Deep Trek: Science of Subsurface Habitability & Life on Mars
A Window into Subsurface Life in the Solar System

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1. Motivation: Mars Subsurface, an Unprecedented Opportunity to Explore Life

One of the main drivers for planetary exploration has been the search for signs of life beyond our planet. Mars, in particular, has been a target for orbital and landed planetary missions, **but to date these missions have focused primarily on the search for signatures of extinct, ancient life preserved on the Martian surface**.

One of the biggest lessons from forty years of Mars exploration is that **the Martian surface is currently inhospitable to life as we know it**, and may have been uninhabitable since ~3.1-4 Ga. Organics on the surface are being degraded by oxidizing radicals and bombarded by harsh radiation to a yet-to-be-determined depth (e.g., Eigenbrode et al., 2018). Liquid water is not stable on the Martian surface. Observations by *Phoenix* have shown that, for short timescales, small amounts of metastable salty brines can form on the surface and in the shallow subsurface. However, recent experimental work shows that such transient brines do not satisfy habitability criteria (Rivera-Valentin et al., 2020). **Our understanding of subsurface thermal gradients suggests that liquid water is stable for long timescales at depths of kilometers**. Locally, shallower liquid reservoirs are possible if salts are present in high concentrations but with much lower water activity (Clifford et al., 2010).

In the subsurface—protected against these effects—liquid water is feasible, with water activity and temperatures at habitable values, negligible ionizing radiation levels, and water-rock and gas-rock reactions fueling subsurface Martian life. **Such deep environments on Mars are likely similar to those found in Earth's subsurface where the majority of microbial terrestrial biomass resides. Hence on Mars, subsurface organisms similar to the ones found in the Earth's subsurface can exist.** This is in contrast to surface or near-surface Mars environments—including ices, hypersaline brines, caves, or salts—where any hypothetical extant Mars microbes would require, in relation to life as we know it, as yet unknown adaptations to their cellular physiologies in order to survive.

The Martian subsurface is one of the most promising places on Mars for life to still exist today. Despite this, we have yet to send a dedicated mission to investigate the modern-day subsurface habitability of Mars or to search for signs of extant subsurface life. A spectacular scientific opportunity awaits!

2. Science Goals & Objectives

Tightly linked to MEPAG Goal I (see Section 3), we can define two science goals: **(G1) quantify the changes in modern-day subsurface habitability as a function of depth** by assessing: (A) *Liquid water*: existence & composition of liquid water in the subsurface, (B) *Energy & nutrients*: subsurface geochemistry, lithochemistry (including isotopes and trace elements), organic chemistry, variability of redox species as a function of depth, redox disequilibria, and sources of potential life-sustaining redox compounds (including their size, depth locations, and underlying production processes), and (C) Potential for *Cellular Stability*: the stability of biomolecules as a function of depth. **(G2) search additionally for signs of extant subsurface life** by determining (D) Biomarkers/biosignatures of *metabolic activity* and their changes with depth. **Mission strategies that respond to these science goals are discussed in our companion paper "Deep Trek: Mission Concepts for Exploring Subsurface Habitability & Life on Mars".** These science goals are also linked to seeking signs of extinct ancient life, reconstructing climate history, the geophysical structure of the crust & human exploration (Goals I-IV in MEPAG), but these are not discussed here (see Stamenković et al., 2019).

3. Community Efforts

Recently, the National Academies Committee on the Search for Life in the Universe (NAS, 2019) recommended to "**go deep**" and to focus on subsurface habitability and subsurface life, with Mars as a prominent target. This is also reflected in the recently revised MEPAG Goals Document, where a new emphasis has been given to "*Extant Life*", "*Subsurface*" and "*Subsurface Waters*". As stated on page 10 of the new MEPAG document *"if Mars ever supported life, an earlier Martian biosphere might have found* *refuge in the subsurface, where liquid water aquifers and rock-water reactions could provide all the needed bioessential resources, similar to the deep subsurface biosphere on Earth. …For these reasons, the subsurface should be considered an exciting new frontier for Mars exploration, and a particularly promising target environment to address the objectives presented in Goal I (Life).*

