WIDESPREAD SURFACE WEATHERING ON EARLY MARS: A CASE FOR A WARMER AND WETTER MARS

J. Carter[1], D. Loizeau[2], N. Mangold[3], F. Poulet[4] and J.-P. Bibring[4]
[1]European Southern Observatory, Santiago, Chile (jcarter@eso.org). [2]Laboratoire de Géologie de Lyon, France. [3]Laboratoire de Plantéologie Géodynmaique de Nantes, France. [4]Institut d'Astrophysique Spatiale, Orsay, France.

Introduction: If Mars is today a cold, hyper-arid planet with a tenuous atmosphere incapable of sustaining surface liquid water, ample evidence for past water flow at its surface is recorded in the form of fluvial and lacustrine morphologies [1,2]. The recent discovery of widespread hydrous clays on Mars further indicates that diverse and widespread aqueous environments existed on Mars, from the surface to kilometric depths, which have altered the planet on a planetary scale [3,4]. Despite intense scrutiny a major unsettled question remains: whether the planet ever experienced a warm and wet climate capable of sustaining liquid water on its surface over geological timescales. The case for such a durably warm and wet early Mars has been challenged by the inability of models to predict atmospheric conditions compatible with sustained liquid water at the surface [5,6] and geochemical investigations suggesting a subterraneous or non-aqueous origin of Martian clays [3,7]. Yet this question is paramount to assess the past habitability of the planet but also to assess how good a proxy can Mars be to the conditions on early Earth, of which little to no record has been kept due to plate tectonics and other resurfacing processes.

Using combined compositional and morphological data from the Mars Reconnaissance Orbiter, we examine several lines of evidence which lead us to propose that extensive surface weathering existed on Mars, suggesting that Mars experienced durable episodes of sustained liquid water on its surface.

Method: This study is based on a planetary-wide search for weathering sequences on Mars using surface reflectance data from the CRISM instrument. A weathering sequence is identified as a vertical stratification of the top meters of the surface, which become altered both mechanically and chemically by liquid water, resulting in the precipitation of clay and clay-like minerals gradually replacing the parent rock. Specifically, the thicknesses and compositions of the resulting clay-rich strata, can be used as a proxy for past pedogenesis as on Earth (e.g. [8,9]). We processed a large fraction of the entire CRISM dataset as described in [4] and found over 950 new sites on Mars which exhibit the spectral signatures of hydrous clays. Here, we discriminate detections between Fe/Mg-rich clays, Al-rich smectites and Al-rich kaolins through their diagnostic absorption bands [10].

Results: Within this clay-rich sample, 90% exhibit Fe/Mg clay signatures, while over 50% exhibit Al clay signatures, the latter comprising of kaolins and smectites in about equal amounts when distinguishable. The spatial distribution of Al-rich clays broadly mimics that of Fe/Mg-rich clays, and they are present in almost all Noachian-aged regions. The majority of observations with Al-clays also exhibit Fe/Mg clays within the field of view of the instrument, we thus investigated possible weathering sequences by looking for juxtaposed deposits of Fe/Mg and Al clays within the field of view. Over 150 candidate weathering sequences were pre-selected and verified manually for confirmation by additionally using altimetry data and high-resolution imagery. The precise stratigraphy could not always be derived, leading to a down-selection of 104 deposits with clear vertical stratigraphy interpreted as weathering sequences. As shown in figure 1, they are widely distributed over the southern highlands and can be sorted into regional clusters: Arabia Terra (40 sites), Terra Sirenum (23), the northern Hellas basin region (10), South-East Valles Marineris/Thaumasia Planum (13), South Terra Sabae (8), Nili Fossae (6) and the

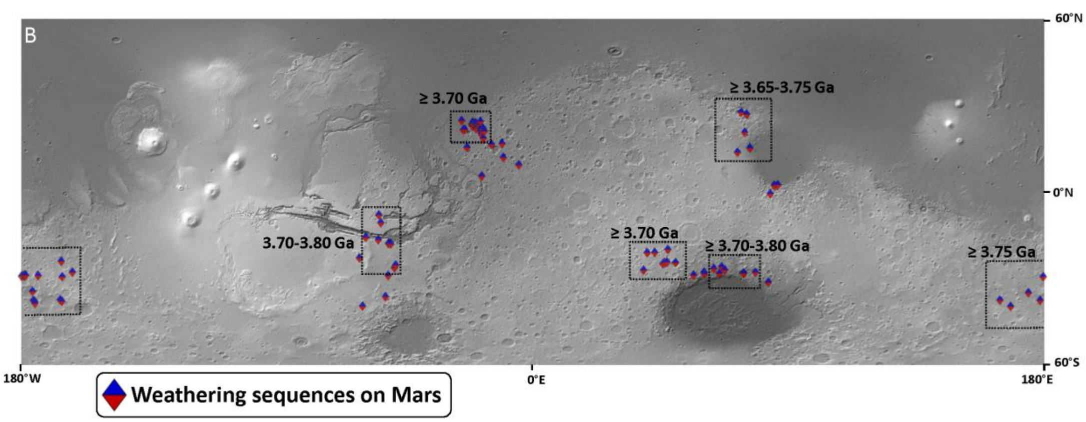

Fig. 1 The diamonds indicate the location of the 104 established weathering sequences on Mars identified to-date using CRISM. The dotted boxes indicate the regions for which the units could be dated.

