CONSTRAINING THE CLIMATE OF ANCIENT MARS USING TERRESTRIAL ANALOGS. M. T. Thorpe[1,2], J. A. Hurowitz[3], and K.L. Siebach[2], [1]NASA Johnson Space Center, Houston, TX 77058; michael.t.thorpe@nasa.gov; [2]Rice University, Houston, TX; [3] Stony Brook University, Stony Brook, NY.

Introduction: As in fluvial environments on Earth, sediments and sedimentary rocks are generated on the surface of Mars through chemical and physical weathering, physical abrasion and sorting, diagenesis and lithification. However, the source material for this sediment is fundamentally different between these planets because the Earth's exposed crust is dominated by geochemically evolved granodiorites [1] while Mars' exposed crust is chiefly composed of basalt [2]. Therefore, our terrestrial reference frame can sometimes prove inadequate for understanding the sedimentary record of Mars. This has made the interpretation of the sedimentary record at locations such as Gale Crater, which contains basaltic sedimentary rocks formed in an ancient fluvio-lacustrine setting [3-4], more difficult. Complicating matters further, the paleoclimatic conditions and atmospheric composition that allowed these fluvial conditions to prevail remain unclear [5,6]. Therefore, this work aims to provide improved constraints on the paleoclimate of Gale Crater, Mars by investigating weathering processes across a range of climates in basaltic fluvial systems on Earth.

Methods: Major element geochemistry of *in-situ* martian targets from Gale crater was obtained using the Alpha-Particle X-ray Spectrometer (APXS) onboard the Curiosity rover. Selected targets used in this study were compiled from literature for mudstones from (i) the Sheepbed member of the Yellowknife Bay formation [7] and (ii) the hematite-phyllosilicate (HP) facies of the Murray Formation [8].

For our terrestrial field sites, data was compiled from sediment in southwest Iceland [9] and northwest Idaho, USA [10]. These environments are reasonable terrestrial analogs for ancient Gale Crater fluvial systems because the catchments are dominated by a basaltic provenance and represent first-cycle sediments, i.e., generated directly from an igneous progenitor. In addition to these two analog field sites, reference values from the literature were also gathered for (i) basaltic weathering profiles [11-18] and (ii) fluvial sediments [13,19], with the aim of developing a larger suite of relevant terrestrial samples.

Results: The weathering history of terrestrial mud-sized sediments (<63 µm; grain size classes of silt and clay) and martian mudstones are compared using the Chemical Index of Alteration (CIA), a value calculated from the molar ratio of $[Al_2O_3 / (Al_2O_3 + CaO + K_2O + Na_2O)] * 100$ (Fig. 1). We note the use of the as measured CaO abundance resulting in uncorrected CIA values, largely because cations in the non-silicate phases of martian targets are not well understood [20]. Therefore, this uncorrected CIA value is a minimum and any sort of correction would only increase the CIA values [20]. In sediments and sedimentary rocks, the CIA value is thought to reflect the degree to which the sources of sediments and sedimentary rocks have been affected by chemical weathering processes [21]. As chemical weathering progresses, feldspar dissolution and the formation of aluminous secondary minerals results in a weathered residuum with higher CIA values [12,21]. Consequently, the overall CIA value preserves a signature of climate, as weathering rates vary with temperature and precipitation (Fig. 2).

Discussion: In the terrestrial study sites of Iceland and Idaho, the degree of chemical weathering increases as grain size decreases, resulting in the most chemically altered material preferentially concentrated into the finest grain size, i.e., the clay size fraction (<2 µm) of fluvial sediments. However, on Mars, the Sheepbed mudstones display low CIA values (avg = 33.8) that are nearly identical to the martian crust (36.9), illustrating little to no element mobilization. These CIA values are significantly lower than those observed in the Iceland (avg = 51.6) and Idaho sediments (avg = 70.9), suggesting a Gale Crater paleoclimate considerably colder and more arid than both terrestrial analogs, and consistent

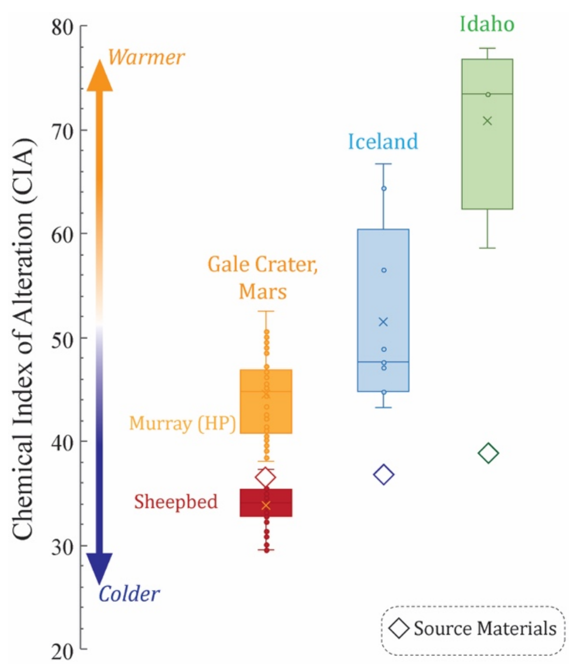

Figure 1. The Chemical Index of Alteration (CIA) plotted for terrestrial and martian mud-sized sediment and mudstone, respectively

with the paleoclimate interpretations of *McLennan et al.* [7]. On the other hand, the Murray HP mudstones display higher CIA values (avg = 44.5), thus demonstrating evidence for element mobility and a change in weathering, possibly driven by climate variation [8]. When Murray HP mudstone CIA values are compared to the terrestrial analogs, we observe a closer correlation with the Iceland mud sized sediments (Fig. 1), suggesting this subarctic climate is a reasonable candidate for paleoclimate conditions during transport and deposition of Murray mudstones. While the CIA values for the Murray HP mudstones are still lower than those of the Iceland sediments, we note that the overall range of the CIA values of the Murray HP mudstones extends into the range of Icelandic values. Furthermore, as the Curiosity rover continues to traverse up the Murray formation, it has encountered mudstone targets with even higher CIA values, as evidenced by the ChemCam analysis of the Sutton Island member (CIA ~63) [22]. These higher CIA values are still within the range of the mud-sized (<63 µm) sediment from Iceland, but may also

