
Introduction: Since its landing, the Curiosity rover has traversed 17 km towards the layered rocks at Mt. Sharp (also named Aeolis Mons), spending >1700 sols (Martian days) at the surface of Mars. On sol 750, the rover entered into continuous light-toned layers named the Murray Formation marking the base of Mt. Sharp [1]. This study focuses on the Chemical Index of Alteration (CIA) within the Murray Formation.

Stratigraphy: The Murray formation was divided into four areas from their facies [2]. The base of the Murray was analyzed by ChemCam at the location named Pahrump Hills (named Murray-PH hereafter) and is composed of various facies including laminated mudstones and fine- to coarse-grained sandstones [1]. From there, the Murray formation includes two areas at similar elevation separated by the Naukluft plateau. Referred as Murray-HV (for Hartmann’s Valley) hereafter, this second area of Murray consists of silt to very fine-sand [2]. The third area is named Murray Buttes and is composed of more regular laminated mudstones. The fourth area, informally named the Upper Murray, displays more heterolithic mudstones and sandstones [1]. The facies is interpreted as having been deposited in lacustrine and lacustrine-margin environments [1,2] with evidence in the form of desiccation cracks to indicate at least partial drying out [3].

Method: ChemCam determines the chemistry of rocks over series of points with diameters close to the laser beam, ca. 0.3-0.5 mm. Bulk chemistry for each target can be established only by averaging several points, especially for coarse-grained targets that display strong point-to-point variations. Each target is assigned a bulk composition that is the result of the average of >5 points. Although 5 points are not sufficient for good statistics on coarse-grained rocks, mudstones and fine-grained sandstones have grain sizes smaller than the laser beam ensuring good statistics. In addition, all points corresponding to obvious diagenetic features such as light-toned veins [4, 5] are removed to obtain a composition devoid of obvious post-depositional modifications.

Indications of alteration from chemistry can be evaluated using various indexes such as the Chemical Index of Alteration (CIA), which is defined as CIA=100*Al₂O₃/(Al₂O₃+CaO*+Na₂O+K₂O) (molar). The CIA index starts to reflect the influence of chemical weathering when CIA>50 for felsic rocks, and 40-45 for mafic rocks [8]. CaO* is the CaO abundance limited to silicate minerals. While carbonates have never been observed at Gale, apatite or anhydrite could be significant contributors to the total CaO. As we have systematically avoided points with evidence of Carbonates to limit the effect of this ubiquitous diagenetic episode, the calculation of the CIA becomes closer to the actual CIA*, although it still remains a lower bound.

Figure 1: A-CN-K ternary diagrams (top) Diagram with total CaO reported (lower bound of CIA). (bottom) Similar diagram with an upper bound of CIA.

Results: The CIA index has been below 50 for all aqueous sediments studied before Pahrump Hills, including the Sheepbed mudstones where phyllosilicates were detected [6]. Starting at Pahrump Hills, and then...
through the entire Murray Formation so far, values >50 are frequent, especially in the Murray Buttes and Upper Murray for which the CIA index reaches 60 (Figures 1 and 2, red and dark red), a value usually suggesting significant weathering [7]. The A-CN-K ternary diagram (Figure 1) shows that the two upper areas plot above the plagioclase/K-spar line that bound any mixing of primary silicate minerals. This diagram therefore shows that no mixing of primary minerals is able to explain the high CIA observed here linking to open system weathering. This observation may be related to the presence of phyllosilicates at the 20-25% level in the Murray formation at the three drill sites analyzed at Murray Buttes and Upper Murray [8].

Chemical variations along the stratigraphy show that the increase in CIA is correlated with a decrease in CaO abundance, which becomes <2% in many targets or Upper Murray outcrops. This negative correlation is not found for Na2O or K2O. Leaching of calcium is a reasonable explanation for the low CaO abundances and high CIA from alteration of Ca-pyroxene and/or plagioclase. While both minerals were present in many rocks analyzed so far, CheMin analyses on recent Murray rocks show only low amounts of mafic crystalline phases (<5%) [8].

Interpretations:

The origin of the alteration identified from high CIA is not always obvious to determine, with three main candidates possible: weathering at the source, weathering during deposition, or alteration by diagenesis. The drift from the CN-A join towards higher K abundance is usually due to the potassium metasomatism in association with the formation of illite (Figure 1). This trend cannot explain the high CIA and corresponding alteration. Indeed, higher potassium tends to decrease the CIA toward lower values, not increase it. The calculation of the CIA on terrestrial rocks is usually corrected from effects of potassium [10]. The presence of potassium feldspars has also a similar effect: for instance, potassium feldspars were observed at Kimberley [11], but Kimberley sedimentary rocks plot far beneath the alteration lines as a distinct trend (black dots, Figure 1). Diagenesis cannot explain the high CIA, but the observed trend suggests that diagenetic effects were able to start potassium metasomatism.

Numerous terrestrial studies have shown the link between climate and variations in CIA values. Conditions producing a CIA of 60 vary from semi-arid to temperate humid conditions, but a cold and dry climate is not able to generate such alteration indices, as shown from studies in Arctic [12]. Previous results from the Curiosity mission indicated the presence of substantial fluvial and lacustrine sedimentation, in what appeared to be a relatively cold and dry location according to geochemical markers, but lacking obvious glacial/periglacial landforms [1]. The finding of significant weathering from chemical variations fills a gap in this history, showing that the lacustrine activity was coupled, at least for some time during its existence, with substantial open-system weathering indicative of more temperate surface conditions.

Figure 2: (Left) Stratigraphic section of the Murray formation (from [2]), (Right) Corresponding plot of CIA for all targets of the four areas of the Murray formation considered.