

HIGH-MN SANDSTONE AS EVIDENCE FOR OXIDIZED CONDITIONS IN GALE CRATER LAKE.

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Introduction: The NASA *Curiosity* rover has detected high concentrations of Mn with the ChemCam instrument during its traverse in Gale crater [1–2]. Manganese is an important indicator of redox and pH conditions of surface and subsurface water on Earth. Concentration and precipitation of Mn oxide is controlled by the availability of liquid water and strong oxidants. On Earth, the deposition of Mn in the geologic record is closely tied to the rise in atmospheric O₂ due to the rise of photosynthetic life [3].

Manganese abundance is typically very low in the “Murray” basal unit of Aeolis Mons (Mt. Sharp). A localized increase in bedrock Mn abundance was observed in the Murray formation during the Mars solar day (sol) range 1685–1689 near -4280 m elevation (Fig. 1). The increased bedrock MnO_T coincided with the “Newport Ledge” transition area between two stratigraphic members of the Murray, “Sutton Island” and “Blunts Point.” The Sutton Island member is composed of heterolithic mudstone sandstone and is interpreted as a marginal lake setting, while the Blunts Point member is primarily finely-laminated mudstone interpreted as forming in a suspension/fall-out lacustrine setting [4].

Observations at Newport Ledge: *Curiosity* observed Mn-rich deposits at Newport Ledge and nearby bedrock have textures that may indicate traction transport. Newport Ledge, AEGIS post 1685a, and Sugarloaf Mountain are all planar sandstones (Fig. 2). Sandstones found near Newport Ledge over a ±11 m elevation range have on average 4.6 wt.% MnO_T in dark-toned rocks and 1.5 wt.% MnO_T in light-toned rocks. The mean MnO_T content in the typical Sutton Island and Blunts Point members is 0.5 wt.% MnO_T. Dark-toned sandstones also tend to have ~2 wt.% FeO_T more on average than other sandstones or typical Murray bedrock. ChemCam targets with the highest MnO_T are Denning Brook, Newport Ledge, and Knight Nubble have up to 16 wt.% MnO_T and are coarse silt to fine sandstones based on the GINI index [5].

Discussion: *Interpretation of depositional environment.* The rover observed sandstone and mudstones throughout Sutton Island, which led to the interpretation by [4] that Sutton Island represented a fluvial lake margin. In Blunts Point, *Curiosity* mainly observed

laminated mudstones [4]. These observations could indicate that the rover left the dominantly lake margin setting and traversed through an off-shore plume deposit or other littoral zone into the dominantly lacustrine setting. Based on [4,6], we suggest that the sandstones at Newport Ledge likely formed of the margins of the plumes entering the lake from a delta. Figure 3 shows a top down view of a braided river delta where plumes extend into a lake and deposit material in a subaqueous environment. Planar sandstones (Fig. 2) would have been deposited in the delta deposit close to shore and near the edges of active channels [6]. Fine sandstones and coarse silt would have been deposited along the margins of active and previously active channels and/or near the base of the subaqueous upper fan to mid-fan areas [6].

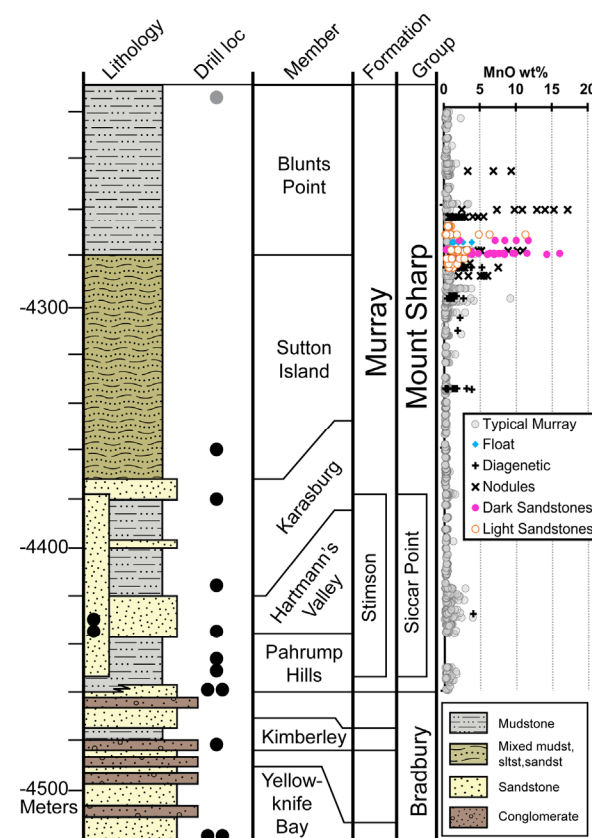


Figure 1: Summary stratigraphic column for Gale crater with MnO_T abundance in Murray bedrock, diagenetic materials [12–13], and sandstones.

