SCIENTIFIC RATIONALE FOR EXPLORATION OF THE MARTIAN SUBSURFACE. H. M. Sapers[1], J. F. Mustard[2], A.-C. Plesa[3], T. Spohn[3], B. Knapmeyer-Endrun[4], S. Perl[5], J. Hao[6], J. Michalski[7], C. Magnabosco[8], K. Miljkovic[9], D. Paardekooper[10], D. Pan[11], B. Sherwood Lollar[12], S. Vijendran[10], F. Wang[11], F. Westall[13], K. Zacny[14]. [1]York University, ON Canada (hsapers@yorku.ca), [2]Brown University, Providence, RI USA, [3]Institute of Planetary Research, DLR, Germany,[4]University of Cologne, Germany,[5]Jet Propulsion Laboratory, USA,[6]University of Science and Technology of China, [7]University of Hong Kong, [8]ETH Zürich Switzerland,[9]Curtin University, Australia, [10]ESA Netherlands,[11]Shanghai Jiao Tong University, China,[12]University of Toronto, Canada,[13]CNRS, 45000 Orléans, France, [14]Honeybee Robotics, USA

Introduction: The subsurface of Mars is likely the longest-lived habitable environment accessible to exploration within the coming decade that could host ancient biosignatures of past life or even extant microbial life [*1*].

Here we consider 3 aspects of subsurface exploration on Mars and address the driving science questions: 1) the crustal environment and spatial architecture of Mars; 2) the nature of subsurface volatiles and transport pathways; and 3) implications for habitability of the Martian subsurface. The technological aspects of subsurface access are addressed in a companion abstract [*2*].

The Crustal environment of Mars Underground:

1) *What is the physical structure of the crust within the upper crust (porosity, permeability)?*
2) *What is the thermal state of the subsurface and the surface heat flow (temperature gradient, thermal conductivity)?*
3) *To what depth would salts and brines raise the cryosphere with respect to groundwater flow?*

The NASA InSight mission has put rigorous constraints on key properties of the crust, including thickness, layering, porosity, density and inhomogeneities [*3*]. InSight's heat flow probe (HP^3) unfortunately failed to reach the required depth of >3m for a heat flow measurement [*4*] but provided data on the mechanical and thermal properties of the topmost ~40 cm of the regolith at the site [*5*]: A ~1 cm thick layer of mildly cohesive sand overlies a duricrust of 7-20 cm thickness, below which sand was found with an increasing concentration of gravel and stones with depth. The density was found to be 1000-1300 kg/m^3, increasing to 1600 kg/m^3 with depth and porosity ~60%. The thermal conductivity increased from ~15 to 35 to 60 mW m^{-1} K^{-1} and varies with atmosphere pressure [*6*]. The seismic compressional and shear wave velocities in the layer are ~120 and ~60 m/s, respectively.

Crustal porosity has been estimated based on seismic velocities from InSight and inferred density of the crust from global crustal thickness models [*3*] derived from gravity and topography data. Two crustal seismic discontinuities at 8±1.5 km and 22±3 km depth [*7*] that were found at the InSight landing site could indicate the depth of viscous pore closure [*3*, *8*] and/or a different composition of crustal layers [*3*]. Porosity in the top-most layer needs to be at least 5% to explain the measured low velocities [*9*]. While there is no evidence for a cryosphere in the upper 8 km of the crust below InSight, the increase in seismic velocities at ~8 km depth could be explained by the presence of mineral cement, that in turn could indicate past water activity [*10*]. However, the layered structure observed beneath the InSight location is likely not representative for all of Mars, as indicated by the recent analysis of surface waves [*11*].

The depth of the Martian cryosphere is poorly constrained. Early impact processes could have led to the formation of hydrothermal systems, by locally increasing the subsurface temperature and fracturing the crust [*12*]. Models indicate a present-day cryosphere depth of 2-4 km in equatorial regions, in areas covered by a thick insulating crust [*13*, *14*]. In polar regions, colder temperatures push the groundwater to depths beyond 10-16 km [*13*, *14*]. However, brines saturated in Ca and Mg perchlorate salts could be present at much shallower depths, as indicated by bright radar reflections at the south pole of Mars which were interpreted as the presence of subglacial water bodies [*15*, *16*].

