The next frontier for planetary and human exploration

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The next frontier for planetary and human exploration

The surface of Mars has been well mapped and characterized, yet the subsurface — the most likely place to find signs of extant or extinct life and a repository of useful resources for human exploration — remains unexplored. In the near future this is set to change.

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Exploration of the Martian subsurface, to depths from a few metres to many kilometres, offers an unprecedented opportunity to answer one of the biggest questions contemplated by humankind: was or is there life beyond Earth? Simultaneously, Mars subsurface exploration 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 as part of future robotic missions to Mars.

The search for life leads underground

Data collected from orbiters and rovers indicate a once warmer and wetter Mars that may have been supportive of life as we know it[1,2]. Results from the MAVEN mission[3] suggest that a significant fraction of the Martian atmosphere was likely lost early in the planet's evolution — sometime between the Noachian and Amazonian periods — which would have led to surface temperatures dropping, to an increase in harmful radiation reaching the surface, and to the boundary between cryosphere and liquid groundwater moving to greater depths below the surface, where the temperature and pressure would have been high enough to sustain liquid water.

Regardless of whether life may have ever emerged on or below the surface of Mars, it would have likely been transported with the receding groundwater towards greater depths[4]. In the subsurface — shielded from the harmful effects of ionizing radiation, reactive chemical oxidants and desiccation — life could have been sustained by hydrothermal activity, radiolysis, degassing, and water–rock reactions as found in terrestrial subsurface microbial communities[5,6]. Therefore, the most likely place to find biosignatures of putative modern day extant life is in the subsurface, where groundwater (likely in the form of brines containing pure water mixed with salts) could still be stable[7] (see Fig. 1 for stability depth).

Recent results from the Curiosity rover[8] suggest the preservation of complex organic molecules even in near-surface settings. However, molecular biosignatures are likely best preserved at depths of at least a few metres, where they are shielded from ionizing radiation and reactive chemical oxidants that can obscure or destroy structural complexity that is indicative of biogenicity, independent of whether putative ancient Martian organisms once inhabited surface or subsurface environments[9]. Results from terrestrial cratons 2.7 billion years old have recently demonstrated that fluid components can be preserved in subsurface fracture groundwaters for billions of years[10]. The practical challenge we face on Mars is to identify the subsurface sites that have been least exposed to surface conditions.

To date, only the Viking landers — launched over forty years ago — have sought direct evidence of extant life, but they focused on the Martian surface alone. Subsequent missions have focused instead on the related question of the ancient habitability of Mars and the search for biosignatures of extinct life in materials accessible on the Martian surface. In the search for life, extinct or extant, the Martian subsurface likely holds the key for answering the ultimate question of Mars exploration: was there ever or is there still life on Mars?

Pristine cores for high-resolution climate reconstruction. Beyond the search for evidence of life, direct access to the subsurface would help reconstruct the long-term climatic and geochemical evolution of Mars, with a level of detail and temporal resolution that is beyond the reach of surface instruments, which typically have to deal with samples that have been altered by damaging atmospheric photochemical oxidants or solar/cosmic radiation. Extended subsurface cores of lake sediments or volcanic deposits would provide an unprecedented record of geochemical conditions and atmospheric composition dating back hundreds of millions to several billion years. Deep cores of polar ice deposits would help reconstruct orbit-driven climate excursions over shorter timescales of tens of millions of years.

