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# **Workshop Report On Deep Mars: Accessing The Subsurface Of Mars On Near-Term Missions**

*Compiled and Edited by:*

*Stephanie Langhoff*

*Chief Scientist*

*Ames Research Center, Moffett Field, California*

Report of a workshop  
sponsored by and held at  
NASA Ames Research Center  
Moffett Field, California  
on March 1-2, 2008

**July 2008**

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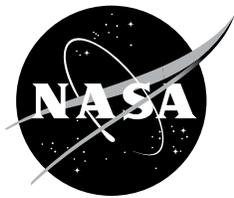
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## Executive Summary

On March 1 and 2, 2008, NASA Ames Research Center hosted a two-day weekend workshop entitled “Deep Mars: Accessing the Subsurface of Mars on Near-Term Missions.” This workshop is part of a series of informal weekend workshops hosted by the Ames Center Director, Pete Worden. The workshop agenda was structured to bring together the science and engineering communities who have a common interest in drilling technologies and exploration of the Martian subsurface.

The agenda blended three major themes:

- (1) The scientific objectives of drilling, such as the search for clues to the existence of past life and to the geological and climate history of the planet. Key questions are where and how deep to drill? Planetary protection issues were stressed as an important consideration in the design of any drilling mission.
- (2) Architectures for drilling missions that included an overview of most of the current drills in operation that would be applicable to drilling on Mars. Considerable emphasis was placed on remote operation and drilling automation technologies.
- (3) Alternatives to conventional drilling included underground moles, horizontal drilling, penetrometers, impactors, and access through subsurface cavities.

In the afternoon of the second day, the participants broke into two groups to discuss possible missions that could access the subsurface of Mars in the near term (that could be launched within five years) and in the longer term with improvements in technology and with/without human involvement.

In the first session focusing on the science objectives, it was noted that the picture we have of Mars has significantly changed due to recent scientific studies. For example, the MER rovers have found incontrovertible evidence that water once flowed on the surface. Pictures of gullies on Mars suggest that outflows of liquid water occur today. Warm spots have been observed on the Martian surface and methane has been observed in the Martian atmosphere. Also, recent work in astrobiology has shown that microbial activity occurs even at extremely cold temperatures. All of these recent discoveries suggest that life could exist in the shallow subsurface of Mars and could be found without drilling to great depths. Therefore, if currently active sites are discovered, such as outflows of liquid water, they would be excellent targets for drilling. The next best alternative might be an old lakebed where one expects uniform sediment. Drilling missions to both the south and north poles were also suggested. While the scientific objectives and required drilling depths would be different for south and north polar missions, the ice would be much easier to drill through than surface rock.

Architectures for drilling missions were discussed in considerable depth at the workshop. The lunar experience has shown that drilling on planetary surfaces will be challenging even with humans in the loop. The difficulty in drilling on Mars is exacerbated by environmental and physical constraints such as low gravity, pressure and temperature, large temperature fluctuations, dust storms, and the presence of water ice. Technological challenges such as the transmission delays, power and mass restrictions pose additional problems. There was considerable discussion about the current state-of-the-art in autonomous drilling methodology. There was general agreement that there needs to be an infusion of technology development funds to bring many of the currently operating drills to a higher Technology Readiness Level (TRL).

In addition to conventional vertical drills, other mechanisms for accessing the subsurface of Mars were discussed, such as penetrometers that use a hammering or pushing mechanism for forward and reverse propulsion, horizontal drills that might be applicable on steep terrain where there is recent evidence for liquid water, and impacts to create craters. One interesting possibility is finding natural subsurface cavities, such as lava tubes. The possibility exists that a lava tube could evolve into a permanent ice cave lake that could be a safe haven for ice particles, organics and microbes trapped for potentially several billion years.

In the breakout sessions the participants discussed the possible missions that could be undertaken in the short and long term. A key observation was that an impactor and/or penetrator mission could be done today either as a standalone or add-on mission for relatively low cost. Current technology would be able to hit a predetermined target on the surface at a time that the impact could be observed by orbiting spacecraft. This could expose the surface below the oxidized zone and create a new crater that would be an ideal target for a follow-on drilling mission. This mission concept is so compelling that the group decided to write a white paper to describe the low-cost impactor mission more fully. In the longer term it was felt that a dedicated drilling mission could achieve a depth of 40–50 m operating the drill autonomously. Human missions could probably reach considerably deeper, although this would require a fairly massive drill. However, with the next generation heavy launch vehicle such as an Ares V, it would be possible to put such payloads on the surface of Mars.

# **Workshop Report On Deep Mars: Accessing The Subsurface Of Mars On Near-Term Missions**

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## **I. Introduction**

A workshop entitled “Deep Mars: Accessing the Subsurface of Mars on Near-Term Missions” was held at Ames Research Center on 1–2 March 2008. This workshop is part of series of informal weekend workshops hosted by the Ames Center Director, Pete Worden. The organizing committee included Stephanie Langhoff, Chris McKay, Carol Stoker, Geoffrey Briggs, Larry Lemke, and Brian Glass of Ames Research Center, Tullis Onstott (Princeton), George Cooper (UC, Berkeley), Michael Hecht and David Beaty of JPL, and Michael Meyer of NASA Headquarters. The workshop agenda was structured to bring together the science and engineering communities who have a common interest in drilling technologies and exploration of the Martian subsurface. Approximately 45 persons representing the government, industry, and academic communities attended (see list of attendees).

The agenda blended three major themes: (1) The scientific objectives of drilling, which center around the search for clues to the existence of past life and to the geological and climate history of the planet. Key questions are where and how deep to drill? Planetary protection issues were stressed as an important consideration in the design of any drilling mission. (2) Architectures for drilling missions included an overview of most of the current drills in operation that would be applicable to drilling on Mars. Considerable emphasis was placed on remote operation and drilling automation technologies. (3) Alternative to conventional drilling that included underground moles, penetrometers, horizontal drilling, impactors, and access to the subsurface from subsurface cavities. Except for two 30 minute foundational talks designed to provide overviews of the science objectives and drilling architectures, all contributed talks were 15 minutes. Ample time was provided for discussion. The final afternoon was devoted to interactive discussions, organized around designing possible missions for subsurface exploration, in the near and longer term.



## II. Science Objectives

To set the stage for the discussion of methods to access the subsurface of Mars, the participants first discussed the science objectives, which center around the search for evidence of life. This raises questions of where and how deep we need to search and how to accomplish these objectives within planetary protection guidelines. We began the session with a presentation by T. C. Onsott. He began his overview by noting what we knew (or thought we knew) about the potential for life in the subsurface of Mars 10–12 years ago before recent results from the MER rovers and the Mars Reconnaissance Orbiter (MRO). We knew then that life prospers in many extreme environments on Earth. For example, life is found down to 3 km and in 3 million year old (myr) permafrost. On Mars permafrost would lie at great depths (order of kms) at low latitudes and water would lie below that. Since the surface of Mars is exposed to ultraviolet and cosmic radiation and is highly oxidized (e.g., by hydrogen peroxide), this requires us to look well below the surface to look for extant Martians. What is thought to lie beneath the crust of Mars at low latitudes is shown in figure 1. The figure suggests that to find extant life at low latitudes one would have to drill a substantial distance through ice and rock.