Subsurface Volatiles (H_2O+H_2+CH_4):

1) *What is the nature of the cryosphere at depth and transition to liquid water and/or brine?*
2) *What is the temporal record of subsurface water/brine?*
3) *What are the subsurface sources and sinks of methane?*
4) *What active processes generate H_2 and to what extent?*

The extensive porosity hypothesized from the InSight data and the broad scale character of the crustal architecture permit H_2O + H_2 + CH_4 volatiles to be readily present to 10 km depth.

Water: Discoveries over the last 10 years have hinted at liquid water reservoirs in the deep subsurface of Mars but have also shown that subsurface aqueous activity is long-lived, well into the Hesperian [*17, 18*] with the capacity to sustain extant subsurface life [*19*, *20*] and to host ancient biosignatures. Several analyses put broad limits on the volume of water in the upper 10 km to around 500 m GEL [*21*]. While it is unlikely the pore space is saturated with water, close association of water and radioactive elements in the rocks would facilitate generation of H_2 and CH_4 via radiolysis at a rate comparable to the Earth's crust [*20*]. In addition, progressive aqueous alteration of subsurface rock would release H_2 and CH_4 [*22*, *23*] driving the fluid chemistry towards more reducing and alkaline, likely similar to the (ultra)mafic serpentinization springs on the Earth.

Methane: While serpentinization and associated reactions may generate CH_4 in the Martian crust, the amount generated is insufficient to explain the variability suggested by current observations [*24–26*].

SAM TLS, onboard the Curiosity Rover, has made 12 ground-based CH_4 measurements [*24*, *25*] defining three main methane cycles: 1) large seasonal variability increasing during the Northern spring and summer from persistent background levels [*27*] and consistent with adsorption and diffusion within the regolith if the regolith is supplied with CH_4 through microseepage [*28*]; 2) diurnal variability indicating CH_4 accumulation overnight [*29*] as a result of limited nocturnal mixing due to suppression of the planetary boundary layer [*30*]; 3) short lived episodic methane plumes reaching local concentrations as high as 45 ppbv requiring both an unknown source and sink for methane [*31*, *32*].

Hydrogen: H_2 production is likely a key energy source as an electron donor produced through the reaction between anaerobic ground water and Fe-rich mafic and ultramafic rocks via serpentinization-type reactions. Fe oxidation coupled to nitrate reduction can regenerate Fe^{3+} for subsequent biological reduction. H_2 along with H_2O_2, O_2, and short-lived oxidants are also generated through radiolysis in all rock types and mineralogies [*33*].

The Martian Subsurface as a Habitable Environment:

1) *Is the current subsurface habitable and over what spatial and temporal scales?*
2) *What is the preservation potential of organic biosignatures in the subsurface?*
3) *Is there evidence of past or extant life in the Martian subsurface?*
4) *What is the gradient of habitability within the cryosphere to the stable subsurface fluid regions?*

If life existed on Mars, or potentially still exists, it is more likely to be found in the subsurface [*1*]. Regardless of either an early warm wet and/or cold add dry Mars, by the time the earliest evidence for life on Earth was recorded in the rock record, or shortly thereafter, the surface was largely inhospitable due to the ionizing radiation and instability of surface water [*34*, *35*]. It can be argued that the lack of continued habitable conditions on the surface of Mars, a surface biosphere never evolved. Further, a km deep global cryosphere on Mars would limit surface/subsurface communication [*36*]. This would suggest that even ephemeral surface habitability later in Martian history may not have had both the spatial and temporal connectivity to sustain a putatively inhabited environment to establish colonization. Rather, early chemosynthetic metabolisms, as the surface became uninhabitable, likely dominated in the relative refugia of the subsurface [*37*].

Over 70% of all extant bacteria and archaea on Earth are estimated to inhabit the subsurface. Within this diverse habitat, multiple examples of subsurface ecosystems decoupled from oxygenic photosynthesis have been reported [*38–40*] and sustain themselves through chemotrophic processes that are consistent with potential processes in the Martian subsurface (e.g. H_2 and CH_4 produced via serpentinization and subsequent reactions can sustain subsurface microbial communities on Earth). Deep subsurface life on Earth is largely constrained by energy availability. Exploration targeting the physical properties of the Martian subsurface and understanding volatile flux will lead to a more robust assessment of the possibility of both extinct and extant life on Mars [*see 2*].

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