One Year in Glen Torridon: Key Results from the Mars Science Laboratory Curiosity Rover exploration of clay-bearing units. V.K. Fox[1], K. A. Bennett[2], A. Bryk[3], R. Arvidson[4], T. Bristow[5], E. Dehouck[6], B. Dietrich[3], B. Ehlmann[7], C. Fedo[8], N. Mangold[9], C. O'Connell[10], L. Rampe[11], F. Rivera-Hernadez[12], L. Thompson[10], R. C. Wiens[13] and the MSL Science Team. [1]University of Minnesota, Minneapolis, MN (vfox@umn.edu), [2]USGS Astrogeology Center, Flagstaff, AZ, [3]UC Berkeley, CA. [4]Washington Univ. St. Louis. [5]NASA Ames Research Center. [6]LGL-TPE, Univ. de Lyon, France. [7]Caltech, JPL, Pasadena, CA. [8]Univ. of Tennessee. [9]LPG, Univ. De Nantes, France. [10]Univ. of New Brunswick, Canada. [11]NASA Johnson Research Center. [12]Dartmouth College. [13]Los Alamos National Lab

Introduction: In January of 2019 (sol 2300), the Curiosity rover descended off of the hematite-bearing Vera Rubin ridge (VRR) to begin exploration Glen Torridon(GT), a more recessive region that is strongly associated with smectite clay minerals in CRISM infrared observations from orbit. In-situ exploration of the clay mineral bearing strata within GT has been a major mission milestone, as these outcrops, which underlie hydrated sulfate layered deposits, were interpreted as potential records of a period of significant environmental and climatic change on ancient Mars [e.g.1-3]. Indeed, the rover observations of the region have provided important ground context that improve upon orbitally-based interpretations of the lithologies and landforms, and uncovered evidence for changing environmental settings within the ancient Gale Crater lake system.

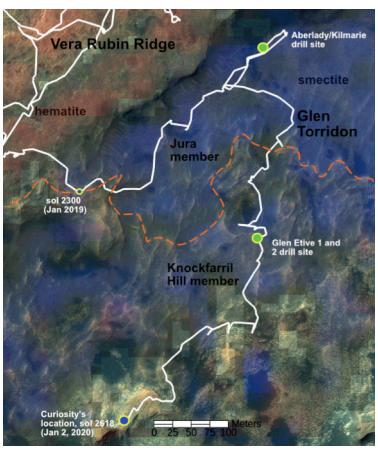

Figure 1. The Curiosity rover traverse through Glen Torridon. Drill locations are indicated by green circles.

This abstract provides an overview of the rover team's major findings within GT, initial interpretations, and key implications for the Gale crater hydrological systems on early Mars.

Key Findings: The strata within Glen Torridon have been divided into at least two stratigraphic members, both with a range of lithologic expressions [4]. The rover team has conducted a year-long expedition to survey the diversity, making two lateral surveys connected by a traverse moving uphill (Fig.1) that encapsulated the different morphologies and strata as observed in orbital imagery, as well as targeting regions with particularly strong CRISM smectite clay mineral signatures. So far, Curiosity has completed four drilled sample analysis campaigns and in all samples confirmed the clay mineral abundances predicted from orbit [5,6], and performed the first wet chemistry experiments on a drilled sample that found evidence for native organic molecules [7].

Stratigraphy: Imaging observations support the interpretation that the GT strata are conformable with underlaying strata and are members of the Murray formation. In fact, the lower GT region, which is predominately characterized by low relief, periodic bedrock ridges (PBRs) [8] and cm sized laminated mudstone clasts, is stratigraphically equivalent to the Jura member identified on the VRR [4]. A key supporting observation of this equivalency was of a distinctively weathered facies, with alternating resistant and recessive layers, at the same elevations on both the northern side of VRR and within GT [4,9]. Overlying the Jura member is the Knockfarril Hill member, a cross-laminated sandstone that forms more resistant caps on some of the PBRs and has been correlated laterally across GT (Fig2).

Elemental Composition: Measurements by the ChemCam and APXS instruments demonstrate that both the Jura member and Knockfarril Hill targets elemental compositions that are in family with those measured in previous Murray formation strata. There are at least two distinct compositional populations within both members that are also associated with particular outcrop morphologies. Within the Jura member, mudstone clasts or highly fractured bedrock are generally enriched in K (>1% K_2O abundance) and have lower MgO values, whereas more resistant, blockier have higher Mg and lower K values [10,11]. This trend continues in the Knockfarril Hill member, although ChemCam observes compositions that more frequently fall somewhat in between the extrema of the compositional populations [10].

Quantitative Mineralogy: Each of the four drilled samples so far from GT have contained ~30 wt.% clay minerals as measured by CheMin, the highest measured abundances so far in the mission [5]. The clays are Fe^{3+}-bearing dioctahedral smectites, which is consistent with the prediction of nontronite from the CRISM spectral analyses[1,3]. The first two samples, Aberlady and Kilmarie, were drilled into a low-K/high-Mg slab within the Jura member, near the lowest point explored within GT and within a region associated with a strong CRISM signature. The second pair of drill holes, called Glen Etive, were sampled from within the Knockfarril Hill member. Overall, the mineralogy between the two pairs of drills was very similar. Notably, there is only minor hematite in the GT samples (<3%), despite being stratigraphically

equivalent to VRR where some of the highest hematite abundances were measured [5,6]. Additionally, CheMin and SAM EGA analyses of the Kilmarie sample are consistent with minor quantities of siderite, the first time carbonate has been measured above the detection limit [12].

