GLEN TORRIDON MINERALOGY AND THE SEDIMENTARY HISTORY OF THE CLAY MINERAL BEARING UNIT. M. T. Thorpe[1], T. F. Bristow[2], , E. B. Rampe[1], J. P. Grotzinger[3], V. K. Fox[3], K. A. Bennett[4], A. S. Yen[5], A. R. Vasavada[5], D. T Vaniman[6], V. Tu[1], A. H. Treiman[7], S. M. Morrison[8], R. V. Morris[1], D. W. Ming[1], A. C. McAdam[9], C.A. Malespin[10], P. R. Mahaffy[9], R. M. Hazen[8], S. Gupta[10], [11]R. T. Downs, [11]G. W. Downs, D. J. Des Marais[2], P. I. Craig[6], S. J. Chipera[12], N. Castle[7], D. F. Blake[2], and C. N. Achilles[9]. [1]NASA JSC, Houston, TX (michael.t.thorpe@nasa.gov), [2]NASA Ames Research Center, Moffett Field, CA, [3]Caltech, [4]USGS, [5]JPL/Caltech, [6]PSI, [7]LPI, [8]Carnegie Institute, [9]NASA GSFC, [10]Imperial College, [11]Univ. Arizona, [12]CHX Energy.

Introduction: Clay minerals are common in ancient terrains on Mars and their presence at the surface alludes to aqueous processes in the Noachian to Early Hesperian (>3.5 Ga) [1]. Gale crater was selected as *Curiosity's* landing site largely because of the identification of clay mineral rich strata from orbit [2]. On Earth, the types of clay minerals (i.e., smectites) identified in Gale crater are typically juvenile weathering products that ultimately record the interaction between primary igneous minerals with the hydrosphere, atmosphere, and biosphere [3]. Trioctahedral and dioctahedral smectite were identified by *Curiosity* in units stratigraphically below the Clay Mineral-Bearing Unit (CBU) identified from orbit [e.g., 4,5]. Compositional and sedimentological data suggest the smectite formed via authigenesis in a lake environment and may have been altered during early diagenesis. The CBU is stratigraphically equivalent to a hematite-rich unit to the north and stratigraphically underlies sulfate-rich units to the south [6], suggesting a dynamic environment and evolving history of water in the ancient Gale crater lake. Targeting these clay mineral rich areas on Mars with rover missions provides an opportunity to explore the aqueous and sedimentary history of the planet.

Sedimentary Rocks of Glen Torridon: After six years of traversing the fluvial-deltaic plains of Gale crater and climbing the sedimentary stack of lower Aeolis Mons (informally known as Mount Sharp), *Curiosity* started to explore the highly anticipated CBU, informally dubbed Glen Torridon (GT), early in 2019. A few units in GT are distinct from orbit: (i) the smooth CBU, which looks smooth from orbit, (ii) the fractured CBU, which shows fractured bedrock from orbit, and (iii) the intermediate fractured CBU, which is also fractured but brighter than the fractured CBU [7]. From orbit, GT is a valley with a sharp topographic transition with the hematite-bearing Vera Rubin ridge (VRR), suggesting a change in environmental conditions between the units. However, *in-situ* investigations with *Curiosity* demonstrate that the sedimentary facies of GT are similar to the underlying units in the Murray formation, i.e., GT is largely composed of fine-grained, laminated lacustrine rocks. Therefore, the GT campaign aims to address the nature of this contrast in mineralogy and geomorphology. Here, we characterize the mineral assemblages of four GT targets, with an emphasis on clay mineralogy to aid in determining the sedimentary history of Gale crater.

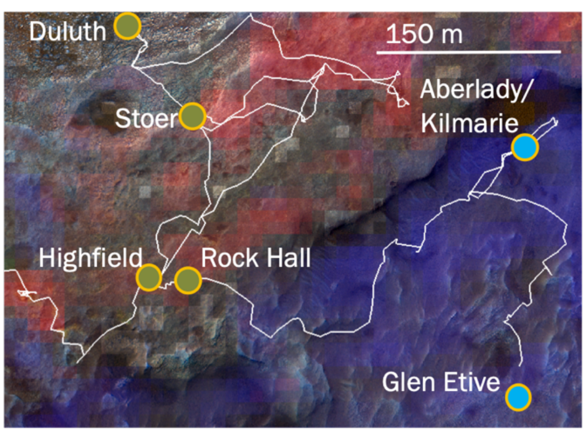

Figure 1. HiRISE view of the MSL traverse area and drill targets, with orbital CRISM detections of hematite (red) and Fe/Mg smectite (blue) in the VRR and GT.

Drill Targets in GT: Four targets were drilled in GT: (i) Aberlady, (ii) Kilmarie, both from the smooth CBU and (iii) Glen Etive 1, and (iv) Glen Etive 2, both from the fractured CBU. Aberlady and Kilmarie are from *Curiosity's* 3rd waypoint in the GT campaign, while the two subsets of Glen Etive are from the 6th waypoint. Drill powder from each sample was delivered to the CheMin X-ray diffractometer (XRD). Rietveld refinement and FULLPAT analysis of CheMin patterns allows for the quantification of crystalline phases and X-ray amorphous materials with a detection limit of ~1 wt.% for minerals [8,9]. Evolved gas analyses of Kilmarie, Glen Etive 1, and Glen Etive 2 by the Sample Analysis at Mars (SAM) instrument allow us to constrain clay mineralogy based on the temperature of H_2O releases [e.g., 10].

