A STRATEGIC FRAMEWORK FOR THE EXPLORATION OF THE MARTIAN SUBSURFACE

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A White Paper

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Workshop on the Martian Hydrosphere & Deep-Drilling on Mars (J. Blacic and G. Briggs, 1998)
Astrobiology Roadmap Workshop (D. Morrison, 1998)
Workshop on Revolutionary Drilling and Sampling Technologies (P. Smealie, C. Peterson, and G. Briggs, 1999)

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Executive Summary

The martian subsurface is of interest for two reasons: First, the only place water has the potential to exist in liquid form on Mars today is in the subsurface. Second, subsurface sedimentary rocks may record information about the history of both the climate and of extinct life.

The abundance and distribution of water (both as ground ice and groundwater) have important implications for understanding the geologic, hydrologic, and climatic evolution of the planet, the potential origin and continued survival of martian life, and the accessibility of a critical resource for sustaining robotic outposts and possible future human explorers. For these reasons, a principal goal of the Mars science, astrobiology, and the HEDS programs is to determine the 3-D distribution of subsurface H_2O, at a resolution sufficient to permit reaching any desired volatile target by drilling. The three targets most often discussed are: groundwater, massive deposits of near-surface ground ice (associated with the ponded discharge of the outlfow channels or the relic of a former ocean), and ice-saturated frozen ground. An added benefit of drilling (although probably not its primary justification) is the opportunity it provides to read the sedimentary record.

To minimize the level of risk associated with this task, we recommend the following general strategy for exploring the Martian subsurface:

- **Geophysical Reconnaissance**: Understand the characteristics of subsurface water (including 3-D distribution, quantity, and state), the gross thermal and physical properties of the upper martian crust (including heat flow, density structure, permittivity structure, etc.), and both planetary- and local-scale geologic structure (especially including depth to bedrock). To this end, we propose a two-stage geophysical approach consisting of:
  1. Global- and Regional-Scale Characterization:
     Potential missions:
     - Advanced Orbital Radar Sounder: a dual receiver (either boom-mounted or on a co-orbiting satellite), variable wavelength polar orbiter capable of assessing the 3-D distribution and state of water within the top 5-10 km of the crust.
     - 20-Station Global Geophysical Network: seismic and electromagnetic network with stations clustered in groups of 4 to provide higher resolution investigations of promising local sites identified by the Advanced Orbital Radar Sounder. NETLANDER will be a pilot mission for this network.
  2. High-Resolution Investigations of Promising Local Sites (<10 km^2) Identified from the Global Data:
     - Potentially including high-density local geophysical networks or radar sounding by surface rovers, airplanes, aerobots or balloons.
- **Target Identification**: Identify and prioritize potential drilling/sampling targets with specific geographic locations and depths. There are a variety of possible volatile targets in the subsurface, each with its own expected range of depths, physical and thermal characteristics, scientific questions, and unique engineering and operational challenges that apply to any attempt to successfully access and sample them.

- **Drilling:** Physically access the identified subsurface targets for *in situ* analysis or sample retrieval. TBD is whether cuttings will be sufficient, or whether core is required. Potential applications include: understanding the geologic, volatile and climatic history of a particular site (and the planet, by repeating such investigations at multiple sites); identifying evidence of extinct or extant life; assessing the geotechnical characteristics and potential subsurface hazards associated with a candidate site for a future human outpost; and water production (either by accessing and melting near-surface ground ice or by retrieving liquid water from beneath the cryosphere).
- **Analysis**: The subsurface targets need to be evaluated using some or all of downhole sensors, analysis of samples in an on-Mars surface laboratory, and return of samples to Earth. The many advantages of returning samples to Earth have been summarized elsewhere, and will not be repeated. The technology for many of the required measurements is already proven, but for others a new generation of instrumentation will be required. Contamination control during sample collection and sample preservation after acquisition will be big issues in addressing the science questions. Obviously, there will be substantial planetary protection concern regarding the possible return to Earth of certain types of subsurface samples.
- **Utilize** the water for objectives still to be defined in detail, but which include the production of rocket fuel, the support of a robotic outpost, and ultimately, the support of human explorers.

Although the time scale for pursuing this sequence is dependent on funding level, several strawman mission schedules (ranging from “aggressive” to “conservative”) are included as attachments to this document.

Outline

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Strategic Considerations for Exploring the Martian Subsurface

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9. Technology R&D needed to support this strategy.

Proposed exploration scenarios

Introduction

The search for water is a primary focus of Mars exploration. At the surface of Mars, water is present only as ice in the polar ice caps and in trace quantities in the atmosphere. In order to discover liquid water, we will need to search in the subsurface. The abundance and distribution of water (both as ground ice and groundwater) have important implications for understanding the geologic, hydrologic, and climatic evolution of the planet; the potential origin and continued survival of life; and the accessibility of a critical *in situ* resource for sustaining future human explorers.

The purpose of this document is to present a draft strategic framework for the exploration of the martian subsurface which can be used to stimulate discussion among interested people, and to identify and guide the development of the principal required components.

The present document summarizes input derived from numerous individuals and several major meetings held since 1998. Its compilation is the outgrowth of a series of e-mail exchanges, small meetings, and one major integration meeting, all of which took place approximately between June 1 and July 15, 2000.

Strategic Considerations for Exploring the Martian Subsurface

1. **Definition of subsurface targets and associated scientific objectives.** Scientific questions about the subsurface can be framed according to four main volatile zones, which are listed in order of increasing depth. The significance of the science steadily increases through the third zone, and the value for HEDS is primarily in the fourth zone. The fifth target is geologic in nature, and is of value in understanding planetary volatile history. For each zone, we have attempted to list the scientific questions in approximate priority order (and we invite discussion of these priorities).

1.1. **Desiccated Zone**: Region between the surface and the shallowest occurrence of ground ice. The expected depth could be from 0-1 km below the surface at equatorial latitudes, depending on geographic and stratigraphic variations in the local thermal and diffusive properties of the crust. At high-temperate and polar latitudes the maximum thickness of this zone will likely be reduced to several tens of meters.

