RELATIVE STRENGTHS OF ROCKS DRILLED AT MARS' GALE CRATER [1]G. H. Peters, [1]R. C. Anderson, [1]W. Abbey, [1]L. Beegle, [1]E. M. Carey, [2]J. Watkins, [1]R. Kinnett, [1]J. M. Morookian, [1]D. E. Klein, [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA, [2]California Institute of Technology, Pasadena, CA, 91125, USA, (email: ghpeters@jpl.nasa.gov)

Introduction: The Sample Acquisition/Sample Preparation and Handling (SA/SPaH) system aboard the Mars Science Laboratory (MSL) rover is comprised of a robotic arm and a suite of instruments, including a rotary/percussive drill-sample acquisition system, a scoop for unlithified sample acquisition, and a sample preparation/sample delivery system. In the process of drilling into rocks on Mars, the drill creates cuttings and draws the cuttings into a collection chamber in the drill bit assembly. After the drilling operation completes, SA-SPaH transfers the cuttings from the drill bit assembly into CHIMRA for processing and delivery to the SAM and CheMin instruments [1].

Both rotary and percussive mechanisms are employed in order to drill into select rocks to a commanded target depth. Full-depth drilling typically concludes near 65 mm depth. The percussive function of the drilling system is provided by a voice coil. This type of percussion system is mechanically decoupled from the rotary drive and holds the advantage that it allows for multiple percussion energy levels regardless of rotary spindle velocity. During drilling, the drill software selects between six discrete Voice Coil Levels (VCLs) which provide variable impact energies from 0.05 to 0.8 Joules [1]. The drilling software also provides the ability to configure a maximum percussion level to be allowed by the drilling algorithm for each drilling operation. The team typically sets the maximum voice coil level to 4. In addition to percussion, a rotary component is also employed to assist in cutting the rocks and to transport cuttings (powder) into the sample handling system and to otherwise remove them from the borehole.

Background: Typically, the term "rock strength" refers to a rock's resistance to specific stress modes. For instance, the Uniaxial Compressive Strength (UCS) of a rock can be described as its resistance to compressional force in one direction without lateral restraint. In the UCS case, the stress vectors are confined to one direction by loading a cylindrical or cubed sample between two platens and applying a compressive force between them. Other feasibly applied and measurable stresses include tensile and shear modes. However, rotary percussive drilling stresses the rock in a more complex, dynamic manner. As such, "rock strength" in the context of this abstract does not refer to practicably applied, or even measurable tensors. Instead we describe "rock strength" herein as each rock's resistance to the complex stress modes applied by the operation of rotary percussive drilling.

MSL Drilling Algorithm: The MSL drilling algorithm monitors the Rate of Penetration (ROP) and the Weight on Bit (WOB) while drilling and autonomously adjusts VCL to maintain ROP and WOB between parameterized thresholds. Since landing in 2012, the project has employed two distinct sets of ROP and WOB VCL control thresholds for flight drilling operations. The first four drilling campaigns (John Klein, Cumberland, Windjana, and Confidence Hills) were conducted using a "standard" configuration designed to minimize the total duration of a drilling operation by biasing toward the highest VCL allowed for that operation. In 2014, the drill engineering team developed a second, more adaptive "reduced percussion" configuration with ROP and WOB thresholds which guides the VCL control algorithm toward the lowest VCL possible while still maintaining reasonably fast progress into a rock (Table 1).

Table 1: Comparison of Standard and Reduced Percussion Configurations

Parameter	Standard	Reduced Percussion
Initial percuss level	4	1
Step-up min ROP (mm/sec)	0.16	0.05
Step-down max ROP (mm/sec)	disabled	0.13
Step-down min WOB (N)	50	50
Fault min ROP	0.025	0.025

Once a rock fractures along the borehole, cuttings from that borehole cannot be transported to the sample handling system. The geologic setting at Gale has thus far only provided weakly lithified, sedimentary rocks. After fracturing the rock Mojave during a "mini-drill" test sequence on Sol 867, it was determined that the reduced percussion configuration would not pose any dangers to the system and may avoid inducing rock fracture. Since the Sol 882 full drill of the Mojave 2 rock, the system has been operated using the reduced percussion configuration.

ROP and WOB are active feedback parameters allowing autonomous control of the drilling operation. ROP and WOB are also performance parameters allowing SA/SPaH engineers and Rover Planners to determine the health of the drill. In addition, because ROP and WOB vary as a direct result of the mechanical properties of the rock, the combination of

ROP and WOB, plus the Total Depth Drilled and the Drill “On-Time” can be used to determine the relative strengths of the rocks drilled using this system.

