rock reactions. Also, the stability depth for liquid water in Gale crater would be ~4 km, which is well within the detection limit for our proposed investigations.

2.1.7 Drill Depth and Science Return Traceability: A Start

An appropriate compromise for a first-generation subsurface explorer between risk management and science return maximization, and also reduced planetary protection issues by not sampling directly potential habitats at km depths, is to drill to at least ~ 10 m and preferably to ~ 100 m. Drilling to 10 m would be, conservatively, sufficient to mitigate surficial temperature variations for subsurface heat flow measurements (~ 5 m), to test different hypotheses on cellular degradation and stability due to oxidizers (e.g., perchlorates) and ionizing radiation as a function of depth, and to be far enough from the oxidizing and radiation-intense surface environment to observe signatures of an isolated deeper subsurface and associated geochemical gradients with depth. A drill depth of ~ 100 m would allow us to measure large-scale redox gradients and changes in porosity that would enable us to formulate and test models of subsurface water (liquid and frozen) and subsurface habitability, thereafter extrapolating measurements down to regions at km-depths where life might still exist.

2.2 Enabling Technologies

2.2.1 Sounding for Subsurface Water

We have discussed in Section 2.1.2.1 the limitation of orbiting radar, such as MARSIS and SHARAD, when searching for liquid water in the Martian subsurface. Here we present alternative techniques, in particular Transient Electromagnetics (TEM), which we conclude to be one of the most appealing methods to search for liquid groundwater. Inductive low-frequency electromagnetic (EM) techniques exploit the much higher electrical conductivity of saline water in comparison to ice and dry rock (several orders of magnitude) by measuring the EM response to an external EM field, if the latter is sufficiently strong. We do not know whether there are sufficiently strong naturally occurring EM signals on the Martian surface. An artificial EM source allows the EM response to be measured without relying on ambient fields. Direct-current based Transient Electromagnetics (TEM) is a classical method that uses a coil on the surface to generate the necessary external EM field. Scaling to groundwater detection on Mars indicates that aquifers as deep as several kilometres or greater can be detected with a small system below 10 kg and several tens of Watts (W) [71]. We favor low-frequency EM methods as the principal approach to detection and characterization of groundwater on Mars because they have high sensitivity to water containing even modest quantities of dissolved salts, yet in the context of Mars they are only weakly sensitive to other geological heterogeneity. We select TEM as the principal method because it does not depend on unknown or incompletely characterized natural sources, and deep sounding at high SNR can be achieved by appropriate experiment design and integration time. We

also find that in comparison to landed ground penetrating radar, seismology, and surface nuclear resonance methods, it is by far the technique that—with modest investments in mass, power, and volume—can sound for liquid water to the largest depths [38].

However, seismometers and GPR can significantly enhance the capabilities of TEM when sounding for liquid water and a combination of all three approaches should be studied in more depth.

TEM measures the ground response to a step-like change in a transmitted waveform, typically using a closed, ungrounded loop. A static magnetic field is maintained while the current is on; at turn-off, the electromotive force generated according to Faraday's law causes secondary currents beneath the transmitter, whose decay causes currents to flow at greater depth. [38] first assessed TEM for Mars groundwater exploration, finding that a transmitter loop 100-m in diameter could characterize an aquifer at depths of kilometers. The model assumed that the dry rocks overlying the aquifer had effectively zero electrical conductivity. [71] developed a TRL 4-5 Mars TEM prototype that featured gas-powered ballistic deployment of a triangular loop. A flight system with total mass <6 kg, deploying a 200 m triangular loop, could detect the top of an aquifer at 3-5 km depth, using the same response model.

2.2.2 Drilling for Accessing Subsurface Samples

2.2.2.1 Drilling 10-100 m: capabilities, resources, TRLs

There are numerous approaches to subsurface access depending on required depth, sample size, sample type (powder vs core), and others. The history of Mars subsurface access has been relatively short. Mars Phoenix Icy Soil Acquisition Device (ISAD) penetrated ~1 cm into Martian ice in 2008. Curiosity drill cut into Mars rocks to a depth of 5 cm. The next Mars mission, Mars 2020, will not drill much deeper, however, instead of capturing of powder for sample analysis (as is done on Curiosity) it will capture core samples for a sample return mission. The ExoMars rover will finally expand this geochemical exploration into a depth of 1-2 meters.

