COMPOSITION, SETTING AND TIMING OF CLAYS ON MARS: AN EVOLUTIONARY PATHWAY

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Introduction: The recent discovery of hydrous minerals on Mars, both from orbit and in-situ [e.g. 1,2] has spawned a new era of intense scrutiny of its ancient aqueous environments. Because they can capture, concentrate, catalyze and preserve organic material, hydrous minerals (hydrated clays in particular) are potential tracers of pre-biotic and even biotic activity [e.g. 3]. As such, they are a main science driver for current and forthcoming landed missions including the Mars Science Laboratory.

Using the OMEGA and CRISM imaging spectrometers [4,5], global investigations [e.g. 6,7,8] have shown that hydrated clays were widespread on early Mars (> 4 Gyrs), and dominated by Fe/Mg-rich smectites and/or vermiculites. While smectites are the dominant phase, many other types of minerals have been found, including kaolins, carbonates, serpentines, chlorites, sulfates, chlorides, zeolites, micas, opaline silica and several hydroxydes. This diversity points towards very diverse geo-chemical environments. By combining the composition to the morphology using imagery data, it is possible in some cases to derive likely geological formation/transformation scenarios, some of which may have a strong exobiological potential.

Despite an intense scrutiny and the large amount of data collected, key questions regarding the aqueous alteration on Mars remain un-answered, including whether liquid water was stable or not on the surface for geological timescales. The case for a long-lasting warm and wet early Mars with widespread surface clay precipitation is challenged by climatic models [e.g. 9] and investigations of the hydrous mineralogy [7] which propose massive sub-surface formation. No definite answer has been found yet owing to the degraded state of the oldest Martian terrains and lack of ground proof.

By conducting a large survey of the composition and morphological context of hydrous minerals on Mars, we present new evidence for surface formation of hydrous minerals on Mars during geological timescales, from (at least) the middle Noachian to the Late Hesperian. The diversity of compositions and settings points towards the existence of a clay cycle on early Mars which had some similarities with the clay cycle of today's Earth, and as such required an active, integrated surface and sub-surface hydrological system.

Investigations: We used NIR (1-2.65 micron) reflectance data from the OMEGA and CRISM imaging spectrometers, with spatial binning from 4.1 km/pix down to 18 m/pix. We identified over 1240 individual exposures of hydrous minerals on Mars, and investigated their distribution, composition, terrain age and morphological context.

Global trends: Global trends are detailed in [8] and summarized here:

i) Roughly 3% of the surviving Noachian surface exhibits hydrous minerals, and this fraction is homogenous over all the southern Noachian highlands.

ii) The Noachian crust was similarly altered in the southern highlands and in the northern plains before the emplacement of km-thick lavas flows and sediments.

iii) Fe/Mg phyllosilicates are dominant, seconded by Al phyllosilicates, the latter almost systematically cover the Fe/Mg ones, suggesting enhanced surface weathering.

iv) We find indications of very diverse geochemical environments from low-grade alteration minerals (smectites, opaline silica) to high-temperature metamorphic and hydrothermal assemblages (prehnite-chlorite/pumpellyite, the zeolite analcime and epidote).

v) The dominant morphological types are central peaks and ejecta of impact craters, followed by sedimentary deposits, crustal outcrops and alluvial fans or deltas.

Within this large sample of detections, dozens of representative sites of interest where investigated further with the goal of searching an evolutionary pathway and the existence of a past clay cycle on Mars.

A clay cycle on Mars? On Earth, clays form, are transformed and accumulate according to 6 pathways (Figure 1): pedogenic (on the surface, in soils), detrital (as sedimentary deposits), authigenic (formation during the deposition), diagenetic (transformation during the burial of sediments), metamorphic (transformation at greater depth) and hydrothermal (formation with a heat source at various depths). Detailed mineral/morphological investigations of sites of interest reveal that all these geological contexts are also found on Mars (Figure 1) and question the existence of a clay cycle during the Noachian.

Pedogenic. Dozens of locations, which exhibit a vertical stratigraphy of Mg/Fe smectites overlain by Al-smectites or kaolins, are present throughout the planet. These observations are consistent with weathering sequences as part of pedogenesis as seen on Earth [e.g. 10]. Previous observations [11,12] revealed that most of these sequences were found in the Arabia Terra/Mawrth Vallis region. Our analyses show that these sequences are common on Mars, and at times buried at shallow depth suggesting they may be more widespread than inferred from orbit.

