**THE MECHANICAL STRENGTH OF ROCKS ENCOUNTERED AT MERIDIANI PLANUM, MARS.** T. J. Seyglinski and B. J. Thomson, Department of Earth and Planetary Sciences, University of Tennessee, Knoxville 37996 (tseyglin@vols.utk.edu).

**Introduction:** The Mars Exploration Rover (MER) *Opportunity* conducted science investigations on the martian surface from January 2004 until June 2018, setting a distance record for longest rover traverse (45.16 km). During that time, the rover encountered a variety of rocks, outcrops, and surface features, many of which were analyzed for information on texture and chemistry [1-5]. Vital for these investigations, and the primary subject for this study, is the Rock-Abrasion Tool (RAT), which was used to abrade the outer surface of rock targets to expose fresher, less-altered material beneath [6]. Power consumption during these grind events can be directly correlated to the physical properties of the material being abraded using a technique already demonstrated on rocks encountered by MER *Spirit* in Gusev crater [7]. The work presented here seeks to add to these data, further constraining a correlation between RAT grind energies and bulk physical properties of targets investigated by *Opportunity*.

*RAT Operation.* The RATs onboard both *Spirit* and *Opportunity* served the purpose of a geologist's rock hammer by revealing fresh material below surface rinds for further analysis via APXS, MI, etc. [6]. This material is a better representation of martian lithology, and understanding its mechanical behavior makes it possible to constrain some aspects of the formation and modification history of rock units, including perhaps the regimes of pressure and temperature they experienced.

**Methods:** The investigation proposed here requires the procurement of engineering data for use with a derived relation between RAT specific grind energy (SGE) and unconfined compressive strength (UCS) from [7]. Specifically, RAT motor currents will be used to estimate the UCS of various rock targets. Coupled with this will be porosity measurements for each target following the methods of [8] and [4]. This step is necessary in order to produce quantitative measures of the contact surface between the grind bit and target material that will further refine UCS estimates.

Due to the irregular surface of rock targets and the chemical alteration of their exteriors, grind parameters are only considered over the last 0.25 mm of grind operations. This ensures that the grind bit is in full contact with the target and that UCS will be estimated from the freshest material possible.

**Discussion:** Over the course of the mission (Figure 1), *Opportunity* documented many different morphological features at Meridiani Planum, from rocky outcrops to impact debris and impactors themselves. Of particular interest were sedimentary outcrops with enough stratigraphic exposure to suggest a more regional extent. At Meridiani Planum, *Opportunity* was able to distinguish at least 4 distinct, spatially extensive stratigraphic units (Figure 1) [9]. These are, in order from oldest to youngest, the Matijevic Formation, Shoemaker Formation (lower and upper), Grasberg Formation (lower and upper), and the Burns Formation (lower, middle, and upper). Unconformities exist between each unit as evident by erosional contacts [9]. Brief descriptions of each unit are given below.

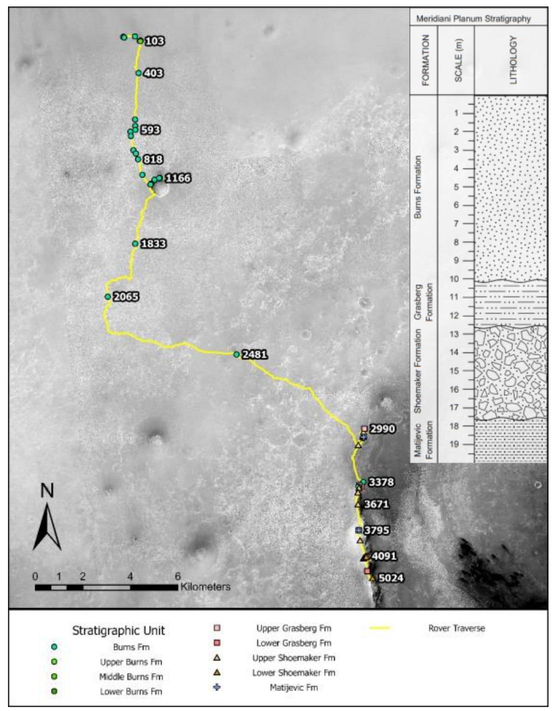


**Figure 1.** A map layout showing the traverse of MER *Opportunity*. Plotted along the traverse are points where the RAT brushed or abraded targets, symbolized by their respective stratigraphy. Numbers shown are the Sol of operation. Also shown is a stratigraphic column of the units investigated by *Opportunity*. A total of 92 grind events have been gathered, however, this number may vary depending on the viability of data from individual grind operations.

*Matijevic Formation.* The Matijevic Formation is a pre-Endeavor substrate that may be a part of ancient Noachian-age deposits identified by Hynek and Di Achille [5, 10]. While ambiguity remains as to its regional extent and, thus, its exact stratigraphic placement, it is generally understood that this unit was emplaced prior to the Endeavor impact [5]. The Matijevic Formation is composed of a fine-grained matrix that exhibits some jointing and dark veneers, and RAT SGE values group these rocks with the Burns Formation in terms of resistivity (2.8 $J/mm^3$) [3]. However, due to limited outcrop exposures (Figure 1), the origin of this unit remains poorly constrained [9]. For more, see [3, 5, 9, 11].