With respect to 10 m class drills, MARTE drill used Oil and Gas drilling approaches and drilled down to an 8 m depth. The Planetary Deep Drill (PDD), utilizing a wireline approach (most frequently used in Antarctica), penetrated to 10.5 m and 13.5 m in gypsum quarry; gypsum having hardness greater than consolidated sediments. Autogopher 2 reached 7.5 m. Both the PDD and Autogopher 2 drilling stopped once the target depth was reached but they could have been used to drill deeper. A modified Autogopher 2 drill and a repackaged Mars 2020 Sherlock instrument have been just tested in Greenland to a 100 m depth in June/July 2019 (WATSON Drill). Figure 8 provides additional details about potential drill systems, see [15] [16] [17] [14] [18] [72] [73].

We can also utilize miniaturized wireline drilling approaches that could enable drilling, from just meters beneath the surface to many hundreds of meters (theoretically to kilometers) depth, without significant changes in payload mass. In this case, *in situ* compressed CO₂ harvested from the atmosphere could power the drill and act as a drilling fluid instead of water. The ASGARD (Ares Subsurface Great Access and Research Drill) concept under study at JPL is targeting a capability to drill down to kilometres within one Martian year using a low-mass (<100 kg) and low-power (on average <100 W) solar-powered system that is consistent with planetary protection protocols in competent rock, such as consolidated sediments that MSL is, and Mars 2020 will be, exploring [25]. This system would return all the cuttings to the surface in approximate stratigraphic order, so that a surface instrument suite could do "triage" on the stream of cuttings. Wireline Drilling approaches are based on old and tested technology on the Earth and are promising tools for exploring depths beyond 100 m in consolidated sediments. RedWater utilizing Coiled Tubing Drilling is currently being developed for penetrating 10s of meters on Mars for the purpose of

water extraction. Both approaches can be used for delivering samples. In some of the drilling approaches such as wireline and Coiled Tubing Drilling (CTD), there is no significant difference in the system design for 10 m or 100 m depths. The risk of something going wrong increases with depth and this needs to be considered for Voyage 2050. However, the system designed for 10 m can drill to 20 m and more through minor modification to the tether length (for wireline) or the boom length (for CTD).

The ExoMars drill plans to drill 1-2 m into the Martian subsurface in 2021 and there is current development in process to be able to extend this capability to much greater depths.

Depth [m]	Drill example	TRL	Testing	Status	Reference
1-5	lcebreaker/ TRIDENT	6	Mars and Lunar TVac Antarctica, Arctic, Atacama, Greenland	Being implemented with PlanetVac pneumatic sample transfer	[62]
10	MARTE	4	Limestone quarry, 8 m	Project completed in 2006	[68]
10-10 ²	RedWater	6	To be tested in Mars TVAC	Project started under BAA	[63]
10 ²	Planetary Deep Drill	4	Gypsum quarry, 10.5 and 13.5 m	Project completed	[65]
10-10 ²	Autogopher2	5	Gypsum quarry, 7.5 m	Project completed	[67]
10-10 ²	WATSON	5	Greenland	To be tested in Greenland	[66]
10 ² -10 ³	SLUSH	4	TVAC in 2021	Project started	[64]
10 ² -10 ³	ASGARD	3-4	Mojave in 2021	Project started in 2018	In prep.

Figure 8: Examples of various drill systems in the 1-100 m regime. We will also use any heritage/lessons from the ExoMars rover drill, planned to be deployed in 2021.

2.2.2.2 Proposed drilling technology and relationship to InSight/HP³

It should be noted that the excavation system needs to be able to penetrate through competent material and rocks. The HP³ mole was designed for penetration through relative loose soil, free of bigger rocks but with sufficient friction. Unfortunately, the system did not penetrate to any significant depth, so far, for various reasons that are currently being investigated. Nevertheless, a mole-like device would not be baselined for any of the missions that requires penetrating through competent formations as we propose here.

2.2.3 In-situ Biogeochemical Analysis: From Habitability to Life

A multi-analytical approach to assessing the spatially correlated mineralogical, chemical, and molecular complexity of putatively habitable environments remains the most promising strategy for biosignature detection. Mass spectrometry, often coupled with gas chromatography, is a proven technique for detection of volatile and refractory organics in planetary environments. Mass spectrometry can be coupled with various front-end sample introduction techniques including lasers for spatially resolved compositional measurements and capillary electrophoresis for water soluble organics. The most recent examples of mass spectrometers designed for flight are the Sample Analysis at Mars (SAM) instrument [74] on the Mars Science Laboratory (MSL) and the Mars Organic Molecule Analyzer Mass Spectrometer (MOMA-MS, [75]) that is flight qualified (TRL 8) as a core contribution to the international MOMA instrument for ESA's 2020 ExoMars

