DISTRIBUTION AND ANALYSIS OF CALCIUM SULFATE-CEMENTED SANDSTONES ALONG THE MSL TRAVERSE, GALE CRATER, MARS M.A. Nellessen[1], A.M. Baker[1], H.E. Newsom[1], R.S. Jackson[1], M. Nachon[2], F. Rivera-Hernandez[2], J. Williams[3], R.C. Wiens[4], J. Frydenvang[4], P. Gasda[4], N. Lanza[4], A. Ollila[4], S. Clegg[4], O. Gasnault[5], S. Maurice[5], P.-Y. Meslin[5], A. Cousin[5], W. Rapin[5], J. Lasue[5], O. Forni[5], J. L'Haridon[5], D. Blaney[6], V. Payré[7], N. Mangold[8], L. LeDeit[8], K. Edgett[9], R. Anderson[21], [1]U. New Mexico, Albuquerque, NM 87131, USA (Newsom@unm.edu); [2]UC Davis, CA; [3]Western Washington University, WA; [4]Los Alamos Nat. Lab, NM; [5]IRAP/CNRS, FR; [6]Caltech/Jet Prop. Lab, CA; [7]U. Lorraine de Nancy, FR; [8]Lab. de Planet. et Geodynam. de Nantes, FR; [9]Malin Sp. Sci. Sys., San Diego, CA; [10]USGS, Flagstaff, AZ.


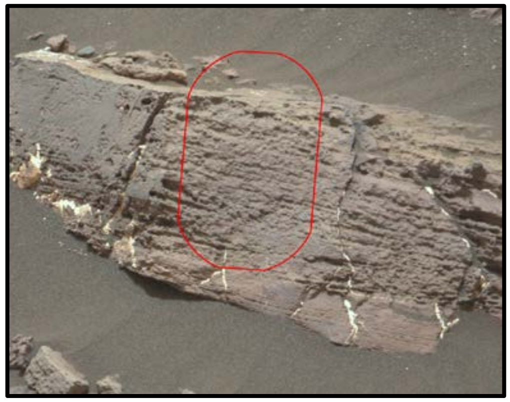
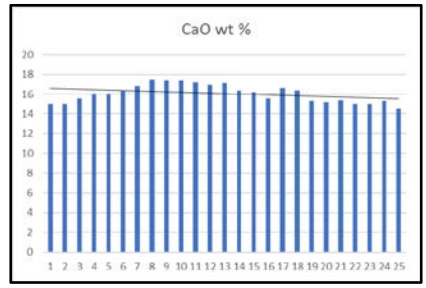

Fig. 1 A. ChemCam RMI image mosaic merged with Mastcam color of a portion of the Murray formation (Bobonong target, Sol 1477), with light-toned materials consistent with the presence of pore-filling calcium sulfate cement. B. Location of the RMI and ChemCam LIBS observations C. Shot to shot data showing the relative homogeneity of the Shot to Shot data. The 25 shots do not include the first 5 shots that are mainly dust.

Introduction: The Mars Science Laboratory Rover Curiosity has observed calcium sulfate veins in all of the bedrock examined to date in Gale Crater, with the exception of the Bradbury Rise or Rocknest Outcrop areas. The veins are also ubiquitous in the Murray formation, which is mudstone-dominated. But recently (e.g. **Fig. 1**) when the rover reached the Murray Buttes above the Old Soaker target on the lower slopes of Mount Sharp, the presence of light-toned rocks with moderate Ca and S have been observed, suggesting the presence of a cemented porous sandstone. The substantial increase in ChemCam analyses consistent with cemented sandstone (instead of mudstone) (**Fig. 2**), along with changes in other sedimentary structures may signal a change in the depositional environment and/or provenance of the lake deposits.

Detection of calcium sulfate cement: We have frequently targeted calcium sulfate veins with ChemCam, by using Laser Induced Breakdown Spectroscopy (LIBS) chemical analyses [1]. There is only a small chance that the laser beam can partly hit a vein plus matrix material. However, in sandstone, typical porosities vary between 5% by volume up to ~ 30% by volume, with poorly sorted materials having less pore space. Because the sulfate is less dense (~ 2.7 g/cm^3) than the basaltic sand (~2.9 g/cm^3), the maximum fraction by weight of calcium sulfate would be 20%. Thus CaO abundances around 20 wt% would be consistent with a cemented sandstone.

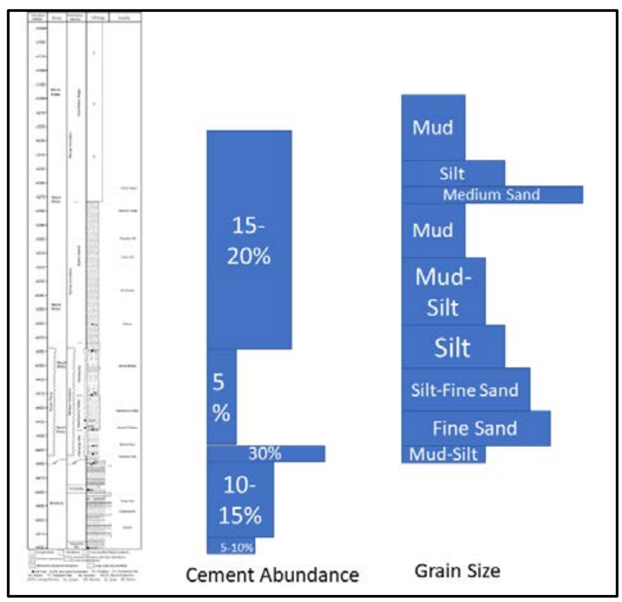

Fig. 2 Frequency of ChemCam points likely to be porous-sandstone (rather than mudstone) cemented with calcium sulfate related to the stratigraphic column of Mount Sharp on Mars during the MSL mission. Also compared is the average grain size analysis of the targets [6].