4. Why Now?

4.1. Various Mars Data Point to a Potentially Habitable Subsurface

Intriguing data suggest active processes related to habitable environments in the Martian subsurface today. Short-lived spikes in atmospheric methane observed at a similar time both with *Mars Express* and *Curiosity,* a non-detection with *TGO,* as well as seasonal background level changes (Webster et al., 2018, Giuranna et al., 2019; Korablev et al., 2019) are compatible with subsurface release and fast surface destruction. There is also potential evidence for liquid water beneath the South Pole at 1.5 km depth (Orosei et al. 2018), from Mars Express radar data, though the interpretation is controversial. **However, no past (or current) Mars mission had (or has) the capability to quantify the potential of the Martian deep subsurface to host life today.**

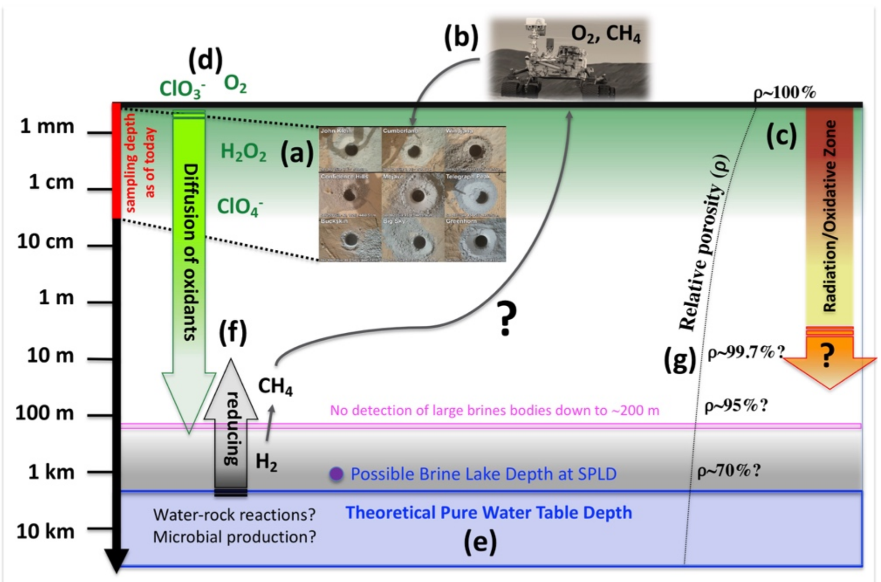

Fig. 1: Deep Science *(a) Redox state transition in the upper few cm as shown by Curiosity drill samples, indicating diverse subsurface properties under similar surface conditions. Current sampling depth is ~7 cm. (b) Fluctuations in atmospheric methane and oxygen levels are most likely due to processes taking place in the subsurface. (c) Penetration depth of oxidants and radiation vary up to 7.5 m. (d) Oxidants in near-surface environments, possibly linked to CH_4 destruction. (e) Depth of "pure" water table is in the km to 10s of kms range. Brines can be shallower locally but then have a low water activity. (f) Water-rock reactions produce H_2 (e.g., radiolysis, serpentinization, oxidation of ferrous silicates) that can be transformed into CH_4 with Sabatier reactions. (g) Porosity & permeability decrease with depth; they help quantify the potential for deeper groundwater. Pink denotes the depth of ~200 m above which large-scale brines seem uncommon based on orbital radar.*

4.2. An Unexplored World: The Mars Underground is a Mars 2.0

We have currently *sampled* the Martian subsurface *in situ* to no deeper than a few cms (the *InSight* mole will hopefully reach greater depths, but without any (bio)geochemical *sampling*). Orbital radar has not been capable of sounding deeper than ~200 m except for special regions (see Section 6.1)—and therefore has not been able to probe the common depths of groundwater at many kilometers. Gamma Ray Spectrometers can probe ≤~1 m depth. This makes the subsurface of Mars an as-yet unexplored world, which might be significantly different and more habitable than the surficial Mars explored so far. Indeed, the difference between surface and subsurface is already evident in the drill cores from *Curiosity,* which show subsurface colors distinct from a homogeneous oxidized, red surface—indicating significant transitions in redox state and mineralogy with depth (see *Fig. 1*). **What is hiding even deeper beneath the wheels of our rovers?**

