# Increasing occurrence of sandstone cemented with calcium sulfate on Mount Sharp, Gale Crater, Mars

## Conference or Workshop Item

**INCREASING OCCURRENCE OF SANDSTONE CEMENTED WITH CALCIUM SULFATE ON MOUNT SHARP, GALE CRATER, MARS** H.E. Newsom[1], R. Jackson[1], R.C. Wiens[2], J. Frydenvang[2], P. Gasda[2], N. Lanza[2], A. Ollila[2], S. Clegg[2], O. Gasnault[3], S. Maurice[3], P.-Y. Meslin[3], A. Cousin[3], W. Rapin[3], J. Lasue[3], O. Forni[3], J. L'Haridon[3], S. Banham[4], S. Gupta[4], B. Cohen[5], J. Schieber[6], S.P. Schwenzer[7], J. Grotzinger[8], D. Blaney[8], J. Schroeder[8], F. Calef[8], R. Francis[8], B. Ehlmann[8], N. Thomas[8], N. Stein[8], J. Watkins[8], D. Rubin[9], N. Bridges[10], J. Johnson[10], V. Payré[11], N. Mangold[12], L. LeDeit[12], K. Edgett[13], D. Fey[13], R. Gellert[14], L. Thompson[15], M. Schmidt[16], G. Perrett[17], L. Kah[18], R. Kronyak[18], R. Anderson[19], K. Herkenhoff[19], J. Bridges[20], [1]U. New Mexico, Albuquerque, NM 87131, USA (Newsom@unm.edu); [2]Los Alamos Nat. Lab, NM; [3]IRAP/CNRS, FR; [4]Imperial College, UK; [5]NASA MSFC, AL, [6]Indiana U., IA, [7]Open U., U.K.[8]Caltech/Jet Prop. Lab, CA; [9]UC Santa Cruz, CA; [10]App. Phys. Lab, MD; [11]U. Lorraine de Nancy, FR; [12]Lab. de Planet. et Geodynam. de Nantes, FR; [13]Malin Sp. Sci. Sys., San Diego, CA; [14]U. Guelph, Can.; [15]U. New Brunswick, Can.; [16]Brock U., Can., [17]Cornell, NY; [18]U. Tenn., TN; [19]USGS, Flagstaff, AZ; [20]U. Leicester, UK.

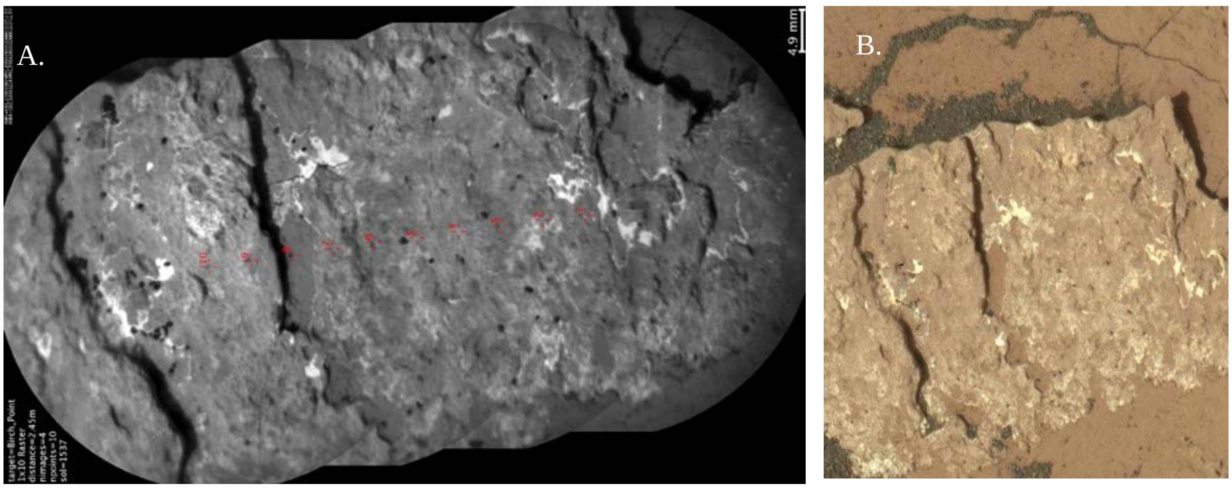


**Fig. 1** A. ChemCam RMI image mosaic of a portion of the Murray formation (Birch Point target, Sol 1537) with light-toned materials consistent with the presence of pore-filling calcium sulfate cement. All points but #8 are elevated in CaO. B. Mastcam.

**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 area. The veins are also ubiquitous in the Murray Formation, which is interpreted as fine-grain mudstone. But recently (e.g. **Fig. 1**) when the rover reached the Murray Buttes on the lower slopes of Mount Sharp, the presence of light-toned rocks with moderate CaO have been observed, suggesting the presence of a cementd 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. The first significant detection of cemented sandstone, with CaO abundances greater than the pure silicates but less than pure sulfate, was documented in Stimson formation material at Marias Pass [2]. In this case elevated CaO and evidence from MAHLI and RMI images supported the identification of the cement [2].