<u>*Primary science questions related to this target:*</u>

- ✓ Are hydrous minerals present?
- ✓ Organic geochemistry: Are organic molecules present? What is the depth of action of the surface oxidant?
- ✓ What is the variation in the partial pressure of water vapor between the ground surface and the top of the cyrosphere? Can we infer anything from this about the global water cycle, and in particular its rate?
- ✓ What is its volatile history? (e.g., was there a monotonic advance of the sublimation front to greater depths? Or did the depth of desiccation undergo climatically- or geothermally-induced fluctuations?)
- ✓ How does the depth of desiccation vary geographically? How large is this variability at km- to m- size scales?
- ✓ What are the thermophysical and diffusive properties of the regolith (e.g.: heat capacity, thermal conductivity, heat flow, density, composition, grain-size distribution, pore-size distribution, specific surface area, extent of induration, strength, cohesion, coefficient of friction, etc.), and how do they vary with depth?
- ✓ Is there evidence of sedimentologic features such as stratigraphy, rounding, sorting, or diagnostic minerals? This can give information about deposition mechanisms, possibly as well as aqueous history (e.g vadose zone).
- ✓ What is the local thermal history of this region (climatic and geothermal)?
- ✓ Are inorganic biosignatures (e.g. magnetite, isotopes) present?
- ✓ Is there evidence for saline microenvironments? (Saline microenvironments are conditions favorable for the conservation of life and therefore for the preservation and identification of macromolecules or cellular structures).
- ✓ Please add additional questions here

1.2. **Ground Ice:** Ground ice can occur anywhere within the cryosphere (that region of the crust whose temperate remains continuously below the freezing point of water). Ice may exist in one of two forms within the cryosphere – occupying crustal porosity in various degrees of potential saturation, or as massive segregated lenses ranging from ~1-100's of meters thick (e.g. frozen lakes, oceans). It is expected that the volatile stratigraphy of the cryosphere will be quite complex. Current models suggest that the depth of frozen rock averages about 2.5-5 km near the equator and about 8-13 km at the poles. However, variations in heat flow and the thermophysical properties of the crust could result in significant local departures from these average values. Because the internal heat flow of Mars is thought to have declined with time, the cryosphere is generally expected to have been frozen for the longest period of time at shallow depth beneath the planet's ancient Noachian terrain.

<u>*Primary science questions related to this target:*</u>

- ✓ Same questions as above zone, but in addition:

- ✓ How does the distribution of ice in the cryosphere vary geographically and with depth?
- ✓ Are volatiles other than H_2O present (e.g., carbon dioxide- and methane-hydrates)? If so, what is their composition and distribution?
- ✓ What processes have contributed to the current distribution of volatiles in the upper crust?
- ✓ Can the ice be dated?
- ✓ Is there evidence of extinct or extant life? Is there evidence of dormant life?
- ✓ Please add additional questions here

1.3. **Unsaturated zone**: Zone below the base of the cryosphere and above the underlying water table. The intergranular porosity will be occupied by a mixture of gas and liquid water. The presence of a geothermal gradient in the crust is expected to result in the convective cycling of water within this region, possibly creating perched aquifers. The moist conditions are likely to be one of the most accessible targets in the search for extant life. The thickness of the unsaturated zone is expected to be greatest under regions of high elevation and minimized (or absent) beneath lower elevations. Under high elevations, the maximum thickness of the unsaturated zone could exceed 10 km.

Primary science questions related to this target:

- ✓ Same questions as above zones, but in addition:
- ✓ How does the distribution of water (both as a liquid and vapor) vary within this zone? What are the degrees of water and gas saturation?
- ✓ What is the gas chemistry and pressure? Is there any evidence of communication with the planet's atmosphere and, if so, on what time scale?
- ✓ Are there perched water tables?
- ✓ What is the chemistry of this water (dissolved species, concentrations, pH)?
- ✓ How has the movement of water through this region affected the composition, lithology, and evolution of the parent rock?
- ✓ Do the conditions for extant life exist?
- ✓ Is there evidence of extant martian life?
- ✓ What effect will the Martian atmosphere have on the stability of formations in this zone if it is introduced as a drilling fluid?
- ✓ Please add additional questions here

1.4. **Saturated zone**: The region of fully-saturated rock that lies below the water table.. Beneath low surface elevations, the base of the cryosphere and groundwater may be in direct contact (at a depth of ~2.5-5 km). Under regions of higher elevations, the groundwater table, if present, may lie at depths >10 km. Malin and Edgett's recent observations have raised the possibility that as yet unknown geologic processes have caused liquid water to exist locally at much higher levels in the crust than has been predicted to date by theoretical modeling. It is unclear whether this water is the result of surface melting (associated with high obliquities or the decomposition of gas hydrate) or originates from beneath the local cryosphere. Given the current number of unknowns about the nature of the martian crust and the magnitude of recent climate change (within the past ~10^6 years), the range of possible interpretations is currently wide.

Primary science questions related to this target:

- ✓ Same questions as above zones, but in addition:

- ✓ Is there a water table on Mars and, if so, what is its three dimensional configuration?
- ✓ Is groundwater water present in producible quantities and at accessible depths?
- ✓ What is its composition, origin and age? Do these properties vary geographically and at depth?
- ✓ What are the host formation's physical and hydraulic characteristics? What kind of yield would they support from a potential martian water well?
- ✓ Please add additional questions here

1.5. **Geology**: Several questions of relevance to martian volatile history and life can be addressed from study of the subsurface geology. Although of primary importance, the search for water is not the only target. Fossil bacteria, if any, are more likely to be preserved in dry, non-oxidized sediments.

<u>Primary science questions related to this target:</u>

- ✓ Did standing bodies of water ever exist on Mars (e.g., is there evidence of marine or lacustrine sedimentary rocks)?
- ✓ Is the martian climate history interpretable from the geologic record?
- ✓ Is there evidence of a fossil record?
- ✓ Is there evidence for geothermal processes?
- ✓ Please add additional questions here

2. **<u>Sampling requirements</u>.** To answer the questions described above will require the collection and analysis of samples from the subsurface. Two primary considerations are whether these questions can be answered with core samples or cuttings, and whether analysis should be done on Mars or on Earth.