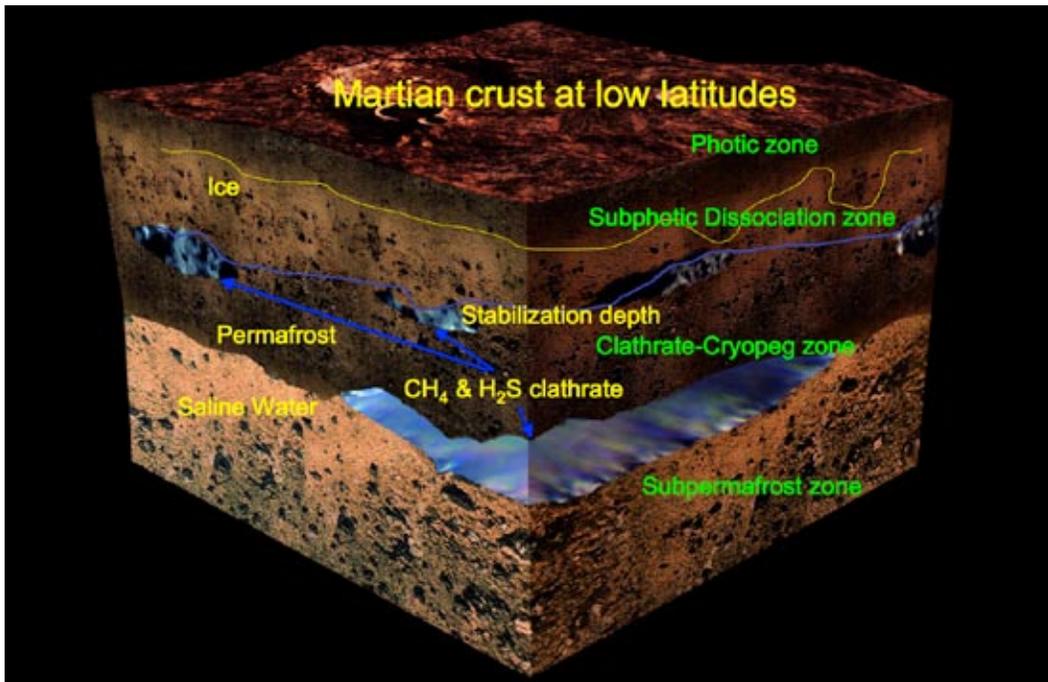


Figure 1. Based upon the physical properties of the Martian crust down to 5 km at low latitudes and the equations of state of  $H_2O$  and  $CH_4$  four different types of environments or potential biomes exist in the Martian subsurface. The mean annual surface temperature is  $218^\circ K$  and mean annual surface pressure is 6 millibars. The uppermost vadose lies above the ice, which sublimates at a depth dependent rate of  $\sim 0.03\text{-}0.07$  m/myr. About 1.5 meters below that ice surface the pressure is great enough to stabilize clathrates such as  $CH_4$  clathrates. This mixed clathrate/ice zone may contain pockets of saline down to a depth of 2 to 2.5 km at which point brine becomes pervasive. The depth of this permafrost zone extends downwards over time at a rate of  $\sim 0.5$  m/myr as Mars cools. Four distinct zones exist under which different metabolic processes and rates can occur. By relating potential energy fluxes to biodensity the potential biomarker fluxes can be calculated and their potential release into the atmosphere estimated.

Since then, a number of scientific discoveries have changed our thinking about Mars. For example, the MER rovers have found incontrovertible evidence that water once flowed on the surface of Mars. These recent data refute the theory that the fluvial-appearing features on Mars are caused by liquid CO<sub>2</sub>. In addition, there is very recent evidence that the surface of Mars is very active. For example, before and after pictures of gullies on Mars suggests that outflows of liquid water occur today. We now know that Mars is currently in an interglacial period with ground ice thawing and producing recent landslides and debris aprons. We have discovered warm spots on the Martian surface that are related to deep open volcanic conduits that undoubtedly have still deeper lava tubes. We have carried out ground penetrating radar from orbit to map the ice caps, but have failed to detect distinct subsurface reflectors that may be related to subsurface permafrost brines. We have discovered methane in the Martian atmosphere, which could be a biomarker of subsurface life on Mars.

Recent work in astrobiology has shown that microbial activity occurs even at extremely cold temperatures and can live in very extreme environments. Recently microbiologists have discovered ultra-small, saline tolerant microbes in 120 kyr Greenland ice and have reported microbial life growing at -15 °C and apparently synthesizing amino acids at -80 °C. We have found that chemolithotrophic microbial communities are prolific, complex in permafrost cave environments, and can exist in extreme environments such as pH 10 fracture water in ultramafic rock. Microbiologists using environmental chambers simulating Martian environments have found that microorganisms, in particular methanogens, can survive Martian conditions if protected from UV. Recently scientists have speculated that life forms could exist in a very oxidizing environment based on a hydrogen peroxide water cycle (carbon dioxide plus water producing formaldehyde and hydrogen peroxide). Microorganisms based on this chemistry would be sensitive to hyperhydration—death by exposure to water.

All of these recent discoveries suggest that life could exist in the shallow subsurface of Mars, and that to find life on Mars may not require drilling to great depths to tap the brine beneath the permafrost. Based upon this new information and the concept of biological biomes, figure 1 subdivides the Martian crust into potential habitats.

Any drilling that will be carried out on the surface of Mars will have to be done within the guidelines of planetary protection. Catharine Conley, NASA's Planetary Protection Officer, presented the current planetary protection policy. The two key objectives are to avoid forward contamination to preserve planetary conditions for future biological and organic constituent exploration, and to avoid backward contamination to protect Earth and its biosphere from potential extraterrestrial sources of contamination. Five mission categories have been designated based on mission type and planet priorities depending on the astrobiological interest in the target and the probability of forward contamination. For example, an Earth-Return mission from any solar system body would rate as mission category V due to the potential for backward contamination. For missions with lander systems carrying instruments to investigate extant Martian life, the entire landed system must be sterilized to levels driven by the nature and sensitivity of the particular life-detection experiments, or to limits imposed by planetary restriction regulations, whichever is more stringent. Alternatively, only subsystems involved in the acquisition, delivery, and analysis of samples need to be sterilized, if methods for preventing recontamination of the sterilized systems and material are in place.

Dr. Conley described the new Committee on Space Research (COSPAR) policy that designates special regions on Mars. A Special Region is defined as either a region within which terrestrial organisms are likely to replicate or a region that has a high potential for the existence of extant Martian life. This translates into areas or volumes within which sufficient water activity and sufficiently warm temperatures permit replication of Earth-like organisms. Specifically, the limits on water activity are between 0.5 and 1.0. The lower limit for temperature is  $-25\text{ }^{\circ}\text{C}$  with no upper limit. The timescale within which limits can be identified is 500 years. This means that observed features for which there is a significant probability of association with liquid water, e.g., gullies, pasted-on terrains, and the subsurface, are classified as Special Regions. In the future other Special Regions may be created based on geothermal activity, spacecraft induced activity, or the inference of possible Martian life forms.

Finally, the constraints that planetary protection requirements place on drilling on the Martian surface were discussed. Deep drills (below 5 m) will be accessing Special Regions and therefore must be cleaned (and re-cleaned) to levels deemed appropriate for landers (currently  $<0.3$  spores per meter<sup>2</sup>). She ended by describing how this could work on the surface with a combination of robotic and human presence. Some regions would be determined to be safe zones from precursor missions. The habitats and laboratories would be established in safe zones. Other sites that would be characterized as Special Regions would be subject to more stringent sterilization constraints, depending on characterization from ground data and remote sensing. One of the key conclusions from her presentation is that drilling can proceed on Mars, but the drills will require sterilization to meet the requirements for Special Regions. This can be affordably done as, for example, with Viking, but it is a cost that needs to be factored into total mission cost.

Peter Doran presented a paper entitled “Drilling as a Science Driver for Human Exploration.” He described the results of a study performed by the Human Exploration of Mars Science Analysis Group (HEM-SAG) in March 2007. Their charter was to develop the goals and objectives for the scientific exploration of Mars by humans. The main assumptions were that there would be three missions beginning as early as 2030, that scientific objectives will be set about 5 years prior to launch, and that robotic exploration will operate continuously until human missions begin. The HEM-SAG concluded that three independent sites is preferable to revisiting the same site, that a “long-stay” (~500 days) is preferable to a “short stay” (~30 days), and that human mobility needed to be at least 200 km. They also determined the vertical subsurface access (drilling) to be ~300 m for access to potential subsurface liquid water zones, less (5–50 m) at multiple sites on traverses. Finally, selective recoverable coring, e.g., on polar ice, would be needed for depths from 300 m to 2 km. Two advantages of human presence was the ability to do lab work on site and the possibility of drilling deep into the subsurface.