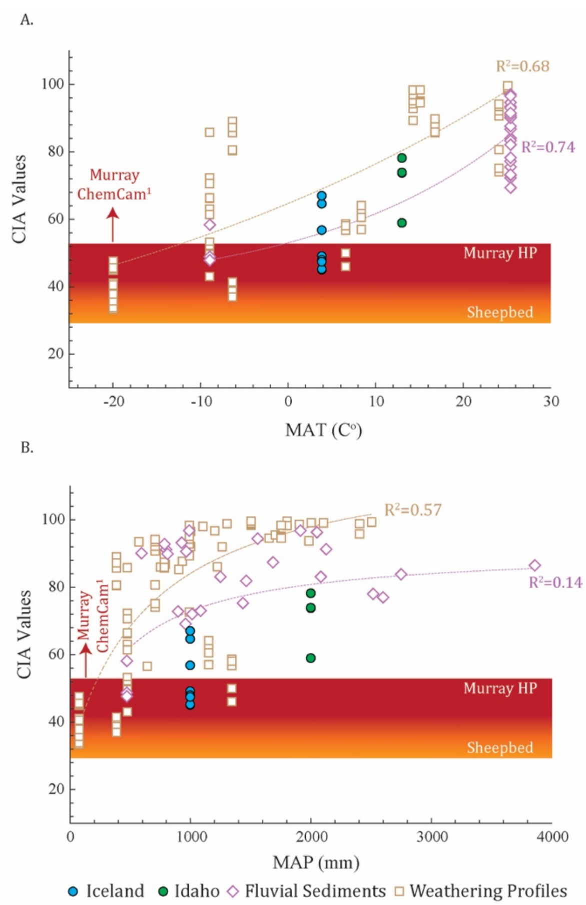

Figure 2. CIA values plotted against the climate variables of mean annual temperature (MAT) and mean annual precipitation (MAP) compared to CIA ranges for the Sheepbed and Murray HP mudstones and ChemCam analysis of stratigraphically higher portions of the Murray formation [22].

suggest even more temperate climate conditions, e.g., Idaho. The dataset compiled from the literature for (i) basaltic weathering profiles and (ii) fluvial sediments, provides further insight into the effects that mean annual temperature (MAT) and mean annual precipitation (MAP) have on CIA in mafic terrains (Fig. 2). While an Icelandic-like climate still serves as a reasonable analog for the paleoclimate during the Murray formation, we also observe that conditions could be slightly warmer and wetter to generate these fluvial deposits, as long as the temperature and precipitation values are below those observed for the Idaho sediments. In contrast, the Sheepbed mudstone generation likely occurred in a paleoclimate with temperatures that were generally frigid and runoff potentially driven by melting during short-term temperature excursions, however, these warming events are not resolvable at the scale of rover observations.

Conclusion: Comparison of the geochemistry of the Sheepbed mudstone to that of terrestrial analogue materials indicate that environmental conditions could have been as cold as those measured where weathering profiles are presently developing in Antarctica [11] and as wet as climates where soils are developed in Svalbard [18]. During the formation of the Murray HP mudstones the paleoclimate shifted and Icelandic-like conditions prevailed [19]. As Curiosity continues to uncover higher CIA value targets [22], even warmer and wetter climates are possible scenarios for the paleo-conditions of Gale.

References: [1] Taylor, S.R. and McLennan, S.M. (1985), *Blackwell Scientific Publications*. [2] Taylor, S.R. and McLennan, S.M. (2009), *Cambridge University Press*. [3] Grotzinger, J.P. et. al. (2014), *Science*. [4] Grotzinger, J.P. et. al. (2015), *Science*. [5] Bristow, T.F. et al., (2017), *PNAS*. [6] Tosca N.J. et al., (2018), *Nature Geosciences*. [7] McLennan, S.M. et. al. (2014), *Science*. [8] Hurowitz, J.A. et al. (2017), *Science*. [9] Thorpe, M.T. et. al. (2018), *GCA submitted*. [10] Thorpe, M.T. and Hurowitz, J.A. (2018), *JSR submitted*. [11] Gibson, E.K. et. al. (1983), *JGR*. [12] Nesbitt, H.W. and Young, G.M. (1992), *AJS*. [13] Pokrovsky, O.S. et. al. (2005), *GCA*. [14] Porder, S. et. al. (2007), *EPSL*. [15] Ma, J.L. et. al. (2007), *GCA*. [16] Rasmussen, C. et. al. (2010), *Geoderma*. [17] Caner, L. et. al. (2014), *Geoderma*. [18] Yesavage, T. et. al. (2015), *Icarus*. [19] DeCarlo, E.H. et. al. (2005), *Applied Geochemistry*. [20] Siebach, K.L. and McLennan, S.M. (2017), *LPSC abstract # 2694* . [21] Nesbitt, H.W. and Young, G.M. (1982), *Nature*. [22] Mangold, N. et. al. (2018), *Icarus*.

Acknowledgments: This work was supported by a NASA Earth and Space Science Fellowship (award #NNX15AT58H to M.T.T.) and the NASA Solar System Workings program (award #NNX16AR38G to J.A.H.).