2.1. **To answer astrobiology questions**: We require uncontaminated samples that have not been thermally altered. A maximum temperature constraint needs to be proposed. With regard to size, cuttings should be sufficient (many times larger than a bacteria). The problems of potential contamination are significant and may be difficult to overcome. It may be possible to reduce contamination by collecting a core, then subsampling the interior (although this would obviously require sterile subsampling equipment and procedures).

2.2. **To answer sedimentology questions**: To analyze the sedimentology of the rock, core is either strongly advantageous or required. Cross-bedding and other changes in grain size can help identify whether a particular sedimentary rock was the result of aeolean or water transport/deposited. The orientation of cross bedding can also assist in reconstructing paleo-environments (like where was the water flowing from, or what was the orientation of the prevailing winds).

2.3. **To answer mineralogical and elemental questions**: Most questions related to mineralogy and petrology (e.g. history and extent of aqueous and thermal alteration, elemental and mineralogical composition, age, shock metamorphism, etc.) can probably be answered with cuttings.

2.4. **To answer questions of in situ stress**: Another benefit of core can be their utility in making in situ stress measurements. A small gage can be affixed to the bottom of the hole prior to extracting core. Then as the core is extracted the, core rebounds as it is no longer confined by in situ stress. The gage can be used to measure this rebound and calculate in situ stress. This information has been used extensively on earth to interpret the effects of plate tectonics on the edges and relatively stable interior of continental plates. The data has always shown some effect and such measurements on Mars would certainly help understand any similar subterranean activity.

3. **Physical access to Subsurface Targets.** A large number of systems for accessing the martian subsurface have been proposed. It is beyond the scope of this report to either describe or evaluate them—that task is left to the Los Alamos group led by Jim Blacic.

4. **Principal Risks of failing to reach the target.** Terrestrial drilling experience (in relatively well-characterized environments and with well-proven equipment) has taught us two lessons: 1. The cost and risk of drilling (or other methods of rock penetration) increases exponentially with depth. On Mars the exponent is likely to be very large. 2. In a set of holes drilled in a given area, by far the most difficult is the first hole. It is customary to refine the engineering of the second and subsequent holes based on results from the first hole. Thus, drilling the first hole on Mars to significant depth will be associated with substantial risks. The principal risks can be categorized as follows:

   4.1. **Hole instability.** For holes drilled completely within competent rocks (e.g. in mines), holes on Earth can commonly be drilled to at least 500 m without casing. However, for holes drilled either through surficial regolith or through incompetent rocks, stabilization is required (or at least a countermeasure to an unstable hole). On Earth, stability is normally achieved by two means: 1. The use of high-density drilling fluid (mud) to keep the wellbore pressure higher than the formation pressure (this is normally used to keep the hole open during the drilling operation – the fluid also produces a filter cake that seals permeable formations to minimize the exchange of fluids between the bore the permeaable formations because introduction of foreign fluid also causes stability problems. Sometimes the salinity of the fluids is tailored to mimic in situ fluids or non-aqueous fluids are used to minimize the effect), and 2. The use of casing (normally used for long-term stability after drilling). The former approach is probably impossible on Mars for a variety of reasons, and the latter approach is mass intensive.

   A special category of hole instability problems on Earth are caused by encountering unexpectedly high fluid pressures, sufficient to result in damage to the drilling rig or even an uncontrolled "blow out". Where long sections of uncased hole are exposed to such a zone the lithostatic pressure at the top of the open zone may be less than the formation pressure (less the hydrostatic pressure of the mud) at the bottom of the zone and an underground blowout may occur when the flow is shutin. Collapse of the surface under the rig is one possible outcome of an underground blowout. One scenario on Mars where this could happen involves the decomposition of gas hydrates.

   - ✓ At STP 1 m^3 of hydrate will decompose into ~0.87 m^3 of liquid H_2O and ~80-90 m^3 of gas (the most likely candidates being CO_2 and CH_4). The release of this much gas in so small an initial volume (0.13 m^3) is capable of producing gas pressures that significantly exceed lithostatic pressures down to depths of several kms.

   4.2. **Stuck equipment**. A common failure mode for terrestrial drill holes is a stuck bit. This in turn has two primary root causes—hole instability (described above) and incomplete removal of the cuttings. Furthermore in boreholes that deviate from vertical, the bottom hole assembly and much of the drill string can become differentially stuck (the drill fluid pressure presses the drill stem into a lower pressure formation where the filter cake has been eroded by the drill stem, key-seated (tool joints are pulled into a grove worn into a soft dogleg), or frictionally locked in the hole. The specific volume of cuttings is almost always higher than the specific volume of in-place rock, so penetration cannot proceed if the cuttings are not cleared. The bit can easily become stuck if more than a few meters of the cuttings fill are allowed to fall back on it. Another possibility is situations where the drill bit passes through a non-normal joint plane, which can cause deviation of the bit to follow the fracture and build-up of asymmetric stresses that can bind the drill bit.

4.3. **Mechanical failure**. "Fishing" of bottom-hole drilling assembly components or parted drill stem is not uncommon in deep oilfield drilling. Fatigue, erosion, and corrosion failures of highly stressed components in the subsurface are difficult to prevent when drilling environment can not be totally defined. NASA does not have a good track record of operating complex mechanical systems on interplanetary space missions. Constant maintenance and repairs are a critical part of keeping drills on Earth operating. The opportunities for repairs will be severely limited on Mars. A specific example will be what to do if the bit mechanism fails, or if it encounters a rock type it cannot cut.

4.4. **Incorrect target depth**. If the target is deeper than the drilling system can reach, failure is inevitable. This could happen, for example, by incorrectly interpreting the depth to ground ice, and using this information to make critical design decisions. Also, for deep holes (e.g. 1 km or more), the ability to maintain a straight hole can make a significant difference in the total drilling depth.

5. **<u>Risk Reduction Strategies</u>.** The above risks can be mitigated in several ways.

