MEETING THE TECHNICAL CHALLENGES OF MEASURESMENTS IN THE MARTIAN SUBSURFACE.

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Introduction: Recent advances across disciplines have demonstrated the breadth and diversity of life in Earth's subsurface. Key science questions and scientific context for the exploration of the Martian subsurface are summarized in the companion abstract [1]. Coupling those advances with the history and nature of subsurface fluids on Mars [e.g. 2, 3] presents a compelling case for advancing our knowledge of the subsurface [4]. While the subsurface is regarded as one of the next frontiers for Mars exploration [4, 5], accessing the subsurface presents challenges. The compelling nature of the science questions for the subsurface and their complementarity to ongoing surface exploration and sample return missions necessitate an evaluation of subsurface access strategies.

Subsurface processes, highly dependent on crustal porosity and local permeability, inevitably contribute to surface properties of the atmosphere, hydrosphere, and any possible biosphere [4]. Mars subsurface exploration opens the door to measurements of gas fluxes, fracture systems, and geochemical properties vital to understanding past and present Mars. It also lays the foundation for self-sufficient human settlements beyond our own planet and provides an emerging potential for synergistic collaborations with the rising commercial space sector and traditional mining companies. Our understanding of the Martian subsurface and the technologies for exploring it, with a dual focus on the search for signs of extinct and extant life, and resource characterization and acquisition, have matured enough for serious consideration of subsurface studies as part of future robotic missions to Mars

Current Access to the Subsurface.

Geologic processes are capable of exposing deep sections of the Martian crust. Impact cratering is the most common, and has been used effectively to detect and map buried water ice over the course of the MRO mission [e.g. 6] but impacts can also be exploited to access deep into the crust as demonstrated by [7] in terrains associated with the Isidis Basin. The challenge with impacts is that the fundamental geologic context can be obscured and active processes (e.g. gas flux) disrupted by the impact process. Fault scarps such as along the walls of Valles Marineris or Nili Fossae are another type of terrain providing access to the third dimension.

The capabilities to explore the subsurface have steadily been increasing (Table 1 and Table 2). Missions and instruments that have been involved in direct sensing the properties and characteristics of the subsurface include Mars Odyssey Neutron Spectrometer (MONS), soundings from the MARSIS and SHARAD radar systems on Mars Express and MRO respectively, the seismological investigations of the InSight lander [8], gravity field [9] and its combination with topography data to probe the subsurface [10], excavation of buried ice by recent impacts [6, 11] and ground penetrating radar with RIMFAX on the Perseverance Rover [12] and RoPeR on the Zhurong rover [13]. Direct sensing through sampling and near surface drilling has been accomplished by the Phoenix lander and the Curiosity and Perseverance rovers, and is included on the planned ExoMars rover to 2 m.

The InSight mission included a penetrometer in its Heat Flow and Physical Properties Package HP^3 that was planned to reach a depth of 5m. Unfortunately, the penetrometer did not reach beyond approximately 40 cm because of unexpected cohesion in the top 20 cm of the regolith that did not allow the recoil of the penetrometers' hammer mechanism to be fully compensated. The penetrometer measured the soil mechanical and thermal properties of the regolith [14]. [15] have considered how penetrators could be modified to deal with more cohesive soils. Other mechanisms for penetrators have been proposed [see 16]). To reach greater depths, there are a number of technologies in development. Technologies for reaching 100 of meters is at TRL6 while technologies for reaching 1 km is at TRL 4/5.

Using EM frequencies lower than GPR techniques it is possible to reach deeper. Deep and shallow liquid water can be resolved with inductive low-frequency EM techniques that sense the higher electrical conductivity of saline water in comparison to ice and dry rock by measuring the EM response to an external EM field. An artificial EM source can be used to generate an EM response. For example, direct-current-based transient electromagnetics (TEM) uses a coil on the surface to generate the necessary external EM field. Scaling current terrestrial TEM capabilities to achieve groundwater detection on Mars indicate that aquifers as deep as several kilometers or greater can be detected with a small system (e.g. [17]). Currently, a collaboration between the Jet Propulsion Laboratory (JPL) and the Southwest Research Institute is developing a small (~5 kg, ~tens of W) TEM prototype called TH$_2$OR (Transmissive H_2O Reconnaissance) to search for deep groundwater and characterize its salinity from the Martian surface. Moreover, the JPL Deep Access Subsurface Extraction & Retrieval (DASER) system is designed to reach several meters to 100m in depth for borehole science and in-situ investigations onboard a future MLE-type of lander.

Selecting a site for subsurface exploration, whether through electromagnetic, geophysical (heat flow and seismology), or drilling methods, will have a number of factors to be considered, leading with relevance to the science objectives of an investigation and factoring in landing site safety. The science objectives of a fundamental electromagnetic investigation feeds into precursor regional assessments evaluating the geologic and geophysical context of sites for the possibility of having subsurface aqueous deposits. This will begin with a broad evaluation of the geologic and geophysical criteria. First order criteria may include a) Presence of extensive outcrops of hydrated minerals [18] b) Exposed bedrock surfaces assessed by THEMIS/TES maps thermal inertia c) Presence of fracture systems or vents with evidence of outflow (volcanic or aqueous) d) Association of trace gas plumes.

Prospective landing sites will also need to meet engineering criteria for landing site safety. Previous Mars missions typically have relied on the following categories defined by the entry, descent and landing system (EDL), post landing mission operations requirements such as mobility, if needed, and power considerations.

Technologies to enable future missions targeting subsurface exploration include drills, melt probes, tethers, submersibles, communication nodes, telemetry from the probe/drill tip, and materials of meeting stringent planetary protection requirements. Additional possibilities include modified robotic exploration of lava tubes or caves; and possible sound probes.

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Table 1: Existing Subsurface Measurements through Drilling/Penetrometry

		Mission	Sensing Depth
Brushing, Drilling, and Digging	Existing	Mars Exploration Rovers: Dust Removal Tool (DRT), wheel track	mm to cm
		Curiosity: DRT and drill	up to 6.5 cm
		Phoenix: scoop	18 cm
		Perseverance: Coring	60 mm
		InSight-Mole	37 cm
	Future	ExoMars to 2 m	2 m
		IMPACT (RedWater)	100 m
		WATSON	1 km

Table 2: Existing Subsurface Measurements through Sensing

		Mission	Sensing Depth
Sensing	Existing	MeX MARSIS	up to 5 km
		MRO SHARAD	up to 1 km
		Odyssey GRS MONS	1 m
		Perseverance RIMFAX	1-10 m
		Zhurong RoPeR	100 m
		InSight	km
		Geophysics (Gravity, Topography	km
	Future	ExoMars-WISDOM	meters
		International Mars Ice Mapping (I-MIM)	cm to meters

Table 3: Capabilities for Subsurface Measurements through Sensing and Drilling

		Technique	Sensing Depth
Potential	Sounding	MTF	0.1-1 km
		TEM	0.01-1 km
		GPR	0.01-0.1 km
		SAR	1-10 m
	Drill	Next Generation drilling	0.01-0.1 km

MTF: Magnetic Transfer Function, **TEM**: Transient Electromagnetics, **GPR**: Ground Penetrating Radar, **SAR**: Synthetic Aperture Radar