4.3. Natural Next Step in the Mars Program

Mars exploration in the last two decades and currently planned missions, including *Perseverance*, the *ExoMars* rover and *Mars Sample Return (MSR)*, have been and will be focused on seeking signs of ancient and extinct habitable environments and life in previously aqueous surface environments. The *ExoMars* rover plans to drill in 2023 to a depth of 1-2 m and probe composition in rather loose and altered soil and sound to ~1 m depth via neutron spectroscopy. Expansion of such exploration, as proposed here, incorporating the study of subsurface modern habitability & extant life is a critical extension of Mars Exploration and complementary to *MSR*, *Perseverance* & the currently studied *Ice Mapper* mission concept. The scientific goals presented here also benefit the growing "Artemis" Program in preparation for human exploration, as subsurface habitability questions are closely related to subsurface *in situ* resource utilization.

4.4. Technology is Ready

Citing Jakosky et al. (2003), "*The Martian subsurface today is generally thought to meet the environmental requirements necessary to support life. Liquid water likely is the limiting factor and can occur at depths of hundreds of meters to kilometers, where temperatures are warmer than at the surface. Geochemical energy is available there through reactions of the water with the surrounding rock or by mixing in hydrothermal systems, and terrestrial organisms, at least, are able to take advantage of these sources of energy to support metabolism.* ***While the deep subsurface is, therefore, a likely place to find life, it is difficult to access for exploration.***"

As we show in our companion paper "Deep Trek: Mission Concepts for Exploring Subsurface Habitability & Life on Mars", enabling technology has advanced rapidly during the last 17 years since the statement above was made—enabling us to now explore the science discussed in this paper with low-cost Small Spacecraft or New Frontiers class missions. **This makes Mars subsurface exploration with a focus on modern subsurface habitability & life not just feasible, but timely.** The mission concepts described in our companion paper have been vetted through JPL's Team X.

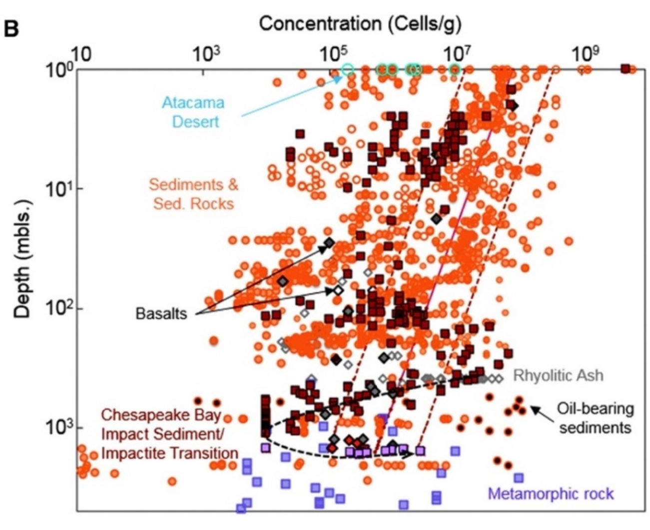

Fig. 2: *Biomass in Earth's subsurface. Plot of cell concentration vs depth for rock & soil cores from nonpolar regions. See Onstott et al. (2019) (mbls = meters below land surface).*