5.1. **Geophysical investigations**. Geophysics can supply data in the following areas:

- ✓ Improved estimates of the depth to the target. Even more important, the information can be used to select a place where the target is shallow.
- ✓ Knowledge of the depth to bedrock, which is necessary for an effective casing strategy.
- ✓ Knowledge of the physical properties of both bedrock and regolith. This is important for design of bit and cuttings removal systems, as well as for predicting hole stability.

5.2. **Selection of the appropriate drilling techniques for the target area**

- ✓ Keep the drilling system simple and flexible at the same time.
  - Minimize assembly and dissembly requirements (bit changes)
  - Use modular designs that allow maximum reconfiguration of sub-components to maximize reconfiguration flexibility
- ✓ Minimize the interruptions of the drilling process
  - Schedule interruption to drilling to occur with bit changes or power interruptions
- ✓ Provide alternate methods for accomplishing critical high risk tasks so if plan A does not work plan B can readily be implemented.
- ✓ Select drilling procedures that minimize the damage in the event of a mishap.

5.3. **Drilling engineering test bed(s).** Testing of robotic drilling systems under simulated martian conditions is critical. Laboratory or bench-scale testing with various degrees of Mars environment simulation needs to be followed by field testing. Such tests will expand the range of conditions that the rig can tolerate (depth, temperature, lithostatic and fluid pressure). As drilling depths increase, the equipment will need to be designed to operate over a wider range of unknown environmental conditions. This means that the deeper systems will need to be much more flexible and robust.

- ✓ The probability of encountering very dry, unconsolidated material with boulders is a challenging environment which suggests beginning field test drilling in that environment before moving to permafrost conditions. Mr. Wayne MacIntosh, who was with the Corps of Engineers during the planned lunar drilling program, designed a 100 ft deep test bed of carefully engineered material in an above ground column of steel drums. The test bed was used. Drill bits and systems were tested against this standard material so comparisons could be made without the possibility of geologic inhomogeneities affecting results from site to site.
- ✓ Cryogenic Testbeds.
  - JPL has proposed a large-scale cryogenic testbed to aid in the development of sub-surface explorers to support several in situ missions. The testbed will simulate the atmospheric, surface, and sub-surface conditions that might be encountered in the in situ environment. The testbed will include a 5 m tall, 1 m diameter cryogenic, vacuum-jacketed column to contain the simulated in situ environment and materials. It will have differential thermal control along the 5 m depth, vacuum or expected atmospheric conditions at the experimental surface, in situ instrumentation, and the ability to create a wide variety of ices, regoliths, dust/ice mixtures, varying porosity materials, and layers. Contact: Jacklyn R. Green, JPL.
  - The Space Power Facility (120 ft deep x 100 ft diam.) at Plum Brook Station can support full scale testing with sustained high vacuum, simulation of solar radiation, and cryogenic temperatures with an LN2 cold wall.
  - NTS Rye Canyon Altitude Chamber (60 x 25 x 21 ft high) in Valencia CA can support tests to pressures as low as 5mb.
- ✓ Field testing. Exhaustive field testing of prototypes under as realistic conditions as we can get is essential. Testing sites can be chosen to challenge the equipment with a variety of bedrock and soil lithologies, thicknesses, ice content and ambient drilling environments (e.g. permafrost at Devon Island (in the Canadian arctic), Iceland, Alaska, Siberia, and the Dry Valleys of Antarctica).

5.4. **Mobility**. If the drilling is too difficult in the first place chosen, it will be a distinct advantage to have the option of pulling up, moving, and trying again (if the drill is not stuck and we have not used up our resources when we find out it is too difficult!!).

6. Geophysical Investigations of relevance to reducing subsurface exploration risk.

6.1. **Overall geophysical objectives:** Geophysical investigations are needed to support exploration of the above subsurface targets by supplying answers to the following questions:

- ✓ What is the planet-wide distribution, concentration, and state of water in the upper ~5-10 km of the crust?
- ✓ What are the thermal, diffusive, and physical properties of the upper crust that are of relevance to volatile transport and drilling?
- ✓ What are the physical properties of the upper martian crust that are of relevance to drilling (depth to bedrock, density, rock strength (compressive, tensile, shear), elastic

constants, cohesion, coefficient of friction). Most of these require samples or in situ measurements, but inferences can be made on the basis of seismic measurements.

6.2. **EM Sounding**: Radar imaging represents the single most promising technique to assess the 3-D distribution of water and ice in the upper 5-10 km of the Martian crust. Radar will have the best probability of gathering useful information on the appropriate scales about the martian subsurface in the near term. The fact that it is controllable (active source) and can perform global orbital surveys are key strengths. It may also provide a crucial test of the hypothesis recently proposed by Malin and Edgett for the presence of shallow (100-200 m) liquid water. Scattering could affect radar penetration. Grimm has calculated that scattering losses could be 1-100 dB/km one-way. Furthermore, the ubiquitous 10-m scale layering will limit penetration due to reflection losses by some 10 dB/km one-way. In addition, it must be recognized that radar might detect the first occurrence of subsurface water or slush and not be able to see anything deeper due to conductive losses.

Possible approaches:

- ✓ The MARSIS instrument, currently planned for Mars Express, should provide initial information, and a test of the presence of liquid water within the shallow subsurface. However, the ability of MARSIS to discriminate between ice-rich and ice-poor frozen ground, as well as its ability to detect liquid water at greater depths (>1 km) given less than ideal surface properties, appears limited. Our understanding of MARSIS is that there are 2 frequencies; the higher one may not penetrate too deeply into the subsurface and the lower one will suffer from ionospheric interference. It is also our understanding that the spacecraft will not orbit later than 9 o'clock local time, so the radar cannot take advantage of the late-night collapse of the ionosphere. We need verification of these facts, as well as an independent assessment of its potential.
- ✓ Second generation orbital GPR. We recommend that a higher-resolution and higher-powered, radar imager be considered as soon as possible to provide a comprehensive map of the distribution of ground ice and groundwater at greater depth. Designs may include a dual-receiver (either boom-mounted or, ideally, on a co-orbiting satellite), variable wavelength (centimeter to 100s of meters) system, a synthetic aperture system at HF frequencies (whose operation would be limited to shallow (i.e., ~0.01-10 m) depths), or a “coherent radio echo-sounding device” such as the UKANSAS CARDS system.
- ✓ Radar imaging from aerial platforms. If the resolution of orbital GPR is insufficient, we need to consider either airplane- or balloon-based instrumentation This would give coverage at a scale of perhaps ~10^3-10^4 km^2, rather than global coverage, but the resolution may be greatly improved.
- ✓ The MAGNET experiment on NETLANDER will use the Magnetic sounding method to investigate the Martian interior, in particular with the view to measure the water/ice content.
- ✓ Ground-based GPR. GPR at the surface will be an important tool for shallow exploration, but in order to image depths of 100s m to kms, the radar would practically have to dominate the exploration plan. This follows from the same considerations as seismic, that line lengths must be comparable to the depth of interest. We would probably want to use common-midpoint stacking at a minimum