Glen Torridon Mineralogy: CheMin has discovered the most clay mineral rich targets to date in GT (>30 wt% of the bulk sample). The position and breadth of the clay mineral XRD basal reflections (~10 Å) is consistent with a collapsed smectite. Furthermore, the unit-cell dimensions inferred from the 02ℓ smectite peak of the GT samples suggest a dioctahedral Fe-bearing smectite phase similar to nontronite, with almost half the octahedral sites occupied by Fe^{3+}. The SAM evolved gas analyses of GT samples determined dehydroxylation temperatures that are also consistent with Fe-bearing smectites [10]. Additionally, the GT samples contain a significant fraction of X-ray amorphous material (>40 wt%). Each sample contains plagioclase (>10 wt%) and Ca-sulfates (i.e., bassanite and anhydrite). Minor constituents (<5 wt.%) identified in each sample include hematite and pyroxene. Siderite is above the detection limit of CheMin in the sample Kilmarie. The identification of siderite is the first identification of carbonate by CheMin. SAM EGA data are also consistent with siderite in GT samples [11].

Diagenetic History of GT vs. VRR: Although VRR and GT are syndepositional, the mineralogy of the GT and VRR samples are fundamentally different, which provides clues into their sedimentary history. The main distinctions in mineralogy between GT and the VRR is in the overall abundance of hematite and clay minerals. The VRR samples are enriched in hematite (up to 15 wt.% of the bulk sample [12,13]) relative to the GT rocks, in which only trace amounts are identified (~1-2 wt.%). In contrast, the GT targets are significantly enriched in clay minerals compared to VRR, and in some cases, contain six times the amount of clay minerals. The clay mineral identified by CheMin in the GT is consistent with a collapsed nontronite with a basal spacing of 10 Å. The clay minerals on VRR, however, have a basal spacing of 9.6 Å, consistent with acid-altered smectite or ferripyrophyllite [12,13]. These mineralogical differences suggest that Vera Rubin ridge was the site of a diagenetic front that might have altered the Fe-bearing smectite to precipitate hematite and amorphous silica [12,13]. GT did not experience diagenesis from these same fluids, as evidenced from the low hematite and high smectite abundances. The precipitation of hematite and amorphous silica mechanically strengthened the VRR, creating an erosionally resistant ridge and leaving a recessive valley for the GT. Comparing VRR to GT suggests GT was spared from the diagenetic fluids that altered the rocks on VRR. Therefore, GT may reflect the original clay mineral assemblage and has the potential to provide information on the paleoclimate and may preserve organic molecules.

Implications of clay mineralogy in Gale crater stratigraphy: The discovery of the most clay mineral rich samples analyzed by *Curiosity* in GT provides ground-truth to the orbital observations [6]. However, it is also important to note that, excluding the VRR samples, most lacustrine rocks drilled by *Curiosity* have a significant fraction of clay minerals [4-5]. Smectites have been the dominant class of clay minerals identified lower in the Murray formation, and the variation in smectite structure and composition may provide information on the aqueous history of Gale Crater. Comparative clay mineralogy across the Murray formation includes smectites ranging from ferrian Mg-rich trioctahedral, Al-rich dioctahedral, and Fe^{3+}-rich dioctahedral varieties [5]. Differences in discrete smectitic phases suggest a range in paleoaqueous alteration conditions. Although detrital clay mineral sources (e.g., clay minerals formed in weathering profiles in the source terrains) have been proposed [e.g., 15], a systematic change from trioctahedral smectite lower in the Murray to dioctahedral smectites higher in the stratigraphy suggest a transition in the aqueous conditions within the ancient Gale crater lake waters or groundwater [5]. The most Fe-rich dioctahedral smectites are found in the VRR and GT, supporting a change in the water chemistry to a more oxidative environment compared to lower in the Murray [5,14]. Furthermore, the clay mineral type and abundance of the GT is most consistent with open system chemical weathering and continues to shed light on the sedimentary history of Gale crater.

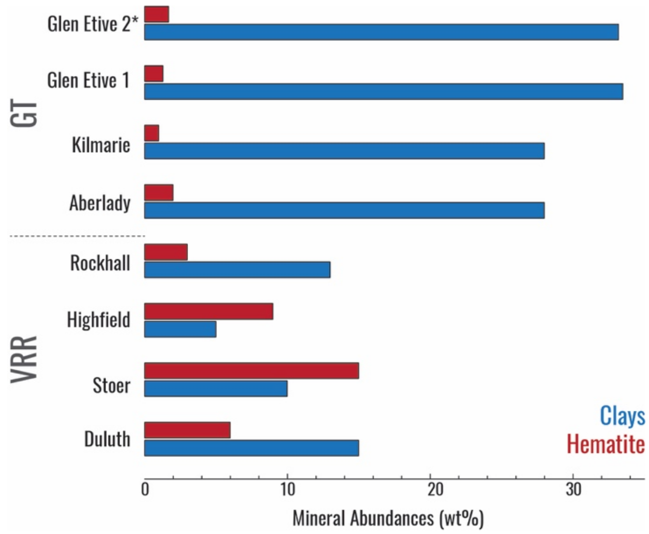

Figure 2. Clay mineral and hematite abundances for Glen Torridon and Vera Rubin ridge drill samples. GT abundances from [14]; VRR abundances from [12,13]. Glen Etive 2* are still preliminary CheMin abundances. *Figure modified from* [7].

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