Deep Trek: Mission Concepts for Exploring Subsurface Habitability & Life on Mars
A Window into Subsurface Life in the Solar System

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1. Motivation: An Unprecedented Scientific Opportunity

A companion white paper entitled "Deep Trek: Science of Subsurface Habitability & Life on Mars" highlights the immense science return potential of Mars subsurface exploration. Here we focus on mission concepts, driving science objectives, and technologies that enable access to a major new frontier in planetary science, **the Martian subsurface**, with a focus on modern subsurface habitability & life. Different mission architectures spanning **small spacecraft (SSC), Discovery, New Frontiers, to Flagship classes** will generate major discoveries relating to the potential for life in the Martian subsurface.

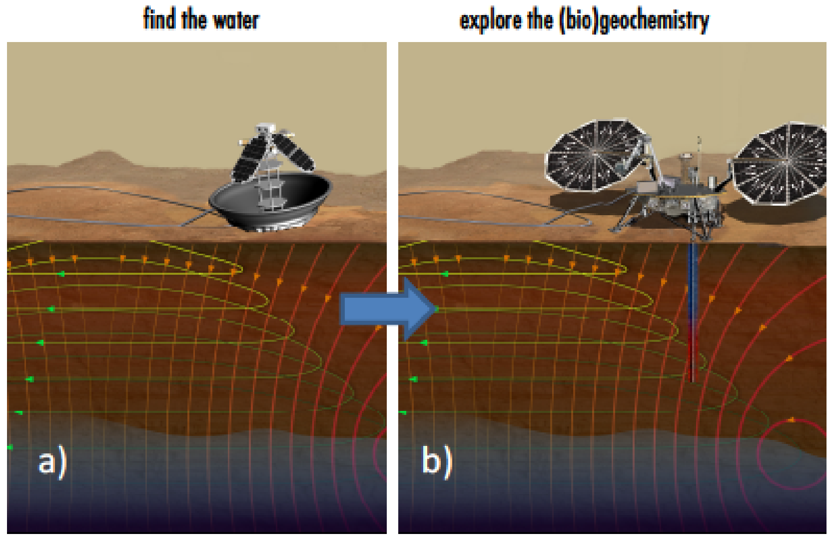

Fig. 1: Exploration of the Martian subsurface with SSCs, New Frontiers & Flagship mission concepts using the VALKYRIE concepts. SSCs with liquid water sounders can detect groundwater to depths of many kilometers (a). New Frontiers-type mission concepts would allow more advanced & complete characterization of subsurface habitability with drills accessing samples to depths of 10-100 m (b).

The architectures shown here belong to a class of mission concepts called VALKYRIE: "Volatiles And Life: KeY Reconnaissance & *In-Situ* Exploration". Building a bridge over four decades from the first daring mission that searched for signs of extant life on Mars with the 1976 *Viking* landers, the VALKYRIE mission concepts re-address the question of whether there could be habitable environments and/or life on Mars today. However, VALKYRIE focuses on the most likely potential modern habitable environment, the Martian subsurface, implementing cutting-edge technologies & leveraging our scientific understanding of Mars and terrestrial subsurface life, all of which have greatly improved since the *Viking* mission era.

2. Science Goals & Objectives

The mission concepts proposed here aim to respond to some or to all of the two science goals specified in our companion paper. These science goals are: (G1) quantify modern Martian subsurface habitability and (G2) search for evidence of extant subsurface life. Our Mission Goal (1), subsurface habitability exploration, has three objectives (**see our Science Traceability Matrix, STM in Fig. 3**): **(A) locate & characterize liquid water, (B) identify energy & nutrient sources, and (C) assess molecular and cellular stability potential with depth**. Whether liquid water exists on Mars today is explored with the first objective. The second objective focuses on the availability of redox nutrients and energy gradients that could drive microbial metabolic activity by determining the (bio)geochemical and mineralogical state of the subsurface. The third objective investigates molecular and cellular stability, by determining how deep ionizing radiation and oxidizing radicals penetrate into the Martian subsurface. This leads to a fourth objective, directly addressing Mission Goal 2, to **(D) search for signs of extant subsurface life** by looking for biomarkers & signs of metabolic activity. Landing sites have been discussed in our companion paper "Deep Trek: Science of Subsurface Habitability & Life on Mars". Our mission concepts are also linked to secondary science goals such as seeking signs of extinct life, reconstructing climate history, geophysical structure of the crust, resource prospecting & human exploration (see Stamenković et al., 2019).