and probably migration tomography since this will be a one-of-a-kind data set. If we are just looking for water, we can probably get by with smaller offsets as long as we can identify reflection hyperbolae from scatterers, from which velocity, thence dielectric constant, thence composition, can be inferred.

- ✓ Other EM systems (e.g. magnetotellurics and VLF sounding) are still in the feasibility stage, and we don't know whether they are realistic possibilities.

6.3. **Seismic Investigations**:

6.3.1. <u>Passive Seismic</u>. A widely spaced passive seismic array is the best method of resolving large-scale internal structure and for detecting and locating marsquakes (which is of value in understanding the current tectonic environment of the planet). Multiple receivers within a small area are required for high-resolution surveys, while a large number of widely dispersed receivers are necessary for global studies. However, for several reasons imaging of geologic interfaces using natural seismicity will be difficult. Even on Earth, where seismicity is thought to be much greater than on Mars, passive seismic techniques rarely yield a signal which is clear enough to interpret unambiguously.

<u>Possible approaches:</u>

- ✓ A global network of 20 receivers distributed in local clusters of 4 could provide both local and planet-scale coverage. If the receivers have a long enough lifetime, active sources can be deployed on subsequent missions to improve local imaging capability. Ideally, other geophysical investigations, such as GPR and magnetotellurics, should also be employed by each station of such a geophysical network.
- ✓ The NetLanders (currently proposed by CNES for 2005) will contribute to the above objective, but at a regional rather than global scale.
- ✓ The TUGS (Tactical Unattended Ground Sensor) system for seismic monitoring needs to be looked into, because of the potential for long service life.

6.3.2. <u>Active Seismic</u>. Active seismic methods (with an acoustic source) are potentially of use to acquire information on things like the depth to bedrock, structure and stratigraphy, and rock properties, each of which could contribute significantly to refining the drilling design. Such investigations would need vertical resolution of 10s to 100s of meters (increasing with depth). However, since the dimensions of a seismic survey at the surface need to be comparable to the depth imaged, our information would be limited to the 1-10 km patch selected. A key strategic question is whether we would want to return to the same place for a subsequent drilling mission (which would make selection of the location of the seismic survey critical), or whether our intent is to extrapolate the information from one part of Mars to another. The latter case is more realistic, given current landing capability, but it also reduces the value of the seismic information.

An important issue for all seismic exploration on Mars that must be answered is the role of scattering. The thick regolith of the Moon was found to be a very efficient scatterer of seismic energy. If the martian regolith similarly has abundant wavelength-scale heterogeneity, it may be difficult to identify any arrivals after the direct wave. This will strongly constrain global seismological studies, but it will utterly eliminate seismic reflection as an exploration tool. Refraction can still be used but requires even longer line layouts, has poorer resolution, and fails for certain velocity structures (the well-known blind-layer and velocity-inversion problems).

Possible approaches:

- ✓ Inline (2D): Once source sizes have been determined, seismic acquisition should begin with a simple "line" geometry, in which recording sensors (small seismometers, with telemetered data communication) are planted by a rover every 100 or so meters, over a course of a few kilometers. The rover can place the explosive charge at the same time, at about the same interval and over the same distance. If a rover is not available, alternatively sensors could be placed on the pads of the lander, and a mortar used to launch explosives out to increasing distances, to get a "profile" of data along a line. This experiment would yield less information than the former, rover-assisted experiment. The receivers need to be spaced closely enough so that the shallowest horizon of interest can be imaged and so that energy is not spatially aliased. This means that we would need receiver layouts several km in size with receiver spacings of maybe 100 m, which in turn means that we would need 10-100 stations for a 2D line.
- ✓ Areal (3D): A more ambitious experiment, and likely more feasible for a later mission when more is known about the near-surface acoustic properties, is to deploy sensors and sources in an areal pattern about a kilometer on a side. But given the average density of sensor coverage (about equal to a dominant seismic wavelength, say several hundred feet) at least a few tens of sensors (and a smaller number of sources) would need to be deployed. The sensors might be deployed directly from the orbiter prior to landing, in a "cluster-bomb" delivery. It is not necessary that the sensors be regularly aligned, and a cluster delivery would only have to ensure that all sensors landed within, say, a kilometer-wide patch [we have to accurately know the relative locations of the sensors for this approach to very useful].
- ✓ Shallow seismic refraction is the method of choice for resolving permafrost stratigraphy in the Arctic and would be ideal for the upper km of the martian surface.
- ✓ It may be possible to do active seismic data collection using a passive array of penetrators by deploying active sources nearby (either an explosion or an impact event). If the receivers have a long enough lifetime (i.e., ~10 yrs, or sufficient to operate over several launch opportunities), the sources could be deployed on subsequent missions. However, there is concern that direct emplacement from orbit would not have the relative accuracy to place receivers at 100 +/- 100 m spacings to form even an irregular grid. In addition, the number of penetrators required may be so large that mass becomes a significant issue.
- ✓ Source type: Terrestrial experience has demonstrated that the energy required to obtain a reflection from a depth of several kilometers is equivalent to ~0.5-10 pounds of dynamite per source location. However, at shallower depths, the combination of Mars' low atmospheric pressure and the expected occurrence of higher near-surface porosities is likely to result in an appreciable attenuation of seismic energy. Therefore, near-surface seismic imaging would benefit from some initial fundamental acoustic experimentation to address the following questions:

- What size source effort (charge size) is needed to produce and propagate energy that can be recorded for at least 5 seconds after the shot?
- Do the charges and/or the receivers need to be set below the surface to achieve good coupling? Even partial or very shallow burial greatly increases coupling.
- If a certain source energy requirement is deemed necessary, how much integration time/energy would be required for a low-energy, repeatable source, using some mechanical device which itself consumes energy?
- Alternatively, what is the least mass of explosive that is needed for local, regional and global studies, respectively? This topic has received some study – insensitive but energetic explosives designed to increase safety of nuclear weapons could be used effectively.
- Are there other potential sources of seismic energy (e.g., generated by the impact of penetrators or other kinetic vehicles) that could serve this purpose?

