USING CURIOSITY'S DRILL TO INDCATE THE UNIAXIAL COMPRESSIVE STRENGTHS OF ROCKS DRILLED AT GALE CRATER, MARS. G.H. Peters[1], E.M. Carey[1], R.C. Anderson[1], W.J. Abbey[1], R. Kinnett[1], J.A. Watkins[2], M. Schemel[2], M.O. Lashore[1], M.D. Chasek[3], W. Green[1], L.W. Beegle[1], A.R. Vasavada[1], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA; email: ghpeters@jpl.nasa.gov, [2]Division of Geologic and Planetary Sciences. California Institute of Technology, Pasadena, CA 91125, USA. [3]Department of Geoscience, [3]Chadron State College, Chadron, NE 69337, USA.

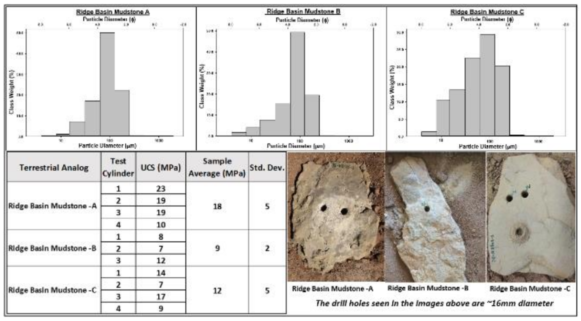
Introduction: Measuring the physical properties of geological materials is important for understanding geologic history. Yet there has never been an instrument with the purpose of measuring mechanical properties of rocks sent to another planet. The Mars Science Laboratory (MSL) rover employs the Powder Acquisition Drill System (PADS), which provides direct mechanical interaction with Martian outcrops. While the objective of the drill system is not to make scientific measurements, the drill's performance is directly influenced by the mechanical properties of the rocks it drills into. As such, we have developed and reported **([1] Peters, 2017)** a methodology that uses the drill to indicate the uniaxial compressive strengths of rocks through comparison with performance of an identically assembled drill system in terrestrial samples of comparable sedimentary class. During this investigation, we utilize engineering data collected on Mars to calculate the percussive energy needed to maintain a prescribed rate of penetration into sedimentary rock outcrops and correlate those to rock strength.

The MSL Powder Acquisition Drill System (PADS) is located on the turret assembly at the end of the rover's arm. PADS produces powdered drill cuttings for analysis by the SAM (Sample Analysis at Mars) and CheMin (Chemistry and Mineralogy) instruments [2], [3]. Percussive energy delivered to the drill bit is provided by a voice coil mechanism that uses a magnetic field to oscillate a free mass. The free mass acts as a hammer and transfers percussion energy to the drill bit. The voice coil mechanism is decoupled from the rotary drive, adding the capability of varying the percussion energies into the rock regardless of spindle rotational velocity. Onboard software during the drilling process, choses a discrete Voice Coil Level (VCL). VCLs 1 through 6 provide single impact energies ranging from 0.05 to 0.8 Joules with energy delivery at six levels, 0.05J, 0.20J, 0.31J, 0.45J, 0.61J and 0.80J, respectively. The percussion rate remains 30.1 Hz regardless of VCL. In order to allow autonomous drilling, the system automatically adjusts the percussion level to maintain the prescribed rate of penetration (ROP) and weight on bit (WOB) between parameterized thresholds. The percussion level, determined prior to launch, has been held to a maximum of VCL-4 for all MSL drill campaigns to date.

During reduced percussion, the drill begins at the lowest percussion energy and then reacts to stronger rocks by incrementally increasing VCL until the rocks begins to fail under the bit at the prescribed ROP. Similarly, to determine the strengths of rocks, geotechnical instruments deliver increasing force in a systematic manner [4]. For instance, the pressure at which the rock fails in compression determines the compressive strength of a rock. If more force than necessary were immediately delivered, one would only know that the strength of the rock had been exceeded. However, rock strength would not be quantifiable. A systematic lead-up to failure is essential for both, typical rock strength measurements in the laboratory, and when using drill performance as an indicator of rock strength. In order to normalize the data, the energy (J) is calculated over the volume (cc) of rock comminuted during the generation of the borehole. Prior to reaching the VCL that maintains the prescribed ROP, the system works at lower VCLs; percussive energy is expended but there is little, to no progress into the rock. Therefore, no significant volume is excavated from the borehole, resulting in disproportionately high energies per-unit-volume.

Drill performance herein is reported for full-depth drilling operations only. Prior to drilling, a hole-start operation is performed. During "hole-start", a divot of five millimeters depth is created. This safeguards concentricity to the projected hole by ensuring that the tapered end of the bit is fully engaged into the rock. As such, the cross section of the drill bit remains constant as does the volume-per-unit-depth-excavated throughout the drilling operation post hole-start.

