GEOCHEMICAL ENDMEMBERS PRESERVED IN GALE CRATER: A TALE OF TWO MUDSTONES AND THEIR COMPOSITIONAL DIFFERENCES ACCORDING TO CHEMCAM. C. C. Bedford[1], S. P. Schwenzer[1], J. C. Bridges[2], R. C. Wiens[3], E. B. Rampe[4], J. Frydenvang[5], and P. J. Gasda[3], [1]The Open University, Walton Hall, Milton Keynes, UK, (candice.bedford@open.ac.uk). [2]Leicester Institute for Space and Earth Observation, University of Leicester, Leicester, UK. [3]Los Alamos National Laboratories, Los Alamos, New Mexico, USA. [4]NASA Johnson Space Centre, Houston, Texas, USA. [5]Natural History Museum of Denmark, University of Copenhagen, Copenhagen, Denmark.

Introduction: Gale crater contains two fine-grained mudstone sedimentary units: The Sheepbed mudstone member, and the Murray formation mudstones [1,2]. These mudstones formed as part of an ancient fluviolacustrine system [1,2]. The NASA *Curiosity* rover has analysed these mudstone units using the Chemistry and Camera (ChemCam), Alpha Particle X-ray Spectrometer (APXS) and Chemistry and Mineralogy (CheMin) onboard instrument suites. Subsequent mineralogical analyses have uncovered a wide geochemical and mineralogical diversity across and within these two mudstone formations [3-6]. This study aims to determine the principal cause (alteration or source region) of this geochemical variation through a statistical analysis of the ChemCam dataset up to sol 1482, including the lower to middle Murray formation.

The Sheepbed mudstones are >1.5 m thick [1] and rich in primary mafic minerals (forsterite, augite and pigeonite), and smectitic clays [3]. They possess relatively thick, poorly defined laminations and contain many diagenetic features such as raised ridges [7], nodules (hollow and filled) [8] and mineral veins [9]. Hydrous alteration models of these diagenetic features suggest that they formed in a mostly closed system, at a low water–rock ratio (<1000) and neutral–alkaline pH [10].

The Murray formation mudstones are laminated with some interstratified, cross-bedded sandstones and ~150 m thick within the area of our study [2]. They are richer in felsic minerals (plagioclase feldspar, alkali feldspar) and X-ray amorphous materials than the Sheepbed mudstones, and poorer in clays [6]. Diagenetic features present in the Pahrump Hills region (sols 755–944) at the base of Murray include: nodules, raised ridges, and both light and dark mineral veins [11]. Further up the stratigraphic succession in the Marias Pass and Bridger Basin regions (sols 995–1190) fracture-associated diagenetic halos occur [12].

Methods: ChemCam acquires major, minor and trace element compositions through investigating a target host rock or soil between 2.2–7 m from the rover mast with Laser-Induced Breakdown Spectroscopy [13,14]. Between 30–50 spectral analyses are collected per observation point (OP) and averaged to give the OP compositions used here. We have grouped ChemCam OP analyses into a “host rock” dataset according to stratigraphic unit (Sheepbed and Murray) and locality for the Murray formation (Pahrump Hills, Marias Pass, West and East Naukluft Plateau, and Murray Buttes). We have also categorised diagenetic features (raised ridge, nodule, vein, halo) and separated them into their own “alteration” dataset (Fig. 1). Target classification is based on RMI, MastCam, MAHLI and NavCam images. Any OP that has hit soil, float, pebbles, drill tailings or dump piles have been removed. To remove targets affected by open-system weathering, we have only included those in the dataset with totals between 95 % and 105 %. As ChemCam OP compositions do not include S or H, targets extensively altered by hydrolytic or acid-sulfate weathering should possess lower totals [15] and will hence be excluded.

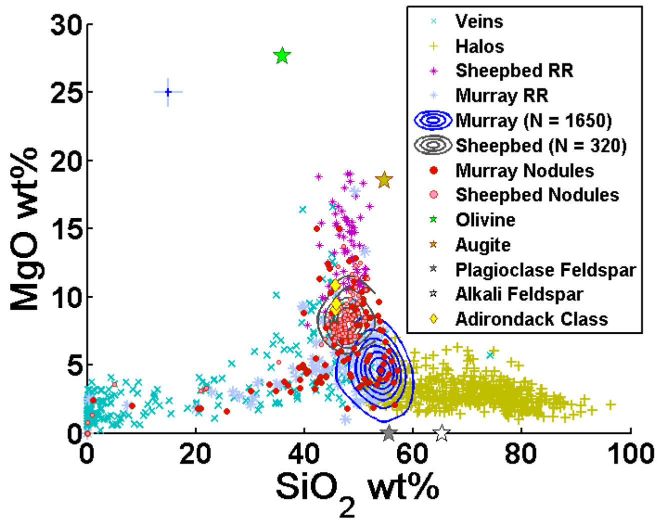

Figure 1: ChemCam analyses showing host rock density contour and alteration feature scatter trends for the Gale Crater Sheepbed and Murray mudstone units. Alteration feature scatter trends plot away from mudstone contour focal compositions indicating minimal influence of alteration features on host rock compositions. Cross at left shows accuracy (thin) and precision (wide lines).

Due to ChemCam’s small sample footprint (350–550 µm), host rock bulk compositions are simulated using density contours to illustrate the focal compositions and geochemical trends for the dataset. Each contour represents an equal amount of data plotted onto the (x,y)-space. Alteration trends and modelled Gale crater mineral compositions are plotted as scatter points to highlight trends associated with these features (Fig. 1).