Furthermore, cemented sandstones have very homogeneous shot-to-shot trends with a low standard deviation (<2.0) (**Fig 3**). We compiled all of the shot-to-shot data from targets averaging 10 to 25 wt% CaO and plotted each shot for every target, omitting the first 5 shots as this is assumed to be mostly Martian dust, which will give inaccurate data on the target rock. It was noted that most targets (~80%) with moderate CaO exhibited a homogeneous trend. This indicates that almost all locations with intermediate CaO represent cemented rocks and not the edge of a vein. This has been verified by examination of the RMI and Mastcam context imagery. We then compiled all of the moderate CaO targets into two lists: one for the homogeneous, cemented targets and one for those displaying heterogeneous targets.

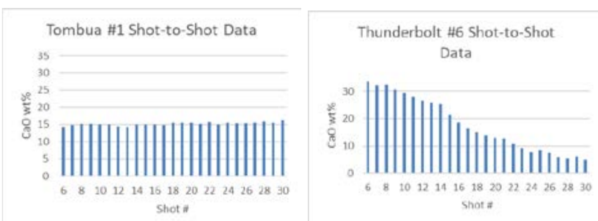

Fig. 3 A. ChemCam shot-to-shot data for target depicting homogeneous calcium sulfate cement, Sol 1378. B. ChemCam shot-to-shot data displaying heterogeneous trend caused by hitting the edge fo a vein, Sol 1033.

To confirm that these elevated CaO detections are actually calcium sulfate, evidence for the presence of sulfur is needed. Recent work by Clegg et al. [3] on sulfur calibration for ChemCam indicates that ChemCam may be able to quantify sulfur down to the ~1 wt% level. That capability will be particularly useful for detecting analytical points with low volumes of cement in mudstones,< 13 wt% CaO. It will also be particularly helpful more accurately quantify sulfur as well as determine the other missing components. Until that capability is deployed, we have used the so-called missing-component (100% – the oxide total), to approximate the abundance of SO_3 when totals are less than 100% and CaO is elevated over the normal matrix abundances. Examination of all the ChemCam data from the beginning of the mission to Sol 1550 for the signature of substantial cement (CaO between 10 wt% and 25 wt%), resulted in over 750 candidate points. The obvious correlation between CaO and the missing component supports the interpretation that most of these analyses are of sandstone cemented by calcium sulfate.

Distribution and Origin of Calcium Sulfate Cement: The Murray formation contains abundant calcium sulfate veins, usually ~1 mm to a few mm thick, that commonly cross cut the depositional layers at sub-vertical angles [4]. The Murray formation from the Pahrump Hills to the Murray Buttes contains many occurrences of interbedded sandstone. At elevations below the Murray Buttes, the Murray formation apparently consisted largely of mudstones that had very limited porosity when calcium sulfate bearing fluids were present.

The Murray formation from Pahrump, through Marias Pass to the Murray Buttes has little evidence for cement. However, as noted above the character of the bedrock changed at the Murray Buttes above Old Soaker (around Sol 1550), with a variety of sedimentary structures including laminated, wavy/irregular/cross-laminated or cross-bedded layers with clear geometric truncations based on preliminary analysis [5]. This area is where the Ca sulfate cemented sandstones are much more common (**Fig. 2**). The increased abundance of sandstone and the other changes indicate a change in the original depositional environment, sediment flux, or provenance.

We will begin comparing the location and abundances of targets with cement to various types of veins. This will include the vein occurrence that appears along bedding planes (as compared to cross-cutting the unit), which has been seen frequently in images [4]. Furthermore, minor element abundances, such as Br and Mn, may potentially discriminate different facies including low-stand types.

Grain Size Analysis: We hope to utilize ChemCam to determine grain size by analyzing point-to-point chemical heterogeneity, as this has not been done yet with targets bearing cement. Relative grain size has varied throughout the mission from fine muds and silts to coarser sands (**Fig. 2**). This would use the Gini ndex method [6]. This will involve analyzing the porosity of the rocks and correlating this to grain size. Part of this will involve looking at how the compositions of major elements vary outside of Ca and S in order to analyze grain size patterns. Calibration will be needed to apply this variance to Ca and S grains to analyze grain sizes of the cemented rocks.

Conclusions: In contrast to the ubiquitous calcium sulfate veins, since entering the Murray Buttes the presence of calcium sulfate cemented porous sandstone has become common, both visually, and in ChemCam analyses. The presence of the cemented sandstone and changes in sedimentary structures suggest a change in depositional environment, including sediment flux and possibly provenance of the lake deposits.

References: [1] W. Rapin et al. EPSL, 452:197-205, 2016. [2] Newsom et al. 2016 LPSC, and 2017 LPSC, and in preparation. [3] Clegg et al., 2018 LPSC, this volume. [4] Nachon M. et al. (2017) AGU, #230348. [5] Grotzinger et al., 2016, AGU [6] Rivera-Hernandez, 2018, submitted, and LPSC 2018.