Deep drilling on Mars would be valuable for determining the large-scale vertical structure and chemical and mineralogical composition of the crust. Sampling ground ice would assess recent climate change and water cycling. Deep drilling could provide insight into the nature of crustal magnetization, could ground truth remote sensing methods such as ground penetrating radar, and could document the tectonic history of the crust. In addition to these geophysical reasons, drilling could provide a baseline chronology of the climate history and provide evidence of extinct or extant life. Several examples of interesting places to drill were presented based on recent evidence for liquid water near the surface.

A number of issues were identified that will require handling prior to human arrival. For example, deep drilling in the ice caps requires understanding how to drill in dirty ice while meeting planetary protection issues. Drilling elsewhere on Mars will require determining the feasibility of drilling several hundred meters without fluids within reasonable weight and size limits. Other feasibility issues include getting humans and/or robots to drill on steep slopes and making the drill sufficiently mobile that it can reach interesting drill sites. Other questions raised by the HEM SAG group were what are the limits of robotic drilling, do we have to line the hole, and can astronauts drill effectively in EVA suits under planetary protocol restrictions. Therefore, if we need to drill deep on Mars to answer the important scientific questions, is human presence required? If so, then deep drilling may be a driver for human exploration.

In the workshop, we did discuss some of the questions raised above. However, most of the focus of the workshop was what can be done with existing technology to drill on the surface of Mars remotely. Where are the best places to drill, how deep do you need to drill, and what are the limits of autonomy for not only drilling, but alternatives to drills such as moles?

Dr. Chris McKay discussed two potential missions to Mars, one to the north pole and one to the south pole. The purpose of the north-pole mission is to search for evidence of liquid water, organics, and preserved organisms in five million year old ice. This would require relatively shallow drilling to a depth of between four to ten meters. For liquid water to survive at the surface it requires ice, temperatures greater than zero degrees centigrade, and pressures greater than 6 millibar. These conditions have been attained in the north polar region at least in the recent past. Today the obliquity of Mars is 25 degrees, but five million years ago the obliquity of Mars was 45 degrees, which produced twice the incident sunlight in the polar summer (see figure 2).

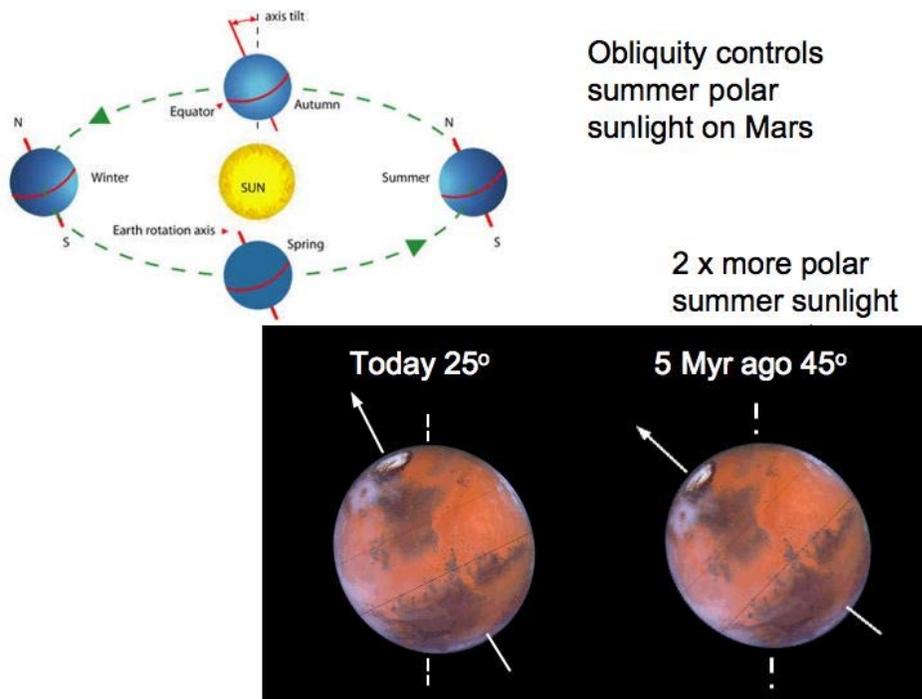


Figure 2. Today the obliquity of Mars is 25 degrees, but five million years ago the obliquity of Mars was 45 degrees, which produced twice the incident sunlight in the polar summer.

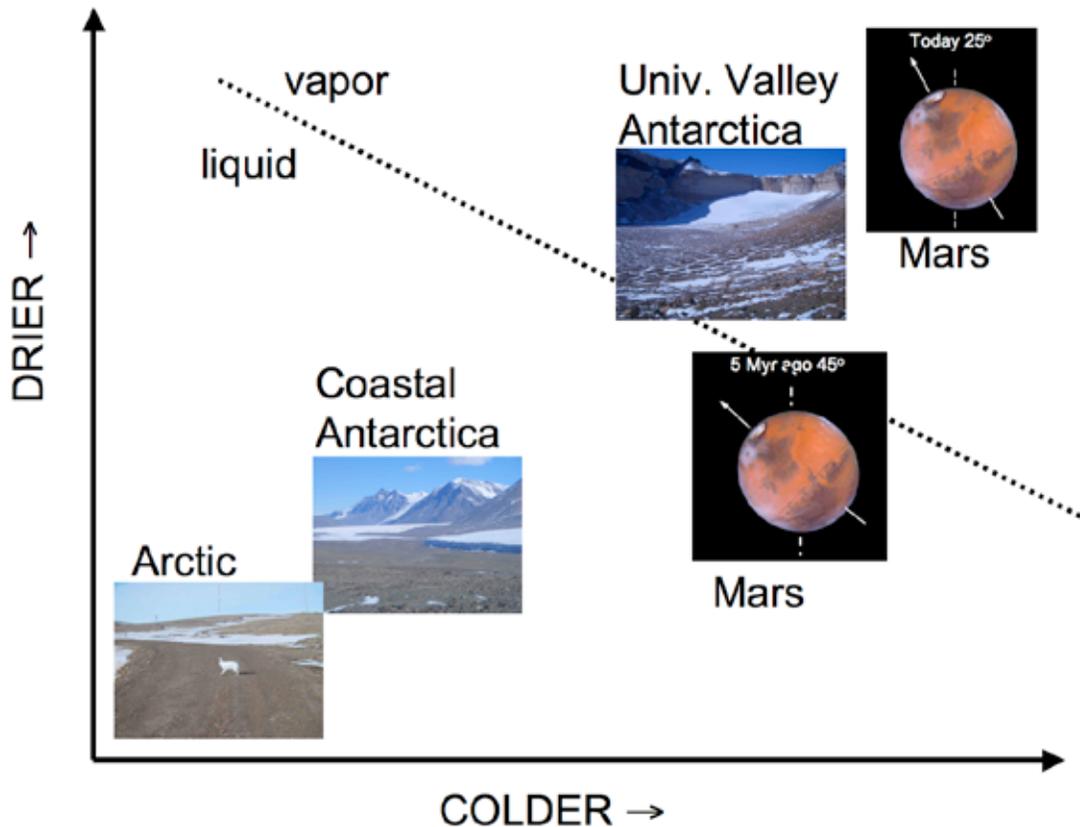


Figure 3. A plot of temperature versus dryness comparing Mars five million years ago with Mars today.

Shown above in figure 3 is where Mars five million years ago would have fallen on a plot of temperature versus dryness. At the higher obliquities, the surface temperature could have exceeded zero degrees centigrade, thereby permitting water to exist on the surface.