Detrital. Smectites have been found associated with layered infilling in basins, deltaic features and alluvial fans which suggest transport of detrital clays from a source region [e.g. 13,14]. One striking new detection of these detritic clays was found in a sedimentary unit in Gusev crater [14].

Authigenic. Authigenic formation of clays is difficult to detangle from detrital deposition, however global investigation of deltas and alluvial fans on Mars [15] reveal that the vast majority exhibit opaline silica (a clay precursor), which is seldom found in the Martian crust, and thus likely an authigenic product.

Diagenetic. Diagenetic transformation of clays has been postulated for many exposures [16]. We found clear evidence for such transformation in Terby crater. This crater exhibits km-thick layers deposited in a deltaic environment [17]. The mineralogical composition (including zeolites, opaline silica and Fe/Mg smectite) suggests deep-sea zeolitisation of detrital smectites deposited in the sub-aqueous environment.

Metamorphic. The presence of prehnite which can only form at depth on Mars [18] is a strong indicator of burial metamorphism on Mars. We found prehnite excavated by craters both in the southern highlands [see also 19] and in the northern plains [20].

Hydrothermal. Hydrothermal formation of carbonates and serpentine has been inferred for the exposures in Nili Fossae and Gusev [21,22]. We report the detection of a new hydrated mineral on Mars, epidote, found in volcanic units of Hesperian age, suggesting hydrothermal formation near the surface at high temperatures (>200-250°C).

Open questions: All these contexts collectively suggest the presence of a clay cycle on early Mars. However, their spatial and temporal relationship still remains to be established. In particular, the lack of plate tectonics on Mars renders less likely the possibility of multiple cycles on Mars: metamorphic minerals can only be recycled at the surface when excavated by large impact craters. However the clear association between fluvial structures and hydrated minerals for some deposits supports that alteration at the surface could have occurred. In other locations, the degraded contexts, younger resurfacing processes and inherent limitations of orbital remote sensing make it difficult to constrain the alteration and putative clay cycle during the Pre- to Early-Noachian eons, while the observations suggest a complex system of transport and deposition over large extents of the Martian surface (e.g., from the Terra Tyrrhena highlands down to the Hellas Planitia basin).

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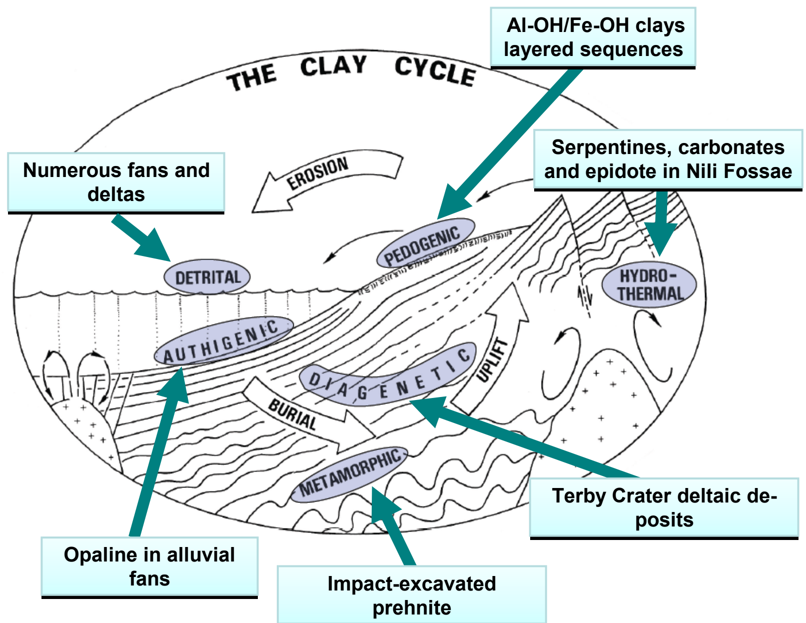

Figure 1. The clay cycle on Earth (adapted from *Eslinger and Pevear, 1988*) and examples of settings detected on Mars.