Icarus 248 (2015) 373–382

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Widespread surface weathering on early Mars: A case for a warmer and wetter climate

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ARTICLE INFO

Article history:
Received 6 September 2013
Revised 7 August 2014
Accepted 9 November 2014
Available online 15 November 2014

Keywords:
Mars, climate
Mars, surface
Mineralogy

ABSTRACT

Early Mars (>3 Ga) underwent aqueous alteration as evidenced by fluvial/lacustrine morphologies and the recent discovery of widespread hydrous clays. Despite compelling evidence for diverse and localized aqueous environments, the possibility for sustained liquid water globally on the martian surface and over geological timescales is still highly debated. Instead, a durably cold and dry Mars scenario is often proposed. By studying specific Fe/Mg and Al-rich clay stratigraphies on Mars by means of a planetary scale orbital investigation, we present new evidence that Mars experienced an early era (>3.7 Ga) of widespread aqueous alteration consistent with surface weathering.

1. Introduction

Although today Mars is 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 morphological features (e.g. Fasset and Head, 2008; Hynek et al., 2010; Ansan et al., 2011). 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 and which have altered the planet on a planetary scale (Poulet et al., 2005; Squyres et al., 2006; Morris et al., 2010; Murchie et al., 2009; Carter et al., 2010; Fassett and Head, 2011; Ehlmann et al., 2011).

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 some models to predict atmospheric conditions compatible with sustained liquid water at the surface (e.g. Colaprete and Owen, 2003; Wordsworth et al., 2013) and mineralogical investigations suggesting a subsurface or non-aqueous origin of martian clays (Ehlmann et al., 2011; Meunier et al., 2012). Yet this question is paramount to assessing the past habitability of the planet, and also to assess how good a proxy Mars can be for the conditions on early Earth, of which little to no record has been preserved due to plate tectonics and other resurfacing processes.

Observational evidence for or against the possibility of widespread aqueous surface weathering on Mars is scarce and difficult to interpret; remote sensing methods are limited by the fact that they probe the surface composition down to a few micrometers at most, that the ancient surface may only be accessed within occasional dust-free erosional windows, and finally because the ancient surface is also the most reworked by impact gardening as well as aeolian or fluvial erosion/deposition. As a consequence, the original signal is heavily disrupted and entangled with the subsequent Gyrs of surface activity. In this work, we focus on new observational evidence that lead us to propose that global surface weathering on Mars was likely, based on both planetary scale and localized in-depth analysis of specific clay-bearing deposits.

2. Methods

2.1. Approach

Weathering sequences are defined on Earth as a vertical stratification of the top meters of the surface, which become altered both physically (mechanical erosion) and chemically by liquid water. These stratigraphies are derived by surface, top-down leaching processes leading to the formation of various secondary minerals, broadly: salts which precipitate out of the leached fluids and hydrous clay or clay-like minerals which form in-situ,

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http://dx.doi.org/10.1016/j.icarus.2014.11.011
0019-1035/

gradually replacing the parent rock (e.g. Velde et al., 1995; Wilson, 2004). A vertical zonation appears as meteoric water becomes less available at depth (also leading to a decrease in acidity), which in turns leads to different compositional and textural horizons. The main secondary minerals formed in the residual weathering profiles are Al-rich hydroxides and hydrous clays in the uppermost (higher leaching) horizons, which overly Fe/Mg-rich clays, while the parent rock textures becomes more heavily disrupted upwards of the sequence. Terrestrial studies on (basaltic) weathering have shown that the thicknesses and compositions of the resulting clay-rich strata are governed by temperature and precipitation (hence climate), and can therefore be used as a proxy for past pedogenesis and paleoclimatic reconstruction on Earth (Velde et al., 1995; Weaver, 1989; Singer, 1984; Allen, 1997; Thiry, 2000; Gaudin et al., 2011; Horgan and Chhristensen, 2013). The detectability of such clay-rich stratigraphies on Mars from orbital spectroscopy, in association with sub-meter scale imagery and topography allows for the possibility of paleoclimatic reconstruction at Mars.

This study is based on a planetary-wide search for weathering sequences on Mars using combined compositional and morphological data from the NASA/Mars Reconnaissance Orbiter (MRO), and in particular near infrared surface reflectance data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument (Murchie et al., 2007). It builds upon previous investigations which had found a few similar clay stratigraphies in select locations of Mars (Bishop et al., 2008b; Noe Dobrea et al., 2009; Loizeau et al., 2010; Gaudin et al., 2011; Le Deit et al., 2012).