3. Science Traceability & Objectives

3.1. Objective A: Is There Groundwater Today?

Liquid water with sufficiently high water activity is essential for life as we know it. On Mars, following the (liquid) water leads us to depths of many kilometers. The proposed investigations would determine the amount of adsorbed subsurface water as a function of depth, as well as the depth, thickness, and chemistry of the putative groundwater table hypothesized to exist many kilometers below the surface (A1, A2). This may be achieved by using a transient electromagnetic sounder (TEM) **from the surface without any drilling**, which measures the electrical conductivity of the subsurface and inverts those data into profiles of liquid water abundance, hydration and salinity and has been one of the most common techniques to search for groundwater on the Earth in the last three decades. The electrical conductivity will help us to determine the concentration of ions in the groundwater by relating the measured electrical conductivity to potential ionic compositions. Measurements of the subsurface geothermal gradient with depth (A5→M3, M7) will help further constrain the composition of the groundwater through comparison with data for freezing-point depression in the presence of salts. Measuring the porosity change with depth will allow us to extrapolate, beyond the accessible drilling depth, the water storage capacity and the physically habitable space available (A3). **It is important to note that even in the unlikely case of a local non-detection of groundwater, this finding would allow us to put constraints on global water inventories (in combination with measurements of the porosity, the unaltered hydration state and the salt content with depth) and be a significant and surprising discovery by itself.**

3.2. Objective B: Geochemical Gradients with Depth

The proposed investigations would allow us to determine the geochemical (B1) and mineralogical (B2) properties of the Martian subsurface to depths of at least 10 m (threshold) but aiming for 100 m (baseline). Drilling to 10 m would be sufficient to mitigate surficial temperature variations (below ~5 m), to test hypotheses on cellular degradation as a function of depth due to presence of chaotropic oxidants (e.g., perchlorates) and ionizing radiation, and to be conservatively far enough from the highly oxidizing and radiation-intense surface environment to observe physico-chemical conditions more representative of an isolated deeper subsurface. **However, drilling to ~100 m would increase scientific return considerably by permitting measurements of larger-scale redox gradients, which would enable development of new water inventory and subsurface habitability models. This will form the basis for extrapolating measurements and models down to regions at km-depths where groundwater with a higher water activity is more likely (which VALKYRIE would not access physically).** Of particular focus will be the characterization of chemical redox gradients and disequilibria, and specifically the oxidation states of S, Fe, N and Mn compounds in soil (M8) and minerals (M9) as a function of depth, unaltered from hostile surface conditions. The Fe-Mn pair provides especially good constraints on redox conditions and water availability with depth, as Fe and Mn need very different concentrations of oxidants and liquid water to be oxidized. **Exposed scarps on the surface and shallow caves are continuously altered by the atmosphere and do, hence, not provide the insight that deep vertical drilling provides.**

3.3. Objective C: Cellular Stability with Depth

Proposed investigations would test existing hypotheses and models of the abundance of oxidants (C1) and ionizing radiation (C2) as a function of depth. By accessing samples to at least ~10 m, we include the worst-case predictions of the depth where cells could still sustain damage (Dartnell et al., 2007).

3.4. Objective D: Whiffs & Fingerprints of Extant Life

We propose a threefold strategy for searching for signs of extant life in the Martian subsurface. This focuses on organic (D1) and inorganic (D2) indicators of life, by measuring the relative abundances of amino acids, lipids, biomolecules, metabolic byproducts, isotopic signatures in multiple organic and inorganic carbon 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 deep biosphere. Adding sampling of trace gases or volatile metabolic byproducts (D3) and their variability with depth and time will provide further information regarding the likelihood of observing the first evidence of extant subsurface life.