*Shoemaker Formation.* The Shoemaker Formation consists of coarse, dark-toned impact breccias in a fine-grained, light-toned matrix and are likely associated with the formation of Endeavor crater [3, 9]. SGE values from targets within this unit indicate that the resistivity of Shoemaker samples is similar to that of Burns Formation sandstones (~1.6 $J/mm^3$ from target "Salisbury") [9]. The Shoemaker Formation can be distinguished into 3 subdivisions based on distinct morphological features that typify each subdivision. These are, in order from bottom to top, Copper Cliffs, Chester Lake, and Greely Haven [9]. The lowermost unit (Copper Cliffs) contains spherules sourced from the underlying Matijevic Formation and shows chemical evidence of mixing between the 2 units, likely during the emplacement of Endeavor crater [5, 9]. See [3, 5, 9] for more on the Shoemaker Formation.

*Grasberg Formation.* The Grasberg Formation stratigraphically overlies the Shoemaker Formation and consists of lighter, finer-grained material that lacks sedimentary structures [5]. The SGE of RAT targets within this unit suggest that these rocks are some of the more cohesive in Meridiani Planum (7.6 $J/mm^3$) [9], but are still weak relative to terrestrial samples. It is divided into lower and upper units based on a variation in color, the lower unit being comprised of somewhat darker material [5]. While recognized as a separate unit than the overlying Burns Formation, both units appear to be sourced from the same precursor basaltic material and have underwent similar diagenetic alterations, though their transport and deposition mechanisms likely differed [12]. For more on the Grasberg Formation, see [5, 9, 12].

*Burns Formation.* The Burns Formation is set of geochemically related cross-bedded eolian and fluvial sandstones that commonly contain abundant sulfates and hematite concretions ("blueberries") [13]. This was the only unit encountered by *Opportunity* for almost 3000 Sols (Figure 1). The sediments comprising these sandstones were sourced from a primary basalt component and appear to have been exposed to repeated inundations with fluctuating groundwater [1, 2]. These sediments exhibit millimeter-scale laminations and are loosely cemented by sulfate material, resulting in an overall weak unit [9]. It is divided into 3 subunits based on chemical and morphological distinctions: lower (eolian dune facies), middle (eolian sand sheet facies), and upper Burns (mixed sand sheet/interdune facies) [2]. More details on the Burns Formation can be found in [1, 2].

*Past Work and Future Directions.* The scientific objective of the MER missions was to characterize the geologic history of their landing sites with a primary goal of assessing the potential for past fluvial activity [13]. *Opportunity* was able to accomplish this with the suite of instruments included in the Athena science payload [14], on which much literature has already been produced. However, an area that has been overlooked is a more rigorous analysis of what can be inferred from RAT SGE values. This project aims to add to what has already been done on this topic [7] and establish the efficacy of the technique for use with future missions. This will be accomplished by taking a quantitative look at ~92 RAT SGEs within the aforementioned stratigraphic units and observing any trends in mechanical response within and between them. By doing so, it is possible to infer more about the deposition of these units (i.e., burial depth and duration, temperature, pressure, etc.) and the overall environmental history at Meridiani Planum.

**Conclusions:** MER *Opportunity* led a very extensive and successful scientific campaign on the martian surface. A wealth of literature has already been produced from the mission, but there is still more to gain from data returned by the rover. Proposed here is one such way we might further build upon the findings of past studies. By looking at these data through a new lens, it is possible to gain new information from data that already exist and further refine our ideas on the geologic history of Meridiani Planum.

**Acknowledgments:** The NASA PDS hosts much of the data that are necessary for the completion of this project, made accessible through the MER Analyst's Notebook at the Geosciences Node of the PDS.

**References:**

[1] Squyres S.W. et al. (2006) *Science*, *313*. [2] Grotzinger J.P. et al. (2005) *EPSL*, *240*, 11-72. [3] Arvidson R.E. et al. (2014) *Science*, *343*. [4] Nahm A.L. & Schultz R.A. (2007) *GRL*, *34*. [5] Mittlefehldt D.W. et al. (2018) *JGR-Planets*, *123*, 1255-1306. [6] Gorevan S.P. et al. (2003) *JGR-Planets*, *108*. [7] Thomson B.J. et al. (2013) *JGR-Planets*, *118*, 1233-1244. [8] Okubo C.H. (2007) *GRL*, *34*. [9] Crumpler L.S. et al. (2015) *JGR-Planets*, *120*, 538-569. [10] Hynek B.M. & Achille G.D. (2017) *USGS*. [11] Mittlefehldt D.W. et al. (2021) *JGR-Planets*, *126*. [12] McCollom T.M. & Hynek B. (2021) *EPSL*, *557*. [13] Squyres S.W. et al. (2006) *JGR-Planets*, *111*. [14] Squyres S.W. et al. (2003) *JGR-Planets*, *108*.