The Scientific Rationale and Technical Approach for Drilling on the Moon and Mars C. R. Stoker, NASA Ames Research Center, M.S. 245-3, Moffett Field, CA 94035, cstoker@mail.arc.nasa.gov

Introduction: Introduction: Drilling is a key science activity for both robotic precursor missions and human missions on both the moon and Mars. Drilling is needed to explore the third dimension in understanding global processes on both bodies, as well as to answer many key questions. Furthermore, to get samples that are stratigraphically preserved, date from an epoch of interest, or are unaltered by surface weathering processes requires access to the subsurface.

Science Objectives: Science Objectives for the Moon that require drilling have been recently outlined [1] and include the following. Table 1 summarizes the drilling depth required to meet each class of objective.
Regolith Properties: All lunar samples that have been analyzed come from the regolith, and characterizing and understanding the regolith is crucial since it will be the source of Lunar resources. The Apollo cores consisted of numerous discrete layers, and the properties and composition of layers continued to change with depth down to the maximum depth obtained (3m), while fractionation of the more volatile elements was clearly decreasing with depth. To understand the regolith, samples of a complete depth profile are needed.
Volcanism: Objectives include determining the origin and variability of basalts, determining the age of the youngest mare basalt, the compositional range and extent of lunar pyroclastic deposits, and the flux and time evolution of lunar volcanism. Core samples of bedrock basalts are needed from a variety of locations.
Impact processes: Catering is one of the most important processes operating on any planetary body and our understanding of this process derives largely from the moon and limited sampling. To test hypotheses, vertical samples of a basin melt sheets are needed and the structure of large multi-ring basins needs to be mapped through drilling.
Polar environment: This is the least studied region of the moon, and determination of the chemical and physical properties of these materials and their heterogeneity is needed with a particular focus on determining the composition of polar volatiles, their sources, and their alteration history. Furthermore, horizontal surveys complemented with periodic strategraphically preserved core samples are needed to characterize the abundance and distribution of volatiles to determine whether extraction of these potential resources is feasible.
Astrobiology: Objectives include characterizing the environment of Earth during the Hadean (4.4-4.2 BY ago), and during the late heavy bombardment (3.9 BY ago). Life originated during this period and may have had multiple origin and extinction episodes. Fossil regoliths that were formed during that period and subsequently covered by flood basalts may hold a pristine record of the Early earth and conditions it experienced that can only be accessed from the moon. These regoliths may plausibly contain samples from the early Earth that preserve the record of conditions during that key time.

Table 1.

Objective	Type of drilled Sample	Depth Required
Study regolith formation and weathering processes on anhydrous airless bodies	Regolith Cores	10 m
Sample a variety of Lunar volcanic deposits to determine the origin and variability of basalts, how old is the youngest basalt, what are the range of lunar pyroclastic deposits, what is the flux of lunar volcanoes and how did it evolve through time	Bedrock samples from strategically selected sites	20 m
Study impact processes on Planetary Scales	Core samples from impact melt sheet	100 m
Characterize the regolith at the lunar poles particularly lateral and vertical distribution of volatiles	Shallow core samples at many locations, deep core samples at a few locations	2 m shallow, 50 m deep
Determine the environment of the Earth during the Hadean. Search for samples of the Hadean Earth	Regolth samples buried by ancient subsequent lava flows	100 m or more

Drilling and core sample analysis is also very important for addressing the key science questions on Mars. The highest level goal of the Mars exploration program is the search for life. The surface of Mars is hostile to the preservation of signatures of life due to the harsh oxidant and UV light environment. The subsurface is most likely to hold the preserved record of biological activity on Mars. The sediments exposed at Sinus Meridioni may also contain biological signatures best accessed by analyzing drilled cores from these deposits. Should life survive on Mars to the present epoch, it might experience growth spurts during periods when orbital forcing increases the solar flux in the Northern plains regions resulting in ice in the near surface sediments melting to provide a liquid water niche for modern life. By drilling 5 m in the Northern plains, a record of 10 M years of cycles of freezing and thawing may be accessed [2]. The growing evidence that liquid water occurs in the Martian subsurface, in some locations at relatively modest depths (100-500 m) [3], suggests searching for current life in Martain aquifers. This liquid water would also be readily accessible as a resource since it could be extracted by pumping.

Technical Approach: Modular, reconfigurable, autonomous and human-tended drilling systems are needed for use initially on Lunar and Mars precursor missions and ultimately by crewed missions. The thickness of the regolith varies from ~5 m on the Luanr Maria to ~10-15 m on the highlands. Thus, obtaining regolith samples through full depth is achievable with a 10-20 m drill, and such a system could also obtain bedrock samples and be used to emplace heat flow measurements. The average particle size of Lunar regolith is less than 100 micrometers so drilling through or below it may require the use of casing. Similar depth of drilling on Mars could assess the preservation of biosignatures in sedimentary rocks as at Meridioni Planum, and could assess whether liquid water occurs episodically in the Northern Plains. Highly automated fluidless drilling systems capable of supporting these objectives in a robotic mission have been developed with support from NASA. Deep drilling (> 10s of meters) will require massive equipment if that same approach is used but could be implemented in a low mass system that uses side wall expansion anchors for downhole support and the drill motor located near the bit. In this type of system, now under development, additional depth of penetration requires only the addition of more cable. Cuttings removal is the major issue for drilling deep. In terrestrial drilling, this involves the use of water based cutting fluids although gases or cryogenic fluids are sometimes used. For use in space, cuttings removal may require use of gases to move cuttings or augering into a bailer that is periodically dumped.

A fluidless, low power, highly autonomous coring drill, capable of autonomous core ejection into a core clamp, and instruments for inspecting and documenting the core, subsampling, crushing, and performing in situ analysis for biosignatures was developed for the MARTE project and field tested in a mission simulation to 6 m depth [4] (Figure 1). A drill system of this design could be landed on the moon or carried on a capable Lunar rover, although the relatively large mass needed for this approach (50 kg) dictates a large rover.

Wireline drills capable of much lower mass are under development: a10 kg system could achieve 10 m depth and the mass increase for deep drilling is modest. Design issues to be addressed for a deep drill include operational simplicity, bit development and change-out strategies to respond to bit wear, the need to cut a range of materials, cuttings removal approach, systems for anchoring the drill string in the hole and providing weight on bit, and casing for hole stability in lunar regolith. While a fully automated or Earth supervised shallow drill is feasible, deep drilling would benefit greatly by human tending the drill at crucial junctures. Astronaut field surveys are also needed to determine where to drill.

Figure 1 MARTE coring and sample handling system

Conclusions: Key science questions can be addressed on the Moon by obtaining drilled core samples. The drilling technology developed for this purpose also applies to Mars exploration, so work on the Moon feeds forward to Mars. Depth scales required to address science questions range from a few to hundreds of meteres. Shallow drilling is feasible to accomplish autonomously, but deep drilling will require crew interaction. Drilling activities should be factored into science planning and astronaut training for human missions. Development of a small, lightweight, highly automated drilling system extensible to shallow or deep drilling is needed.

[1] Nat. Res. Council Scientific Context for exploration of the Moon, interim report, 2006. [2] McKay, C.P. et al., 38th LPSC 2007. [3] Heldmann, J. and M. Mellon, Icarus 168, 2004. [4] Stoker, C. and MARTE team, 37th LPSC Abs. 1537, 2006.