4. Instruments

4.1. Groundwater Sounders: Find the Liquid Subsurface Water Without Drilling

The most plausible method at present for groundwater detection to depths of many kilometers is transient electromagnetic (TEM) sounding from a planet's surface (orbiting assets cannot address the existence of groundwater on Mars at the sounding depths that are needed), which operates at lower frequencies than radar measurements, thereby penetrating far deeper. The Transmissive H_2O Reconnaissance (TH_2OR) TEM instrument under development at JPL has achieved a TRL of 4 with anticipated TRL of 6 by 2023, <10 kg, 3u, <500 Wh/sol). This low-mass instrument is key for a subsurface mission to Mars of any budget class, as it will robustly test for the presence of groundwater and determine the physical and chemical properties of groundwater reservoirs that extant Martian life could inhabit. Penetration depth into the Martian subsurface by the orbiting radar MARSIS on Mars Express and SHARAD on MRO has likely been limited to depths of ~100-200 m, except for "regions with favorable subsurface conditions" with ice or volcanic ash (see Stillman & Grimm, 2011). Ground penetrating surface radar and a seismic station can assist TEM sounders to better constrain groundwater inventories, by determining distinct subsurface layers.

4.2. Drills: Access Subsurface (Bio)Geochemical Gradients

The drill on *Curiosity* has been used to access depths of ~7 cm and the *Perseverance* drill is designed to reach similar depths. Drills reaching 1–10 m in typical Mars subsurface materials (competent & friable rocks) have been demonstrated under simulated or Mars analogue conditions at TRLs of 5-6 and are compatible with New Frontiers-class lander missions (e.g., *ExoMars* Drill, *Icebreaker*, MARTE, Planetary Deep Drill [PDD]). The PDD wireline drill (at TRL 5 and 70 kg) from Honeybee Robotics has drilled 13.5 m into gypsum (*drilling could have progressed deeper but was halted due to limited funding*).

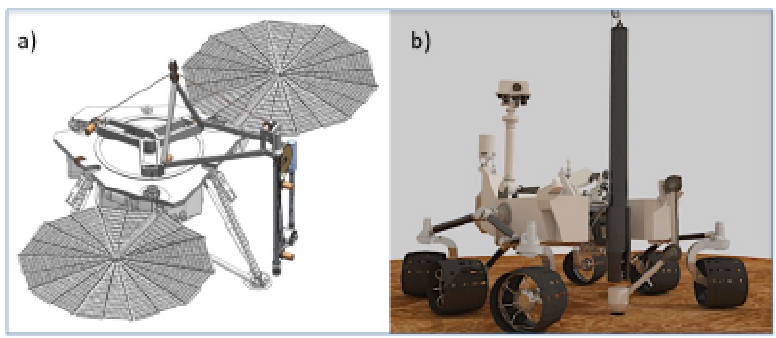

Fig. 2: (a) Wireline drill ASGARD. Drilling is feasible to 100 m with New Frontiers cap on InSight-like platform. (b) Mobile PDD.

To get to depths of ~100 m and more, while still remaining compatible with a New Frontiers class lander mission, wireline drilling approaches are appealing. PDD, for example, was tested successfully in 2019 to a depth of 111 m in ice (Eshelmann et al., 2019; Bhartia et al., 2019), which has a similar hardness to rocks in Gale crater. JPL's Ares Subsurface Great Access & Research Drill (ASGARD, Fig. 2a, TRL 5 targeted in 2020) is another miniaturized wireline drill with a target mass below 50 kg, using on average less than 100 W of solar power and compressed CO_2 harvested *in situ* from the Martian atmosphere as drilling fluid. For both wireline drills, cuttings would be delivered in stratigraphic order with a resolution capability of ~centimeters. Using in-borehole instruments (as for an *enhanced* mission scenario) can increase this stratigraphic resolution to mm (this has been demonstrated by PDD in Greenland). **The advantage of wireline drills is that drilling can proceed to depths much greater than ~100 m without any significant increase in instrument mass—**

