Deciphering Mars's Early Aqueous Environments: Ferromagnesian Clay Diversity across the Crustal Dichotomy

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Introduction – Over the past two decades, numerous studies have revealed widespread aqueous activities on Mars' surface, particularly during the Noachian to Hesperian epochs [1,2]. Ferromagnesian (Fe,Mg-rich) clays, often associated with ancient water activity on Mars, are considered prime targets to reconstruct its aqueous environments, evaluate its habitability (potential for past life), and organize for future exploration [3]. Indeed, clay minerals form exclusively in the presence of liquid water, typically under neutral to slightly alkaline conditions, environments considered favorable for the transition from prebiotic to biotic chemistry [4,5]. Their fine-grained, layered structure also enables them to accumulate and preserve organic molecules, protecting potential biosignatures from radiation and oxidation over a long period of time [6,7], and thereby enhancing the chances of detecting ancient life. Possible co-occurrences of carbonates together with clays further enhances their value for biosignature preservation and relevance regarding life-seeking missions.

This study builds on earlier works [8] by analyzing hyperspectral data cubes from the CRISM instrument aboard NASA's Mars Reconnaissance Orbiter [9]. Focusing on the 1–2.6 µm spectral range, we conducted a comprehensive survey over 1300 cubes and searched for hydrated minerals (particularly ferromagnesian clays) along Mars' crustal dichotomy – boundary between the ancient, cratered highlands and the northern lowlands, including exposures located near Mawrth Vallis, Nili Fossae, Libya Montes and Oxia Planum [10]. Detailed characterization of these deposits is crucial for identifying promising sites in the search for past life on Mars. It also refines both the spatial and compositional mapping of clays across the planet.

Data & Methods – CRISM "*targeted*" cubes are initially processed using the CAT ENVI toolkit to perform basic atmospheric and photometric corrections. Corrected cubes are then denoised to minimize the noise and residual atmospheric contributions, amplifying diagnostic features in the "*ratioed*" spectra. Once the cubes are corrected and denoised, we calculate the band depths at 1.9 and 2.3 µm to identify pixels with strong paired absorptions, selecting only pixels with band depths above the 1% detection threshold. This allows us to outline the clays, and thereby define the regions of interest (ROIs) for each cube. Mean spectra of these ROIs are computed and analyzed. Spectral features are also examined in the 2.2–2.5 µm range in order to assess possible additional mineral phases, including aluminous (Al-rich) clays and kaolinites, hydrated silica, sulfates, chlorites, or eventually carbonates.

Results & Discussion – During our survey, we identified approximately 1020 cubes containing hydrated minerals. Of these, 750 cubes exhibit spectral signatures characteristic of ferromagnesian clays, with typical absorptions at 1.4, 1.9, 2.3, and 2.4 µm (e.g., nontronites, saponites, vermiculites). In the remaining 270 cubes where ferromagnesian clays are not detected, we observe other hydrated minerals with diverse absorptions in the 2.2–2.5 µm range.

Among the 750 cubes with ferromagnesian clays, only 465 cubes display distinct and confidently identified spectral signatures, while the remaining 285 cubes yield poorly resolved clay signatures. For the cubes where clays are clearly detected, we retrieved the exact positions of the band centers for all ROIs within the key absorptions (1.4, 2.3 and 2.4 µm) – following continuum removal to emphasize the absorptions. Band centers observed for the clay deposits show some variations from one region to another, as expected from ferromagnesian clays on Mars (Figure 1), with average values near 1.39–1.42 µm, 2.29–2.32 µm and 2.38–2.41 µm.

Exact position therein depends on the relative abundance of iron and magnesium in the clay structure, or even the oxidation state of iron [11]. Nontronites (Fe-rich) dominate Mawrth Vallis, while saponites (Mg-rich) are more prevalent in Nili Fossae and Libya Montes. Interestingly, Oxia Planum (ESA's "*Rosalind Franklin*" rover landing site) reveals more "intermediate" clays such as vermiculites or ferrosaponites [8,12]. Intermediate clays are primarily composed of Fe-rich species, notably ferrous smectites with a trioctahedral structure. Conversely, nontronites are rather ferric smectites characterized by a dioctahedral structure. Interestingly, ferric smectites may originate through the oxidation of ferrous smectites. The reducing conditions of early Mars would have favored the formation of ferrous smectites, while their subsequent oxidation would account for the presence of ferric smectites observed nowadays [13,14].