Accessing resources for human exploration. Human exploration of Mars remains a primary long-term objective for NASA. Relative to the Moon, Mars offers more in situ resources in the form of ices, hydrated minerals, and CO_2 — enabling a more sustainable human presence that would not depend heavily on frequent deliveries from Earth. However, to select the most advantageous site for human exploration, we need to better grasp the

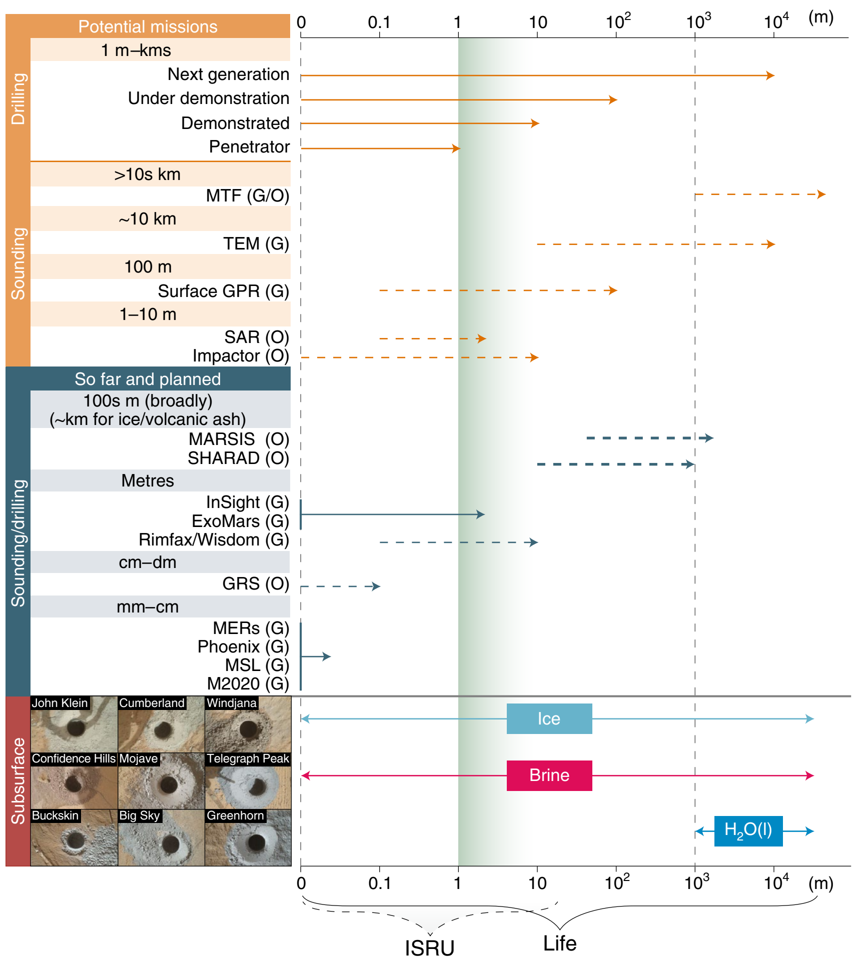

Fig. 1 | Sounding and drilling capabilities on Mars. We plot the sounding (dashed arrows) and drilling (solid arrows) depths for missions that have already been delivered to Mars or are scheduled (navy blue) versus selected potential instruments that could help explore the Martian subsurface (orange). The arrows indicate the reach of sounding and drilling (minimum and maximum). For drilling, we show current capabilities that have been (~15 m) or are currently being demonstrated (~100 m) under simulated Mars conditions, and next generation drills under development (>1 km). O and G indicate orbital and ground-based missions, respectively. G/O indicates that orbital and ground-based assets need to work together. MTF, magnetic transfer function; TEM, transient electromagnetics using own active EM source; GPR, ground-penetrating radar; SAR, synthetic aperture radar; M2020, Mars 2020; GRS, Gamma Ray Spectrometer on Mars Odyssey; MERs, Mars Exploration Rovers Spirit and Opportunity; MSL, Mars Science Laboratory/Curiosity rover. The arrows for MARSIS/SHARAD illustrate a penetration depth of less than 200 m outside of ice or volcanic ash overburdens, and around 1 km in such zones (mainly poles). Depths where ice (cyan), brines (pink), and pure water (blue) could occur are indicated by colour. While near-surface liquid brines are possible, pure liquid water could only be thermodynamically stable at depths of about 2–20 kilometres, as restricted by the local thermal gradient and surface temperature. In shaded green, we highlight that at a depth of a few metres organic molecular biosignatures are thought to be better preserved[9]. ISRU (in situ resource utilization) is mostly concerned with the first tens of metres of depth, requiring easy access to resources, hence focusing on ice, brines and clays. The search for life is tightly coupled to liquid water and brines. Understanding the modern-day distribution of subsurface ice calls for better modelling of liquid groundwater flow across geologic time, bridging ISRU to life exploration. Images of drill holes with MSL illustrate the abundance of subsurface environments through the diversity of subsurface colours below a uniform surface colour[14,15]. Drill hole images credit: NASA/JPL-Caltech/MSSS/UofA/USGS-Flagstaff.

