Icarus 226 (2013) 816–840

Contents lists available at SciVerse ScienceDirect

Icarus

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

Multiple working hypotheses for the formation of compositional stratigraphy on Mars: Insights from the Mawrth Vallis region

Joseph R. Michalski [a,b,*], P.B. Niles [c], J. Cuadros [b], A.M. Baldridge [d]

[a] Planetary Science Institute, 1700 E. Fort Lowell, Suite 106, Tucson, AZ 85719, USA
[b] Dept. of Earth Sciences, Natural History Museum, Cromwell Road, London SW7 5BD, UK
[c] Astromaterials Research and Exploration Science, NASA Johnson Space Center, Houston, TX 75080, USA
[d] St. Mary's College of California, 1928 Saint Mary's Road, Moraga, CA 94556, USA

ARTICLE INFO

Article history:
Received 8 October 2012
Revised 30 April 2013
Accepted 18 May 2013
Available online 6 June 2013

Keyword:
Mars
Infrared observations
Mineralogy
Geological processes

ABSTRACT

A unique aspect of martian geology is the presence of similar compositional stratigraphy observed in many locations throughout the surface. Where the Al-rich and Fe/Mg-rich clay minerals occur together, aluminous clays typically overly layered ferromagnesian clays, possibly indicating that precipitation-driven leaching occurred in a warmer, wetter climate. Sulfates generally occurring stratigraphically above clays could be relics of a global environmental shift between clay-forming and sulfate forming epochs. These compositional relationships speak to an important aspect of the martian geosystem that is yet poorly understood. We synthesized recent ideas to produce several working hypotheses for the formation of compositional stratigraphy on Mars and tested the hypotheses on well-exposed sulfate- and clay-bearing rocks found in the Mawrth Vallis region. In the Mawrth Vallis area, interpretations of compositional stratigraphy are strongly constrained by the fact that the sulfates and clays occur within a friable unit (probably loessite or tephra) that was deposited unconformably onto cratered terrain of fundamentally different character. Within the friable unit, the presence of aluminous clays over ferromagnesian clays might represent evidence for leaching associated with rainfall, but the presence of montmorillonite, beidellite, and sulfates argue against intense leaching as a dominant process. We suggest that ice/snow-mediated chemical weathering of dust could produce a deposit consistent with the observations through hydrolysis reactions facilitated by acidic, briny solutions within the icy dust deposit. Slow downward transport of Mg^{2+} and possibly Fe^{2+} in these solutions could potentially have produced the crude compositional stratigraphy, but regional scale leaching of basaltic bedrock by rainfall is unlikely to explain the observations. Because both clays and sulfates are found within draping, friable sedimentary deposits that occur at a range of elevations, formation of the alteration minerals by upwelling groundwater is implausible. The locations where compositional stratigraphy is observed may not be relics of a global environmental change, but rather they cold represent the locations where significant deposits of snow/ice and dust/ash once existed.

1. Introduction

Recent spectroscopic remote sensing results have revealed a complex, diverse history of aqueous alteration recorded in the martian crust (Bibring et al., 2006; Murchie et al., 2009; Noe Dobrea et al., 2010). One of the most interesting observations is that similar compositional stratigraphy is observed in many locations on Mars (Murchie et al., 2009; Noe Dobrea et al., 2010; Carter, 2010; Ehlmann et al., 2011). One type of compositional stratigraphy corresponds to variation in the record of phyllosilicate-bearing rocks. The most common phyllosilicates on Mars are Fe/Mg-rich clays (Ehlmann et al., 2011), but in many locations, aluminous smectites and/or kaolinite-group clay minerals are observed (Loizeau et al., 2007; Noe Dobrea et al., 2010; Poulet et al., 2005). Where the two occur together, the aluminous clays nearly always overly the ferromagnesian clay (Murchie et al., 2009; Noe Dobrea et al., 2010; Ehlmann et al., 2011; Le Deit et al., 2012). Another general trend is that clay mineral-bearing terrains are typically stratigraphically lower than sulfate-bearing terrains (Bibring et al., 2006). Exceptions exist, but most observations suggest a general compositional stratigraphy on Mars from Fe/Mg-clay-bearing rocks, to discontinuous strata of Al-clay-bearing rocks to sulfate-bearing rocks. The full transition between these three compositional strata is typically not well exposed, but all three categories of rocks are observed in the Mawrth Vallis region.

