EVIDENCE OF REDOX SENSITIVE ELEMENTS ASSOCIATED WITH POSSIBLE SHORELINE SEDIMENTS IN GALE CRATER.

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Introduction: Over 5 years of investigating Gale crater, NASA's *Curiosity* rover has revealed that the crater once hosted a habitable stratified lake fed by rivers and streams [1–4]. Even as the lake disappeared and lake sediment was buried by eolian deposits and exhumed multiple times, multiple episodes of groundwater circulated through fractures that formed within the ancient lakebed deposits (informally the "Murray" formation), transporting Ca sulfate, silica, borate, Fe, and Mn and prolonging habitable conditions [5–8]. Recent chemical and sedimentological observations from sols ∼1520–1800 are consistent with potential temporary shoreline environments where ChemCam [9–11] observed highly enriched deposits of Mn, Mg, Fe, and P [12,13]. Stratigraphic relationships suggest the presence of possible shoreline or lowstand deposits, including mudcracks and other dessication features, bedding-parallel calcium sulfates and rhythmic laminations, and coarsening of bedrock grains [14,15]. We present a possible interpretation of the observations: shallow water Mn oxide precipitation, supported by the association of high Mn with possible shoreline deposits.
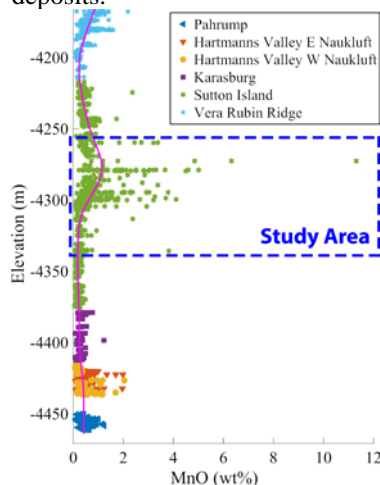

Figure 1: Murray bedrock manganese abundance by elevation [18].

Manganese abundance is typically very low in primary igneous rocks (MORB = 0.2 wt% MnO; mean Mars crust = 0.5 wt% MnO) [16,17]. Thus, the mean ChemCam value of ∼0.4 wt% MnO observed in the lower strata of the Murray reflects the average Mars crust Mn abundance [18]. High Mn deposits require highly oxidizing aqueous conditions to form. Ideal locations for Mn oxide precipitation are oxic groundwaters and shallow water lakes and seas [19,20]. These environments can also precipitate Fe oxides and a range of phosphate species [e.g., 21]. On Earth, these shallow water environments become oxidizing through contact with an oxidizing atmosphere.

Chemical observations: Overall, the Murray fm. has a low abundance of Mn. However, there is a substantial increase in Mn found in the bedrock at elevations -4275– -4340 m (Fig. 1). For example, the target Newport Ledge contains ∼6.4–11.5 wt% MnO (shot averaged) (Fig. 2). The target Denning Brook (Fig. 3) is P-rich and contains ∼2.3–16 wt% MnO (shot averaged). These dark-toned deposits typically have higher MnO and FeO than nearby light-toned targets and lower SiO_2, Al_2O_3, and K_2O.

Sedimentological obervations: Mn enrichment is found primarily in dark-toned sandstone targets. Nearby light-toned materials display low-angle cross stratification that is suggestive of traction transport; possible lenticular bedding of materials around Newport Ledge may indicate oscillatory flow. Calcium sulfate veins and bedding parallel sulfate appear confined to the light-toned facies. Newport Ledge is a laminated possibly medium to coarse sandstone, while Denning Brook is possibly fine to coarse sandstone [15]; typical Murray fm. bedrock is mudstone. Denning Brook also has thicker laminae that may either indicate a change in depositional environment or a different erosional style.
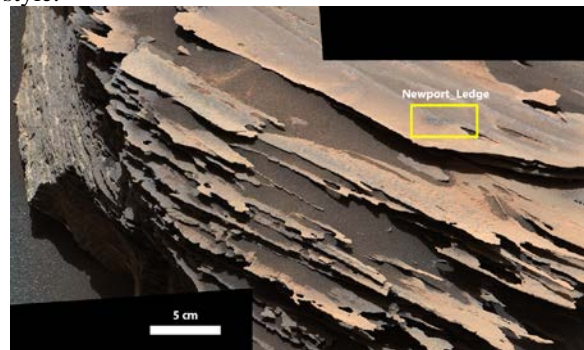

Figure 2: Mastcam mosaic of Newport Ledge.