following: (1) the geographic distribution and depth of shallow ices and other potential resources (for example, brines, hydrated minerals, clathrates, useful gases and metals) in the first 10–50 m at lower latitudes — a region of particular interest to human space exploration due to the optimal levels of solar insolation and solar power production throughout the year and more benign temperatures; (2) potential chemical and particulate hazards in the subsurface; and (3) the local likelihood at the landing site for extant life (and hence also liquid water) and to preserve signs of extinct life, to make sure we minimize possible cross-contamination and do not alter a potential ecosystem.

Diverse subsurface environments

While Mars subsurface exploration is still in its infancy, the little data we do have support the idea of a diverse and exciting Martian subsurface. Specifically:

(1) Gamma-ray spectrometers and neutron detectors on Mars Odyssey have provided on a global scale the elemental abundances of hydrogen, iron, chlorine, silicon, potassium and thorium in the very shallow Martian subsurface (cm–dm).

(2) Orbital radars — the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) on Mars Express and the Shallow Radar (SHARAD) on the Mars Reconnaissance Orbiter (MRO) — have provided rich datasets for characterizing the stratigraphy of polar regions to a depth of 1–3 km. MARSIS data were recently used to establish the possibility of perchlorate-containing water beneath the south polar layered deposits at a depth of 1.5 km (ref. [11]). Data from both radars suggest the presence of relatively shallow ice deposits in a few non-polar regions (for example, Deuteronilus Mensae[12]). However, both instruments are 'blind' to the top ~10 m, and have poor depth perception beyond 200 m other than through ice or volcanic ash overburdens, and hence their effectiveness is mainly limited to the poles[13]. Hence, both instruments have not been able to conclusively reveal shallow ices closer to the equator or subsurface liquid water (Fig. 1).

(3) Rovers like Curiosity have directly sampled the Martian subsurface down to a depth of approximately six centimetres. The Phoenix lander managed to scoop one sample from 18 cm beneath the surface. Although we have barely scratched the Martian surface, we observed a diversity of subsurface environments reflected in the many subsurface sample colours underlying a homogeneous red surface layer — suggesting large mineralogical, chemical and redox variations[14,15] (see Fig. 1, bottom left). We also see widespread hydraulic fracturing and mineralization in veins, which imply a long and rich history of water in the subsurface[16].

(4) Various missions — in situ ground-based, but, although more controversial, also orbital via spectroscopy — have provided evidence of salts that, when mixed with water, may form brines with low eutectic

temperatures[17]. For perchlorates specifically, experiments suggest frequent formation during dust storms[18]. The existence of various salts would allow for shallow briny subsurface waters locally (see Fig. 1, bottom right).

(5) Measurements at Gale Crater by Curiosity related to seasonally variable concentrations (including intermittent peaks about one order of magnitude above background levels) of methane and the presence of complex organics and nitrates in near-surface drill samples, and calculations on the potential availability of dissolved O_2 suggest ongoing subsurface processes that could provide the electron donors and acceptors to support subsurface life in the present[19–22].

Enabling Mars subsurface exploration

Mars subsurface missions can today capitalize on recent technological achievements for sounding, drilling, cave exploration, and in situ sample analysis, on progress in our scientific understanding of the Martian subsurface, and on commercial and small spacecraft opportunities.