The purpose of the south-pole mission is to search for preserved organisms of life that may have existed 3–4 billion years ago when Mars was much warmer. This would require sampling in the south polar permafrost to much larger depths, probably 100 m. There is evidence that viable bacteria exists in 3.5 million year old permafrost in Siberia. There is evidence for metabolism in permafrost down to –15 degrees centigrade. Metabolism appears to be limited mainly by nutrient transport, not temperature. Micro-organisms in permafrost at 10 degrees centigrade are inactive, not because they are frozen, but because they are starving. Dr. McKay showed several instances where bacteria existed under extreme conditions on Earth. These provide analogs for believing that evidence for ancient Martian life could be preserved in the south pole ice. One could at least expect to find fossils of ancient life on Mars. This would tell us that life once existed on Mars, but would not tell us the nature of that life or its relationship to life on Earth.

Dr. Lyle Whyte from McGill University spoke about permafrost microbial biodiversity and ecology. The research objectives were to expand fundamental knowledge of microbial diversity and ecology in unique Canadian arctic ecosystems, to determine the cold temperature limits for life, and to explore these extremely cold environments as extraterrestrial analogs. Permafrost is an

example of an extreme cryoenvironment. It consists of an upper active layer (0.5–10 m) where the temperature fluctuates with air temperature, a permafrost table, and permafrost below that down as far as 1450 m. The environment is characterized by subzero temperature, background radiation for geological time scales, low water activity, and extremely low rates of nutrient and metabolite transfer.

Dr. Whyte discussed work that was carried out under the Astrobiology Science and Technology Instrument Development (ASTID) Mars drill project in 2003 in Eureka, Nunavut. The goals of this work were to develop ground ice and permafrost aseptic drilling techniques and to explore the microbial biodiversity in this environment. Several cores were drilled down to approximately 15 m. Although the predominant classes of bacteria found were actinobacterial and proteobacteria, there was considerable phylogenetic diversity in the core sample. The permafrost microbial activity was studied at subzero temperatures using CO<sub>2</sub> flux as a measure. Culturing bacteria at these temperatures required the development of low-temperature growth media. The low-temperature limit for microbial growth was observed to be –12 degrees centigrade. On Mars we expect very low microbial biomass and extremely low rates of microbial activity. Analysis of the ice core samples will, therefore, need the requisite sensitivity. He ended his presentation by talking about the cold saline springs microbial communities that are found in these permafrost regions.

The morning session ended with a panel discussion entitled “Why, where and how deep?” The panelists included T. C. Onsott, Cassie Conley, Chris McKay, Jim Green, and George Cooper. On the question of where to look, it was noted that the best targets for drilling are active sites, such as newly formed craters, or places where there is evidence of methane or liquid flow near the surface. In these sites, life may be closer to the surface, precluding the need to drill too deeply. However, we don’t currently know of any active sites, so that drilling in an old lakebed where one expects uniform sediment may be the best alternative. Even so, the drill would need limited mobility to avoid rocks. It was also noted that dirty ice is better than pure ice as a host for bacteria. Dirty ice would not pose a drilling problem, but ice with embedded rocks would be much more difficult to drill.

Another discussion topic was how deep to drill and whether humans needed to be in the loop. It was generally agreed that having humans in the loop would be very beneficial, not only because of their intelligence, but because they are universal system engineers, and with hammer in hand can do many tasks easily that are difficult to automate. Humans may also be important in choosing a good drilling site, if the goal is to drill as deeply as possible without getting stuck. Drilling through a basalt block is unproductive. It was also noted that cold is your friend when drilling. Drilling quickly could melt the ice around the bit, resulting in jamming of the drill when refreezing occurs. Cold drilling is also better from the standpoint of preserving evidence for life.

### III. Architectures for Drilling Missions

In the afternoon of the first day, the workshop changed its focus to drill architectures that are applicable to drilling on the Martian subsurface. Kris Zacny gave the foundational talk that provided an outstanding introduction to planetary drilling and an overview of the available drill systems. He began his talk by giving a brief history of lunar drills, which were 500 watt, battery powered, and human operated rotary percussive drills. Drilling on the lunar surface was difficult, as it required two astronauts to remove the drill stem from the hole. The lunar experience showed that drilling on another planetary surface is difficult even with humans in the loop. Mars would represent an even greater challenge than the moon, because of the far greater geological uncertainty. The difficulty on Mars is exacerbated by environmental and physical constraints such as low gravity, pressure and temperature, large temperature fluctuations, dust storms, and the presence of water-ice. There are technological challenges as well, such as transmission delays of up to 20 minutes (one way) and power and mass restrictions on the drill.

Dr. Zacny noted that drilling includes augering, that is, there must be a method of removing the cuttings from the hole. He discussed the principles of drilling such as weight-on-bit, which determines the stress exerted on the rock. The weight-on-bit must be sufficient to overcome the compressive strength of the rock. As drill bits get dull, higher weight-on-bit is needed to maintain penetration. He noted that revolutions per minute (rpm) is proportional to drilling power, core temperature rise, and auger throughput, which underscores the importance of efficient augering. Augers generally work best when conveying dry, loose granular material over short distances and at high rpm. An alternative to augering is to use compressed gasses for cuttings removal, and this has been shown to be quite efficient at low Martian atmospheric pressure. Drilling at low temperatures is more difficult, because the compressive strength of rock increases with decreasing temperature. He also noted the concerns for dry drilling, which include an auger for cuttings removal, higher bit wear, and higher core temperature rise.

One issue in drilling on Mars is the loss of ice from the heat generated in penetrating the formation. Since ice is relatively easy to penetrate, heat input will sublime a low fraction of the ice in the cuttings. However, for a material like basalt, which is difficult to drill and has low porosity, all of the trapped ice (if present) is predicted to sublime. Since adsorbed water on any surfaces tends to escape under Mars conditions, the friction of the two sliding surfaces is reduced, making drilling more efficient. However, if for some reason (such as drilling into hard rocks at high power levels) the drill bit reaches higher temperatures, the overlying surface oxide layers escape increasing the friction and, in turn, drilling power.

As part of his overview, Dr. Zacny discussed the existing options for deep drilling. Drilling methods include drill string systems that produce weight-on-bit by using a heavy lander or ground anchoring, and autonomous tethered systems that produce weight-on-bit using borehole anchoring. He overviewed the Johnson Space Center-Baker Hughes and Raytheon-United drills, which are wire-line rotary coring drills that acquire 2.5 cm diameter and 10 cm long cores. He discussed the JPL gopher drill, which is a wire-line percussive coring drill that acquires 4.5 cm diameter

cores, and the Swales-ATK rotary coring drill that acquires 1–2 cm cores. Also discussed were the Honeybee/Ames drills (Drilling Automation for Mars Exploration (DAME) and Mars Analog Rio Tinto Experiment (MARTE)) that are autonomous “smart drills.” Most of these drills were discussed in more detail in subsequent presentations.

Dr. Simon Auclair discussed a simulated Mars mission carried out at the Flashline Mars Arctic Research Station located on the rim of Haughton Crater some 900 miles from the North Pole. This four-month mission was carried out as realistically as possible, including living in tight quarters and using space suits on the 89 Extra Vehicular Activities (EVAs). The main scientific objective was to acquire knowledge of the biology and geology of the permafrost as the Arctic winter-to-spring transition occurred. The main technical challenge was penetrating the permafrost. The best option for accessing the subsurface was a portable core drilling system, such as a Hilti rotary hammer. In particular, they used the Hilti TE 56-ATC CombiHammer, which had three modes of operation, namely, rotation, hammer, and dual. The alternate drill modes helped prevent getting the drill stuck in deep holes. They drilled at a number of sites to a usual depth of 32 cm in the permafrost (after removing the top active surface with a shovel). A maximum depth of 1.5 meter was reached in a polygonal field, and bringing the core up to the surface proved to be a difficult task. Analysis of the samples aims at correlating the variations in microbial activity with soil type, water ice content, depth, atmospheric conditions and time. The mission was successful in demonstrating that drilling could be successful in a Mars analog with humans in the loop.