rover. In particular, the MOMA instrument represents one of the most advanced mass spectrometer suites developed for flight to date, and features both laser desorption and pyrolysis front ends, derivatization mass spectrometry, and an ion trap mass spectrometer capable of tandem MS. MOMA already meets the requirement (Figure 4, D1, M11) to detect sub-picomolar amounts of molecular biosignatures such as amino acids and lipids, the distribution of which are strong indicators of biological processes. Mass spectrometry also detects the lower molecular weight volatiles representing products of respiration of extant life (Figure 4, B1, M8; C1, M8). Finally, the SAM quadrupole mass spectrometer has demonstrated stable isotopic measurements of carbon [76], nitrogen [77], and sulfur [78], thus meeting the stable isotope measurement requirement (Figure 4, D1, M12). IR spectroscopy, such as the Tunable Laser Spectroscopy (TLS) on the SAM instrument, is a high TRL, proven technique for measurement for abundance and isotopic composition [79] of trace gases of biological interest (e.g., methane, [80], [81]) that complements mass spectrometry and other compositional analyzers. Electrochemistry is another proven technique for chemical analysis relevant to habitability that has already been implemented on the surface of Mars. The Wet Chemistry Laboratory (WCL) deployed on Phoenix revealed the presence of perchlorates on the Martian surface [49]. This high TRL instrumentation meets the requirement to measure the chemical composition of soils as a function of depth and can detect ions that are potentially important to constrain redox reactions (Figure 4, B1, M8; C1, M8).

Additional instruments may include chemical mapping through X-ray and fluorescence spectrometry such as PIXL, chemical analysis through laser-induced breakdown spectroscopy (LIBS) (ChemCam, SuperCam), organic mapping with Raman spectrometers (SuperCam, SHERLOC) and mineralogy with visible imaging spectrometers. DUV Raman spectroscopy is especially intriguing due to the ability to detect small concentrations of aromatic organics through resonance enhancement. Recent studies suggest that DUV Raman can leverage variations in molecular complexity to differentiate between organic material and the organization of that organic matter within a living system providing a spectroscopic threshold for life detection. Notably, Raman may be paired with LIBS using a single laser, as is done for the SuperCam instrument suite, thereby providing both molecular structural information and chemistry from the same instrument. This pairing of techniques reduces uncertainty in the interpretation of both habitability potential and biosignatures, should they be present.

2.2.4 Technological Challenges and Solutions

A large fraction of the needed technologies has high TRL > 6 or has been already flown to Mars (especially the biogeochemical analysis tools and our baseline landing platform). Critical technology that has not yet been flown or has lower TRL is related to the liquid water sounder and to drilling. As we have shown above, the TRL of drills reaching > 10 m is 5-6, and tests are currently in progress to bring these systems to a TRL of 6 within the next two years. Drilling technologies to reach a depth of 100 m are still at lower TRLs of 4-5. However, the limiting factor to test those drills under relevant Mars conditions so far was limited funding and less technological limitations—deep drilling on the Earth to kilometers depth is common and well established. Liquid water sounders, in particular TEM systems, have been successfully used on the Earth in the last five decades to search for groundwater. The electronics of such systems is well suited for Mars applications. Adaptation to the space environment and Mars is currently in process. The current level of various Mars TEM systems ranges from 4 to 5+ and ongoing efforts plan to bring this TRL to 6 within the next three years. Liquid water sounders for Mars can beneficially profit from Cold

Tech Development for Europa where currently TEM-related systems are being further developed [82].

2.2.5 Baseline Mission Concept for M- to L-Class

We propose a baseline mission concept consisting of (Figure 9):

- A Phoenix/InSight-type lander (or equivalent) with a liquid water sounder: The latter has been used on the Earth for decades to search for liquid water. Such sounders are currently in development for Mars and Europa and can constrain the amount and salinity of liquid water to a depth of at least ~5 km on Mars (see [38]). The water sounder uses a simple wire loop for detection and it has a ballistic loop deployment system, which has been already field-tested (see [71]). Current TRL is 4-5, with ongoing work to reach TRL 5-6 in <2 years.
- A drill allowing us to access samples to a depth of at least ~10 m. We could use Autogopher 2 or the Planetary Deep Drill as our initial model drills due to their high TRLs. We could also explore extensions of the ExoMars Drill, especially as it is planned to be operating on Mars by 2021.
- The drill will also contain a thermal probe to measure the thermal state of the subsurface and thus indirectly constrain the temperature of the water table. Together with measurements of groundwater salinity obtained with the liquid water sounder, estimates on the geotherm will better constrain models of water composition.

