ROCK HARD SCIENCE: MULTISPECTRAL AND MINERALOGICAL INVESTIGATIONS TO UNDERSTAND BEDROCK SPECTRAL PROPERTIES AND STRENGTH AT VERA RUBIN RIDGE, GALE CRATER, MARS.

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Introduction: Since the beginning of the Mars Science Laboratory (MSL) mission, Vera Rubin Ridge (VRR) has been a location of interest to the MSL science team because of its apparent erosional resistance and strong near-IR (~860 nm) absorption feature seen from orbit in the Mars Reconnaissance Orbiter mission's Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) data [1,2]. The strong CRISM absorption feature along VRR was hypothesized to be primarily associated with an increased abundance of crystalline hematite compared to lower Mt. Sharp units. However, surface multispectral and mineralogic data, from the Mastcam [3,4] and CheMin [5] instruments onboard the Curiosity rover, suggest hematite is not the only mineral contributing to the near-IR absorption feature measured in VRR or the reason for its relative hardness.

Rover Drilling Activities: There have been three drill targets (Stoer, Highfield, and Rock Hall) on VRR that have achieved full drill depth (~40 mm), and three full drill attempts where the bedrock was too resistant for the drill to penetrate more than a few mm. Two additional attempts to drill the ridge in "rotary only" mode also failed to achieve a sufficient depth for sampling. Peters *et al.* [6] estimated the uniaxial compressive strength of the Murray mudstone drill sites visited earlier in the mission based on the energy and percussion levels needed at each site to fracture the rock. Murray drill targets, such as Marimba, Quela, Sebina, and Oudam, were drilled using a drilling algorithm that biased for lower percussion levels. The lower percussion algorithm lent itself well to estimating the strengths of the rocks [6]. The drill reacts to stronger rocks by increasing percussion energy until an acceptable rate of penetration is reached. In December of 2016, Curiosity lost the ability to feed the drill relative to the stabilizers. Targets Duluth, Stoer, Highfield and Rock Hall were thus drilled in the Feed Extended Drilling (FED) configuration in which the stabilizers are not used. During FED, the robotic arm provides the reaction force against the rock instead of the drill feed mechanism, a rotary-only component to the drilling has been added, the weight on bit has been increased, and the targeted borehole depth has been decreased. These changes have altered the performance of the drill, making rock strength estimations more uncertain compared to earlier drilling methods.

Results: The 867 nm absorption feature measured by Mastcam varied dramatically among the eight VRR drill sites, which included targets that are among the lowest and highest 867 nm band depths measured on the ridge (Fig. 1). Comparing Mastcam 867 nm band depths to quantitative mineralogy from CheMin [7] shows that XRD-measured crystalline hematite abundance actually has a weak negative correlation with the depth of the 867 nm absorption feature. This is contrary to the simplest explanation for the variability observed in spectral data, which is simply to increase/decrease hematite abundance. Further examination of the two datasets revealed that the measured phyllosilicate abundance has a notably strong positive correlation with this spectral feature (Figs. 2 & 3). The phyllosilicates identified by CheMin are predominantly smectite clay minerals [7]. Comparisons between CheMin-derived mineralogy and rock strength reveal that the abundances of certain minerals, like Ca-sulfates, are positively correlated with rock strength (Fig. 4), while the abundances of other minerals such as hematite have no correlation with bedrock strength (Fig. 5).

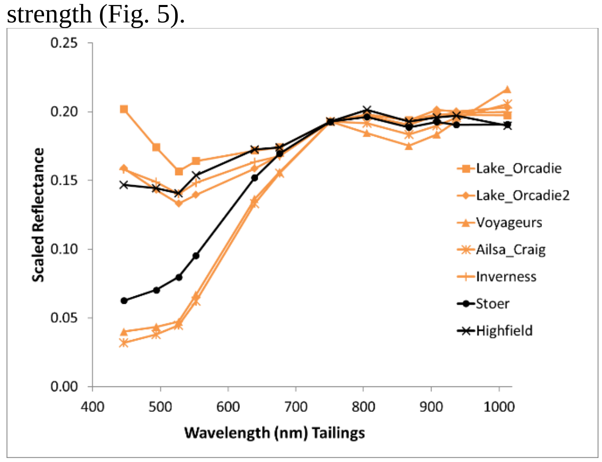

Figure 1: Scaled spectra of VRR drill site tailings showing variations in the Mastcam-derived 867 nm absorption feature. Black spectra are from drill sites that reached full depth. Orange spectra are from drill attempts that did not reach full depth. Spectra scaled to Stoer target at 751 nm.

Discussion: The fact that crystalline hematite abundance does not correlate with the depth of the 867 nm absorption feature suggests that hematite could be present as both a crystalline phase and a nanophase component [*e.g.*, 8,9]. CheMin can detect crystalline hematite, but nanophase hematite might be detected only as unidentified "amorphous material". No matter how crystal size affects the way CheMin detects hematite, the strong correlation in Fig. 3 and ChemCam passive spectra suggest that other ferric phases are present and could be a major contributing factor to the 867 nm absorption feature [10]. The correlation between Ca-sulfate and rock strength suggests that a Ca-sulfate cement is likely present in the VRR drill targets. The cement could have infilled pore spaces in the rock, increasing its strength. The correlations between Mastcam multispectral and CheMin mineralogy described here enable the possibility of understanding the mineralogy of other bedrock targets on VRR that were either not drilled or not drilled successfully. For example, the unsuccessful drill target Voyageurs has the strongest 867 nm absorption feature yet measured on VRR, but Fig. 5 implies that it might not actually have the greatest abundance of crystalline hematite. Regardless, the slight increase in CheMin-derived hematite abundances in the Stoer and Highfield targets supports the hypothesis that VRR parent materials might have undergone more in-place oxidative weathering than those from lower Mt. Sharp units.

