A DECADE OF QUANTITATIVE MINERALOGY ON MARS: RESULTS FROM THE CHEMIN X-RAY DIFFRACTOMETER ON THE MARS SCIENCE LABORATORY ROVER *CURIOSITY.*

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Introduction: For more than a decade, the CheMin X-ray diffraction instrument on the Mars Science Laboratory rover *Curiosity* has been returning definitive and quantitative mineralogical and mineral-chemistry data from ~3.5-billion-year-old (Ga) sediments in Gale crater, Mars. To date, 36 drilled rock samples and 3 scooped soil samples have been analyzed over the course of a 30+ km transit. These samples document the mineralogy of more than 600 vertical meters of flat-lying fluvial, lacustrine and aeolian sediments that comprise the lower strata of the central mound of Gale crater (Aeolis Mons; informally known as Mt. Sharp) and the surrounding plains (Aeolis Palus). The principal mineralogy of the sediments is basaltic, with evidence of early and late-stage diagenetic overprinting. The rocks in many cases preserve much of their primary mineralogy and sedimentary features, suggesting that they were never strongly heated or deformed. Using aeolian soil composition as a proxy for the composition of the deposited and lithified sediment, it appears that in many cases diagenetic changes observed are principally isochemical. Exceptions to this trend include secondary nodules, calcium sulfate veining, and rare Si-rich alteration halos. A striking hematite-rich feature in lower Mt. Sharp called Vera Rubin Ridge is interpreted to be diagenetically altered lake sediment. A surprising and yet poorly understood observation is that nearly all of the ~3.5 Ga old sedimentary rocks analyzed to date contain 15-70 wt.% X-ray amorphous material. Overall, this 600+ meter vertical section of sedimentary rock explored in lower Mt. Sharp documents a perennial shallow lake environment grading upward into alternating lacustrine/fluvial and aeolian environments.

Mineralogy of the Global Mars Soil: CheMin's analysis of the <150 μm component of the Rocknest sand shadow provided the first quantitative mineralogic analysis of Mars soil [1]. The similarity among soils and aeolian materials analyzed at Gusev Crater, Meridian Planum, and Gale Crater implies locally sourced, globally similar basaltic materials, or globally and regionally sourced basaltic components deposited locally at all three locations [2].

Discovery of an Ancient Habitable Environment: Basaltic minerals in John Klein and Cumberland drill samples of the Yellowknife bay mudstone are similar to those in the Rocknest soil (used as a proxy for the unreacted initial mineralogy of the sediments). However, the mudstone contains magnetite and ~20 wt. % clay mineral identified as Fe-rich saponite, proposed to have formed close to the time of sediment deposition by isochemical aqueous alteration of detrital olivine [3-4]. By providing possible substrates for chemo-lithoautotrophs and constraints on pH during deposition, the clay minerals are key indicators of a potential ancient habitable lake [5].

Evidence of Low Hesperian P_{CO2}: The absence of carbonates in the Yellowknife bay sediment's shallow lakebed environment, together with its hypothesized coupling with the early Mars atmosphere was used by [6] to place a limit of a fraction of a bar of CO_2 in the Noachian/Hesperian atmosphere, calling into question the role of CO_2-based greenhouse warming.

Evidence for a Diverse Basalt Mineralogy on Early Mars: Windjana, the fourth sample analyzed by CheMin, is the most potassic alkali-rich rock on Mars to be analyzed for its mineralogy by XRD. The source lithologies for Windjana's sediments represent a complex igneous province which includes (from their mineralogies) potassic trachyte, plagioclase-rich basalt (i.e., tholeiitic), and mafic basalt (i.e., shergottitic) [7]. This result implies that the northern rim of Gale Crater exposes a diverse igneous complex, at least as diverse as that found in similar-age terranes on Earth.

Changes in Clay Mineralogy and Fe-oxides: CheMin analyses of sedimentary strata within Gale crater have documented changes in the amounts and species of environmentally-sensitive minerals including pyroxenes, sulfates, clay minerals and Fe-oxides. The mineralogical changes observed going up-section from the Yellowknife Bay formation of the Bradbury group into the Murray formation of the Mt. Sharp group include a transition from trioctahedral to dioctahedral clay minerals and from magnetite to hematite (Fig. 1). These mineralogical and Fe oxidation state changes may document the gradual drying out and oxidation of the Martian hydrosphere [8]. The unexpected abundance and diversity of clay minerals in sedimentary rocks at Gale crater and the apparent longevity of this sedimentary system indicate that near-surface aqueous alteration (and habitability) continued into the Early Hesperian on Mars.