5. Life in Deep Earth: An Analogue for Mars

Decades of study of Earth's deep subsurface in mines and boreholes provide a crucial framework for exploring the potential for Mars' subsurface life. Microbial communities have been characterized down to 4.4 km in Earth's continental crust (Purkamo et al., 2020) and to a depth of 2.5 km in seafloor sediments (Inagaki et al., 2015). Terrestrial life most certainly exists at even greater depths that have not yet been explored. Microbial communities are ubiquitous in Earth's subsurface where the following conditions are met: 1) liquid water with sufficient water activity; 2) temperatures between -20 ºC (Clarke et al., 2013) and 122 ºC (Takai et al., 2008); 3) redox energy and CHNOPS availability; 4) protection from high levels of radiation. Earth's subsurface is estimated to contain ~10^{30} cells, **comparable to ~10-60% of the total biomass of the surface biosphere and exceeding the microbial biomass of the surface biosphere** (Magnabosco et al., 2018; Bar-On et al., 2018; Onstott et al., 2019). On Earth, most of this subsurface biomass is independent of surface photosynthetic CO_2 fixation. Rather, energy is obtained from water-rock reactions (e.g., radiolysis, serpentinization), abiotic organic synthesis, reduced forms of Fe, N, and Mn from minerals, sulfides and sulfates, and magmatic or atmospheric gases such as CO_2, CO, and H_2S (see Lefticariu et al., 2010, Li et al., 2016, Onstott et al., 2019, Schrenk et al., 2013, Stevens & McKinley, 2000). **As we show in Section 6.2, these ingredients exist in the Martian subsurface in sufficiently large concentrations to sustain microbial subsurface life.**

For example, radiolysis in ancient terrestrial fluids generates a closed system of redox energy availability, producing both complementary oxidants (sulfate) (Lefticariu et al., 2010; Li et al., 2016; Onstott et al., 2006) and reductants (H_2) (Lin et al., 2006, 2005) wherever H_2O, radionuclides, and even minor amounts of sulfides intersect. In such deep ecosystems, there is no need for any additional nutrient input from younger fluids. **Such groundwaters, which are inhabited by microorganisms, have resided in the continental crust for billions of years with negligible surface nutrient input (Holland et al., 2013), similar to groundwater residence times expected on Mars.**

6. Biologically Sustaining Conditions & Processes in Mars' Subsurface

Below, we discuss our current state of knowledge supporting why we think that the modern-day Mars subsurface is a potential habitable environment.

6.1. Liquid Water at Depth

We know that liquid water is generally not thermodynamically stable on the Martian surface today due to low temperatures and low atmospheric pressures. With depth, the temperature increases along a local geothermal gradient, dependent on local values of heat flow and thermal conductivity. Therefore, at a certain depth and pressure, the local temperature will be warm enough for ice to melt. Clifford et al. (2010) calculated the cryosphere thickness—below which saturated groundwater should exist—using average heat flow estimates of 15 and 30 mW/m^2. Recent models that consider both temporal and the full 3D spatial variations in heat flow and crustal thickness suggest an average heat flow of 25±2 mW/m^2 (Plesa et al., 2016). **Such values indicate an approximate depth to the groundwater table of ~2-7 km in equatorial regions and 11-20 km at the poles** (Fig. 3)**.**

Grimm et al. (2017) considered the importance of subsurface tropical ice in slowing the loss of groundwater on Mars. They concluded that H_2O loss since the Hesperian of a ~60 m global equivalent layer (GEL) of H_2O (from the D/H ratio) is much less than the likely original groundwater inventory of several hundred meters to a kilometer (Carr, 1987 and others)—supporting the existence of groundwater globally on Mars today.