Dr. Carol Stoker discussed the 2005 Mars Astrobiology Research and Technology Experiment (MARTE) robotic drilling mission to Rio Tinto, Spain. The site is a possible modern analog to conditions on Mars that formed jarosite rich deposits at Sinus Meridioni. The coring drill has a 10 m-depth capability, and a fully automated drilling, sample handling, and life detection capability. It has a down hole inspection system that includes a panoramic microscopic imager and a Raman spectrometer that can be deployed after drill removal to inspect the bore hole at depths of 0 to 25 meters. The drill is also equipped with a robust life detection capability that uses microarray technology to detect microorganisms and their metabolic byproducts.

What sets MARTE apart from other drills is the degree of autonomy. All of its instrumentation can be operated remotely to select samples for biological analysis. Samples from a variety of depths can be analyzed for biosignatures. MARTE was able to characterize the geological history of the Rio Tinto area. Visible and near-infrared spectra of the cores showed the presence of iron-ores goethite ( $\text{FeOOH}$ ) and hematite ( $\text{Fe}_2\text{O}_3$ ). Raman spectral analysis revealed organic carbon at some locations in the hole. The life detection experiments show the presence of bacteria at all depths.

In conclusion, the MARTE robotic drilling experiment at Rio Tinto demonstrated autonomous drilling and sample handling to six meters in 30 days of operation. Drilling to search for life successfully identified in situ organisms with populations varying with depth. The experimental suite of instruments was able to characterize the geology of the drill site including mineral identification and the detection of organics. The results show that autonomous robotic drilling to search for life is technically feasible.

Dr. Robin Bolsey gave a brief overview of hot water drilling. He discussed the Ice Core Drilling Services (ICDS) system, which is a 20 liter per minute drill system that uses JP8 fuel to heat the water. He showed examples of other larger drill systems, such as the Ice Cube hot water system at the south pole that can drill 2,500 m, 60 cm diameter holes. Some stone in the ice layer does not prevent drilling, in fact, the hot water approach is fairly tolerant to environmental factors such as debris and component size distribution. Hot water drills on Mars would likely be used as hole-only access drills with objectives achieved at points along the borehole and/or at the bottom.

Dr. Slawek Tulaczyk discussed the Lake and Ice Stream Subglacial Access Research Drilling (LIS-SARD) project. This is an integrative study of marine ice sheet stability and subglacial life habitats in West Antarctica. He showed that Antarctica is a continent with subglacial lakes and rivers below the 2000 meter thick ice sheet (see figure 4). The top level scientific objectives of the project are to determine whether subglacial lakes cause or contribute to the instability of the West Antarctic ice sheet, and whether subglacial lakes have microbial life activity, and if so, what life forms can survive in the dark subglacial ecosystems isolated from the atmosphere. These scientific objectives are not only relevant to potential life under the Martian surface, but to other astrobiologically interesting sites like Europa.

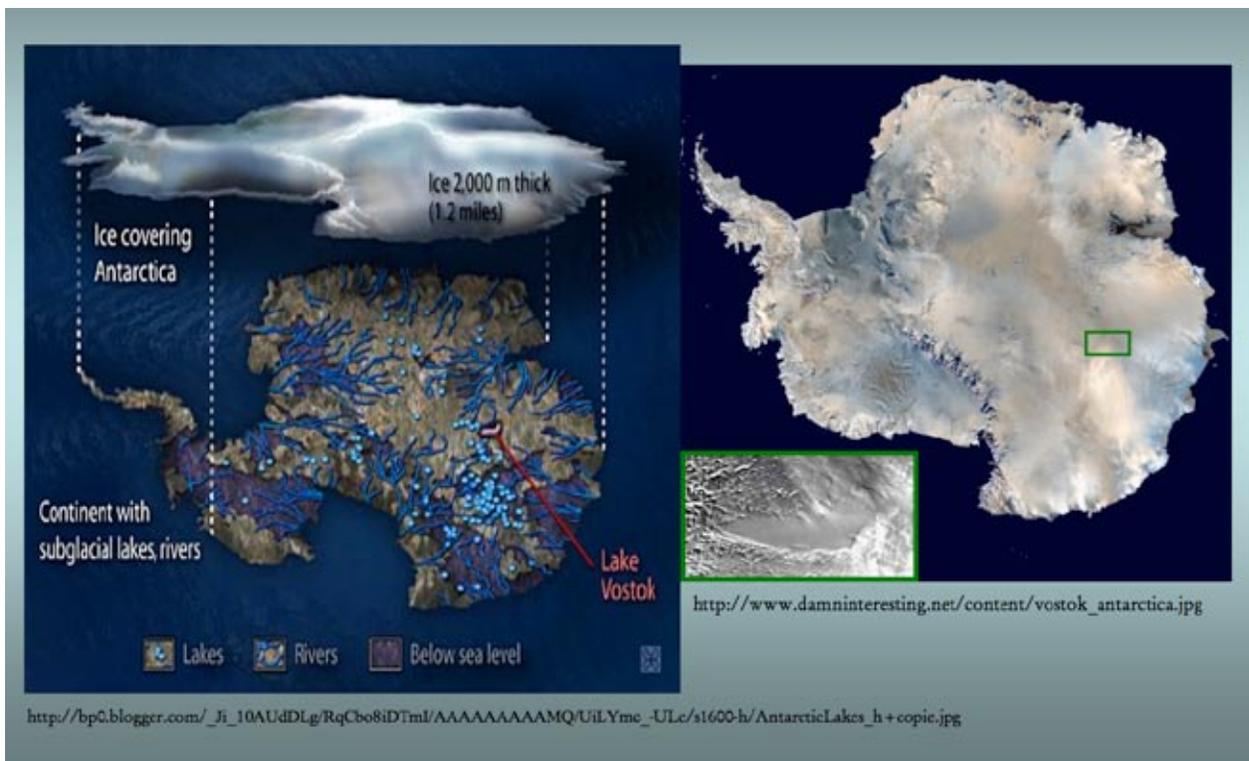


Figure 4. Antarctica is a continent with subglacial lakes and rivers below the 2000 meter thick ice sheet.

Dr. Jim Green discussed the drill requirements, design, performance and difficulties associated with the KOCI drill. The goal was to develop a new dirty ice drill that was capable of taking quality cores from the surface to the bed of Beacon Valley Glacier. Tests of the drill were performed in the Antarctic Specialty Management Area (ASMA). Access is by helicopter, because the rocky terrain prevents the use of sleds. The drill consists of a core barrel and core head, inserted cutters, rock coring bits, and a drilling rig. Metrics used for drill performance include core quality and maximum drill depth. Some of the problems encountered included vibration, penetration rate, heat, gravel layers, and chip transport. This drill would be capable of taking core samples in the polar regions of Mars.

Dr. Brian Glass spoke about the current state-of-the-art in autonomous drilling methodology. Intelligent drills are essential because of the light-speed delays to Mars (7–20 minutes one way), and the lack of knowledge about the geology at the drill site. He described his current automation approach that uses several internal agents with defined roles. These agents include a “quick reflex” capability that is implemented with very fast rules or upon exceeding sensor limits. Fuzzy neural net agents are used to make decisions under normal operating conditions based on incoming data and knowledge of past training examples and known faults. A model-based reasoning module is invoked when a novel fault or situation occurs that the two previous agents can’t handle. Finally, there is an overall executive agent that weighs input from the neural and model-based agents to decide the best course of action.

Dr. Glass discussed two automated deep drills, Mars Analog Research and Technology Experiment (MARTE) and Drilling Automation for Mars Exploration (DAME). The DAME drill employs a structural mechanics neural network monitoring system to detect faults. The DAME drill is autonomously operated by the Model-Based Diagnostic System, which continuously monitors the drilling process and the state of the drill. If a fault is detected, it analyzes the possible fault candidates and reports back to the DAME Executive. The DAME was field tested extensively at Haughton Crater in 2006. A full-scale Mars prototype achieved a total depth of 3.2 meters in ice layers and breccia in eight days of drilling. It was also tested at JPL in a variety of materials such as brick, granite, sand, and plaster with pebbles. It drilled to a meter autonomously in a mixture of these materials without prior knowledge of the composition. DAME has therefore demonstrated that drilling operations can be controlled remotely, thus enabling future subsurface access on other planets. However, for end-to-end capability, these automated drilling capabilities need to be combined with core retrieval and sample handling. Ideally, this autonomous capability should also be demonstrated on other planetary-prototype drill hardware architectures such as wireline, corers, and rotary percussive drills.