The relative strengths of the rocks at Confidence Hills (Sol 759), Mojave 2 (Sol 882), Telegraph Peak (Sol 908), Buckskin (Sol 1,060), Big Sky (Sol 1,119) and Greenhorn (Sol 1,137) were determined by first comparing the total depth drilled at specific VCLs. Rocks where significant depths are accomplished at lower VCLs do not heavily resist the stresses applied by SA/SPAH’s rotary percussive drill and are considered weaker than rocks where a significant amount of the depth was drilled at higher VCLs. This, in and of itself, is a revealing factor. However, where rocks are comparable in depth vs VCL, other parameters can be applied. ROP provides finer resolution within the VCL vs Depth discriminator. For instance, where rocks present equivalent depths at the same VCL, the stronger of the two rocks will present lower ROP values. Finally, the Drill “On-Time” and the Total Depth achieved provides two more parameters used to discriminate rocks by their strength. Where VCL/Depth and ROP are equal, a rock causing the drill to deliver more Drill “On-Time” for less Total Depth is stronger than a rock that allows the drill to achieve Total Depth with less Drill “On-Time”.

Results Following is the rationale used to provide the relative rock strengths, from weakest to strongest as illustrated in Figure 1.

Telegraph Peak: Drilled almost entirely at VCL1 with a reasonable ROP and in a reasonable amount of time. All other rocks included in this study caused the system to step up to higher VCLs.

Mojave 2: Drilled nearly an equal amount of depth between VCL1 and VCL2 and nothing at VCL3 or higher.

Buckskin: Close to the same performance as Mojave 2, except the drill created more borehole depth at VCL2 than at VCL1. Furthermore, the average ROP was lower at level two and it took 90 seconds more On-Drill Time to get to depth than was the case for Mojave 2.

***Confidence Hills**: Was drilled using the standard percussion configuration. As such, the system recorded (and adjusted for) low WOB for three cycles and quickly dialed back to VCL1. However, this means the drill created borehole depth at VCL4 that would not have otherwise been the case had the system started at VCL1. Regardless of this, Confidence Hills is placed correctly as the rock is strong enough that it ended up pushing the system back up to VCL4 for the last half of the operation.

Greenhorn: After violating low ROP cycles, this rock quickly caused the system to adjust to VCL3 and VCL4 (it was strong from the start). Greenhorn caused the system to work at VLC 4 through more depth than any of the other rocks.

Big Sky: Big Sky gets the top spot for strength because, like Greenhorn, Big Sky also caused the VCLs to run mostly at the higher levels. In Big Sky however, the drill experienced a lower overall ROP than seen in Greenhorn. The drill also had more Drill “On Time” and Total Depth achieved ended up being shallower than seen in Greenhorn.

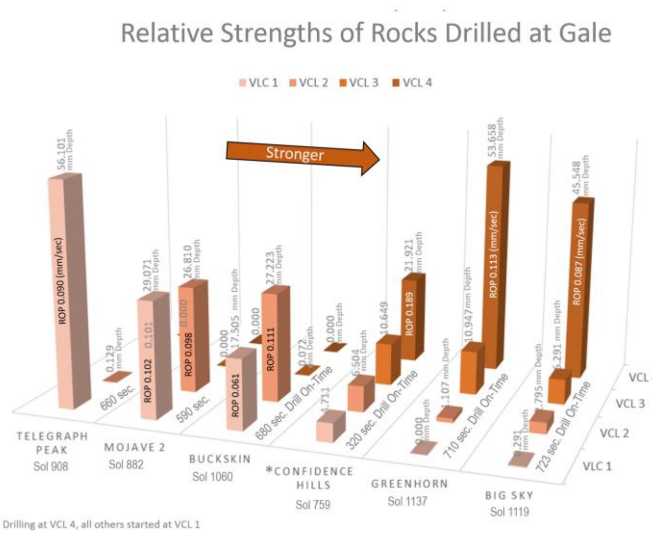

Figure 1. Illustrates the relative strengths, sorted from weakest to strongest drilled at Mars’ Gale Crater since the Pahrump Hills campaign. Data is organized so that each column represents the depth drilled in millimeters. Percussion energy is denoted by Voice Coil Levels (VCL), which are weaker in the front row (VCL1-2) and progressively become more energetic (harder hitting) in the back rows (VCL3-4). Average Rates of Penetration (ROP) for significant depths drilled are shown on each column and the Drill “On-Time” is listed in each rock’s display division.

Discussion: While more work is needed to assign actual strength values, a picture is emerging. We see for sedimentary rocks that strength is a function of sedimentary facies. It is worth noting that while most of the rocks presented here are siltstones and/or mudstones, the two (demonstrably) strongest rocks drilled, Greenhorn and Big Sky, are both from the Stimson sandstone unit.

REFERENCES: [1] A. Okon, (2010) Proceedings of the 40th Aerospace Mechanisms Symposium, NASA Kennedy Space Center, 2010NASA/CP-2010-21623