FIELD AND LAB TESTING WITH TRIDENT DRILL TO HELP PREPARE FOR FUTURE MISSIONS

C.R.Stoker[1], B.J. Glass[1], C. Walter[2] [1]NASA Ames Research Center, carol.stoker@nasa.gov, [2] NASA Ames Research Center and USGS,

Introduction: Field work with instrumentation and technologies that are planned for flight missions is an important means to gain understanding that improves mission performance. This paper reports on results from field work in lunar analog volcanic terrain using an engineering model of the Honeybee Robotics TRIDENT (The Regolith and Ice Drill for Exploration of New Terrains) drill [1]. TRIDENT is a rotary percussive 1-meter class drill that is carried on the PRIME-1 and VIPER (Volatiles Investigating Polar Exploration Rover) [2] missions to the moon scheduled to launch in 2024. A similar drilling system was planned for the proposed Icebreaker Discovery class mission to Mars [3] and the Mars Life Explorer mission recommended by the 2020 Decadal Survey of planetary science [4]. The field work objectives were (1) to use data collected by the drill for operational purposes as a probe of subsurface material properties in formations that are analogous to those that may be encountered on planetary surfaces; (2) to correlate subsurface structures deduced by drilling with those inferred from interpretations of Ground Penetrating Radar (GPR) data.

Methods: In September 2023 two holes were drilled with TRIDENT at each of three sites near Bishop California (Figure 1). Sites DS1B and DS1C were in Bishop Tuff, a welded tuff that resulted from pyroclastic deposits in the eruption that formed the Long Valley Caldera 0.76 Ma ago. The third drill site was in pumice, a low density porous airfall deposit also from that eruption. Drilling was performed using an engineering model of the TRIDENT drill previously used in the ARADS field experiment in Atacama Chile [6,7]. GPR measurements were made using a USRadar Quantum 4 GPR that operates simultaneously in 3 frequencies (1000Mhz, 500 Mhz, and 250 Mhz). The instrument is pushed over the ground while included software provides a real time display of radargram profiles while recording them.

Results: Plots of the drill data (Figure 2) clearly show the interface between the overlying unconsolidated sediments and bedrock in the tuff drill site. The densely welded tuff bedrock was difficult to drill and the auger motor limits were sometimes exceeded causing the auger to stop turning. The pumice drilled quickly and easily, as expected for highly porous material. Fine scale layering was observed in the drill data for the pumice site but no layering was observed in the tuff.

Drilling in densely welded tuff showed the drill can quickly stop rotating when currents in the torque motor exceed operational limits. This behavior was also observed in lab tests with the drill. Prior to stopping the auger torque quickly increased (Figure 2). The drill uses bite sampling where it returns to the surface after drilling an operator specified depth interval. We found the binding was prevented by reducing the size of the drill bites, and progressively smaller bites were needed as depth increased. The smaller bites reduce downhole friction by moving fine cuttings to the surface more frequently.

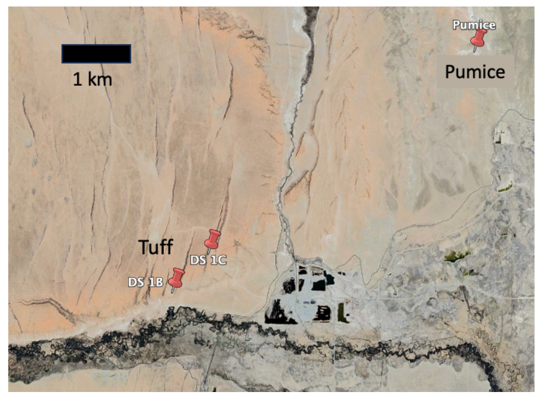

Figure 1. *Drill Locations. The image center is at 37.443º latitude, -118.404º longitude.*

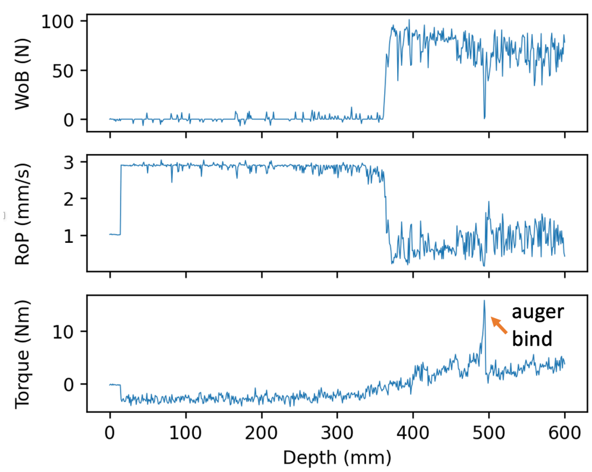

Figure 2. *Drill data recorded for hole 1C. Top to bottom are weight on bit (WOB), rate of penetration (ROP) and auger torque. The spike in torque at 480 mm occurred as the drill stopped turning.*