providing the opportunity to go beyond 100 m in an extended mission mode (the only cost to go deeper is the mass of the tether, which is <1 kg/km of tether, and the time for drilling). **One challenge of wireline systems** is that drilling must occur in geologically competent material to prevent borehole collapse. **Fortunately, (*i*) such materials (including volcanic and sedimentary lithologies) are common and widespread on Mars, (*ii*) they are well-suited targets for astrobiological subsurface science, and (*iii*) borehole stability is generally not an issue in such rocks.** For example, the 13.5 m borehole drilled by PDD in a gypsum quarry in 2015 is still open. Boreholes in petroleum/natural gas injection and production wells, and those from exploration drilling in the mining sector, often remain open for decades. On Mars, due to the lower gravity and the lower seismic stresses, boreholes should remain stable to depths of hundreds of meters (Zacny & Bar-Cohen, 2009). Lastly, all the 100+ m drills discussed here, including coiled tubing drills like RedWater that can drill in any kind of soil, are compatible with *Curiosity*-class rovers that would be Flagship class missions (Fig. 2b for PDD). ***Note:*** *InSight's HP^3 mole (Spohn et al., 2018) was designed for penetration through loose soil. A mole is not baselined for any of the missions proposed here.*

4.3. Bio-geochemical/Radiation Analysis Suite

A multi-analytical approach to assessing the spatially correlated mineralogical, chemical, and molecular complexity of a prospective habitable environment 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 (Mahaffy et al., 2012) on *Curiosity* and the Mars Organic Molecule Analyzer Mass Spectrometer (MOMA-MS, Brinckerhoff et al., 2013), which is flight qualified (TRL 8). Mass spectrometry also detects the lower molecular weight volatiles representing products of respiration of extant life such as CH_4, CO_2, N_2, H_2, O_2 and non-methane hydrocarbons (Fig. 3, B1, M8; C1, M8). The SAM quadrupole mass spectrometer has demonstrated stable isotopic measurements of carbon (Mahaffy et al., 2013), nitrogen (Wong et al., 2013), and sulfur (Franz et al., 2017), thus meeting the stable isotopes measurement requirement (Fig. 3, D1, M12). IR spectroscopy, such as the Tunable Laser Spectroscopy (TLS) on the SAM instrument, is a high TRL, proven technique for measuring the abundance and isotopic composition of trace gases of biological interest (e.g., Webster et al., 2018) that complements mass spectrometry and other compositional analyzers. Additional instruments may include the Wet Chemistry Laboratory (WCL) deployed on *Phoenix* for redox chemistry identification, 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 (SHERLOC) and mineralogy with imaging spectrometers. Deep UV Raman spectroscopy is especially intriguing due to its ability to detect small concentrations of aromatic organics. An on-board radiometer/ high-energy particle tracker would allow for characterization of ionizing radiation levels with depth.

5. Mission Concept Architectures

Because the (bio)geochemistry of the subsurface of Mars has never been explored in detail, the aforementioned instruments can be mixed-and-matched depending on the level of funding available for a given mission. All budget classes have the capacity for significant discovery and advancement of knowledge regarding subsurface habitable environments on Mars and the possibility of extant subsurface life. **The information below on mission cost is an outcome of an architecture Team X study at JPL and work by our internal JPL SSC Team performed in 2018-2020 (Barba et al., 2020).**

5.1. SSCs: Find the Groundwater

We can assess the presence of groundwater from the Martian surface at low cost in this decade. As described in the Decadal Whitepaper by Barba et al. (2020), small spacecraft are an especially important opportunity for Mars subsurface science. We have found that, using fully hosted piggyback opportunities, such as with *Mars Sample Return* or *Ice Mapper* planned for 2026, we can answer some of the leading objectives (groundwater detection & characterization [A1-A2] as well as trace gas localization [D3]) at an A-D cost of ~$120 M total. To achieve such goals, as a priority, this mission would deliver a TEM liquid water sounder to the Martian surface with a rough lander such as SHIELD (see Barba et al. 2020) or the similar TRL 6 Finnish Lander. If launched as a secondary, or primary payload on a dedicated launch vehicle such as Falcon 9, independently making its way to Mars, then A-D costs for one small lander mission would be ~$150-200 M without launch (plus up to ~$60 M for launch costs, e.g., with Falcon 9). If three SHIELD landers, carrying the payload mentioned above, would be merged on a Falcon 9 under Class D requirements, then the costs for A-D would mount to ~$300 M + launch costs. **This multi-unit option improves our ability to extrapolate local results to global water inventories and facilitates a price/unit drop by ~$50-100 M—which could open up doors for sharing with international and commercial partners.**

