

SPECTRAL VARIABILITY OF SULFATE VEINS OBSERVED BY MASTCAM ALONG CURIOSITY'S TRAVERSE IN GALE CRATER, MARS. M. S. Rice¹, D. Dixon¹, J. F. Bell III², D. Wellington², J. R. Johnson³,

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Introduction: Understanding the composition and hydration state of sulfates at Gale crater is important to the Mars Science Laboratory (MSL) mission goal of interpreting past environmental conditions. Mg-sulfates have been detected from orbit in the strata of Mt. Sharp [e.g., 1-2], and throughout its traverse, Curiosity has observed Ca-sulfates in the form of mineralized, fracture-filling veins in almost all major rock units. Observations from multiple instruments indicate that these are diagenetic features that formed during fluid flow events [e.g., 3-4]. In nearly all locations, the Ca-sulfates occur in the form of bassanite, although recent ChemMin observations from the Oudam drill sample indicate that gypsum was present in veins and subsequently dehydrated during the experiment [5]. Observations of veins by Curiosity's ChemCam instrument have also revealed elevated Fe in some locations, interpreted to be in the form of ferric oxides and/or ferric sulfates [6].

In this study, we investigate potential variations in sulfate hydration and iron oxidation in the veins as seen in Mastcam spectra. We also present the results of a laboratory spectral analysis of multi-phase mixtures of Ca- and Mg-sulfates in order to better constrain Mastcam's sensitivity to hydration in sulfates.

Methods: *Mastcam multispectral analysis:* Mastcam is a multispectral, stereoscopic imaging instrument that can acquire visible to near-infrared (VNIR) spectra in 12 unique wavelengths from 400-1100 nm [7]. Mastcam spectra have been calibrated to radiance using pre-flight calibration coefficients and converted to I/F using associated observations of the Mastcam calibration target, and converted to relative reflectance by dividing by the cosine of the solar incidence angle [8]. Effects of airfall dust on the calibration target have been corrected for using two-stream radiative transfer models [9]. Mastcam spectra of veins and host rock were extracted by manually selecting pixels from common regions in the both camera images (avoiding pixels with saturation or shadowing in any filter).

Laboratory analysis of Ca-sulfate mixtures: Reflectance spectra (350-2500 nm) of Ca-sulfates (anhydrite, bassanite and gypsum) and Mg-sulfates (kieserite, hexahydrite and epsomite) were measured with a fixed viewing geometry ($i=0^\circ$, $e=23^\circ$) using an ASD FieldSpec-3 at Western Washington University. Spectra were acquired at a variety of grain sizes (from 65 μm to 2 mm) as pure samples and as two-phase mixtures,

with and without the addition of a Mars dust simulant (5 wt. % JSC-Mars1 [10]). Spectra were measured relative to a Spectralon® standard and were convolved to Mastcam bandpasses [8].

Spectra of hydrated Ca- and Mg-sulfates have an absorption band due to the $2\nu_1 + \nu_3$ H₂O combination positioned centered at 950-1000 nm. This narrow hydration band leads to a Mastcam spectral profile that is "flat" in the near-IR, with a downturn at the longest Mastcam wavelength (1012 nm). This profile is distinguishable from spectra of iron-bearing minerals with broad absorptions near 1000-nm, which have an overall negative spectral slope in the near-IR. We quantify the strength of this absorption in Mastcam spectra as the "1012 nm band depth" (the fractional depth of the reflectance at 1012 nm beneath that at 937 nm).

Results: *Mastcam multispectral analysis:* The 1012 nm band depths measured from Mastcam spectra across the traverse are shown in Fig. 1a (within the Murray formation, sols 950-1750). Band depths vary from 0.07 (an absorption potentially consistent with hydration) to -0.07 (an upturn more consistent with broad absorptions near ~900 nm in iron-bearing minerals). In most instances, the 1012 nm band depths of veins are larger than those of the surrounding host rock. Band depths for both veins and host rock become negative after sol ~1550, which may be indicative of chemical changes near the Old Soaker outcrop [e.g., 6] and the presence of hematite-like spectral signatures later in the traverse.