Methods: Terrestrial, sedimentary rocks from the Ridge Basin Group (Figure 1) in California were drilled at Earth ambient pressure using the arm-mounted drill on the Vehicle System Test Bed (VSTB) in the Mars Yard at JPL. This was done to provide a direct comparison of the drill performances measured during the mission. The VSTB's robotic arm and drill system are mechanically indistinguishable from the drill system and robotic arm aboard the Curiosity rover [5]. The Ridge Basin rocks were selected as Gale crater analogs based on their sedimentary history and morphological characteristic, which are comparative to the Martian rocks encountered by Curiosity to date. Similar to the sedimentary environment at Gale crater, the siltstones and sandstones of the Ridge Basin Group were produced as a result of high-relief infilling into a restricted basin (Link, 2009).



Terrestrial Analog	Test Cylinder	UCS (MPa)	Sample Average (MPa)	Std. Dev.
Ridge Basin Mudstone -A	1	23	18	5
	2	19		
	3	19		
	4	10		
Ridge Basin Mudstone -B	1	8	9	2
	2	7		
	3	12		
Ridge Basin Mudstone -C	1	14	12	5
	2	7		
	3	17		
	4	9		

Figure 1. *Characterization of the Ridge Basin rocks that were used as terrestrial analogs for the Murray and Stimson on Mars. Grain size distribution analysis illustrates that the Ridge Basin rocks are very fine-grained mudstones. (Image: NASA/JPL-Caltech).*

With such a small difference in grain sizes among these siltstones and sandstones, and such a large bit-diameter to grain size ratio, the difference in sedimentary classification among the rocks does not affect the drill performance significantly. As such, the drill energy per unit excavated and the rock strengths for all formations under investigation have been evaluated together.

Discussion: The unconfined compressive strengths of each of the three Ridge Basin samples were determined according to ASTM D7012C on multiple cored samples to ensure a representative distribution of the parent rock (Figure 1). One-inch diameter cores were taken using a wet coring system. However, dry nitrogen replaced water as a working fluid to ensure no adsorbed water infusion into the test articles, which could have weakened them. The cores were cut to 2" length cylinders. UCS testing on the cylinders created from the cores was conducted at ambient atmospheric conditions.

Each of the Ridge Basin rocks were drilled once using the VTSB with the reduced percussion algorithm precisely as they would have been drilled on Mars. Percussion energy per unit volume excavated was calculated in the same way as was done with the drill performance data in the Murray and Stimson outcrops at Gale crater. Percussion energies (J/cc) for the eleven outcrops drilled by PADS were determined using Eq. 1 along with the three Ridge Basin rocks drilled with VSTB.

The indicated UCS of the rocks drilled at Gale are plotted along a strength curve shown in Figure 2. A word of caution when interpreting the Figure 2. The curve, defined by the equation in the figure, is determined using only 3 points, the black squares representing data drilled in the VSTB. This extrapolation, as well as the assumption that the lithologies among the rocks on Mars and the Ridge Basin analogs is not precise. The specific drill energy (J) per unit-volume (cc) needed to drill in at the highest VCL necessitated by the strength of the Ridge Basin rocks was calculated and a strength curve was generated by plotting the percussion energies vs the measured compressive strengths. The specific percussive energy per unit volume excavated measured for each rock drilled at Gale is plotted along the strength curve providing an indication of rock strength. Error for each rock is represented as the standard-deviation in UCS of the Ridge Basin samples. The weakest rocks at Gale are no stronger than adobe bricks (1.5 – 5 MPa) and the strongest rocks drilled can be compared to the strength of a standard concrete sidewalk or driveway (15 – 30 MPa). Rocks drilled at Gale composed of relatively weak rocks when compared to quartz-indurated rocks found on Earth and are more akin to geologically immature, silt and sandstones.

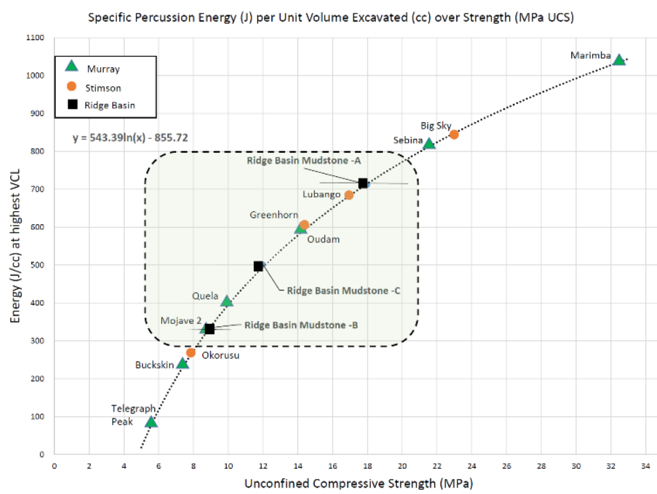


Figure 2. *Illustrates the energy per unit-volume excavated at the highest VCL needed to drill each rock vs the rock strength (UCS).*

While PADS was not designed to be an instrument for measuring rock properties, the method employed has provided a good indicator of the strengths of the rocks drilled at Gale crater. These techniques and methodologies will be useful during future missions during which rotary percussive drilling will be employed.

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