5.2. Discovery Class: Multiple SSCs Rough Landers or One *InSight*-type Lander

The latter 3-unit rough lander concept, for example, carrying a groundwater sounder like TH_2OR, would fit as well under the Discovery cap even if system assurance is increased to a Class B mission. One single heritage-based *InSight*-type lander could also deliver one groundwater sounder within the Discovery budget. The *InSight*-type concept leverages a high heritage and low risk landing system, while the SSC rough lander concept has the advantage of delivering the same instrument at three different locations for a similar price as one single *InSight* lander, probing the unexplored subsurface in different geologic contexts and enhancing the science return by providing a more global perspective on groundwater distribution.

5.3. New Frontiers Class: Physical Access to the Subsurface is Feasible

TEM sounding from the surface for groundwater is a critical objective for the VALKYRIE mission concepts but the science return is significantly enhanced once a drill is added to sample subsurface redox gradients, going beyond objectives A1 and A2. We consider a basic instrument suite such as one TEM, two ICC surface context cameras, a MOMA GC-MS, a TLS, a MET Station, a High Energy Particle Tracker and a heat probe connected to the drill. To minimize planetary protection protocols and total mass, we assume that all baseline instruments will be on the surface as part of an analysis suite, with samples being delivered as they are being drilled. **We find that by using an *InSight*-type platform, we can address all the science goals of VALKYRIE, within a New Frontiers-type budget.** However, it is crucial that the drill remains below 50 kg. This is feasible for a 10 m Honeybee coil tubing drill like RedWater, which could operate in any kind of ground. This mass limit is also in reach for a 100 m wireline drill like JPL's ASGARD with near-term investments (Fig. 2a).

5.4. Flagships: Vertical Exploration with Mobility

Mobility offers the advantage of multiple drill sites but moves the cost into the Flagship Class domain. The class of drills proposed here (10 m and 100 m) is compatible with *Curiosity/Perseverance*-type rovers (see Fig. 2b for a 100 m PDD drill system). The complete *enhanced* VALKYRIE sample analysis payload, as described in Fig. 3, is in many ways similar to the payload on *Curiosity/Perseverance*. In comparison to our New Frontiers-type baseline scenario, our Flagship baseline payload includes additionally a Deep UV Raman instrument (SHERLOC) and the ICC camera is replaced with ChemCam/SuperCam. In an *enhanced* mission scenario, an additional TLS can be added as a down-borehole device to provide better constraints on subsurface trace gases gradients. Additional instruments as shown in Fig. 3 can be included for an *enhanced* mission scenario.

SCIENCE TRACEABILITY MATRIX

GOALS INFUSION

	NASA Strategic Plan 2018 Goals	Visions & Voyages (2013-2022) Goals	National Academy of Sciences Committee on the Search for Life in the Universe Goals	MEPAG Goals
NASA Goals	➢Strategic Goal 1, Objective 1.1: ➢Searching for life elsewhere. ➢"Are we alone?"	➢Understand the potential for life elsewhere. ➢Determine if life ever arose on Mars. ➢Does life exist, or did it exist, elsewhere in the universe?	➢"Go Deep" as a priority for the search for life in the universe.	➢Addresses ALL Revised MEPAG Life 1 Goals (Life) A and B [A1, A2, A3, B1, B2]. Goal 2. A2.2.
Mission Goal	Goal 1 (Modern-day Subsurface Habitability): Quantify the modern-day habitability of the Martian subsurface with a focus on water, energy, and nutrients and their change with depth. Goal 2 (Towards Extant Subsurface Life): Quantify any biosignatures in the subsurface and how they change with depth as well as trace gases, their change with depth and time.			