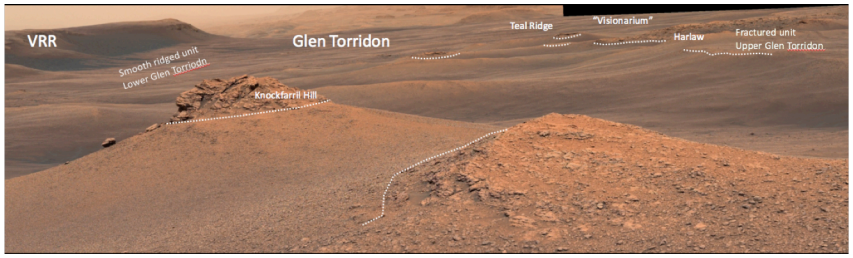

Figure 2. Mastcam 12312, sol 2304, looking east across the Knockfarril Hill type outcrop into Glen Torridon. The white dashed lines notionally show the contact between the Jura mudstones and Knockfarril hill sandstones.

Native Organics: The clay-bearing units within GT were particularly anticipated due to the potential for organic molecule retention within hypothesized especially clay-rich sediments. No organic molecules were detected above background levels in either the Aberlady or Kilmarie drill holes by SAM pyrolysis analyses. However, the Glen Etive drill samples did demonstrate the presence of martian organic molecules, and additional wet chemistry analyses showed the highest measured abundances of Sulfur-compounds as well as other high molecular weight compounds [8].

Correlations with Orbital Predictions: Although most previous Murray formation drilled samples have contained clay minerals, sometimes in significant quantities, the GT region is distinct from the rest of the Murray as seen from orbit. CRISM data show smectite clays throughout GT, whereas in the rest of the Murray formation, orbital clay mineral detections are patchy and weak at best. Curiosity's in-situ exploration has provided key geologic context to better interpret the distribution of orbital mineral detections. Crucially, sand and dust cover obfuscate spectral signatures from bedrock. Clay-bearing units to the north of GT are partially obscured by sand from the Bagnold dune field. Within lower GT, where the strongest CRISM signatures are location, there is very little intact bedrock, and the surface is predominately covered in loose mudstone clasts resulting in a larger contribution of the "bedrock" to the spectral data, both due to increased surface area and reduced surficial dust. The effect of dust cover is illustrated again within the Knockfarril Hill member; smectites are still easily detected in the CRISM observations of the blockier sandstones, but visible dust accumulations on the top surfaces of outcrop explain the somewhat weakening spectral signatures.

Environmental Implications: As hoped for, GT has indeed offered insights into the evolution of the Gale crater lake system and changing environments on early Mars.

Depositional Setting: Despite the elemental and mineralogical similarities between the GT Jura member and Knockfarril Hill member, their sedimentary textures suggests a change in the primary depositional setting. The finely laminated mudstones of the Jura are consistent with lacustrine deposits in low energy settings, but the scale of cross laminations in the Knockfarril Hill member suggest a higher energy depositional environment. Distinguishing between aeolian or fluvial deposition is the subject of ongoing analysis; however, in either case it represents a departure from the relatively deep lake environment that characterizes most of the Murray formation to date.

Diagenesis: The stratigraphic equivalency but significant mineralogical differences between the Jura member on VRR vs. within GT suggest that post depositional alteration significantly influences the geologic record of this area. One possible model is that a diagenetic front preferentially altered and cemented the VRR sediments [13], and the GT region has experienced relatively less diagenesis, allowing the preservation of clay minerals and organic molecules. Future exploration of the Greenheugh Pediment and truncated strata below the unconformity will examine potential regional controls on fluid permeation and alteration pathways [14]. Preliminary observations of strata higher in section in GT, exposed within large buttes, show seem to show greater variation in diagenetic textures and possible bleaching.

Ongoing Exploration: Presently, the rover is exploring mound-forming outcrops in upper GT, near to the contact with the overlying Greenheugh pediment and unconformable Siccar Point group outcrops. Further drill campaigns, to both track mineralogical variation as a function of elevation and to repeat some of the wet organic chemistry experiments, are planned in GT outcrops higher in section. The rover will also explore the contact between (presumably) Murray formation members and the overlying hydrated sulfate layers, gaining further insight into the geologic record of change within Aeolis Mons, Gale crater.

References: [1] Milliken R. E. et al. (2010) *Geophys. Res. Lett.* **37**, L04201 [3]Fraeman A. A. et al. (2016) *J. Geophys. Res. Planets* **121**, 2016JE005095. [4] Fedo et al., *this conf.* [5]Thorpe et.al., *this conf.*[6]Rampe et al., *this conf.* [7]Milan et al., *this conf.* [8]Stack et al., 2019, *LPSC* [9] Stein et al., submitted, *JGR* [10]Dehouck et al., *this conf.* [11] O'Connell et al., *this conf.* [12] Sutter et al., *this conf.* [13]Rampe et al., submitted, JGR. [14] Bryk et al., *this conf.*