6.4. **Single station geophysics:** We need to carefully consider the kinds of geophysical instruments that can be added to a lander which is primarily designed for other purposes, but which could help constrain crustal models, or the design of subsequent missions/instruments.

Possible approaches:

✓ Possibilities include seismometer, GPR, gravimeter, VLF sounder, heat flow measurement.

✓ Magnetometer. Use a three-component fluxgate magnetometer to record the magnetic variations as a function of time. This would reveal whether local crustal magnetic fields vary in response to interactions with the solar wind or lightning. If measurable magnetic fluctuations do occur on Mars, then by measuring all three components, the local subsurface electrical resistivity of the crust could be estimated as a function of frequency, which may provide constraints on subsurface volatile content, phase, and distribution.

Issues. However, it has also been argued that if we measure magnetic fields only, the data are relatively insensitive to static shift, but we need an array of three-component instruments: effectively we compute the electric field from the curl of the magnetic field. A three-component magnetometer at a single station is not sufficient. The NetLanders are supposed to carry magnetometers, but the array geometry is very elongated along the equator and provides poor N-S gradient control. Therefore there will be large uncertainties in any conductivity-depth profile they produce. The second issue is the frequency band. A fluxgate is only good to 10-100 Hz, so it should be able to see sub-hertz variations in magnetic fields due to solar-wind ionosphere interactions and possibly any analogs to micropulsations caused by the "mini-magnetospheres" of the large crustal magnetic anomalies. However, this band is sensitive only to the conductivity-depth product of any subsurface conductor, say saline water. This in itself could provide great insight, but the better information on the depth to a conductor (more relevant to drilling planning) can be gleaned from the 10 Hz - 10 kHz band, where various phases of EM propagation from lightning can be observed. A fluxgate might be able to see Schumann resonances at < 100 Hz, but it couldn't see the high-frequency energy from the flashes themselves. For this we need an induction coil. These get heavy for good performance, so one would need to carefully evaluate the trade-off between diameter, mass, and sensitivity.

- ✓ Electric field. We can derive conductivity from three components of the electric field at a single location. The problems of static shift apply, and we also have to measure a vertical electric gradient that will likely be strongly affected by windborne charged dust particles. This experiment turns out to be easier to do from the air, which in fact was done in terrestrial mining exploration in the 60s and 70s.
- ✓ E&M together. There are constraints both in the frequency band and in the instrument type as to what can be measured. A true single-station experiment will require measurements of both electric and magnetic fields in order to derive a conductivity-depth profile: This is the classical magnetotelluric method. Grimm is presently working on a broadband electrometer to make these measurements at the high-resistivity conditions of the martian surface. A common problem with magnetotelluric measurements, however, is "static shift," which is simply distortion in the electric field caused by local, near-surface heterogeneity. In other words, near-surface structure can bias the magnetotelluric profile unless we have an array or other independent shallow EM sounding information.
- ✓ Active EM. It takes a lot of mass and power to run an EM transmitter, in contrast to radar. It would have to be a loop because we can't effectively ground a dipole on Mars. A good rule of thumb on Earth is that in order to see kilometers down, a loop of comparable size is needed. On Mars, where the crust is thought to be comparatively much more resistive, we may be able to get by with much smaller loop sizes. Regardless, active deep EM sounding would almost certainly be a logistical nightmare for Mars.
- ✓ The bottom line is that if we put a fluxgate magnetometer and a VLF antenna or search coil on a lander we will at least be able to begin to characterize the EM environment, whether that natural energy eventually is used as a sounding signal or is considered noise. Low-frequency EM methods have lateral resolution comparable to the exploration depth, so a single station would give us some general indication of conductivity structure on a horizontal scale of kilometers. A good exploration strategy might be to target prospective areas with radar and then land a surface EM station there. If we see indications of water it's a green light to send a drill to approximately the same location.

6.5. **Gravity Surveys:**

Possible approaches:

- ✓ Planetary-scale data are now available from MGS at 3 x 3 degree resolution [200x200 km].
- ✓ Better resolution will require airborne surveys or gravity gradiometry, which is routinely used on Earth to resolve crustal column density variations at sub-km levels). An airborne or rover-borne gravimeter could be a useful tool in non-intrusive exploration of the local to regional subsurface. Note that a single-station surface gravimeter will be useless - gravity is totally nonunique so we need a network to even begin to construct density-depth profiles.

7. **<u>Post-drilling Analysis</u>.** The answers to many of the scientific questions associated with exploration of the martian subsurface will require the analysis of samples.
   7.1. **Downhole data collection:** Proposed primary objectives are to detect sedimentary rocks, to distinguish clastic from carbonate sediments, to determine the porosity and water saturation, to distinguish liquid from frozen water, to measure the thermal profile, and to interpret as many physical properties of relevance to deeper drilling as possible.
   <u>Possible approaches:</u>
   - ✓ MA_MISS is a miniaturized near-infrared (0.8-2.8 μm) imaging spectrometer designed for studies of Martian subsurface layers designed by ASI. The instrument would be integrated into the drill and the data acquired through a flat window. It will be able to provide an image of a circumferential "ring", to estimate the composition and granularity of different layers and identify the mineralogy of individual grains.
   - ✓ Four easy logs would be the density, neutron (hydrogen ion detection), temperature, and natural gamma ray logs. None of these involve moving parts, and all will work in cased holes. Technology development for Mars application may be minimal.
   - ✓ Of additional value would be NMR (useful for distinguishing water and ice), resistivity (general lithology, water salinity), sonic log (particularly useful for recognizing carbonates), and the carbon-oxygen log (useful for carbonates). However, this latter group of logs will be more difficult. The carbon-oxygen log requires a neutron generator. The sonic tool has engineering complexity. The resistivity and NMR logs require either uncased holes or holes with non-metallic casing. Technology development would be needed on these latter tools.
   - ✓ A variety of other sensors could be used, and further study is needed to define an optimum set for downhole use.