Global monitoring, 4D subsurface science and site selection. High-resolution orbital images have already provided numerous examples of locations with natural entrances into the Martian subsurface, such as lava tubes/caves or highly fractured terrain that could provide outlets for discharge of subsurface fluids and/or gases[23,24]. Orbital instruments (especially in areostationary orbit) can be used to further identify or monitor these sites for sources and sinks of trace gases, such as near-surface CH_4, He or H_2, which might be missed by orbiters that cannot constantly monitor a specific region. Local subsurface trace gas emissions might be generally difficult to detect from orbit due to large dust loads in the lower atmosphere or interfering surface-gas interactions and would benefit from surface and subsurface gas exchange sensors (for example, tunable laser spectrometers, soil resistivity measurements, gas accumulation chambers or equivalent). Areostationary monitoring and surface trace gas sensors might be particularly needed in order to resolve the debate on Martian methane.

We have also gained a deeper understanding of Martian subsurface variability following the recent exploration of deep continental and oceanic subsurface habitats on Earth[5,6], and the modelling of Mars subsurface environments with evolutionary geodynamic tools and Mars general circulation models with variable obliquity[20,25]. Together, these disciplines allow us to better constrain locations where the ice, permafrost and liquid water tables are closer to the surface and where redox gradients amenable to sustaining life might be maintained, today and in the past[20,26]. It is important to remember that Mars offers the opportunity to obtain data from different subsurface depths, locations across the planet's surface, and epochs in time, whereas on Earth plate tectonics has significantly diminished very old rocks[4]. Therefore, in order to validate models with observations, it is quintessential to model the Martian subsurface in 4D (3D in space and one dimension in time across the last 4.5 billion years). Such modelling will soon profit from data obtained with InSight[27]. InSight is preparing to explore the large-scale interior of the planet using seismology, geodesy and measuring the surface heat flow with HP^3. The seismological suite will provide broad-scale seismic data on the structure of the Martian interior that will help to better constrain estimates of crustal thicknesses.

Together, global monitoring and 4D subsurface science will facilitate future mission planning, especially for site selection.

Sounding the subsurface. Advancements and miniaturization in classic radar, synthetic-aperture radar (SAR) with polarimetry, multi-static radar, higher peak power, or array techniques and interferometry could help propagate more energy into the shallow subsurface and provide sufficient reflections to map shallow ices in the first ~10–50 m of the subsurface in lower latitudes, although scattering in regolith is a challenge that limits the depth of exploration. For example, combining an orbital radar sounder at 50 MHz and an orbital SAR with polarimetry (L- or P-band at ~300 MHz) could enable characterization of ice in the upper 10 m of the subsurface. In this context, ice sheet cliffs observed in mid-latitudes[28] and debris-covered glaciers[12] are of special interest. On the surface, the future ESA ExoMars and Mars 2020 rovers scheduled for 2020 plan to have ground-penetrating radar reaching down to a depth of a few metres (sounding depths for ExoMars WISDOM GPR of ~3 m and RIMFAX on Mars 2020 <10 m respectively).

Whereas ground-penetrating radar has limitations in sounding great depths, lower-frequency techniques can reach deeper. When searching for deep and shallow liquid water, 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. We do not know whether there are sufficiently strong naturally occurring EM signals caused by lightning or dust devils, or whether ionospheric EM signals reach the surface. If the latter occurs, then comparison of the fields using a surface and an orbital instrument (magnetic transfer function, MTF) may detect groundwater at depths below one kilometre. By contrast, 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 current terrestrial TEM capabilities to achieve groundwater detection on Mars indicate that aquifers as deep as several kilometres or greater can be detected with a small system[29]. 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_2OR (Transmissive H_2O Reconnaissance) to search for deep groundwater and characterize its salinity from the Martian surface.