Technology	TRL	Rational to Support TRL Claim	Lab Demo Field Demo
Water: Transient Electromagnetic Sounder. Ballistic Loop deployment.	4 now 5+ by 2021	Based on existing technology that has been used for over 40 years. Mars TEM systems are being developed.	Yes. Started.
Heat: Thermal Probe	8	Based on existing technology used on Earth. Simple, robust.	Yes. Yes.
Subsurface Access: Drill (10 m)	5-6	AG2, PDD: Tested to 13.5 m in the field and partially under Mars analogue conditions.	Yes. Yes.
Geobiochemical Analysis: • Trace Gases with isotopologues. • Radiometer for ionizing particles. • UV/Raman Spectrometer • GC-MS • Optical microscope	8-9	All successfully flown on MSL or being prepared for Mars 2020.	Yes. Yes.
Surface Constraints: • Met Station • Camera	9	Successfully flown on Phoenix, MSL	Yes. Yes.

Figure 9: Notional baseline scenario to explore the modern-day Martian subsurface habitability and start seeking signs of extant life.

- Biogeochemical analysis instruments on the surface platform will help us further constrain the subsurface habitability by exploring three aspect of subsurface habitability: the energy derived from redox gradients, the distribution of life sustaining nutrients (CHNOPS), and biomolecule stability by studying how oxidants, radiation, and ionizing particles change with depth. Ultimately, we will extend the habitability-related measurements to search for biosignatures and metabolic byproducts of putative extant subsurface life.
 - The instruments that we intend to use for the baseline scenario is a gas sniffer on the surface (e.g., TLS or alternative on the surface) that can detect at least CH₄, H₂O, SO₂, NH₃ and their associated isotopologues. CH₄ detection sensitivity must be greater than 0.1 ppbv

based on the seasonal variability being measured by MSL to be at ppbv levels. A two channel gas spectrometer (e.g., mini-TLS or alternative with CH₄, and H₂O or SO₂) in the borehole is needed to determine depth variations of released trace gases. Trace gas sniffer operation as a function of time is essential to observe not only depth variability but also changes over time.

- Radiometer for ionizing particles in the borehole to provide constraints on cellular stability.
- UV/Raman Spectrometer, GC-MS, and Optical microscope to measure the overall chemistry, inorganic and organic, as specified in more details in the Notional STM. **MOMA on ExoMars should be a key reference point here.**
- For surface context, we need a camera & MET station (pressure, temperature, wind, radiation).
- The notional duration of the baseline mission should be one Martian year to be able to observe seasonality. An initial target landing site could be at near-equatorial regions due to shallower depths to the water table (see Figure 5). Low altitude landing sites would allow us to test hypotheses related to the interconnectivity of subsurface water.

2.3 Small Scale to L-Class Mission Concepts — Varying the Baseline Scenario

The baseline mission scenario shown in the previous section is a proposed reference point with flexible knobs that can be adjusted to either scale the mission up or down in complexity and cost. In order to scale the baseline mission up towards an L-class mission, we can:

- Go from "just modern-day subsurface habitability" to the search for signs of extant life: This would mainly affect the choice of instruments used for our biogeochemical analysis.
- Extend the Drilling depth from 10 m to 100s m: This would allow us to much better characterize the geochemical flux of nutrients available to putative extant subsurface life today.
- Extend the number of assets and/or add mobility: by increasing the number of landed assets we can better constrain the global inventory of water and the geochemical power to sustain subsurface life. Also, due to a potentially great diversity in subsurface environments, mobility can help to explore this diversity, and narrow down more interesting subsurface exploration targets.

Scaling down the baseline scenario to a smaller scale mission or M-class mission would be possible by narrowing the scientific objectives from A-D to just A, B, or C. For example, we could envision to land only stationary landers that would carry a liquid water sounder to constrain the potential for liquid water. The weight of modern-day Mars liquid water sounders in development is below $\sim 10 \text{ kg}$, and could fit well in a mission below Class M.

2.3.1 Last Words & Conclusion

The motivation for the proposed work comes from a large, diverse, inclusive and international community that believes that the Martian subsurface is the next critical and long-overdue step in planetary exploration. Although there are several reasons for scientific interest in the Martian subsurface, the most important is the search for habitable modern-day subsurface environments and signs of extant life.

The subsurface is widely believed to be the most promising place on Mars where life could still exist today due to its ability to sustain liquid water, shield from harsh oxidizing chemicals and destructive radiation, and enable the redox gradients that fuel life. We believe that the first mission with Mars extant life and subsurface exploration in mind should focus on characterizing the modern subsurface habitability of Mars and our proposal shows that both the technology and the science are ready for the Voyage 2050.

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