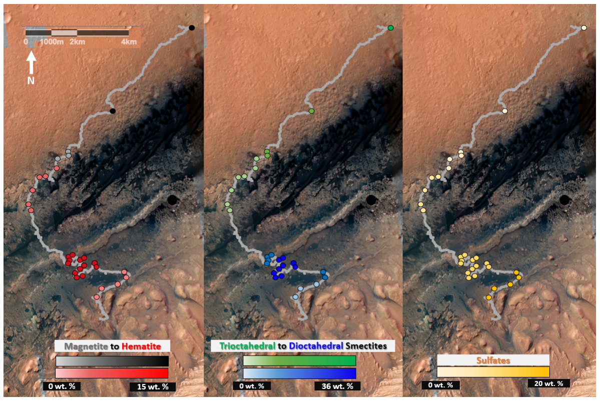

Fig. 1: Changes in Fe-oxides, clay mineralogy and sulfate abundance along Curiosity's track from Yellowknife Bay to the Clay-Sulfate transition.

Early- and Late-stage Diagenesis in the Lower Murray Formation: The lower Murray formation at the base of Mt. Sharp is predominantly comprised of finely laminated mudstone with near-horizontal laminae, deposited in a subaqueous lacustrine environment. After deposition, complex early- and late-stage diagenetic changes occurred under variable pH and Eh conditions. In the Pahrump Hills – Marais Pass region, CheMin documented the loss of mafic igneous phases and clay minerals, and the introduction of secondary diagenetic minerals such as jarosite suggesting the action of weakly acidic fluids [9]. Radiometric K/Ar dating of the jarosite indicates that it was formed 0.5 Gyr later than the original sediment deposition, documenting an extended history of aqueous interactions in Gale crater sediments [10]. The X-ray amorphous component became increasingly rich in silica, and crystalline silica phases were seen for the first time - initially cristobalite, and in the Buckskin sample collected at Marais Pass, (surprisingly) tridymite [11]. On Earth, tridymite is found as a high-temperature low-pressure mineral associated with silicic volcanism, and it was hypothesized that this material could have been washed into the lake as detrital volcanic material. However, it is clear that a late-stage diagenetic event occurred which involved silica-rich fluids (possibly associated with alteration halos observed in Stimson Fm. aeolian sandstone that unconformably overlies the Murray mudstone near the drill site). The petrogenesis of the tridymite therefore remains an open question.

Si-rich Alteration Halos in Stimson Aeolian Sandstone: CheMin performed mineralogical analyses of fracture-associated halos that crosscut both the Murray mudstone and the unconformably overlying Stimson aeolian sandstone [12]. The mineralogical changes in the fracture-associated halos require multiple aqueous alteration stages with fluid chemistries encompassing a wide range of pH. Significant mineralogical changes include the dissolution of original basaltic mineral components (plagioclase, pyroxenes) resulting in the passive enrichment of silica, but mass-balance calculations suggest that additional silica and sulfate were incorporated as well. Amorphous silica enrichment and calcium sulfate veining are pervasive features of the Murray mudstone, the former without disruption of original sedimentary features, and the latter commonly crosscutting them.

Brine-driven Alteration of Clay Mineral-Rich Sediments: *Curiosity* investigated rocks of Vera Rubin Ridge, an erosion-resistant, hematite-rich feature and Glen Torridon, a recessive, clay mineral-rich feature immediately adjacent to it. These mineralogically and lithologically distinct features were found to be depositionally equivalent; both members of the Murray Fm. CheMin analyses revealed that Vera Rubin Ridge rocks contain major amounts of the Fe-oxide minerals hematite, akageneite and jarosite with minor clay minerals, while Glen Torridon contains principally clay minerals. Bristow et al. [13] proposed a diagenetic mechanism for the local mobilization and recrystallization of iron from clay minerals, involving the influx of dense, silica-poor brines from the overlying sulfate bearing unit. Sulfate deposits are distributed globally on Mars; thus, this could be a widespread mechanism for the alteration of older clay mineral bearing strata.

Mineralogical Characterization of the Phyllosilicate-Sulfate Transition: *Curiosity* is now investigating the clay-mineral-rich mudstones of Glen Torridon and the overlying sulfate-bearing sandstones. CheMin documented a decrease in clay minerals and an increase in sulfate minerals and Fe-oxides [14], proposed to be the result of a change from fluvial/lacustrine conditions to dry, aeolian conditions.

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