Seismology on Mars is ideal for investigating large-scale interior structures, as will be demonstrated by InSight in the next two years. Active-source seismology is well suited to image shallow crustal features of interest such as buried ice and lava tubes. To detect groundwater at great depth on Mars, however, seismology offers a lower sensitivity while generally needing active sources, more mass and power than TEM, and is, hence, not the first choice when searching for Martian groundwater. Nonetheless, though less effective than TEM, passive high-frequency seismology can help infer how dry the local crust is, which will be soon tested with InSight.

Accessing the subsurface. In conjunction with sounding, physically accessing and sampling the subsurface gives independent confirmation of remote-sensing observations while also enabling a wide range of scientifically critical investigations. The technologies for subsurface resource characterization and extraction are already developed for harsh terrestrial environments (including the low/high temperature and the vibrational environment that the equipment could be subjected to during launch, landing and drilling operations) but need further development for future Martian missions. Significant progress has also been made in clean drilling and avoiding/detecting contamination in terrestrial rocks[30].Current 1–10 m drills have been demonstrated under simulated Mars conditions, while hundred-metre drills are under demonstration. Drills that can reach depths greater than 100 m under Mars conditions are still under development. HP^3 on InSight aims to go to a depth of five metres in regolith[27]. The drill developed and qualified for the ESA ExoMars 2020 mission has proven capability of acquiring samples at 2-m depth in regolith using a few tens of watts, while being in line with the mission's required high level of cleanliness. Current drills under development, like the rotary-percussive wireline Planetary Deep Drill (PDD, from Honeybee Robotics), the rotary ultrasonic wireline Auto-Gopher-2 (AG2, from a collaboration between Honeybee Robotics and JPL), and the rotary-percussive wireline drill with deep UV/Raman spectrometer WATSON (from a collaboration between Honeybee Robotics and JPL) have been deployed under simulated Mars conditions and/or in Mars-analogue environments (PDD reached 13.5 m and AG2 reached 7.5 m in a couple of days in a gypsum quarry, while WATSON will be tested in Greenland to 100 m in 2019). The coiled tubing drill RedWater could be deployed from a Curiosity-sized rover and penetrate the subsurface to hundreds of metres of depth, whereas next-generation iterations of PDD/Watson/AG2 could reach a depth of 1–2 km (refs. [31–33]).

We can also utilize miniaturized wireline drilling approaches that could enable drilling from just metres beneath the surface to kilometre depths without significant changes in payload mass. In this case, in situ compressed CO_2 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. This system would return all the cuttings to the surface in approximate stratigraphic order, so that a surface instrument suite could perform a triage on the stream of cuttings and pull out samples of special interest.

In addition to direct subsurface drilling, technologies to access and map subsurface voids robotically, in a manner that is safe and compatible with planetary protection concerns, are being developed[34]. Use of swarm-algorithm-controlled small self-propelled units is ideal for the deployment of suites of many units that can sustain high losses and still do the reconnaissance and measurement jobs that are needed for precursor missions, for example, using hopping microbots to spread into a network within a subsurface cavity. Robots that can climb, bounce, crawl, slither and slink are all possibilities for accessing underground terrains[35].

In situ analysis. In situ analyses may be aimed at life and/or biosignature detection, habitability assessment or mineralogical/geological characterization and determining the potential and feasibility of in situ resource utilization. Current technologies for organic, mineral and elemental analysis selected for surface Mars missions (for example, SHERLOC, a deep UV Raman/fluorescence spectrometer on Mars 2020; MOMA, on the ExoMars rover) or those already deployed on the surface (for example, the ChemCam Laser Induced Breakdown Spectrometer on MSL) are adaptable for borehole assessment, either post-drilling or simultaneously while drilling. Deep UV Raman and fluorescence spectroscopy has already been integrated with a wireline tool for terrestrial subsurface analysis of boreholes[36]. In the case of penetration into putative subsurface fluid reservoirs, wireline logging instruments recording temperature, pH, alkalinity, dissolved oxygen, oxidoreduction potential, salinity/conductivity/resistivity, turbidity and select biologically relevant chemical concentrations such as exsolved gasses and Fe^{2+}/Fe^{3+} ratios, would provide pertinent information on chemical gradients and boundary conditions capable of supporting various metabolisms. Gas pumping systems enabling sampling and analysis of subsurface gases, such as methane, can be integrated in situ as well[24].