   7.2. **Data collection at the martian surface**: In support of the previous '03 and '05 MSR missions, ASI designed IPSE, which is a microlaboratory providing the capability of handling several miniaturized instruments accommodated inside its structure. Approximately five selected instruments were to be included within IPSE.
   7.3. **Return samples to Earth for analysis:** Certain kinds of measurements require instrumentation that is currently too complex to fly to Mars, or they require sample preparation which cannot be done on Mars. It has been eloquently argued by many others that until these issues have been addressed, the scientific questions that constitute the justification for exploring the subsurface cannot be answered without an Earth sample return. <u>Special note</u>: Mars sample return will require containment on Earth until the sample can be determined to be non-hazardous.

8. **<u>Production of water from a martian drill hole</u>.** There are several different sources of water which could possibly be produced from the martian subsurface..
   8.1. **Water from hydrous minerals:**. If hydrous minerals are present in sufficient quantity, they could be mined and the water extracted.
   8.2. **Water from the cryosphere:**. The ice could be melted. Unfortunately, ice will not flow at a meaningful rate, so a well would have limited producibility.
   8.3. **Water from the hydrosphere:**. A classic water well. The difficulty here would be the challenge of transmitting the liquid water through the cryosphere without it freezing. In

addition, the amount of energy needed to lift the water many kilometers will require substantial pumps.

8.4. **Possibility of artesian water flow:** At the time of the Late Hesperian, the mean elevation of the major outflow channel source regions was ~0.5-1.0 km. The most widely accepted explanation for the origin of the discharged water is that it came from an aquifer that had a water table of equal or greater height. Since that time, the continued decline of the planet's internal heat flow is expected to have resulted in the further growth of the cryosphere -- trapping a significant amount of the groundwater that existed during the Late Hesperian into the frozen crust. The net effect is that the position of the global groundwater table is likely to have declined with time (although by how much is unkown). Thus, if a deep drill is placed in some low elevation region (like the interior of Valles Marineris), the surrounding water table could lie as much as several kms higher, resulting in an artesian hydrostatic head.

9. **<u>Technology R&D needed to support this strategy</u>**. Several technology developments are prerequisites to implementing this subsurface exploration strategy.

9.1. **On-Mars Life Detection:** The primary scientific objective of subsurface access is to detect life (either extinct or extant). The technology to do this at Mars by robotic means would greatly simplify the mission. If this technology is unavailable, we will be required to bring the samples back to Earth, which would greatly increase the engineering complexity (and therefore risk), and the cost.

9.2. **Advanced Power systems:** It is probably possible to reach our shallow subsurface objectives with solar power. The ability to overcome drilling problems (which are certain to amplify with increasing depth), however, requires additional power. Drilling at high latitudes has been studied by Glenn Res. Center – one needs 10's of kWe to do so and the solar array sizes are just too massive. Production of water to the surface will also require additional power for pumps, processing, and ice control.

9.3. **Long-life geophysical sensors:** Several types of new geophysical sensors need to be developed. One example is a multi-functional geophysical array (at least seismic and thermal sensors). A lifetime of more than one launch opportunity (at least several years and preferable ten years) would be a distinct advantage.

9.4. **Robotic drilling methods:** R&D work is needed into developing and field testing robotic drills under simulated martian conditions, to the depth ranges of interest. Drilling to several kilometers depth can be difficult on earth where the subsurface is relatively known. On mars many unforeseen drilling difficulties seem sure to occur, severely taxing robotic systems.

9.5. **Contamination-free subsurface sampling methods:** Subsurface sample acquisition must be done without subjecting the samples to elevated temperatures, as well as without contaminating the samples with Earth-sourced organisms. There are both scientific and planetary protection concerns that require technology developments to support sampling.

9.6. **Precision landing.** Minimizing the depth to subsurface drilling targets may require drilling in the bottoms of valleys, bottoms of craters, rims of craters, etc. Such accuracy would demand a higher precision landing system than currently exists. Obstacle avoidance has been cited by some as a "necessity" for future missions as well.

- **Downhole data acquisition:** Technology for resolving the primary downhole questions, including lithology, and water, ice, and gas saturation, is commercially available. The hardware will need to be adapted and refined for space application, but a technology breakthrough is not needed. Downhole data acquisition from sensors measuring drilling parameters in real-time will have to be developed if a high degree of autonomy of the drilling process is to be achieved. This capability has to be designed into prototype systems from the beginning to achieve reliable automatic process control.
- **Telecom Infrastructure**. Our capacity to understand MARS surface and sub-surface will be closely dependent on the available telemetry and telecom satellites orbital characteristics. The data transmission rates for some of the missions proposed above will need to be significantly higher than at present.
- **Production Engineering**: Once a drill hole into a water-bearing portion of the martian subsurface is achieved, we will be interested in converting it to a producing water well. This will involve unique engineering challenges. However, R&D funding is probably not required for a few years.