Mastcam parameters indicative of ferric oxides are shown in Fig. 1b (steep "red" slopes from 447 nm to 638 nm, and slopes from 638 nm to 805 nm that are consistent with Fe³⁺). Vein spectra exhibit a wider range of these parameters than the host rock spectra, consistent variations in Fe content and oxidation state.

Laboratory analysis: The Mastcam 1012 nm band depths in lab spectra are controlled by grain size and the amount of hydration (Fig. 2). In all experiments, bassanite (CaSO₄•0.5H₂O) and kieserite (MgSO₄•H₂O) have hydration band depths < 0.01, and this weak hydration band is not expected to be detectable to Mastcam. Pure gypsum at coarse grain sizes has a larger band depth, but this reduces to < 0.1 in mixtures with the dust simulant. Polyhydrated Mg-sulfates at grain sizes larger than 0.1mm have 1012 nm band depths of several percent, even when mixed with dust, and thus are expected to be more easily detectable to Mastcam.

Summary and Future Work: Mastcam spectra of Ca-sulfate veins exhibit considerable variability across Curiosity's traverse, which may be consistent with changes in iron oxidation state. In our ongoing work, these spectra will be compared to variations in chemistry from ChemCam and observations of vein morphology. Vein spectra typically have larger 1012 nm band depths than host rock, but further spectral analysis is required to determine whether this absorption can be uniquely attributed to the presence of H₂O. Lab work shows that Mastcam's 1012 nm band should be sensitive to hydration in coarse-grained gypsum, but the band is easily masked by dust and most likely is undetectable in bassanite and in gypsum-bassanite mixtures.

Mastcam's 1012 nm band is more sensitive to polyhydrated Mg-sulfates, however, and may become a more useful indicator of hydration state as Curiosity approaches the Mg-sulfates in Mt. Sharp.

References: [1] Milliken *et al.* (2010) *Geophy. Res. Lett.*, 37, L04201. [2] Thomson *et al.* (2011), *Icarus*, 214, 2. [3] Wrapin *et al.* (2016), *Earth Planet. Sci. Lett.*, 452, 197-205; [4] Nachon *et al.* (2014), *JGR*, 119, 9. [5] Vaniman *et al.* (2017) *LPSC XLVIII*, 1661. [6] L'Haridon *et al.* (2017), *4th Conf. Early Mars*. [7] Malin, M.C. *et al.* (2017) *Earth & Space Sci.*, 4, 506. [8] Bell, J.F., III *et al.* (2017) *Earth & Space Sci.*, 4, 396. [9] Kinch *et al.* (2015) *Earth & Space Sci.*, 2, 144-172. [10] Allen *et al.*, (1997) *LPSC XXVIII*, 1797.