## IV. Alternatives to Conventional Drilling

On the morning of the second day, attention was turned to alternatives to drilling for accessing the Martian subsurface. Carol Stoker presented the working details of the Mars underground mole (MUM), which was developed as a low-mass and low-cost alternative to drilling. The MUM was developed under the Mars Instrument Funding program as an instrument that could be incorporated on a rover. It uses a Raman spectrometer for the detection of subsurface mineralogy and organics. The MUM uses a hammering mechanism for forward and reverse propulsion. The mechanism is capable of producing a downward impact force of over 63 Newtons at a rate of about 12 impacts a minute. It is capable of reaching depths down to two meters, which is the limit of the tether. An attractive feature of the mole is its low power consumption—peak power draw is 10 watts. The sample collection mechanism collects an average 7 grams of sample, which is returned to the surface for analysis. All logic and control electronics are at the surface.

The MUM has been successfully integrated with the K-10 rover and field tested in the Marscape outdoor test facility at Ames. The MUM executed a ground penetration sequence, sample retrieval, and a mole retrieval sequence, all commanded through a remote computer, but otherwise autonomous. A full system test of MUM was also performed in moist beach sand. In summary, the MUM is a low-mass system that is capable of obtaining geochemical samples from a rover platform. It is an alternative to a drill for penetrating the Martian regolith, but would not be capable of penetrating rock or rocky ice.

Dr. Andrew Mattioda discussed the Site Characterization and Analysis Penetrometer Systems (SCAPS) from a terrestrial viewpoint. The SCAPS system, developed by the Army, Navy, and Airforce for environmental site characterization, works by pushing penetrometers into the ground at a constant rate at the end of a series of rods. One large advantage of penetrometers is that they do not produce cuttings like traditional drilling, thus limiting the potential for cross contamination. Another advantage is that the instrumentation and software have been advanced to high TRL levels here on Earth by the commercial sector. This technology is capable of providing a three-dimensional map of the subsurface soil and water, along with the distribution of organics, metals, etc. Many of the same questions that one asks about the subsurface of Mars are asked here on Earth in the field of environmental monitoring. These systems have been scaled to various sizes, incorporated into barges and submersible systems and automated, thus they are an attractive alternative to conventional drilling.

Dr. George Cooper presented a paper on the slant/horizontal drilling technique. One can imagine many places on Mars where this technique would be advantageous, such as the steep terrain where there is very recent evidence for outflows of liquid water in gullies. Horizontal drilling is used extensively terrestrially to lay pipe under the surface. Typically compressed air is used to push a rod beneath the surface. Issues for deploying this technique on Mars include unknown terrain, target selection, and steering. Since there is a sideways feed force, this could produce unstable footing especially on steep terrain. Friction on the hole wall and hole collapse would be other issues. These challenges may make autonomous operation of such a drill quite challenging. With humans in the loop, however, this technique might be useful at some locations.

Dr. Penny Boston spoke about access to natural subsurface cavities, both robotic and human approaches. Extraterrestrial caves are interesting for a variety of reasons. They are windows into the subsurface (up to 2 km on Earth), and they are potential havens for subsurface microbial ecosystems and repositories for fossils, climate records, sediments, organics, and other signatures of the planet's history. They are also potential human habitats for use on the Moon and Mars that provide shielding from the harsh conditions on the surface, especially ionizing and short wavelength ultraviolet radiation.

One of her main theses was that caves are important scientific targets for planetary missions. We know that lava tubes exist on bodies other than Earth. We suspect that any planet with a surface will develop cracks, and cracks provide a foundation for solutional and tectonic caves. Speleogenesis, which is the origin and development of natural caves, could also result from entirely non-Earth mechanisms such as impacts. In general, cave formation mechanisms include solutional, phase change (e.g., melting and refreezing), mechanical weathering, tectonic events (faulting and fracturing), strain relaxation, bioconstruction (vugs, which are small to medium-sized cavities inside rock), and catastrophic events such as impacts.

One of the more exciting possibilities for Mars is trapped lava tube deposits. The lava tubes would have formed early while volcanoes were still active. Then during the period when Mars was warm and wet, water from rain, condensation, or ground water could have become trapped inside the lava tube. As Mars became colder and ice formed on the surface, the lava tubes could become permanent ice cave lakes. In the modern era the tube neck could collapse isolating the lava tube from surface conditions. These lava tubes could be an ideal target to find ice particles as well as organics and microbes that had been trapped potentially for several billion years. Cave geo-microorganisms could be alive, dead, or fossilized, or could manifest as biospeleothems (mineral secondary decorations created or influenced by organisms, primarily microorganisms), biotextures or biominerals. She showed a number of examples of caves on Earth that demonstrate the wide variety of mineral and biological life forms existing in terrestrial caves.

Dr. Boston contrasted the advantages and disadvantages of robotic versus human approaches to finding and exploring caves. For robotic exploration she discussed REMotes, which is a variant of hopping microbots. Advantages include expendability, sensing and communication capability, agility in rough terrain, simplicity and reliability. Because REMotes are small (~100 mm) and light (100 grams), 100s-1000s of units can be deployed for a mission. They are powered by hyperefficient micro-fuel cells. Humans have the ability to adapt methodology for studying caves on Earth to other planetary bodies, and experience with biosensitive sites. Clearly, caves on Mars would make excellent exploration sites, and efforts to find and characterize them should be done both robotically and later with human missions.

Dr. Michael Hecht presented a paper entitled "A practical method to autonomously obtain vertical profiles of biomarkers in ice sheets on Earth and Mars." The technique employs an open-hole design that uses a heated drill on a tether and returns the meltwater to the surface. The thermal drill consists of a deployment system, a tether, a pumping system, a heater, and electronics for control,

power, and the sensor subsystems. The drill has been demonstrated to 50 meters in Greenland. This technique requires that ice constitute >50% of the drilling medium. MARSIS (a multi-frequency synthetic radar altimeter with ground penetration capability instrument) indicates that the north polar layered deposits are greater than 98% ice, so this drilling technique would be applicable, and given Mars ice temperature and gravity, open boreholes would be stable all the way to the base. By determining the D/H ratio as a function of depth, it would be possible to create a climate history. Even on the north polar cap of Mars, the pressure is above the triple point of water, so that the ice should melt before sublimating. The drill is capable of drilling in dusty ice, albeit somewhat slower. The probability of hitting a rock large enough to cause trouble is extremely remote in the north polar layered deposits. In addition, the drill is designed to operate autonomously, so that this would be a viable drilling method in regions that were predominantly composed of ice.

Dr. Phil Christensen presented an overview of the Tracing Habitability, Organics, and Resources (THOR) Mission. The THOR mission uses a high-velocity impactor to create a crater on the surface and an observer spacecraft containing highly capable infrared (IR) spectrometers and visible cameras. It is designed to provide an in situ investigation of the deep (>4 meter) sub-surface. Targets include the unexplored mid-latitudes with mantles hypothesized to contain water ice. He showed a number of potential targets with the goal of placing the impact site within a 50 km ellipse. A key mission objective is to determine the abundance of water in the deep Martian subsurface where ice can be stable. High spectral and spatial resolution spectra from the IR camera on the observer spacecraft will provide insight into the abundance and origin of key trace gases such as methane, SO<sub>2</sub>, and CO. Other scientific objectives of the mission include testing models of cyclic climatic change and the recent occurrence of liquid water, and the search for organic compounds in the habitable zones. The orbital phase objectives of the mission include a study of the evolution of materials exposed in the crater and to create a new fresh crater for follow-on Mars orbiter and rover missions.

