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Multiple stages of aqueous alteration along fractures in mudstone and sandstone strata in Gale Crater, Mars

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ABSTRACT

The Mars rover *Curiosity* in Gale crater conducted the first-ever direct chemical and mineralogical comparisons of samples that have clear parent (unaltered) and daughter (altered) relationships. The mineralogy and chemistry of samples within and adjacent to alteration halos in a sandstone formation were established by the Chemistry and Mineralogy (CheMin) X-ray diffraction (XRD) instrument and the Alpha Particle X-ray Spectrometer (APXS), respectively. The Stimson formation sandstones unconformably overlie the Murray mudstone formation and represent the youngest stratigraphic unit explored by *Curiosity* to date. Aqueous alteration of the parent sandstone resulted in a loss of half of the original crystalline mineral phases and a three-fold increase in X-ray amorphous material. Aqueous fluids extensively leached Mg, Al, Mn, Fe, Ni, Zn and other elements from the parent material, decreased the pyroxene to feldspar ratio by a factor of two, introduced Ca and mixed-cation sulfates, and both passively and actively enriched the silica content. Leaching of Mg, Al, Mn, Fe, Ni and Zn and enrichment of Si and S are also observed in alteration halos in the underlying mudstone. These observations are consistent with infiltration of subsurface fluids, initially acidic and then alkaline, propagating along fractures crosscutting the Stimson sandstone and Murray mudstone. The geochemistry and mineralogy suggest a complicated diagenetic history with multiple stages of aqueous alteration under a variety of environmental conditions (e.g. both low and moderate pH). The formation of these alteration halos post-dates lithification of the sandstones and mudstones and represents one of the youngest hydrogeologic events presently known to have occurred in Gale crater.

1. Introduction

The primary objective of the Mars Science Laboratory *Curiosity* rover is to assess the habitability of martian environments,

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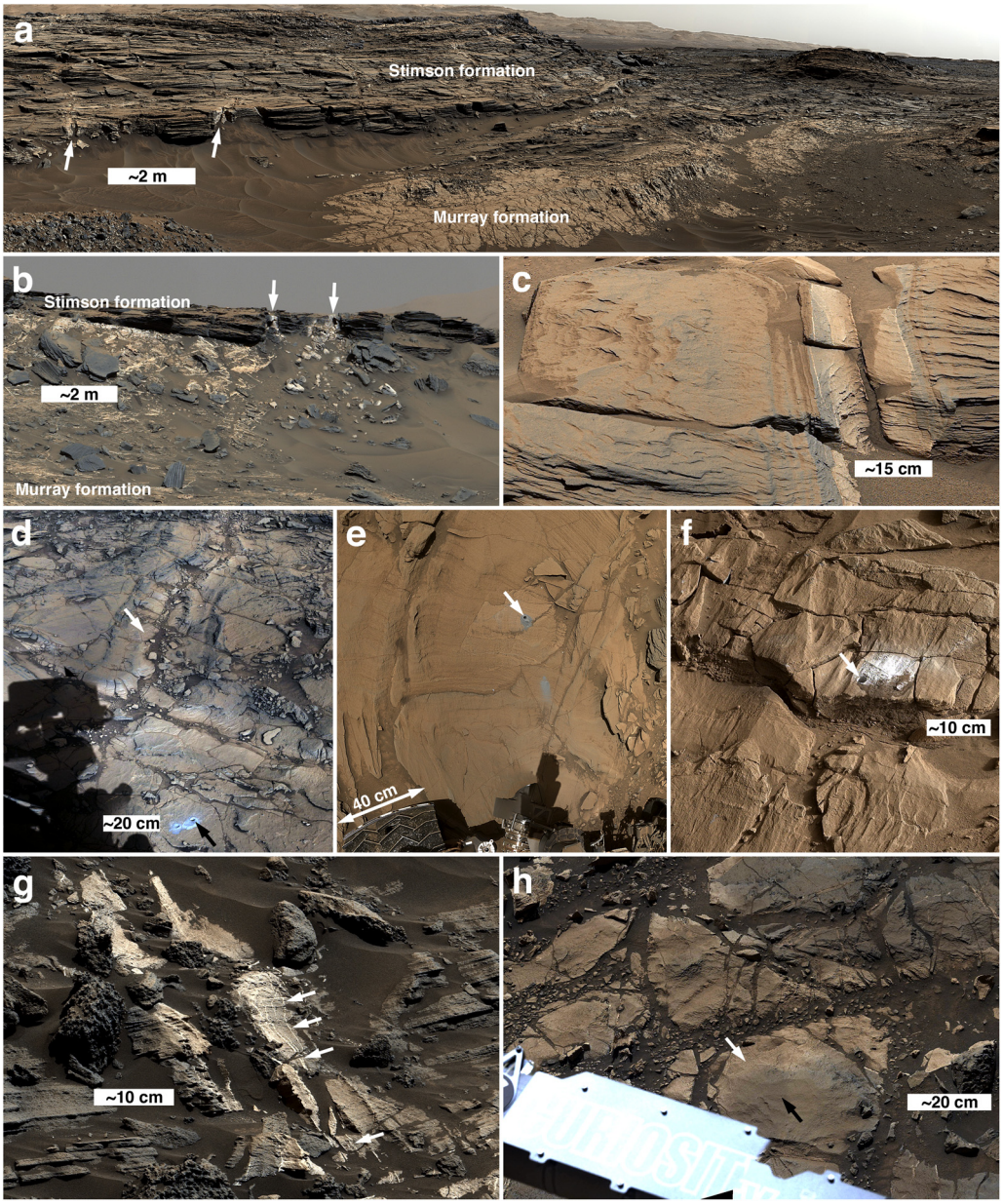