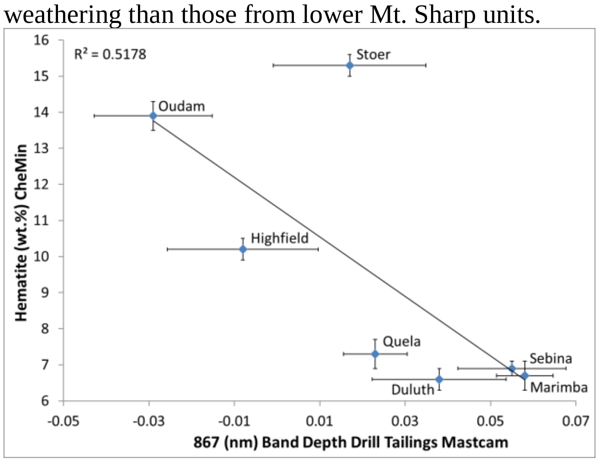

Figure 2: Weak negative correlation between CheMin-derived hematite abundance [7] and the depth of the Maastcam-derived 867 nm absorption feature.

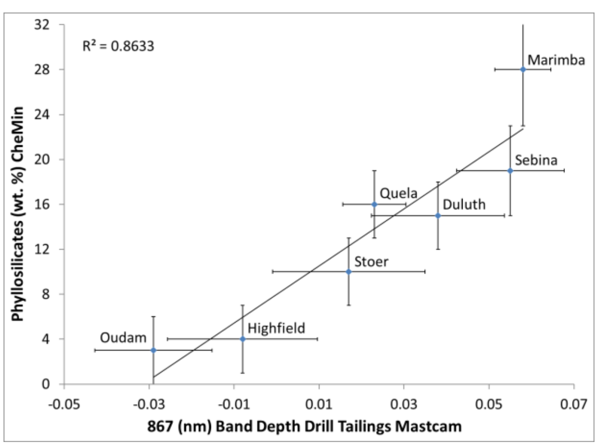

Figure 3: CheMin-derived phyllosilicate abundance [7] compared to the depth of the 867 nm absorption feature.

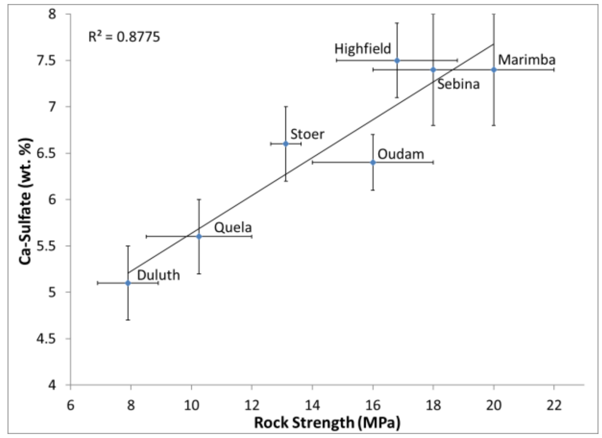

Figure 4: CheMin-derived Ca-sulfate abundance [7] compared to estimated rock strength [6], showing a strong correlation that could indicate the presence of a cement that is increasing the bedrock resistance.

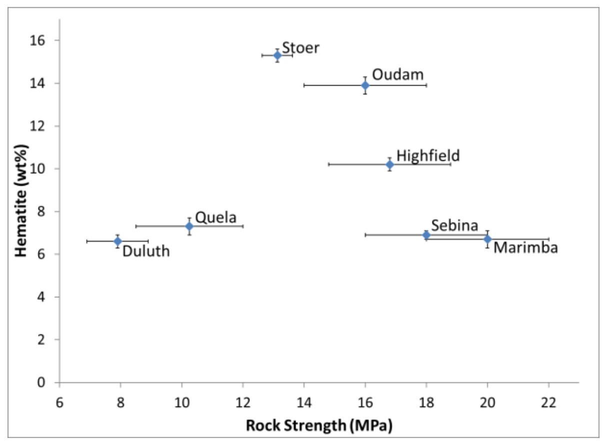

Figure 5: CheMin-derived hematite abundance [7] compared to estimated rock strength [6], showing that crystalline hematite is apparently not a major contributing factor to bedrock resistance.

References: [1] Milliken R.E. *et al*., *GRL, 37*, L04201, 2010. [2] Fraeman A.A. *et al., Geology, 40*, 1103, 2013. [3] Malin, M.C. *et al., Earth Space Sci., 4,* 2017. [4] Bell III, J.F. *et al., Earth Space Sci., 4,* 2017. [5] Blake, D.F. *et al., Space Sci. Rev. 170*, 341, 2012. [6] Peters G.H. *et. al., GRL, 45*, 108, 2018. [7] Bristow T. *et al.*, Sci. Adv., *4*, 2018. [8] Morris, R.V. and H.V. Lauer, Jr., *JGR, 95*, 5101, 1990. [9] Morris, R.V. *et al., GCA, 57,* 4597, 1993. [10] Johnson J.R. *et al.,* LPSC XLVIII abstract 1310, (2017).