Dr. Christensen showed that the depth of diameter of the crater created by the impact depended on the nature of the impact site (wet soil/ dry sand/ ice) and the model used to estimate it. Larger craters are predicted if the impact site contains ice. Both models that were used to model the impact crater showed that a 450 kg projectile would create a crater greater than 4 meters in all soil conditions.

Dr. Yoseph Bar-Cohen spoke about the ultrasonic/sonic driller/corer (USDC) and the challenges of inserting new drilling technology into future missions. Using low axial force, the USDC has been demonstrated to produce core samples from rocks that range widely in hardness and also to acquire powdered cuttings that are mostly several microns in size. The USDC was equipped with sensors on the bit to perform inside the borehole measurements. A thermocouple was integrated into the USDC bit to measure the temperature in real-time monitoring during drilling. Also, a USDC bit was integrated with a fiberoptic sensor and reflectivity measurements from the surface of a rock where measured. The USDC was demonstrated as a rock abrasion tool, rock crusher, as well as deep penetrator of regolith. For a rock crusher, its actuator harmonic motion creates a series of low frequency impacts that quickly crush the sample into fine powder. The USDC can also be used in a rotary hammer system.

The USDC has been demonstrated to drill in cold ice at low temperature environment. A gopher version of the USDC has been field tested in Lake Vida, Antarctica, to a total depth of 176 cm in ice. Several other variations of the USDC were also discussed. The USDC can also be deployed robotically. Therefore, an advantage of the concept is its versatility. Nevertheless, as Dr. Bar-Cohen pointed out, the ability of new technology to address mission challenges is insufficient for insertion as mission hardware. He also noted that because drilling and sampling are critical technologies, there is a need for a focused development with established simulation test beds and facilities.

## V. Breakout Sessions

In the afternoon, the workshop participants broke into two groups to address possible drilling missions. The first group chaired by Chris McKay looked at drilling missions in the near term, that is, what could be done today with existing technology. The second group chaired by Penny Boston looked at possible drilling missions in the mid (20 years out) and long term. The long-term scenario considered the possibility of having humans in the loop. The mission concepts that were considered by these two groups are summarized in this section.

### **GROUP 1: POSSIBLE DRILLING MISSIONS IN THE NEAR TERM (5 YEARS)**

The near-term group focused on missions that could be proposed within five years. This required the use of technology for subsurface access and instrumentation that had already a high technology readiness level (TRL). They ranked missions into four categories based on cost. In order of increasing cost the categories were extra low-cost missions, low-cost add-ons to existing missions, Scout missions, and large focused subsurface missions. Missions that have a technology or science feed towards Mars Sample Return (MSR), as well as ties to the NASA Exploration program, were viewed favorably.

In the extra low-cost mission category were an impactor only concept, an impactor with a shepherding spacecraft (LCROSS model), or landing in a recent 100 meter crater identified by MRO and searching for organics in the exposed dirt. The science objectives are to detect deep ice, and to sample below the ice or the oxidizing zone (for an equatorial impact) a few meters to search for organics. An impact into the deep ice would require an impact mass greater than 500 kg, while an impact in the equatorial region to sample below the oxidized zone would require a smaller mass. It was felt that an impactor mission could be done today either as a standalone or add-on mission. Current technology would be able to hit a predetermined target on the surface, which was timed so that the impact could be observed by MRO or MSO.

An additional add-on, low-cost mission category discussed were penetrators based on penetrometer technology. Utilizing the high TRL level instrumentation developed for commercial penetrometers, penetrators could be developed as add-ons to other missions. Penetrators could be utilized for the seismic investigations, as well as the detection of subsurface water and organics. Such instrumentation, utilized in conjunction with impactor missions such as THOR, could provide information concerning Mars subsurface geology as well as identify organics or water vapor dispersed by the impact.

Proposed Scout missions that were discussed included Tracing Habitability, Organics and Resources (THOR) (a proposed impactor to explore mid-latitude regions for underground water), the Phoenix Mars Lander (on the way to Mars to dig for buried ice in the north polar ice cap), CHRONOS (a proposed mission to thermally drill 10–75 m into the north polar ice cap), and Geophysics network missions. Drilling missions within the Scout Mission program would be more compelling with new evidence for life or water on Mars and with higher TRL for drills.

Large focused subsurface drilling missions are feasible in the near term only if there is some new compelling evidence for subsurface life. Scenarios such as Phoenix or MSL find organics in the ice. Other events that might motivate a large drilling mission include detection of methane, hot vents, or squirting gullies that indicate shallow subsurface aquifers.

This breakout session inspired the writing of a white paper entitled “Low-cost multi-use subsurface access to Mars,” where the low-cost impactor approaches discussed in this breakout session are discussed more fully.

## **GROUP 2: POSSIBLE DRILLING MISSIONS IN THE MID AND LONG TERM**

The second breakout session considered drilling missions that could be accomplished within a longer time frame. They considered drilling, but also other mission types that provide access to the subsurface. To focus the discussion the following assumptions were made.

- (1) Shallow rock core drilling would be a first target (MSL is getting powder, but bedrock will not be obtained).
- (2) ExoMars is going to a 2-3 m depth.
- (3) Technology improvements, while difficult to scope out, must be included in mid- to long-range planning scenarios. Technologies at the TRL 3-5 levels may achieve sufficient maturity for this time frame.
- (4) Automation is absolutely critical, especially when drilling through soil that is inhomogeneous.
- (5) A drilling depth of 40–50 m would be an ambitious, but achievable goal for a dedicated drilling mission.
- (6) Voids (caves or vugs) near the surface are of interest scientifically, but present a significant challenge for automated drilling.

A key question is how deep do you need to go. This is, of course, dependent on where you dig and what science you are trying to answer. The group discussed the tradeoffs. It was felt that a moderate robotic mission could be designed to go to 20–50 m, and more ambitious missions to several 100 m. Human missions are thought to be feasible to 250–500 m (HEM-SAG report with a ~4.5 metric ton payload). The group also discussed the advantages and challenges of drilling from within caves.

The group divided potential drilling missions into categories based on cost, mass, and power. General consensus was that a drilling mission would be too ambitious and costly to fit within the New Horizons mission category, and that a serious drilling mission could not occur until at least 2015-2016. On the low-cost side, the group discussed a lakebed mission, primarily to search for physical and geochemical life traces in a cored stratigraphic column, and an ice drilling mission that potentially would have a higher scientific return, such as living Martians, preserved organics, climate-relevant dust, and isotopic data. Also discussed was a multi-mission staged approach, whereby the first mission would obtain the core and analyze the borehole. A follow-on mission would retrieve the cached sample for in situ analysis. A drilling microlander mission concept was proposed that could be done for approximately \$500 million. This would have a 10 kg payload and could achieve depths of a few meters in a particularly significant site, such as a lakebed, ice, canyon wall, or cave. Robotic missions to 20–50 m are feasible with improvements in drilling methodology and automation. This could be achieved by a wire line system, but other options exist.

Some of the technology issues that need to be addressed are the payload mass and power requirements needed to drill and bit wear issues. The group discussed laser drilling, which repeatedly evaporates a thin layer of material, as an innovative approach for ice missions. Sonic drilling at 140 Hz appears to be a promising new technology being pioneered in commercial circles. This would be worth trying to develop to a higher TRL.