Discussion: We hypothesize that the high abundance of Mn observed in the sol 1500–1800 study area likely represents deposition of Mn oxides by precipitation in a highly oxic shallow water near shore environment. The targets Newport Ledge and Denning Brook, a subset of the wider range of Mn-rich targets here [12,18], are part of the same group of sediments, possibly representing a layer of dark-toned Mn-rich sandstones in the same local area. Newport Ledge is

consistent with the type of sandy sedimentation that is expected for near shore deposits. Denning Brook is coarser grained and has thicker laminae that is consistent with a change in depositional environement. Mn abundance in this location is enriched, with observed average values up to 4.3 wt% MnO in light-toned material and up to 16 wt% MnO in the dark-toned material.
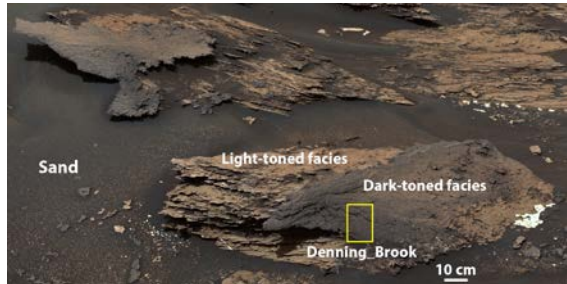

Figure 3: Mastcam mosaic of Denning Brook.

Emplacement Models. In a redox stratified lake, the upper section of the water column becomes highly oxic, enough to precipitate Mn and Fe oxides [3]. The entire water column may be oxygenated above any shallow shelf or shoals. These environments occur during highstands (Fig. 4A) and transgressive surfaces (Fig. 4E). During lowstands, Mn and Fe oxides precipitate onto lower mudstones and sandstones (Fig. 4C). As the water level rises again, Mn oxides remobilize, leaving Fe oxides behind (Fig. 4D). This process could concentrate hematite in finely layered mudstones, providing a possible mechanism to form Vera Rubin Ridge [e.g., 19]. This process also promotes the redeposition and concentration of Mn oxides onto shallower near shore surfaces. Many cycles of this process can lead to multiple layers of Mn oxides among heterolithic and spatially discontinuous beds of mudstone and sandstone materials, consistent with our observations on Mars. Given this model, we hypothesize that Denning Brook and Newport Ledge formed on a transgressive surface or near shorelines (e.g., Fig 4E).

Since Mn is very redox sensitive, a deep lake model [22] would not promote the preservation of Mn oxide deposits. In deeper waters, Mn-rich sediments may form by rapid sedimentation or a diagenetic process. Plunging plumes of Mn-rich sandstones may be preserved from dissolution in deeper anoxic water, but only if those materials are buried rapidly by continued sedimentation to prevent MnO dissolution in anoxic water. The observed color gradation between light and dark-toned materials (Fig. 3) may be an indication of a diagenetic process. Such diagenetic precipitation of Mn oxides in veins emplaced by highly oxidizing groundwater was observed earlier in the mission [8]. However, here the Mn-rich deposits do not appear in those specific diagenentic morphologies [cf. 8].

Conclusion: We favor the shallow water environronment model based primarily on the observations of Mn-rich sandstones associated with sediments suggestive of traction transport. We do not see clear evidence that diagenetic features are consistently tied to high Mn. Plunging sandstones are plausible but require a rapid sedimentation process. Regardless of the emplacement model, high Mn suggests highly oxic water, either in the lake or in the groundwater, and support habitable conditions on Mars. Work is ongoing to study the relationship between redox sensitive elements and their associated sediments to constrain high Mn depositional conditions.
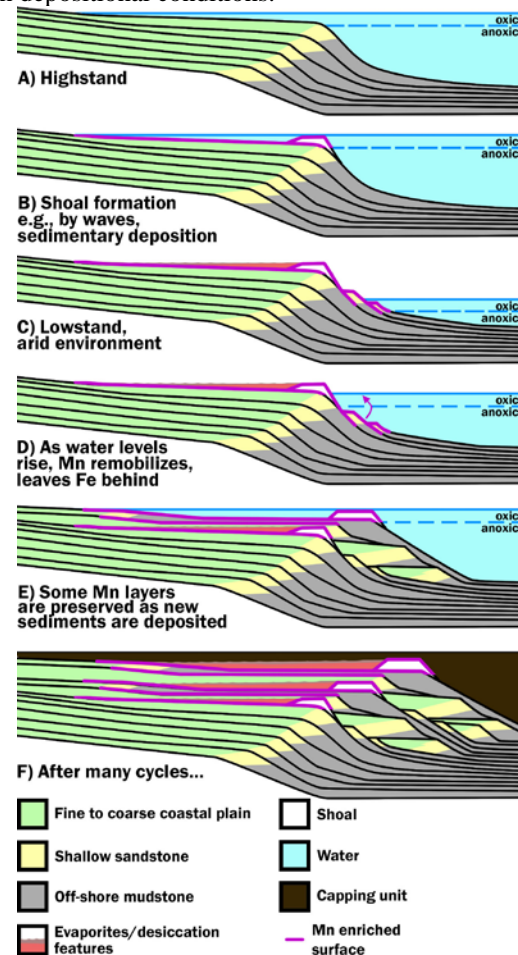

Figure 4: Emplacement model of high MnO.

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