Compositional Clay Stratigraphies as Indicators of Paleoclimate on Early Mars

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Introduction: Some of our best mineral records of the early martian atmosphere and climate are compositional clay stratigraphies (CCS), where Al-rich phyllosilicates overlie Fe/Mg-smectites. CCS are typically interpreted as deep weathering profiles formed due to extended leaching by rain [1]. They are distributed across the southern highlands of Mars and mostly formed prior to ~3.7 Ga (Noachian to early Hesperian) [2]. Here we report highlights from a series of recent [3,4] and ongoing studies using orbital remote sensing datasets to better understand the links between CCS and the ancient climate and atmosphere of early Mars.

Confirmation of a surface leaching origin: Two main hypotheses for the origin of CCS have been proposed: subaerial formation through pedogenic leaching, or subaqueous formation via detrital deposition and/or alteration. We used the CRISM spectral properties and topography of these clay deposits to test between these two hypotheses. The leaching hypothesis predicts that CCS should (1) show consistent and extensive surface enrichment in Al clay overlying deeper Fe/Mg clays, and (2) drape antecedent topography, while the subaqueous hypothesis confines the deposit to a depositional basin and should have a more complex mineralogy. To test these hypotheses, we extracted vertical profiles of clay mineralogy from orbital reflectance spectra at 14 CCS areas, and investigated the relationship with antecedent topography at Mawrth Vallis. Globally, a similar relationship was found where Al clays overlie Fe/Mg clays: at all five regions, >90% of Fe/Mg clay pixels lie beneath the boundary horizon. Where the CCS span across Mawrth Vallis, it is clear the Al-unit drapes the topography of the valley over 1 km of vertical relief, confirming earlier work [5]. These results strongly support the pedogenic leaching model, especially for the upper Al unit [3].

Thickness of CCS compared to Earth analogs: We measured the true stratigraphic thicknesses of clay stratigraphies at 46 outcrops globally. The basal contact of the Al-unit (also the upper contact of the Fe/Mg-unit, hereafter "boundary horizon") was traced using HiRISE in combination with CRISM, along which elevations were extracted at regular intervals. A plane was fit to the boundary horizon, and using the strike/dip of this plane, true thicknesses were obtained for both Al and Fe/Mg-units at each outcrop.

Globally, Al-unit true thicknesses range from 4 to 78 m (mean 26 m), with 20% exceeding 50 m, while Fe/Mg-units range from 1 to 196 m (mean 33 m). High true thicknesses of the Al-unit at Mawrth Vallis (mean 25 m, max 78 m) align with previous findings (41 m true thickness in [5]; 20–25 m vertical thickness in [6]). At the Hellas image, the reported true thickness (64.5 m) exceeds the previously reported vertical thickness (~10 m; [1]) due to the steep dip. Globally, total true thickness (both units added) ranges from 6 to 208 m (mean 59 m). The thickest CCS are found in craters on the western side of Mawrth Vallis, at NE Syrtis, and at Hellas.

Weathering profile thickness depends on several factors, including climate, slope, parent material, and time [7]. Even in the humid tropics, where weathering is at its most intense, the depth of soil and weathered rock is typically only several meters [7]. However, several locations on Earth have similarly thick Al-rich weathering profiles, reaching 162 m in depth [3]. Typically developed on mafic/ultramafic rock in tropical cratons, the low relief and tectonic stability of these settings, as well as the high susceptibility of such rock to chemical alteration, promotes deep weathering [8] - all conditions shared by early Mars. The presence of kaolinite in CCS suggests a hot and humid climate; on Earth, kaolinite is most abundant in highly leached tropical soils where mean annual precipitation (MAP) reaches 1000–3000 mm/yr [9]. Using the rainfall-thickness relationship determined from Hawaiian laterites in [10], our CCS true thickness measurements suggest formation under a MAP of ~1500 mm/yr; however, several factors, including the high oxide/hydroxide abundance in laterites (rather than smectite/kaolinite), makes Hawaiian laterites an imperfect analog for CCS. Using the compilation of global temperate-tropical vertical weathering rates in [10], each CCS may have formed over a duration of ~0.2–8 m.y. [3].

Controls on the distribution of CCS: On Earth, comparable deep leaching horizons on Earth are mainly found in regions with persistently or intensely wet climates, and gentle and geologically stable slopes, where run-off is limited and deep leaching favored. Based on our understanding of terrestrial weathering sequences, we hypothesize that Martian CCS formed concurrently with valley networks, in wet but physically stable regions (for example, low slope, minimal fluvial erosion), which would have been conducive to dominance of chemical over physical weathering. Any additional trends in the distribution of CCS could then be related to climatic variations. To test potential controls on the distribution of CCS and search for climate links, we studied the 150 CCS [1] and compared their characteristics with those of randomly sampled points within other ancient terrains on Mars (typical Noachian and valley-incised terrain older than the early Hesperian), as well as those with other clay mineral detections [4].

Our results indicate that CCS show a strong bimodal latitudinal distribution around both 20–30° N and 20–30° S (~63% fall within this range). This is in contrast to ancient terrains more generally, which are mainly spread across the southern highlands from ~10° S to 50° S, and valley networks, which are also within the southern highlands but nearer the equator, between 0° and 30° S. Other clay mineral detections are largely spread across the southern highlands. This distinct latitudinal distribution of the CCS suggests the potential for a climatic control on their formation. Indeed, the general clustering of the sequences coincides with the tropical–subtropical latitude band, where greater humidity and precipitation could enhance pedogenic weathering processes [4].

