**Introduction:** The > 300-m-thick Murray formation in Gale crater, Mars is subdivided into at least eight stratigraphic members that consist of deposits broadly interpreted as having formed in a perennial lacustrine and lacustrine margin setting [1, 2]. Here, we report on the nature of facies observed in the Hartmann’s Valley and Karasburg members of the Murray formation using orbital data collected from the High Resolution Imaging Science Experiment (HiRISE) and ground-based data collected by the Mars Science Laboratory payload on the Curiosity rover. We evaluate spatial variability and patterns within the stratigraphy in order to propose a depositional model for these members. Ultimately, these efforts are part of a larger goal to determine how depositional environments varied through time at Gale crater.

**Background:** The Hartmann’s Valley member (HVm) comprises ~23 m of Murray formation stratigraphy and was encountered at elevations between ~4435 m and -4412 m. The Curiosity rover traversed laterally across the HVm from east to west during Sols 1100 to 1357, at which point the rover turned south and traversed up elevation across the remainder of the member. The rover traversed across the approximately 40-m-thick Karasburg member (Km) from Sols 1415 to 1468.

**Methods:** Orbiter images and digital elevation models from HiRISE and Mars Orbiter Laser Altimeter (MOLA) data provide context for mapping member boundaries and outcrop locations. All other analyses were done using images from cameras onboard Curiosity. Sedimentary structures at the outcrop-scale were interpreted from Mast Camera (Mastcam) images. Navigation Camera (Navcam) stereo-mesh products covering the outcrops permit measurements of features identified down to the dm-scale. Digital elevation models from HiRISE and MOLA data were used to determine outcrop elevations. Mars Hand Lens Imager (MAHLI) and Remote Micro imager (RMI) images provide a cm-to μm-scale assessment of laminations, bedrock textures and bedrock grain size. In addition to image analyses, grain size in bedrock was estimated using the Gini index mean score (GIMS), a grain size proxy that uses compositional data from the Chemical Camera Laser Induced Breakdown Spectrometer (ChemCam LIBS) [3]. Mineralogical data for drill samples was obtained using the Chemistry and Mineralogy X-ray Diffractometer (CheMin XRD) [4].

**Results:**

**Facies:** The HVm and Km can be subdivided into two facies associations which contain a total of four facies. The first is the sandstone facies association, composed of m and sub-m-scale cross-stratified facies and planar-laminated sandstone. The second is the mudstone facies association, composed of planar-laminated mudstone. The sandstone facies association constitutes the entirety of the HVm and intervals of the Km. The mudstone facies association constitutes the majority of the Km.

**Sandstone facies association:** Planar-laminated facies make up about half of the HVm and consist of inferred sandstone. Outcrops are difficult to trace laterally, and occasionally occur on scales greater than 1 m. This facies is characterized by apparent flat-lying laminations, except in instances where localized topography or bedrock slumping obscures this apparent horizontal lamina. Laminations occur on the sub-mm to cm-scale. Resolution of any grading or sorting is not possible.

**Sandstone facies association:** Meter-scale cross-stratified facies make up about one-third of the observed HVm and less than one quarter of the observed Km. Outcrops of this cross stratification occur at the lowermost and near the uppermost intervals of the HVm, and in the lowermost, middle, and uppermost intervals of the Km. In both members, this facies is identified by truncation surfaces, concave curvilinear laminations, and sets that are measured to be at least 1 m thick.

**Mudstone facies association:** Centimeter-to-decimeter-scale cross-stratified facies is the least common facies in the HVm. The thickest interval of this facies is approximately 2 m. This facies is identified by distinct truncation surfaces, concave-curvilinear laminations, and sets that are measured to be less than 1 m thick. In some regions, distinct cosets are discernable.

**Grain size:** Potential grains in the sandstone facies association range in size from coarse silt to coarse sand, and in most cases are not ubiquitously visible throughout the bedrock [5]. Grain size was inferred in regions...
where bedrock exhibits a rougher texture distinct from overlying dust and sand as well as concretions. GIMS grain size estimates show variability in grain size throughout the facies association, ranging from sub-sand-sized grains to coarser sand grains [3]. ChemMin data from the Oudam drill at -4435 m show a low amount of phyllosilicates present in the lower stratigraphy of the HVm [6] at an interval corresponding to m-scale cross-stratified facies. The lack of clay minerals suggests that the cross-stratified facies at this interval are not composed of mud aggregate grains, but rather primary sand-sized grains. It is unclear whether this mineralogy applies to other intervals of cross-stratified facies in this study. Though these facies contain apparent sand-sized grains, the absence of visible grains throughout much of the bedrock could indicate the additional presence of sub-sand sized grains or silt/clay aggregates. Cross-bedded sand with modal mud occurs in certain environments on Earth [7, 8, 9]. At least one interval in the planar laminated sandstone facies at an elevation of -4419 m contains measurable coarse sand grains.

Within the Km mudstone facies, a lack of visible grains, GIMS data, an increase in phyllosilicate minerals, and a predominance of mm-scale laminations suggests a predominance of mud-sized grains within the member.

**Depositional environments:** To differentiate between possible depositional environments, it is necessary to evaluate the observed facies associations together with the detailed measured column. Any uncertainty in interpretations results from the lateral nature of the rover traverse as well as potential facies changes obscured by sand cover and erosion.

Intervals of m-scale cross-stratified facies are on average 2 m thick and range from approximately 1-3 m. Intervals of planar laminated sandstone range in thickness from 3-7 m. Intervals of sub-m-scale cross-stratified facies range from 0.5-2 m. There is no discernable pattern between facies occurrences and thicknesses within the sandstone facies association. The mudstone facies occur in thick packages ranging from 3-16 m and lack any trend in thickness throughout stratigraphy.

Given the facies present in the sandstone facies association, aeolian and fluvial environments are most appropriate for the overall basin fill. In an aeolian depositional environment, m-scale cross-stratified facies could represent large-scale dunes. Smaller-scale cross-stratified facies could reflect ripple deposits. The coarser planar-laminated sandstone can form as aeolian plane bed deposits. A lack of interdune structures or thin intervals of fine-grained planar-laminated facies suggests that there are no interdune surfaces present, as would be typical of the wet aeolian systems expected in facies adjacent to the lake environment proposed at Gale crater [1, 10]. The extensive thickness of the planar-laminated mudstone facies indicates that this facies is likely not forming in interdune environments. Additionally, aeolian environments can contain a relatively ordered stratigraphy, whereas the facies identified in the HVm and Km lack a distinct pattern or trend [10, 11].

In a fluvial depositional environment, m-scale cross-stratified facies could record barforms. Barforms are typically dominated by sand-sized grains. Planar laminated sandstone facies would indicate upper flow regime conditions. The lack of obvious ordering throughout the sandstone facies association could reflect more stochastic processes, as can be seen in fluvial environments [7, 12].

The extensive planar-laminated mudstone facies in the Km reflects deposition below base level, implying that it records the transition from terrestrial to lacustrine environments. Minor intervals of m-scale trough cross-stratified facies interbedded within this facies could represent auto- or allocyclic changes. Although the exact depositional environments remain somewhat uncertain, facies within the HVm and Km contain variability likely indicative of a transition from the lake margin to lake environment.