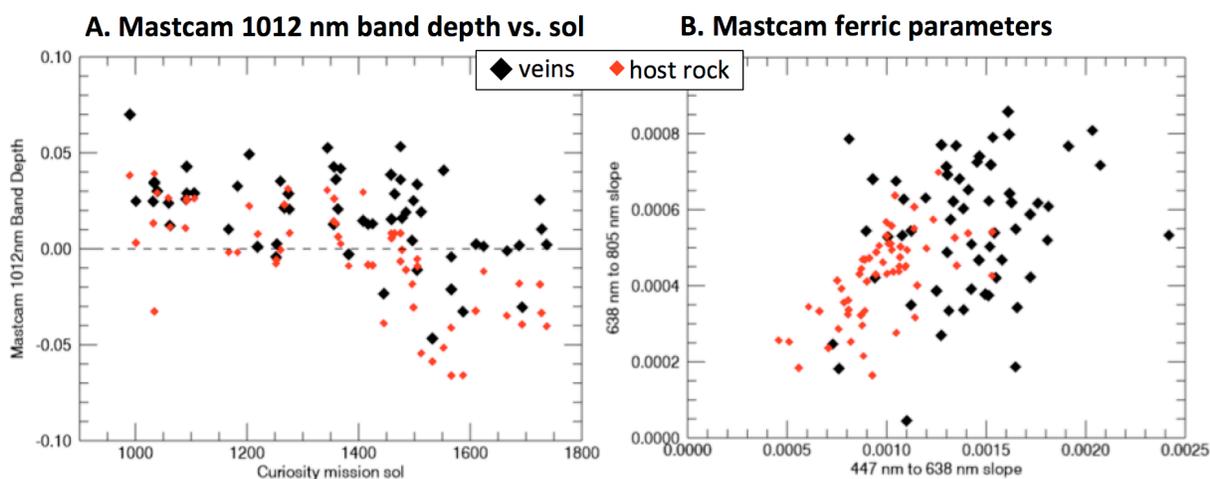


Figure 1. Mastcam spectral parameters for veins and host rock in the Murray formation (sols 950-1750): (a) 1012 nm band depth (can indicate hydration) vs. sol; and (b) 638 to 805nm slope vs. 447 to 638 nm slope (consistent with Fe-oxides).

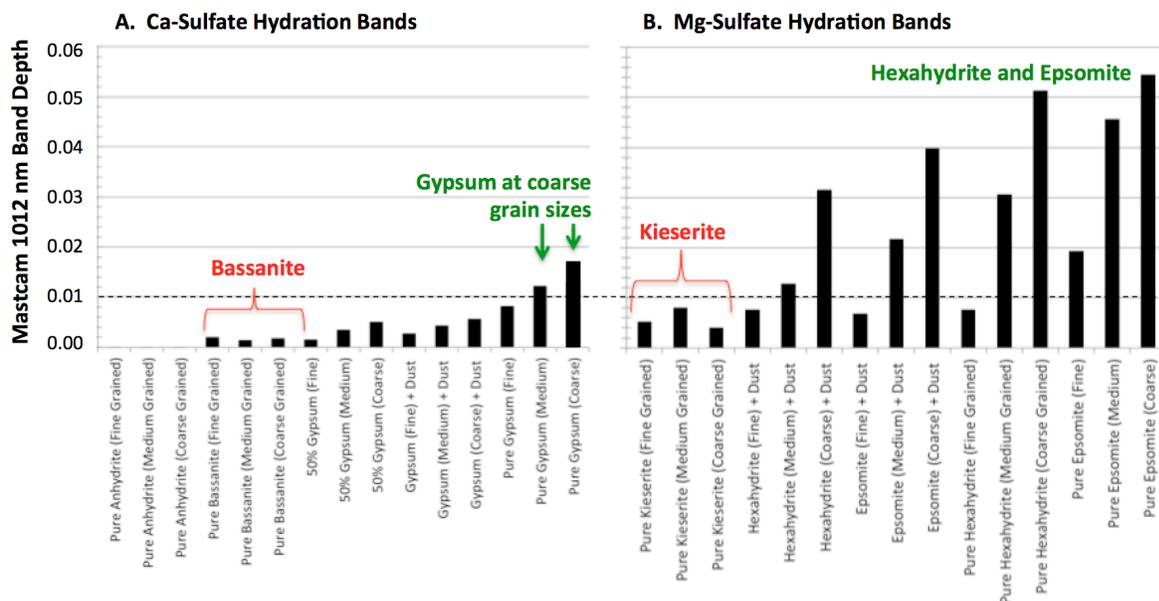


Figure 2. 1012 nm hydration band depths of laboratory VNIR sulfate spectra that have been convolved to Mastcam bandpasses: (a) Ca-sulfates and (b) Mg-sulfates at varying grain sizes and two-phase mixtures.