CCS are generally found in areas of lower elevation compared with other terrain types, and both CCS and clay minerals tend to be in areas with a higher regional slope than ancient terrains and valley networks. CCS tend to occur in regions with less valley network dissection, and tend to occur in regions with shorter and more discontinuous valley networks, neither of which is true for ancient terrains more generally. The CCS also tend to be nearer large basins and generally closer to paleolakes than other terrain types. This result supports the hypothesis that the CCS formed in areas with lower erosion rates away from valley networks, which are mainly at higher elevations, and also suggests that they preferentially formed near bodies of water, potentially indicating at least locally wetter climates [4].

In addition, the development of thick CCS through enhanced chemical weathering on this tectonically inactive planet may have led to an imbalanced weathering–climate feedback compared with Earth. Our results support the hypothesis that long-term irreversible sequestration of water and cations within clay minerals may have inhibited hydrological activity, and potentially carbonate mineral formation, over time.

Redox state of the early atmosphere:

Previous work has shown that the upper horizon of the weathering profiles are gray/blue in color, suggesting iron mobility in reducing fluids. This most likely indicates that the Noachian atmosphere was reduced as well [11]. We are currently investigating the redox-sensitive Fe/S mineralogy of the CCS in more detail to better understand this important constraint on atmospheric chemistry, as well as a record of the redox potential of early surface environments, a key habitability metric for chemotrophic organisms.

Here we report abundant localized detections of iron oxides (crystalline hematite) within martian clay stratigraphies using CRISM MTRDR images. Global automated spectral analyses of CCS sites show that Fe-oxide signatures (860 nm bands) are common in weathering profiles, but are not pervasive, and show significant regional variability [3].

In excellent exposures in Mawrth Vallis, patchy hematite signatures occur within the upper Al-unit only. Possible hematite at Mawrth shows strong 860 nm bands but rarely shows 530 nm absorptions, and so may be coarse grained gray hematite, consistent with the overall bluer hues of the outcrops. Well-exposed outcrops at Maura crater clearly show the patchy distribution of the Fe-oxide signatures here.

Some of the strongest Fe-oxide CCS signatures globally are found south of Valles Marineris [3]. In contrast to the locally patchy Mawrth Vallis detections, we observe discrete ferric-oxide-bearing and potentially clay-poor horizons overlying the CCS. Additional work is needed to determine if the oxidized horizon is part of the CCS or a later deposit.

These observations suggest three potential hypotheses should be considered for the origin of hematite and other Fe-oxides:

***(1) Oxygen oases model*:** Hematite formed in local redox gradients in surface environments under a broadly reducing atmosphere. On Earth, similar patchy redox gradients are observed in reducing wetlands soils, locally oxidized by water table fluctuations, sulfide oxidation, or biology. At Mawrth Vallis, this hypothesis is potentially supported by the patchy distribution of the Fe-oxides within the upper Al-unit only, as well as their association with a more complex mineral assemblage in that unit (e.g., ferrous clays, silica, Al/Fe/Ca-sulfates, carbonates [12]).

(2) Oxidizing atmosphere model: Hematite formed due to oxidative surface leaching. On Earth, laterites often have a surficial highly oxidized and clay-poor red horizon enriched in iron oxides (ferricrete), which can overlie reduced gray to white "pallid" zones produced by reducing groundwater [13]. Near Valles Marineris, this hypothesis is potentially supported by the presence of continuous clay-poor oxide-dominated horizons above the Al-unit.

(3) Late diagenetic bleaching model: Coarse gray hematite in gray to white bedrock can also be produced via late diagenetic coarsening of fine grained hematite, as observed in the bleached zones of the Vera Rubin Ridge at Gale crater [14]. This mechanism could potentially produce the patchy gray hematite observed at Mawrth, and could indicate the past presence of fine-grained ferric oxides in the upper Al-unit. This would imply that the bleached nature of these leaching profiles is secondary and that they may have started out with abundant fine-grained ferric oxides, potentially from formation under an oxidizing atmosphere.

All of these models could be true, at different places and at different times. The atmospheric oxidation state may have varied over time, with more oxidizing excursions producing oxidized surface horizons. Local redox gradients may have formed in some landscape locations with poor local drainage and not in more well-drained sites. Late diagenetic alteration is variable outcrop to outcrop on Mars depending on local burial history. Furthermore, these results suggest that the lack of deeply oxidized leaching profiles could be a preservation issue, as surface oxidizing horizons may have been more common but have been eroded, and surficial oxidation or oxidation at depth could have been bleached by later diagenetic fluids after burial.

Thus, additional work is needed to characterize the redox state of the leaching profiles and how they relate to the ancient atmosphere. This work also has important astrobiological implications, as the presence of redox gradients in ancient surface and near-surface environments would have been important for chemotrophic microbes. Zones of more intense oxidation could have been analogous to oxygen oases on the Archean Earth that served as habitable oases for microbes utilizing oxidizing photosynthesis.

Synthesis:

Much like paleosols in the continental record on Earth, CCS are a remarkable record of the early surface environment and climate of ancient Mars. Our results so far show that CCS are indeed best explained as deep weathering profiles formed during extended surface leaching by rain, on timescales of at least millions of years of continuous or punctuated weathering, and under temperate or even wetter local climates. The disparate ages of CCS across the planet suggests multiple pulses of weathering across the Noachian and early Hesperian [2]. Furthermore, the redox state of clay stratigraphies may place important constraints on variations in the redox state of the martian atmosphere over time. These results as well as other ongoing studies demonstrate the incredible potential of CCS as a record of ancient climate and environment, and suggest that additional insights may be gleaned with further study, both of the mineralogy of CCS and their links to climate.

References:

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