Possible preliminary candidate exploration plans

- **"aggressive"**
- **"low-risk"**

AGGRESSIVE MISSION PLAN

YEAR	*FLIGHT COMPONENTS*
01	
03	**MARSIS (on Mars Express): can be used to test the Malin and Edgett hypothesis of shallow (<200 m) liquid water.**
05	**Second Generation Orbital Radar Sounder: capable of assessing the 3D distribution and state of water within the top 5-10 km of the crust.**
	Single station geophysics package (seismometer, GPR, magnetotellurics feasibility, heat flow, VLF?) on heavy lander.
07	**20-Station Global Surface Geophysical Network: clustered in groups of 3-4 to provide higher resolution investigations of promising local sites identified by the Orbital Radar Sounder flown in '05.**
	French Netlanders: local and regional geophysical investigations ('07 = best estimate of scheduling).
	200 m drill. On-Mars analysis of recovered samples of cryosphere. Possible link to MSR?
11	**Local (2-10 km^2 area) High-Resolution Geophysical Networks: investigations of promising targets identified from the '05 and '07 missions.**
15	**4 km drill. Access water beneath the cryosphere. On-Mars analysis of recovered samples. Possible link to MSR?**

CONSERVATIVE MISSION PLAN

YEAR	*FLIGHT COMPONENTS*
03	MARSIS (on Mars Express): can be used to test the Malin and Edgett hypothesis of shallow (<200 m) liquid water.
05	French Netlanders: local and regional geophysical investigations.
07	Second Generation Orbital Radar Sounder: capable of assessing the 3D distribution and state of water within the top 5-10 km of the crust. Incorporates MARSIS experience into design.
	French Netlanders: local and regional geophysical investigations ('07 = best estimate of scheduling).
	5-10 m drill—instrumented: on heavy lander. Possible link to MSR? In situ drill cuttings analysis (min/pet, organic/inorganic composition).
	Single station geophysics package (seismometer, GPR, magnetotellurics feasibility, heat flow, VLF?) on lander.
09	20-Station Global Surface Geophysical Network: clustered in groups of 3-4 to provide higher resolution investigations of promising local sites identified by the Orbital Radar Sounder flown in '07.
11	Local (2-10 km^2 area) High-Resolution Geophysical Networks: investigations of promising targets identified from the '07 and '09 missions.
13	50-200 m drill (technology demo + science investigations of dessicated zone and ground ice). Possible link to MSR?
17	1 km drill. On Mars analysis of recovered samples. Possible link to MSR?
21	4 km drill. Access the unsaturated zone. On-Mars analysis of recovered samples. Possible link to MSR? Recommend steering capability.

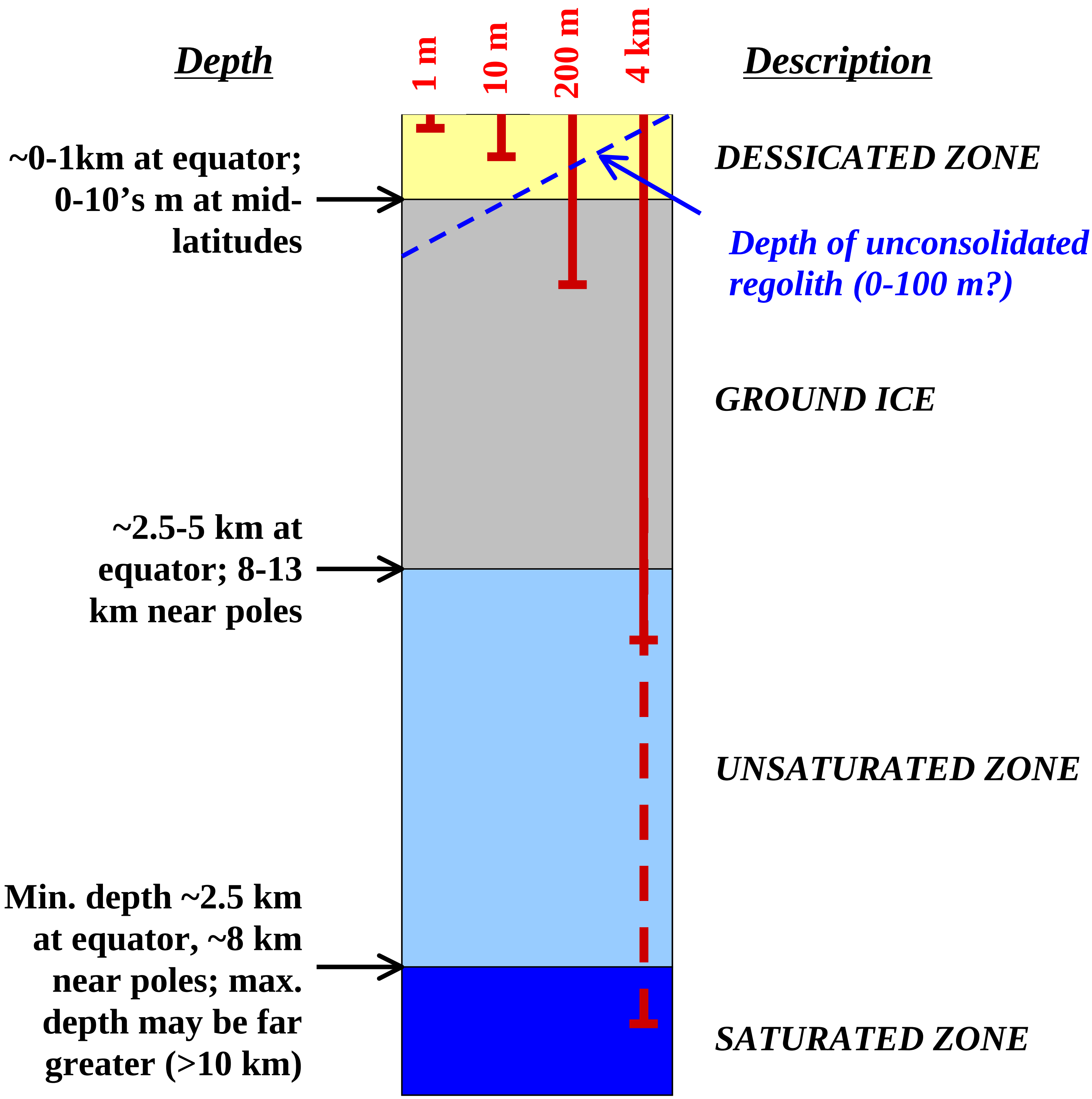

Figure 1. Schematic illustration of the principal martian subsurface targets, and their relationship to possible drill holes.