Fig. 1. (a) Murray formation mudstone overlain by Stimson formation sandstone. Fracture-associated alteration halos (arrows) are visible in the Stimson. This is a portion of Mastcam-100 mosaic mcam04395, acquired on Sol 993. (b) Alteration halos (arrows) crosscutting Stimson sandstone at the eastern edge of the Naukluft Plateau; this is a portion of Mastcam-100 mosaic mcam05931, obtained on Sol 1267. (c) Example of Stimson sandstone stratification preserved across a fracture-associated alteration halo at the Teakettle Junction outcrop; this is a portion of Mastcam-34 mosaic mcam3215, Sol 747. (d) Big Sky drill hole (parent sandstone, black arrow) and Greenhorn drill site (alteration halo, white arrow). This is a portion of a Mastcam-34 mosaic of Sol 1112, 1119, and 1126 images acquired via sequences mcam04954, mcam04956, mcam04986, and mcam05017. (e) Okoruso (parent sandstone; arrow) drill hole in a mosaic of MAHLI images acquired on Sol 1338; rover's left front wheel is seen at the lower left. (f) Lubango (alteration halo; arrow) drill hole as viewed by the Mastcam-34 shortly after drilling on Sol 1321. This is a portion of image 1321ML0063120010406076E01; note the light tone of the drill cuttings as compared to the Okoruso cuttings in (e). (g) Pervasive veins (arrows), inferred from observation of similar veins throughout the *Curiosity* field site to be calcium sulfate, in a Stimson sandstone fracture-associated alteration halo at the Mt. Shields outcrop. This is a portion of Mastcam-100 mosaic mcam04719, Sol 1073. (h) Alteration halo in Murray formation mudstone; target Cody (white arrow) is altered Murray; and target Ferdig (black arrow) is parent/unaltered Murray mudstone. This is a portion of Mastcam-34 mosaic mcam04927, Sol 1108.

both past and present. Since its August 2012 landing in Gale crater, *Curiosity* has completed over 1660 sols of surface operations, climbed 220 meters of stratigraphic section over a ~16 km traverse, collected 15 rock and multiple eolian sediment samples for detailed mineralogical and chemical analyses, and recorded the bulk compositions of hundreds of targets. *Curiosity's* instruments have provided key evidence for an ancient lacustrine environment (Grotzinger et al., 2015) with sediment sources of widely varied compositions (e.g., Treiman et al., 2016; Morris et al., 2016). *Curiosity* has found ample evidence that these sediments were affected by water, as evidenced by the replacement of olivine by clay minerals as recently as the early Hesperian epoch of martian history (Vaniman et al., 2014).

The focus here is on the silica-enriched zones that cross-cut lithified sediments and occur as ~50 cm wide, light-toned alteration "halos" surrounding central fractures (Fig. 1) in both the Murray and Stimson formations. The Murray formation mudstone is the stratigraphically lowest and oldest unit of the Mt. Sharp group sampled by *Curiosity* (Grotzinger et al., 2015). It is characterized by millimeter-scale planar laminations, moderately elevated K and Ge as well as lower Ca and Mg (Thompson et al., 2016) relative to average Mars soil (Table SI), and pervasive veining by