Goal	Objectives	Investigations	Measurement Requirements	Instrument Classes	Model Instruments
Goal 1	A. Habitability I Evaluate at the landing site the existence of liquid groundwater on modern-day Mars and characterize it.	A1. Determine the existence of local liquid groundwater and characterize its size.	M1. 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) like TH_2OR • Alternatives: Ground Penetrating Radar, High-frequency Seismometer (*higher mass for same scientific capability*)
		A2. Provide constraints on the composition of local liquid groundwater.	M2. Measure the electric conductivity of groundwater with a sensitivity of 0.01 S/m.	Electrical Conductivity Sounder	Transient Electromagnetic Sounder (TEM)
			M3. Measure the geothermal gradient of the surrounding rock as a function of depth with a sensitivity of at least 0.01 K/m.	Heat Flow & Thermal Conductivity Sensor	Sensor on HP³ /*InSight* (without the mole)
		A3. Estimate the water storage capacity of the local subsurface.	M4. Measure the porosity change with depth each meter capable to detect a 0.3% change in porosity.	Porosity Sensor	• Micro In Situ Tomography • Optical Microscope (e.g., WATSON on *Curiosity* or equivalent).
		A4. Determine the local geologic layering structure as context to subsurface habitability.	M5. Measure changes in dielectric permittivity of the subsurface with a resolution of 1 m down to 100 m at a median frequency 1-5 MHz.	Ground Penetrating Radar	Ground-based radar (heritage from RIMFAX/WISDOM)
			M6. Map the geologic surface context.	Surface Context Imager	• ICC from *InSight* for the SmallSat and Discovery-class options • For New Frontiers/Flagship classes, ChemCam from *Curiosity* or SuperCam from *Perseverance*
		A5. Determine the local thermal state of the subsurface.	(M3). Measure the geothermal gradient of the surrounding rock as a function of depth with a sensitivity of at least 0.01 K/m.	Heat Flow & Thermal Conductivity Sensor	Sensor on HP³ /*InSight* (without the mole)
			M7. Measure the temperature of the drill as a function of depth with a sensitivity of at least 0.01 K (only useful for 100 m Drill).	Thermal sensor	Thermal Needle (complementary to M3 but only useful if drill depth ~100 m; otherwise sensitivity is too low)
	B. Habitability II Determine the chemical & mineralogical state of the subsurface and its change with depth at the landing site.	B1. Relate the chemical composition of the subsurface with depth to energy & nutrients.	M8. Measure the chemical composition of soil with depth—in particular focusing on the abundance of CHNOPS and redox partners (e.g., the amounts of reductants and oxidants with depth, and S, Fe, N, Mn oxidation states) and also radionuclide concentrations.	Vibrational Spectrometer	• UV/Fluorescence Raman Spectrometer (can be paired with LIBS) • 4-channel Tunable Laser Spectrometer (TLS or equivalent) • Wet Chemistry Laboratory can be added (*Phoenix*) • Neutron spectrometer for radionuclides (miniaturized versions of TRL 9 hardware exist)
		B2. Determine how the redox state and hydration of minerals changes with depth.	M9. Measure the minerology with depth with a particular focus on fugacity, Fe^{2+}/Fe^{3+}, Sulfide/Sulfate, N, Mn oxidation states and hydration.	Mineralogical analysis tool box.	WATSON on *Perseverance* or equivalent
	C. Habitability III Determine how ionizing radiation changes with depth.	C1. Determine the amounts of oxidants with depth.	(M8). Measure the chemical composition of soil with depth— in particular the abundance of oxidants such H_2O_2, ClO_4, and ClO_3.	Vibrational Spectrometer	• UV/Fluorescence Raman Spectrometer (e.g., SHERLOC on *Perseverance* or equivalent) • Wet Chemistry Laboratory also possible as extension (*Phoenix*)
		C2. Determine the amount of ionizing radiation and its change with depth.	M10. Measure the dosage of ionizing radiation with depth (alpha, beta, neutron particles, free ions, and gamma and X-rays).	Radiometer. Neutron spectrometer.	Radiometer/High energy particle tracker (e.g., RAD, as on *Curiosity* or equivalent)
Goal 2	D. Towards Extant Life Determine the existence of biosignatures and their change with depth at the landing site as well as changes in trace gases with depth and in time.	D1. Characterize the presence of organic indicators of life and metabolic activity as a function of depth.	M11. 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.	• Organic Compositional Analyzer • Vibrational Spectrometer	• Gas Chromatograph Mass Spectrometer with chirality and stable isotope analyzers (e.g., QMS and GC from SAM on *Curiosity*, MOMA on *ExoMars* or equivalent) • UV/Fluorescence Raman Spectrometer (e.g., SHERLOC on *Perseverance* or equivalent)
			M12. Measure the stable isotope composition of multiple compounds of organic and inorganic carbon ($^{13}C/^{12}C$) for concentrations as low as 1 picomole in a 1 g sample of soil with a relative standard deviation <5‰.		
		D2. Detect and characterize inorganic indicators and microstructures of life changing with depth.	M13. 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. • Compositional Analyzer	• Optical Microscope (e.g., WATSON on *Perseverance*) • UV/Fluorescence Raman Spectrometer (e.g., SHERLOC on *Perseverance*) • Gas Chromatograph Mass Spectrometer with chirality and stable isotope analyzers e.g., QMS and GC from SAM on *Curiosity*, MOMA on *ExoMars* or equivalent)
			(M12). Measure the stable isotope composition of multiple compounds of organic and inorganic carbon ($^{13}C/^{12}C$) for concentrations as low as 1 picomole in a 1 g sample of soil with a relative standard deviation <5‰.		
		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. Measurements during day & night for CH_4 @ 3.27 µm, CO_2 and H_2O @ 2.78 µm, O_2 @ 0.76 µm or triple S isotopes in SO_2 @ 7.42 µm and NH_3 @ 9.92 µm with a spectral resolution of 10 Å (incl. isotopes).	IR spectrometer	• 4-channel Tunable Laser Spectrometer (e.g., TLS or equivalent), Spatial Heterodyne Spectrometer on surface • Add-on for extended mission scenario: 2-channel Tunable Laser Spectrometer in borehole (e.g., mini-TLS or equivalent)
			M15. 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 *Curiosity* type MET stations. REMS or equivalent. Not a priority, can be downscaled