2.2. Compositional analysis

We use data from the CRISM imaging spectrometer which acquires spectra of the surface between 0.4 and 3.9 μm at a spatial sampling down to 18 m per pixel, spectrally sampled at 6.5 nm. We built spectral parameter maps which measure the strengths of specific metal-OH vibration bands that allow discriminating between various hydrous minerals (e.g. Pelkey et al., 2007; Carter et al., 2013b). Hydrous minerals exhibit absorption features in the 1.3–2.7 μm spectral region owing to overtones and combinations of fundamental OH and H–O–H vibrations which occur longwards of 2.7 μm (e.g. Bishop et al., 2008a). While most hydrous minerals share absorption bands in the 1.4 and 1.9 μm regions owing to OH and H_2O, their discrimination is made possible by more specific spectral features (absorption bands or spectral shoulders) in the 2.1–2.7 μm region. In particular, bands near 2.17–2.21 μm indicate the presence of Al-rich clays from the kaolinite-group, the smectite group, as well as poorly crystalline clay precursors such as Al-rich allophane and imogolite (Bishop et al., 2008a, 2011, 2013). Kaolinite-group clays have a diagnostic doublet band at 2.17/2.21 μm while smectite-group clays (montmorillonite, beidellite) have a symmetrical band which center ranges 2.18–2.21 μm, and allophanic material exhibit an asymmetrical band centered around 2.19 μm. Amorphous (Si–OH bearing) hydrated silica also induce a $\sim$2.2 μm band but the latter is generally broadened towards long wavelengths compared to Al-rich clays/percursors allowing their unambiguous discrimination in most cases (Milliken, 2008; McKeown et al., 2011). Bands in the 2.285–2.33 μm region indicate Fe/Mg-rich clays and their shape allows distinguishing between different groups (including smectites, mica-vermiculites, serpentines, talc and chlorites). Hydrated sulfates and zeolites are identified based on a spectral shoulder in the 2.3–2.5 μm region and an H_2O overtone combination at 1.9–1.95 μm (Cloutis et al., 2002, 2006). Most poly-hydrated sulfates and zeolites do not exhibit diagnostic signatures that are unique enough to be discriminated at the spectral resolution and signal-to-noise of CRISM data resulting in some spectral ambiguity. Spectral parameter maps are filtered for observational biases and thresholds are applied to remove noise as described in Carter et al. (2013b). The resulting mineral maps are then overlain over high resolution imagery data which provide geomorphic context.

We processed a large fraction (over 2200 spectral cubes) of the high-resolution CRISM dataset acquired to-date selected from the sample of Carter et al. (2013a) and found over 1000 new sites on Mars that exhibit the spectral signatures of hydrous clays, significantly expanding the previously established locations of martian clays. For the purpose of this study, we discriminated the clay detections between Fe/Mg-rich clays (smectites, vermiculites and mixed-layered clays) and Al-rich clays. The latter correspond to Al-rich smectites (akin to montmorillonite or beidellite) and Al-rich kaolinite-group clays (kaolinite or halloysite, thereafter referred to as kaolins). Si–OH bearing hydrated silica, chlorites, serpentines and carbonates were also mapped based on specific spectral parameters. We discarded all observations presenting such phases if they also lacked signatures of the aforementioned Fe/Mg-rich clays and Al-rich clays.

2.3. Morphological analysis

We use high-resolution imagery data from the CTX and HiRISE instruments on-board MRO whenever available. In particular, the color channels of HiRISE are used to illustrate compositional differences within the clay sequences at high (<50 cm/pixel) spatial resolution.

Altimetry data and digital elevation models are derived from MOLA/Mars Global Surveyor and HRSC/Mars Express data to verify the stratigraphy and estimate the thickness of the possible weathering sequences.

We estimate the ages of geological units in which the weathering sequences are likely identified using the "Craterstat2" software developed by Michael and Neukum (2010): the crater size–frequency distribution of large surfaces is compared with a crater production function (Ivanov, 2001); then using a chronology function (Hartmann and Neukum, 2001), absolute model ages are estimated.

3. Results

3.1. Occurrence frequency of Al-rich clays

Al-clays on Mars have a typically smaller exposure size than Fe/Mg clays (one order of magnitude smaller on average; Carter et al., 2013a). Their diagnostic spectral absorption band near 2.2 μm is also usually shallower and narrower than the large spectral shoulders >2.30 μm diagnostic of Fe/Mg-rich clays. Collectively, these result in a lower detectability of Al-clays than Fe/Mg-clays when using orbital data, artificially lowering their detection frequency on Mars. Previous global-scale studies have found a substantially lower frequency of Al-clays (about 11% compared to Fe/Mg clays), that were restricted to a few regions of Mars (Mustard et al., 2008; Ehlmann et al., 2011). Within the >1000 clay-rich site population from Carter et al. (2013a), we found that 90% of the sites exhibit Fe/Mg clay signatures, while over 33% also exhibit Al clay signatures, the latter comprising of kaolins and smectites in approximately equal amounts. These Al-clay signatures are in the majority of cases spectrally distinguishable (smectites or kaolin endmembers), while a smaller number of cases are found to have a spectrum consistent with spatial mixing at the sub-pixel scale or kaolinite–smectite interlayering, as proposed in McKeown et al. (2011) and Cuadros and Michalski (2013).

To provide a better assessment of their occurrence frequency, we performed a highly detailed spectral investigation of a subset