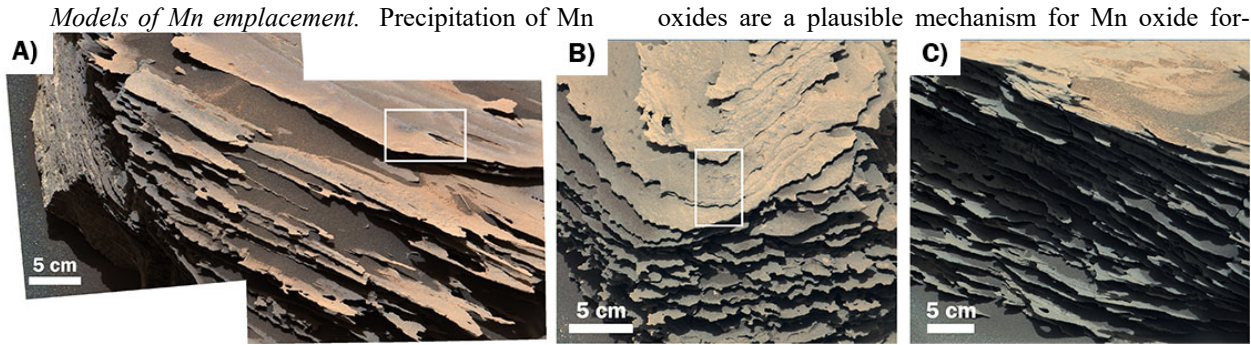


Figure 2: Mn-rich dark-toned sandstones found near Newport Ledge. White boxes indicate locations of ChemCam observations.

mation based on the lake and depositional setting outlined by [4], the redox stratified Gale lake model [7–9], the observation of Mn- and Fe-rich dark-toned planar sandstones at the Sutton Island to Blunts Point member transition, and on Mn-rich sediment terrestrial analogs [10–11]. The observation is also supported by an increasing Mn/Fe ratio in dark-toned features whose textural evolution with stratigraphy could result from higher energy fluids and shallower waters [13]. Mn^{2+} is generally very water soluble except in highly oxidizing conditions. Oxidants, primarily O_2 , slowly react with Mn^{2+} to form insoluble Mn-oxides. These conditions would facilitate the formation of a shallow deposit of Mn- and Fe-rich planar sandstones in a upper to mid subaqueous fan. In many terrestrial examples of Mn-rich deposits since the Great Oxygenation Event (GOE) [3], a shallow shelf of material allows the entire water column to be oxygenated, promoting the large-scale precipitation of Mn oxides [e.g., 10].

Localized textures do not rule out a diagenetic deposition of the Mn in higher porosity sandstone materials. It is possible that groundwater deposited the Mn in these sandstones after their deposition. However, not all sandstone in the area is enriched in Mn. Nearby diagenetic features [12–13] have different chemistry compared to the sandstones [13], are morphologically different than previous Mn-rich veins [2], and many of the features lack significant Mn [12–13].

Implications of high-Mn deposits. Regardless of the emplacement model, high Mn suggests highly oxic water, either in the lake or in groundwater. Since the formation of Mn oxides proceeds slowly with low oxygen or without water Mn oxide precipitation likely occurred in a long-lived lake. We hypothesize that dissolved O_2 oxidized the manganese. O_2 is the strongest candidate for the Mn oxidizing agent because it is the most potent oxidizer that could form naturally, although questions remain as to how O_2 can form on Mars abiotically. Other candidates for oxides include perchlorate, chlorate, and UV photo-oxidation in the

water column, but each of these candidates seem unlikely. Perchlorate is a poor oxidizer in water [14]. Chlorates produce acid during oxidation [15] that would prevent Mn oxide precipitation. Considering that no major terrestrial deposits of Mn oxides occurred prior to the GOE, when terrestrial O_2 atmospheric concentration reached $\sim 1\%$ of present terrestrial O_2 atmospheric levels [3,16], assuming Earth and Mars had similar UV conditions at the surface, UV-driven oxidation of Mn likely occurred on a minor scale.

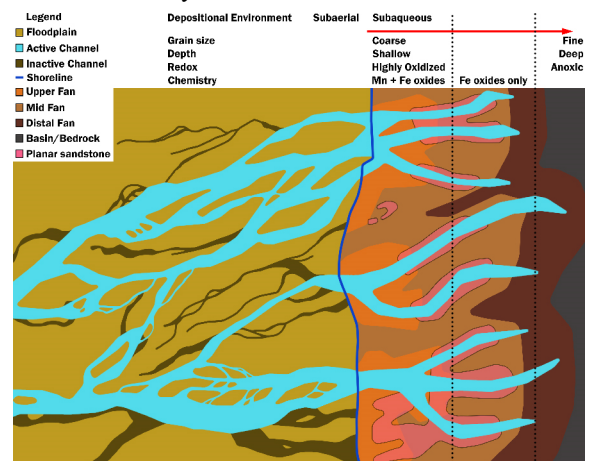


Figure 3: Braided delta depositional model [4] with areas labeled where Mn-rich planar sandstones are most likely deposited near active channels.

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