Hydrous alteration trend discussion: In our dataset, sulfate mineral veins show clear major element oxide depletion for everything except CaO, along with low totals. Fracture-associated halos demonstrate strong silica-enrichment (up to 80 wt%) with depletions in all other major elements except TiO_2 (enriched) and MgO (unchanged [Fig. 1]). The strong deviations away from host rock composition (Fig. 1) and consistency in geochemical trends across stratigraphic groups suggests that these features are the product of open-system weathering occurring within bedrock fractures.

Several nodule and raised ridge analyses show enrichments in MgO or CaO, with depletions in all other major elements (Fig. 1). The raised ridges in the Sheepbed mudstones are substantially more MgO-rich (Fig. 1). Otherwise, a large proportion of the raised ridge and nodule features are compositionally similar to their host mudstone. The phyllosilicates observed by CheMin indicate that chemical alteration of bedrock has occurred, however we assume that it was mostly authigenic and that, with care in selecting the targets, the overprint of alteration can be distinguished and excluded to allow the identification of igneous source compositions.

Source region variation discussion: On average, the Sheepbed mudstones are more depleted in SiO_2, Al_2O_3, and K_2O, but enriched in MgO, Na_2O and CaO compared to the Murray formation mudstones. These compositional differences and associated element correlations relate to mixing proportions between mafic and felsic primary minerals detected in the sediments.

The Sheepbed mudstones possess a similar, if slightly less mafic, bulk geochemical composition to the tholeiitic Adirondack basalts (Fig. 1) analysed by the MER *Spirit* rover [16] and basaltic igneous float and clasts in Gale crater [17].

The Murray formation is notably richer in felsic material, highlighted by its elevated Al_2O_3, alkalis and depleted MgO bulk composition (Fig. 1). A higher average silica content (55 wt% as opposed to 48 wt% for Sheepbed) is also a defining feature. With a basaltic mineralogy identified in Murray drill samples, and with silica-rich diagenetic features removed along with targets that have experienced open system alteration, the source for bulk Murray is hypothesized to be dominated by a silica-saturated tholeiitic provenance. The Marias Pass locality of the Murray formation demonstrates even more elevated silica concentrations (up to 80 wt% SiO_2), though here it is related to a tridymite and cristobalite-rich mineral assemblage identified in the Buckskin drill hole [5]. These minerals have been associated with a strongly silica-rich, likely volcanic source unique to the rest of the Murray formation and have not been identified anywhere else in Gale's stratigraphy.

The lower Murray formation also possesses on average more sanidine (~5 %) according to CheMin analyses [6] which likely accounts for some of its relative K_2O-enrichment. High order sanidine associated with a potassic-rich volcanic provenance [4] or hydrothermally altered source [18] has been detected in abundance within the underlying Kimberley formation sandstones. We hypothesize that this trachytic source may have continued to contribute sediment to the lower Murray formation.

Conclusions: The results of this study show that element remobilisation relating to veins, haloes, raised ridges and nodules does not affect mudstone geochemistry in close proximity to these features, with many nodule and raised ridge compositions largely dependent on that of the surrounding rock. As such, and with authigenic alteration assumed for clay generation, geochemical variation of these mudstone units with similar grain sizes can be linked to changing source region contributions. Hence, four different volcanic/magmatic source regions have been identified within the Sheepbed mudstone and Murray formation:

1. A subalkaline tholeiite; similar in composition to the Adirondack Class basalts [16] and the dominant source region for the Sheepbed mudstones.
2. A more silica-rich, subalkaline basalt; the main contributer to the Murray formation (this work).
3. A highly evolved, silica-rich igneous source; identified by [5] in the Marias Pass, Buckskin drill hole.
4. A potassium-rich volcanic source; identified by [4] in the Kimberley sandstone, Windjana drill hole analysis. This may provide a minor contribution to the mudstones of the lower Murray formation.

Acknowledgements: CCB, JCB and SPS acknowledge support from STFC–DTG and UKSA.

References: [1] Grotzinger et al. (2014) doi:10.1126/science.1242777. [2] Grotzinger et al. (2015) doi:10.1126/science.aac7575. [3] Vaniman et al. (2014) doi:10.1126/science.1243480. [4] Treiman et al. (2016) *doi: 10.1002/2015JE004932*. [5] Morris et al. (2016) doi:10.1073/pnas.1607098113. [6] Rampe et al. (2017) doi:10.1016/l.epsl.2017.04.021. [7] Leveille et al. (2014) doi:10.1002/2014JE004620. [8] Stack et al. (2014) doi:10.1002/2014JED04617. [9] Rapin et al. (2016) doi:10.1016/j.epsl.2016.07.045. [10] Bridges et al. (2015) doi:10.1002/2014JED04757. [11] Nachon et al. (2016), doi:10.1016/l.icarus.2016.08.026. [12] Frydenvang et al. (2017) doi:10.1002/2017GL073323. [13] Wiens et al. (2012) doi:10.1007/s11214-012-9902-4. [14] Maurice et al. (2012) doi:10.1002/s11214-012-9912-2. [15] Morris et al. (2001) doi:10.1029/2000JE001328. [16] McSween et al. (2006) doi:10.1029/2005JE002477. [17] Edwards et al. (2017) doi:10.1111/maps12953. [18] Morris et al. (2018) This conference.