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# Habitable paleoenvironments preserved in pedogenically altered clay-rich sediments at Mawrth Vallis, Mars

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## Abstract

Using detailed analysis of CRISM observations, we show that clay and sulfate minerals near Mawrth Vallis are consistent with pedogenic alteration of volcaniclastic sediments. Based on terrestrial analogs, the mineral assemblage is consistent with surface weathering under a sustained semi-arid climate locally modified by acid-sulphate reactions due to oxidation of reduced Fe/S phases produced in water logged surface environments.

## 1. Introduction

Noachian outcrops in the Arabia Terra region expose a thick stack of light-toned layered deposits that have near-infrared spectral characteristics consistent with a variety of clay minerals [1-10], and these are best exposed surrounding Mawrth Vallis. While origins proposed for these clays include lacustrine, diagenetic, hydrothermal, and pedogenic, few have been able to explain the full diversity of clay minerals, and good terrestrial analogs have been lacking. In this study, we provide a new look at the mineralogy of Mawrth and propose a geologic framework for interpreting the clay mineralogy based on terrestrial paleosol sequences.

## 2. Paleosol Sequences

The majority of terrestrial non-marine clays are formed via pedogenic weathering in soil profiles. When soils are buried, they are preserved as paleosols, and can be used to reconstruct ancient surface environments and climates [11,12]. When sediments are repeatedly deposited (*e.g.*, alluvial, deltaic, or volcaniclastic sediments), paleosol sequences form that can track rapid paleo-environmental changes. Paleosols can be regionally extensive (hundreds of km in extent), especially when they develop on volcaniclastics, as demonstrated by paleosol sequences in the Painted Desert [13,14], the Painted Hills [15], and the North Dakota Badlands. Sub-aerially deposited volcaniclastics have been proposed as the origin for the extensive sediments at Mawrth, and the clay minerals identified at Mawrth are all common pedogenic minerals.

## 3. Spectral Analysis

Here we have used CRISM observation FRT3BFB, on the south flank of Mawrth Vallis [10]. The cube was corrected for atmospheric, phase, and some instrumental effects using the CRISM Analysis Toolkit (CAT) for ENVI. Reference spectra were calculated for each column from the average of all spectra that did not exhibit absorptions due to clays (BD2200/BD2300), ice (BD1500), water (BD1900R), or mafics (HCPINDEX/OLINDEX2). Each column was divided by the corresponding reference spectrum to create a ratio spectra cube. Band depth parameters were then applied to the ratio cube to detect absorptions at 2.16, 2.21, 2.27, 2.29, and 2.31 μm. Depths > 1% are considered a detection.

Based on absorptions in ratio spectra, we have identified both clay- and sulphate-bearing units (Fig. 1). The clays include Fe-smectite/nontronite [1-6] (absorptions at 2.29/2.40 μm), Mg-smectite/saponite (2.31/2.38 μm), Al-smectite/montmorillonite [1-6] (2.21 μm), and another Al-clay consistent with kaolinite/smectite interlayers [16], beidellite [10], or allophane [9,10] (2.19 μm). Some spectra exhibit a strong red slope below 1.8 μm, which is consistent with either ferrous clays [10] or sulphides. However, the lack of diagnostic bands associated with typical ferrous clays suggests that this phase is most likely a sulphide and/or a poorly-crystalline ferrous clay. Sulphates include jarosite [7] or an acid-treated smectite (ATS) [10] (2.27 μm) and alunite (2.17/2.32 μm). Previous studies have interpreted ~2.17 μm absorptions here as kaolinite [*e.g.*, 5], but as the 2.17 μm band is often stronger than the 2.21 μm band, we suggest that the spectra are more consistent with an alunite/smectite or alunite/kaolinite mixture.

## 4. Mawrth Clays and Climate

Hydrolysis (leaching of cations by dissolved $CO_2$) drives clay formation in soils. When cations are not flushed from the system, they are incorporated into smectites. On Earth, precipitation rates <1m mean annual precipitation (MAP) generally produce smectites, above which kaolinite becomes more prominent [11,14,15]. Thus, the widely distributed Mawrth Fe/Al-smectites most likely indicate a sustained, semi-arid regional climate. However, smectite composition is not related to climate, but is instead related to the composition of the parent material. Thus, the stratigraphic change (Fig. 2) from Fe- to Al-smectites at Mawrth may imply a decrease in the Fe/Mg content of the parent sediments, perhaps due to magmatic evolution of a volcanic source.

While the composition of the Al-clays is poorly constrained, all of the likely Al-rich phases require high weathering rates to form. Thus, humid climates (MAP >~1m) and slopes both tend to form kaolinite [17]. However, if small volumes of water are delivered over short periods of time, such as with alpine spring snowmelt or monsoons in tropical deserts, then allophane dominates, and will transform to kaolinite over time ($10^5$-$10^6$y) [18]. Either of these scenarios would imply climate change from the arid sustained climate implied by the smectites. Alternatively, kaolinite/smectite [19] also tends to dominate under acidic weathering, and local acidity may be more consistent with the overall assemblage.

## 5. Acid Sulphate Soils?

The assemblage of Al-clays, ferrous clays, and alunite that we observe at higher elevations at Mawrth is characteristic of water logged surface environments. These environments occur in topographic lows and above impermeable (*e.g.*, clay-rich) layers, and create reducing conditions that lead to the deposition of reduced Fe/S-bearing phases like ferrous clays and sulphides. Oxidation of these phases (usually by a drop in water level and exposure to atmosphere) produces acid, which can alter Al-clays to alunite [20]. The reduced Fe/S-bearing fluids can also oxidize upon emergence at lower elevations, forming additional acid-sulphate deposits [21]. At Mawrth, we hypothesize that alteration due to ponding in the upland terrains formed the alunite/Fe(II)-clays/kaolinite assemblage, while drainage into lower-lying nontronite-bearing regions formed the jarosite/ATS phase (Fig. 2).

## References


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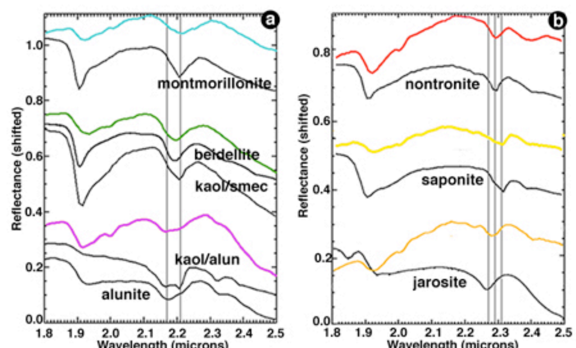


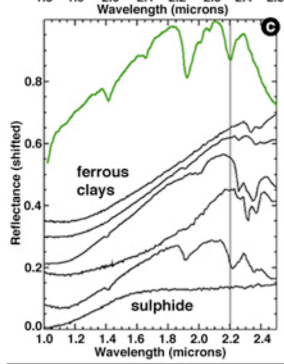


**Figure 1:** Example spectra from FRT3BFB and lab spectra. (a) Al and (b) Fe/Mg clays and sulphates. (c) Fe(II) clay.

**Figure 2:** Map of units corresponding to spectra in 1a/b on HiRISE DTM, purple shows hydration, view is 6 km wide.