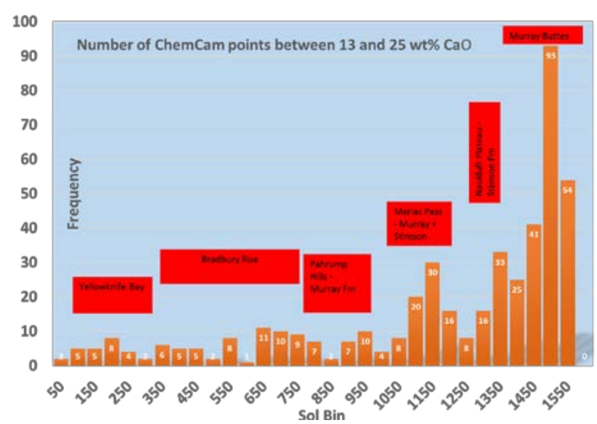


**Fig. 2** Frequency of ChemCam points likely to be porous-sandstone (rather than mudstone) cemented with calcium sulfate as a function of the Sols on Mars during the MSL mission.

To confirm that these elevated CaO detections are actually calcium sulfate, visual evidence for light-toned material is useful (**Fig. 1** and also e.g. target Goose Cove Sol 1568). Furthermore, 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. 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 13 wt% and 25 wt%), resulted in approximately 450 candidate points (**Fig. 3**). The obvious correlation between CaO and the missing component supports the interpretation that most of these analyses are of sandstone cemented by calcium sulfate.

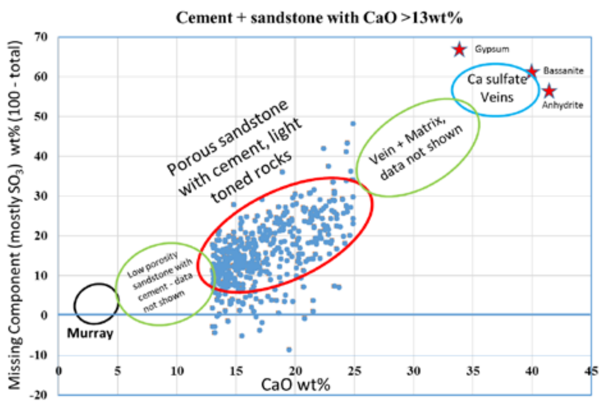


**Fig. 3** ChemCam LIBS detections of CaO in wt% between 13 wt% and 25 wt%, plotted against the missing-component, which is a proxy for $SO_3$.

**Distribution and Origin of Calcium Sulfate Cement:** The Murray Formation contains abundant calcium sulfate veins, usually ~1 mm to a few mm thick, that mostly cross cut the depositional layers at sub-vertical angles. However, the Murray formation from the Pahrump Hills to the Murray Buttes, until about -4390 m in elevation, contains very few occurrences of interbedded or interfingering sandstone. At elevations below the Murray Buttes, the Murray Formation apparently consisted almost entirely of mudstones that had very limited porosity when calcium sulfate bearing fluids were present. Cement at lower volume fractions (e.g. **Fig. 3**) is possible, but is more difficult to convincingly document.

Prior to reaching the Murray Buttes, the only well documented occurrence of a calcium sulfate cemented sandstone is in the Stimson formation that unconformably overlies the Murray. The Stimson has far fewer veins, but in the Marias Pass area, the Missoula Member sandstone just above the contact, appears to be also locally cemented with calcium sulfate, based on data from ChemCam, APXS and MAHLI [2]. Most of the Stimson has cross bedding consistent with an aeolian origin, except for the thin layer of the Missoula Member adjacent to the contact. Portions of this thin (~5 cm thick) layer, including material directly at the contact are light-toned and have the LIBS signature for cement discussed above. The Murray Formation from Pahrump, through Marias Pass to the Murray Buttes has no evidence for cement. However, as noted above the character of the bedrock changed at the Murray Buttes, with a variety of sedimentary structures including laminated, wavy/irregular/cross-laminated or cross-bedded layers with clear geometric truncations based on preliminary analysis [4]. 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.

Because the calcium sulfate veins are ubiquitous in the rocks examined in Gale crater, the presence of sulfate saturated fluids that could fill the pore spaces of sediment is not surprising. However, the deposition of the cement did not have to occur at the same time as the vein deposition, which requires a pressure build up that exceeded the lithostatic pressure needed to hydrofracture the rocks. Another point is that the saturation of the fluids and deposition of the calcium sulfate is probably not driven by a pressure change, but is probably controlled by temperature [e.g. 5]. The physical nature of many of the veins in the area near the locations with abundant cement (e.g. **Fig. 1**), are also different from the occurrences at lower elevations, with lots of irregular vein deposits on bedding planes. The origin of the CaO in the veins and cement is still very much in question. In situ leaching is one possibility, supported by the evidence that the chemistry of the mudstones does not vary much [6], thereby eliminating the need for substantial flow within the sediment package. Evaporation of a 'Gale pore fluid' derived from dissolution of local rock chemistry is another [eg., 7].

**Conclusions**: In contrast to the ubiquitous calcium sulfate veins, only since entering the Murray Buttes has the presence of calcium sulfate cemented porous sandstone become common, both visually, and in ChemCam analyses. The presence of the 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., 2017 LPSC, this volume. [4] Grotzinger et al., 2016, AGU [5] Schieber et al., 2016, Sedimentology. 2016[6] Mangold et al. 2017, LPSC, [7] Schwenzer et al. (2016) MAPS, 51, 2175–2202.