Fig. 3: Science Traceability Matrix (STM). Identical measurements are needed for a few objectives; if so, they are shown in brackets, e.g., (M3, M8 & M12) for A5, C1 & D2. <u>The red boxes indicate investigations that can be addressed without drilling</u> with SSCs (groundwater characterization with sounders and trace gas localization). All other investigations require drilling of 10-100 m (100 m being the baseline target).

6. Planetary Protection

Planetary protection would follow the relevant NASA policies, keeping in mind the *Viking* mission guidelines but with additional requirements to remove left-over organics such as amino acids, nucleobases, and carboxylic acids to minimize the total exogenous organic carbon load. By limiting the use of in-borehole instruments (as in our baseline scenario), only the drill, the sample delivery system, and the CO_2 pumping system (for wirelines) would need to be sterilized. This is feasible because the components are steel/titanium based with no electronics. Dry Heat Microbial Reduction or various types of gas sterilization can also be used to sterilize non steel/titanium components.

7. Synergy with Commercial & Human Exploration

Access to water in the form of hydrated salts, ice or potentially groundwater is key for enabling human exploration and settlement of Mars. The same technologies employed by science-oriented Mars subsurface exploration missions will also enable characterization and utilization of these key water-bearing resources required by future human Mars explorers. Mars subsurface science therefore hosts unique potential for collaboration between SMD and HEOMD, as well as collaboration with international & commercial partners who are interested in enabling human settlement of Mars.

8. Conclusions

Decades of Mars exploration by orbital and landed spacecraft, coupled with knowledge of Deep Life on the Earth, suggest that the subsurface of Mars may still host a long-lived habitable environment that could contain extant life. Exploring this potentially habitable subsurface environment, and searching for extant life there, is the natural progression of the last 2-3 decades that have been focused on ancient life, and is opening up a new exploration pathway that is complementary to MSR and the *Perseverance* rover's science goals. **SSC options for characterizing groundwater and New Frontiers-type missions with drills to determine subsurface (bio)geochemistry are feasible.** Mars is the natural testbed for subsurface exploration that will inevitably be applied to other, technologically more ambitious, targets such as the subsurfaces of icy moons or small bodies. **The proposed mission concepts are not only relevant to NASA's overarching & driving scientific goals, but tap into the primary reason the public finds planetary exploration exciting: the possibility of extant life on other worlds.**

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