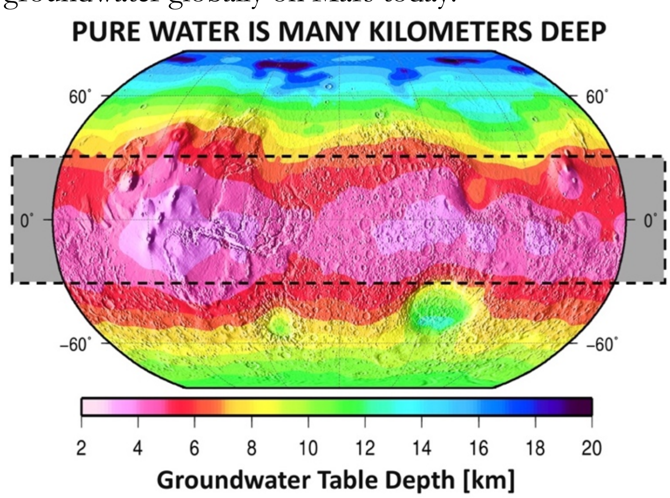

Fig. 3: *Depth to the groundwater table (based on simulated heat flow data from Plesa et al., 2018), depending on surface temperature and on local heat flux. For simplicity, we assume only a latitude-dependent surface temperature model and did not include any salts, which shift the water table, locally, to shallower depths. We highlight typical landing regions within ± 30° latitude; here potential depths to pure liquid water are ~2-7 kilometers. Large potential depths of groundwater beyond ± 60° (due to low surface temperatures and low geothermal gradients) demonstrate that the polar regions are not ideal for liquid groundwater exploration.*

Penetration depth in the Martian subsurface by the orbiting radar instruments MARSIS on Mars Express (Jordan et al., 2009) and SHARAD on MRO (Seu et al., 2007) has been limited to depths of ~100-200 m, except for "regions with favorable subsurface conditions" containing ice or volcanic ash (e.g., Heggy et al., 2006; Stillman & Grimm, 2011). The poles have these favorable subsurface conditions, but due to low surface temperatures groundwater is expected to be especially deep (Fig. 3). Nonetheless, MARSIS data were used to establish the hypothesis of the presence of perchlorate-bearing liquid water, 20 km wide, at a depth of 1.5 km close to the South Pole (Orosei et al., 2018).

6.2. Energy & Nutrients for Subsurface Life

Essential elements needed for subsurface life exist on Mars: besides water, the essential ingredients needed to sustain a wide diversity of microbial metabolisms in the Martian subsurface (see Section 5) exist based on *in situ* measurements and laboratory analysis of Martian meteorites (Stern et al., 2015; Eigenbrode et al, 2018; Trainer et al., 2019; Lanza et al., 2016, Webster et al., 2018; Boynton et al., 2007; Gellert et al. 2004; Ehlmann & Edwards, 2014; Lorand et al., 2005; etc.). This includes measurements on radionuclides, oxidized and reduced forms of iron, nitrogen and manganese present at Gale crater, perchlorates, fixed nitrogen, organics, sulfates, sulfides, and methane.

There is enough power to sustain subsurface life: The redox energy available in the Martian subsurface is sufficient for multiple microbial metabolisms to proceed (Link et al., 2005; Onstott et al., 2006; Carrier et al., 2020; Jones et al., 2018; Dzaugis et al., 2018; Tarnas et al., 2018) . **The source regions for Martian meteorites can produce sufficient sulfate and H_2 via radiolysis to support measurable concentrations of sulfate-reducing microorganisms wherever groundwater exists** (Tarnas et al., 2020). In addition to sulfate-reducing microbes, metabolisms that utilize other redox compounds detected on Mars, including Fe^{2+}, nitrate, CO_2, O_2, Fe^{3+}, CH_4 and CO (Lorand et al. 2005; Ehlmann & Edwards 2014; Stern et al. 2015; Lanza et al. 2016; Webster et al. 2018; Trainer et al. 2019), are fully sufficient to support diverse and high-biomass microbial communities in the subsurface. **This makes the subsurface the most redox nutrient diverse, longest lived, and continuously habitable environment on Mars.**

6.3. Shielding from Radiation & Oxidants at Depth

Oxidative and ionizing radiation conditions on the surface of Mars play a role in the degradation of macromolecular organic carbon. Chemical oxidants such as superoxides and hydroperoxyls (presumably created by reactive decomposition of (per)chlorates, pyrite or other species) drive oxidative damage (Davila et al., 2008; Hecht et al., 2009, Crandall et al, 2017). Not only is this oxidation chemistry extremely destructive to living organisms (Wadsworth & Cockell, 2017), it also degrades *ex situ* organic molecules. 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 conditions to depths of ~7.5 m are harmful to life (e.g., Kminek & Bada, 2006; Dartnell et al., 2007; Pavlov et al., 2012 and many others).