The specific energy of drilling (SE) was computed for each of the boreholes drilled. In previous work [8], we prepared and drilled a set of cements made from lunar simulants obtained from Colorado School of Mines and computed the specific energy required to drill these materials. We measured their unconfined compressive strengths (UCS) then determined a function relating UCS to SE using the procedure described in Peters *et al.* 2018 [9]. We estimate the UCS of the Bishop Tuff in our drill locations was 10 to 20 Mpa, while the Pumice UCS values were between 2 to 5 Mpa.

GPR data was used to select the drilling sites and to estimate bedrock depth prior to drilling. GPR data response was primarily impacted by liquid water content (high dielectric constant) in the sediments overlying the bedrock that experienced recent rainfall. This moisture was concentrated at the base of the sediment layer and above the less permeable bedrock. The bedrock location can be inferred in the radargrams as lying directly below the high amplitude radar reflections (high liquid water content). Radar derived depth estimates are consistent with bedrock locations identified from the drill data (Figure 3).

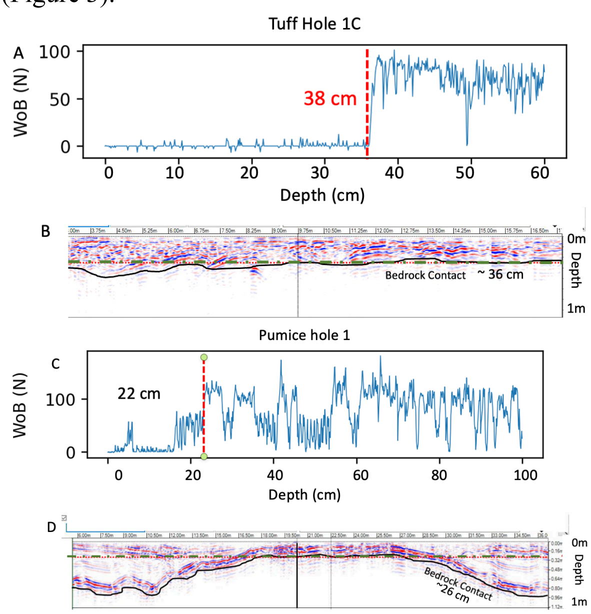

Figure 3. A. drill weight on bit (WOB) from borehole 1C. The bedrock boundary (red line) is inferred from the sharp rise in this parameter at 38 cm. B. Plot of GPR radargram in 1000 Mhz channel. The green dashed line is the inferred bedrock boundary at 36 cm. The vertical black line denotes the borehole. C. Same as A for the Pumice site. Bedrock depth estimated at 22 cm. D. Radar scan crossing the boreholes (vertical black lines), and estimated bedrock depth is 26 cm.

Discussion: The work illustrates the value of drilling in lunar analog materials in the field to help prepare for the operation of drills in upcoming missions.

The drill data (WOB and ROP) clearly show interfaces between materials with different properties. The lab work drilling into materials with measured values of UCS allowed us to estimate the UCS of the materials drilled in the field. This information can provide clues to mineralogy, and structure of materials drilled on other planets.

Information from the episodes where the drill jammed can help mission planners prepare for and prevent this from happening on a robotic planetary mission where it will likely be difficult to recover. Our data suggests that the jams happen too fast for a human operator to take action even on a teleoperated lunar mission but onboard software could monitor drill operational data and autonomously prevent the drill from getting stuck.

The field work also showed the value of using Ground Penetrating Radar in conjunction with drilling as is planned for the upcoming European ExoMars drilling mission on Mars [10]. The GPR data allowed for targeting of subsurface structure (bedrock depth) prior to conducting drilling operations. GPR in a planetary drill mission would similarly help to determine subsurface structure prior to the more resource consuming process of drilling. In this case, the high soil moisture attenuated the signal of the GPR instrument. The objective of drilling on the moon is to access subsurface water ice. Crystaline ice would not block/attenuate the radar signal as we saw in this experiment due to its much lower dielectric constant. We hope to conduct a follow on study in a permafrost region to better assess radar and drill synergy in icey environments.

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