## VI. DISCUSSION OF RESEARCH PRIORITIES AND FOLLOW-ON ACTIVITIES

Pete Worden in his opening remarks noted that subsurface exploration on Mars is necessary to understand astrobiology. He felt that there were near-term opportunities for low-cost missions to leverage existing larger exploration missions going on between our European partners and us, e.g., impactor missions such as LCROSS that can be done for tens of millions of dollars. In addition, the community needs to be positioned to take advantage of a serendipitous discovery, such as the observation of water or organics near the surface. The community should also have a prioritized list of critical technologies that need to be addressed for future subsurface exploration. In the longer term, our research priorities need to be consistent with human exploration and settlement. Finally, he noted that we should be sensitive to the three ways that missions gain impetus for funding, namely interest generated by science advisory committees, such as the space studies or decadal studies board, the congress and the public (advocacy for missions like Pluto Express), and the private sector. For example, unused capacity on NASA vehicles and funding from entrepreneurial investors might present unexplored opportunities.

Impactors are one class of missions capable of accessing the subsurface that can be carried out for relatively low cost and complexity. The key parameters are the mass, delta-V, and degree of precision required to produce useful science. Dr. McKay noted that large mass low-precision targeted impactors would be appropriate for impacts into the polar ice regions. Such a mission could help ground truth the Mars Odyssey global observations of the Martian surface. The possibility of a mission as a secondary payload and of using mass already in orbit was discussed. This latter approach raises issues with rendezvousing and docking. Using a simple impactor is an attractive alternative, because the impact and long-term activity of the impact site could be observed with current assets in place around Mars such as MRO and Odyssey. A subset of the workshop participants led by Andy Gonzales was commissioned to write a short white paper on the impactor concept. Might it be possible to put a relatively inexpensive impactor mission into the queue if the schedule for Mars Science Lab (MSL) slips?

The next issue that was discussed was how to position the community to take advantage of a serendipitous event such as the discovery of organics. One problem facing the community was the current lack of technology investment in drilling technology. Technology development is still vitally needed to produce optimal drilling techniques for the various conditions found on Mars. Ways to address this shortcoming were discussed, such as promoting the necessity of sub-surface exploration, promoting drilling as an important technology to advisory panels, and leveraging off possible technology development done on Earth or for lunar research. It was suggested that we should stress the resource nature of drilling and the importance of this technology for permanent bases on the Moon or Mars. Dr. Zacny noted that the Canadian Space Agency is still investing in drilling technology.

The final issue that was discussed was the use of drills in human missions. It was noted that training of the astronauts would be essential. The Apollo astronauts had considerable difficulty in handling drills on the lunar surface. The question of how to train the astronauts led to the comment that we need to build a culture that uses analog environments and simulations in addition to training the astronauts. There is little effort in this area other than what is being done by the Mars Society. For example, sites like Devon Island provide a realistic field environment to test equipment, communications, and remote operations. Dr. Boston asked the question whether we could generate interest in a Mars simulation space school. Another subset of the workshop participants agreed to pursue the feasibility of such a school.

# Agenda

<b>Deep Mars: Accessing the subsurface of Mars on near-term missions</b>			
		DAY ONE	Sat, March 1st
Time	Dur.m in	Description	Speakers & Discussion leaders
8:00	30	Breakfast	
8:30	5	Logistics	Stephanie Langhoff
8:35	10	Welcome/objectives	Pete Worden
8:45	15	Introduction of participants	Stephanie Langhoff
<b>Science Objectives</b>			<b>Carl Pilcher</b>
9:00	30	FOUNDATIONAL TALK: Drilling for Life on Mars Why? Where and How Deep?	T.C. Onstott
9:30	30	Discussion	
10:00	15	What on Earth is Under There? Planetary Protection for Drilling on Mars	Cassie Conley
10:15	15	Discussion	
10:30	15	Break	
10:45	15	Drilling as a Science Driver for Human Exploration	Peter Doran
11:00	15	Discussion	
11:15	15	Ice as an Astrobiology Target	Chris McKay
11:30	15	Discussion	
11:45	15	High Arctic Permafrost Microbiology	Lyle Whyte
12:00	15	Discussion	
12:15	15	Panel discussion- "why/ where and how deep?"	McKay, Onstott, Conley, Bosley, Cooper, Green
12:30	15	Discussion	
12:45	60	Lunch	
<b>Architectures for Drilling Missions</b>			<b>Geoff Briggs</b>
13:45	30	FOUNDATIONAL TALK: Introduction to planetary drilling and drill systems	Kris Zacny
14:15	30	Discussion	
14:45	15	Studying Seasonal Variations in High Arctic Permafrost Using a Portable Drilling System	Simon Auclair
15:00	15	Discussion	
15:15	15	The 2005 MARTE Robotic Drilling Experiment in Rio Tinto, Spain: Results of a simulated drilling mission to search for life on Mars	Carol Stoker
15:30	15	Discussion	
15:45	15	Break	
16:00	15	Lake and Ice Stream Subglacial Access Research Drilling (LISSARD): Integrative study of marine ice sheet stability and subglacial life habitats in West Antarctica	Robin Bolsey/Slawek Tulaczyk
16:15	15	Discussion	
16:30	15	KOCI Drill for Drilling in Ice, Sand and Rock: Drill requirements, design, performance, difficulties	Jim Green
16:45	15	Discussion	
17:00	15	Drilling Automation Technologies	Brian Glass
17:15	15	Discussion	
17:30	45	Wine and cheese social	
18:15		Adjorn	
19:15		<b>DINNER: Chef Chu's, 1067 N San Antonio Rd, Los Altos</b>	

<b>Deep Mars: Accessing the subsurface of Mars on near-term missions</b>			
		<b>DAY TWO</b>	<b>Sun., March 2nd</b>
<b>Time</b>	<b>Dur. (min)</b>	<b>Description</b>	<b>Speakers &amp; Discussion leaders</b>
8:00	30	Breakfast	
<b>Alternatives to Conventional Drilling</b>			<b>David Morrison</b>
8:30	15	The Mars Underground Mole, a low mass and cost alternative to drilling	Carol Stoker
8:45	15	Discussion	
9:00	15	Site Characterization and Analysis Penetrometer Systems: A Terrestrial View	Andrew Mattioda
9:15	15	Discussion	
9:30	15	Horizontal Penetration from the Cliff Base	George Cooper
9:45	15	Discussion	
10:00	15	Break	
10:15	15	Access to Natural Subsurface Cavities: Robotic and Human Approaches	Penny Boston
10:30	15	Discussion	
10:45	15	Cryobot subsurface sampling system	Mike Hecht
11:00	15	Discussion	
11:15	15	The THOR Impact Mission - an alternative approach to accessing the subsurface of Mars	Phil Christensen
11:30	15	Discussion	
11:45	15	The challenges to insertion of new drilling technology in future missions	Yoseph Bar-Cohen
12:00	15	Discussion	
12:15	60	Lunch	
<b>Breakout Sessions</b>			<b>Carol Stoker</b>
1:15	105	Introduction to Breakout Sessions: (1) Possible missions in the near term (5 years)  (2) Possible drilling missions in mid to long term (with/without human explorations)	Chairs: (1-Chris McKay, 2-Penny Boston, 3-Peter Doran)
3:00	15	Break	
3:15	30	Reporting of breakout groups	Session Chairs
3:45	45	DISCUSSION: Research priorities-where do we go from here?	Pete Worden
4:30		Adjourn	

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<b>14. ABSTRACT</b>  The workshop encompassed three major themes. The first theme was the scientific objectives of drilling, which center on the search for clues to the existence of past life and to the geological and climate history of Mars. Key questions are where and how deep to drill? Planetary protection issues were stressed as an important consideration in the design of any drilling mission. Secondly, architectures for drilling missions were discussed, including an overview of most of the current drills in operation that would be applicable to drilling on Mars. Considerable emphasis was placed on remote operation and drilling automation technologies. Finally, alternatives to conventional drilling were discussed. These included underground moles, penetrometers, horizontal drilling, impactors, and access to the subsurface from subsurface cavities. Considerable discussion centered on the possible Mars drilling missions that could be performed in both the near and longer term. The workshop participants concluded that useful science could be obtained today using low-cost impactors, with or without a shepherding spacecraft.
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<b>15. SUBJECT TERMS</b>  Drilling on Mars, impactors, penetrometers, moles, missions to penetrate the subsurface of Mars
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