6.4. Zones of Particular Interest

Our direct, observational knowledge of the Martian subsurface is very limited. Therefore, vertical exploration in order to begin assessing subsurface habitability with depth is a scientific achievement at any arbitrary landing site. However, there are zones of particular interest including: 1) places where geologically recent surface liquid groundwater release is indicated, such as in the Athabasca and Kasei regions (e.g., Burr et al., 2002), 2) low-altitude zones that permit testing hypotheses of a global water table, and 3) regions where hydrological models predict shallow water table depths (Fig. 3). Additionally, recent observations of methane and oxygen at Gale crater (Webster et al., 2018; Trainer et al., 2019) indicate active hydrological or biologic processes in the subsurface. Faults and impact-altered zones enhance fluid mobility, permeability and the possibility of fluid ascent from much greater depths (e.g., Oehler & Etiope, 2017). Moreover, impact-altered material has been shown to enhance microbial subsurface life (Cockell et al., 2012). This makes fault- and impact-rich regions appealing subsurface exploration targets. Planetary protection is addressed in a companion white paper. **We note that even a non-detection of groundwater at a local landing site allows**

us to better constrain global subsurface water inventories; especially in combination with measurements of the porosity, the unaltered hydration state and the salt content with depth.

7. Mars as a Window into Subsurface Environments Across the Solar System

A common theme of Solar System exploration is that, aside from modern-day Earth, **the subsurfaces of planetary objects typically have higher habitability potential than the surface**. This is the case for modern-day (and possibly even early) Mars, for subsurface oceans on Europa and Enceladus, and possibly for deep brine reservoirs on Ceres and Titan. **Missions to access these compelling scientific and astrobiological targets will thus require specific technological development, implementation, and mission operations experienced in subsurface exploration to optimize and maximize science return.** Mars, as our closest and best understood planetary neighbor, is a natural testbed for the initial implementation of subsurface exploration mission architectures with high science return. This generates scientific & technological development synergy between exploration initiatives for many planetary objects highlighted by NASA's last Decadal Survey.

8. Conclusion

Mars' subsurface is one of the most compelling potentially habitable environments in the Solar System that can feasibly be explored in this coming decade. Questions such as*: "Is there liquid groundwater on Mars*", "*Where and what are sources and sinks of trace gases such as methane*", "*What is the habitability of the subsurface*", and "*Are there signs of extant subsurface life?*" drive our interest in subsurface exploration.

We argue that the same reactions that produce life-sustaining redox disequilibria in Earth's deep subsurface operate on Mars today, allowing for multiple different microbial metabolisms. Therefore, investigating the presence or absence of subsurface water, and its chemistry, as well as mineralogy, and redox disequilibrium with depth, including signs of life should be prioritized in this decade.

Our unparalleled knowledge regarding Mars' crust and its geologic evolution, combined with our enhanced understanding of Earth's deep subsurface biosphere, and sufficient development of technologies required to explore the Martian subsurface, place us in an unprecedented position to investigate the present-day habitability of the Martian subsurface and its potential for extant life.

As discussed in our companion paper, such questions can be addressed by deploying sounders for liquid groundwater and/or trace gas localizers at a small spacecraft budget ($100-300 M). The addition of a drill bumps costs to a New Frontiers-type class and current technologies offer access to 10-100 m depth. Drilling to ~100 m is especially scientifically compelling because it provides enough leverage in depth to set the stage for testing hypotheses on habitability at even greater depths where liquid groundwater might be more common. Mars subsurface exploration provides a scientifically compelling testbed for technologies that can be used in future missions to explore the subsurfaces of other planetary objects, where liquid water & extant life might be lurking.

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