Additionally, a recurrent and shallow absorption near 2.50–2.53 µm across many sites suggests the presence of carbonates with the clays, possibly as siderite–magnesite solid solutions [15]. These findings indicate complex alteration histories and support the potential for biosignature preservation.

By enhancing our understanding of Martian clay and possible carbonate compositions, this study informs site selection and analytical strategies for upcoming missions, including rover explorations and sample return campaigns, advancing the broader search for life on Mars. This study also emphasizes the need for a better characterization of the identified deposits using a future imaging spectrometer to succeed CRISM, which is now retired since 2023 due to cryocoolers failure. Such an instrument would help confirm the presence of carbonates and improve spatial coverage by filling gaps within and between areas previously targeted by CRISM.

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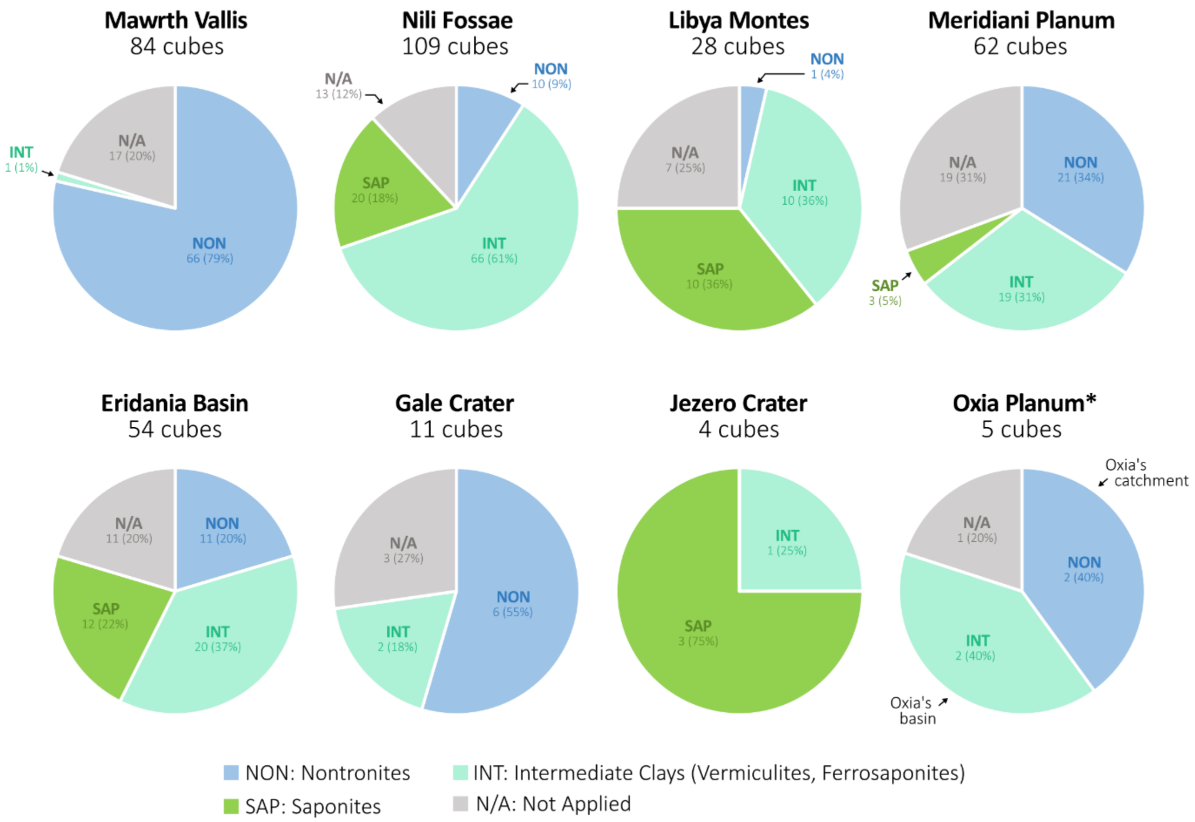

*Figure 1 - Pie charts summarize the compositional variability of ferromagnesian clays identified across selected regions on Mars. "N/A" denotes cases where the ferromagnesian clays are likely present, but the outcrops are insufficiently defined (or too poorly resolved) to support a reliable and accurate band center analysis. *Oxia's catchment area is also included, represented by 2 cubes showing nontronites [8,10].*