New commercial opportunities

Access to space has become a commercial endeavour through companies like SpaceX, Blue Origin, Virgin Orbit, United Launch Alliance, Northrop Grumman, Firefly Aerospace, and Relativity Space among others. Some of these companies, in particular SpaceX and Relativity Space, have added explicit goals to foster human settlements or 3D print in situ on Mars in the coming decade to reduce the need for importing resources from the Earth. Partnerships with such commercial companies may both reduce costs and increase the frequency of opportunities to reach Mars.They also provide additional reasons for studying the Martian subsurface, with a focus on resources, a critical requirement for human presence and 3D printing on Mars.

Many of the goals of Mars subsurface exploration could be addressed using a new class of more affordable small spacecraft[37]. Examples of the observations that could be performed with small spacecraft in orbit include observing the outgassing of trace gases, seeps, fractures, caves, shallow ices, geomorphological and spectroscopic indicators for salts and shallow liquid water, or from landed devices with active or passive mobility. The latter would be in the form of scouts that search for trace gas emissions, shallow ices, and deep groundwater, or that monitor surface–subsurface volatile exchange or sample the shallow subsurface. Moreover, penetrators or networks of fixed stations emplaced by small spacecraft could address similar goals not requiring mobility. Deployment of such smaller missions may profitably thrive in the next decade due to the emerging exchange between NASA, other large space agencies, new international partners and commercial space providers. Given their rapid technical development, such small missions could deliver scientific data of great significance to a diverse science community in the next decade, side by side with a potential Mars sample-return mission that would bring back samples to Earth.

Additionally, collaboration can be extended beyond these companies traditionally involved in space exploration to those employed in harsh-environment terrestrial resource exploration, characterization, extraction and production, as they have much to bring to bear in terms of the technology, equipment and processes needed for subsurface exploration.

A new deep frontier

Orbiters, landers and rovers, especially the two MERs and Curiosity, have delivered data that have revolutionized our understanding of ancient Martian surface environments. Those data support a rich history of groundwater flow and a diverse, and from the surface very different, world hiding beneath the oxidized surficial regolith. InSight and future missions like the ExoMars and Mars 2020 rovers will aim to extend our knowledge of ancient habitable surface environments, to produce unprecedented data on global large-scale interior properties, and to inform us about the shallow Martian regolithic subsurface. However, questions, in particular about whether there ever was or is still life on Mars, how the Martian climate changed over long periods of time, whether there still is liquid water and whether there are enough accessible resources for an extended human presence, will remain unanswered until we start to 'go deeper'. 'Going deep' and using Mars as a testbed for subsurface exploration was recognized as a critical step when searching for life by the National Academy of Sciences Committee on the Strategy for the Search for Life in the Universe[38].

'Going deep on Mars' is an interdisciplinary project that calls for expertise from the whole Mars community. It does not only bridge astrobiology, polar sciences, climate, surface geology, geochemistry, spectroscopy, geophysics and ISRU, but it builds on existing technologies and scientific expertise that are part of current and future missions like Curiosity, InSight, Mars 2020, ExoMars and the present orbiters around Mars. Moreover, Mars subsurface exploration deeply connects planetary sciences with the human exploration program, linking the search for usable resources and hazards to the quest for signs of past and especially present life, ices and liquid water. The emerging capabilities of Mars subsurface science and exploration technology in combination with the commercial space market have positioned the Martian underground as the next great frontier of human endeavors. As such, implementing a bold program of Martian subsurface exploration — with a focus on extant and extinct life, ISRU and past climate — would serve as an ideal central focus for NASA's next Planetary Decadal Survey. ❐

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