Lybia Montes (4).

Properties of the clay stratigraphies: The thicknesses of the sequences cannot be inferred accurately given their small size. We however find that the exposed Fe/Mg clay layers are always relatively thicker (by a factor varying from ~2-10) than Al clays and that the overall thickness is on average of the order of a meter to several meters. When a weathering sequence can be uniquely identified to a geological unit large enough to be dated, a crude assessment of its probable age can be achieved. We found consistent ages for the investigated clustered sequences: ranging from 3.65 Ga to possibly more than 3.80 Ga (Figure 1). All investigated cases point to an active weathering epoch limited to the late Noachian. Figure 2 shows a weathering sequence exposed in the walls of layered buttes in the northern Hellas region. The Fe/Mg smectite layer (red) is overlain by a thinner Al-kaolin clay layer (blue), the sequence is several meters thick and the unit is Late Noachian or older in age.

Discussion: The composition and depth of weathering sequences of basaltic rocks is governed by three major factors: water availability, temperature and time. The first two factors are controlled by the climate and studying these sequences can therefore be used to help constrain past climatic conditions [8,11,12,13]. Weathering under a dry and cold climate results in a thin (< 1 m) upper layer of Fe/Mg rich clays, whereas warmer and wetter climates will generate thicker vertical sequences where Fe/Mg rich clays are overlain by a layer of Al-rich smectites, then by kaolin clays and finally by Al/Fe-rich oxides and hydroxides at the surface. The clay stratigraphies reported here are consistent with terrestrial weathering sequences which form under wet climates over geological timescales (> 10^5-10^7 years). A few similar localized clay stratigraphies have been reported by other works in 3 regions of Mars [13,14,15,16] and a similar origin was also proposed for these. Their frequency is however likely underestimated due to limitations of orbital investigations and re-surfacing processes.

Conclusion: The widespread distribution of weathering sequences and the consistency in their estimated ages are best explained if Mars experienced a period between the middle Noachian (> 3.85 Ga) and the end of the Noachian (~ 3.7 Ga) during which climatic conditions allowed sustained liquid water flow on its surface, while the high degree of degradation of older terrains does not allow affirming nor infirming earlier surface weathering on Mars. The composition and stratigraphy of these sequences are similar to those produced over geological timescales (millions of years) on Earth under temperate climates, but it is yet unclear if the climate was durably wet over the > 150 Myrs reported period or if solely transient surface conditions were sufficient to provide the aqueous alteration. Only the in-situ exploration of Phyllosian/Noachian terrains may provide an answer to this fundamental question.

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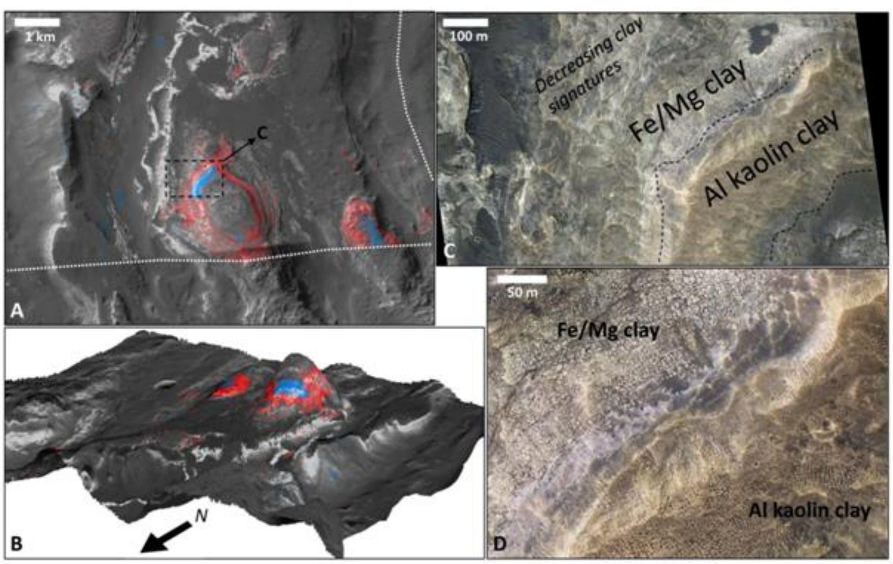

Fig. 2. Weathering sequence in the northern Hellas region (82.9°E, -30.8°N). (A) CRISM mineral map of Al kaolin clays (blue) and Fe/Mg smectite clays (red) overlain on a CTX/HiRISE background. (B) Perspective view using 50m/pixel a DTM from HRSC (vertical exaggeration 40X). (C) And (D) color HiRISE close-ups showing the transition from Al- to Fe/Mg-clays.