* Corresponding author at: Planetary Science Institute, 1700 E. Fort Lowell, Suite 106, Tucson, AZ 85719, USA.
E-mail addresses: michalski@psi.edu (J.R. Michalski), paul.b.niles@nasa.gov (P.B. Niles), j.caudros@nhm.ac.uk (J. Cuadros), amb19@stmarys-ca.edu (A.M. Baldridge).

0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.05.024

The Mawrth Vallis region exhibits one of the best exposures of altered, ancient crust on Mars. The geology of the area has been discussed at length in previous literature (Poulet et al., 2005, 2008a, 2008b; Loizeau et al., 2007, 2010; Michalski and Noe Dobrea, 2007; Bishop et al., 2008; Wray et al., 2008; McKeown et al., 2009; Michalski and Fergason, 2009; Noe Dobrea et al., 2010, 2011; Michalski et al., 2010; Loizeau et al., 2012) and is only briefly introduced here. Eroded, layered Noachian crust contains clear spectroscopic evidence for Fe/Mg-rich clays throughout a stratigraphic section that, in places, is up to 100s of meters thick (Loizeau et al., 2010). The upper 10s of meters of the section contain aluminous clays, such as kaolinite-group phases (kaolinite, halloysite) (Bishop et al., 2008; Wray et al., 2008; McKeown et al., 2009; Noe Dobrea et al., 2010, 2011), aluminous smectites (montmorillonite and beidellite) (Poulet et al., 2005; Bishop and Rampe, 2012), and poorly crystalline materials such as opaline silica (Bishop et al., 2008; Michalski and Fergason, 2009) and possibly allophane (Rampe et al., 2011; Bishop and Rampe, 2012). Wray et al. (2008) evaluated the stratigraphic relationships among these aluminous and Fe/Mg-bearing units and concluded that, in general, the aluminous terrains overly a hydrated unit with unspecified mineralogy, which overlies Fe/Mg-clays; this middle unit of undetermined mineralogy could be a mixture between the two, or a different type of material.

Sulfates also occur in the region. Jarosite has been identified in materials that seemingly overly aluminous clays in the northern part of the region (Farrand et al., 2009). Discreet deposits of gypsum or bassanite occur in the Mawrth Vallis channel and along the channel wall (Wray et al., 2010). The detection of sulfates in the channel floor is particularly intriguing because, in this locality, sulfates underlie Fe/Mg-rich clays, at least locally. However, the geologic context of these materials on the floor of an outflow channel suggests that the deposits might represent stratigraphic relationships that formed due to reworking of materials within the channel rather than primary stratigraphic relationships. One goal of this work was to search for additional detections of sulfates that might elucidate the relationships between sulfates and clays, and between Al- and Fe/Mg-rich clays in this region.

The Mawrth Vallis area lies ~1500 km to the northeast of the well-studied sulfate deposits at Meridiani Planum (e.g. Grotzinger et al., 2005; Poulet et al., 2008a, 2008b; Wiseman et al., 2010) (Fig. 1), therefore the question must be asked as to whether sulfates in the Mawrth Vallis area formed through a similar mechanism as those at Meridiani. Where clays are observed within Meridiani Planum, they occur stratigraphically beneath sulfates (Poulet et al., 2007; Wiseman et al., 2010; Newsom et al., 2010). Stratigraphic relationships between the clay-dominated rocks at Mawrth Vallis and the sulfate-dominated rocks at Meridiani are not well understood due to vast dust deposits that mask the surface between the two regions. But, where the crust is exposed in windows in the dust between the two areas, compositional stratigraphy of Fe/Mg-clays beneath Al-clays is observed (Fig. 1) (Noe Dobrea et al., 2010). Rocks at Meridiani Planum are considered to be Early Hesperian or perhaps Late Noachian (Hynek et al., 2002). Rocks at Mawrth Vallis seem to be Late Noachian up to Early Hesperian (Michalski and Noe Dobrea, 2007; Loizeau et al., 2012). Therefore, stratigraphic correlation between the two regions may be possible.

Understanding the origin of typical compositional stratigraphy and the relationships between clays and sulfates is critical for revealing global-scale aqueous geologic processes on Mars. In this work, we provide new observations of compositional stratigraphy in the Mawrth Vallis area using recent data showing some deposits not previously discussed in the literature. In addition, we carry out regional mapping to search for evidence of sulfates that may occur as isolated, patchy deposits or admixtures along with the clay-bearing deposits. We use high-resolution images to interpret the geologic context of the deposits. From these observations, we test specific aspects of various hypotheses for the origin of the

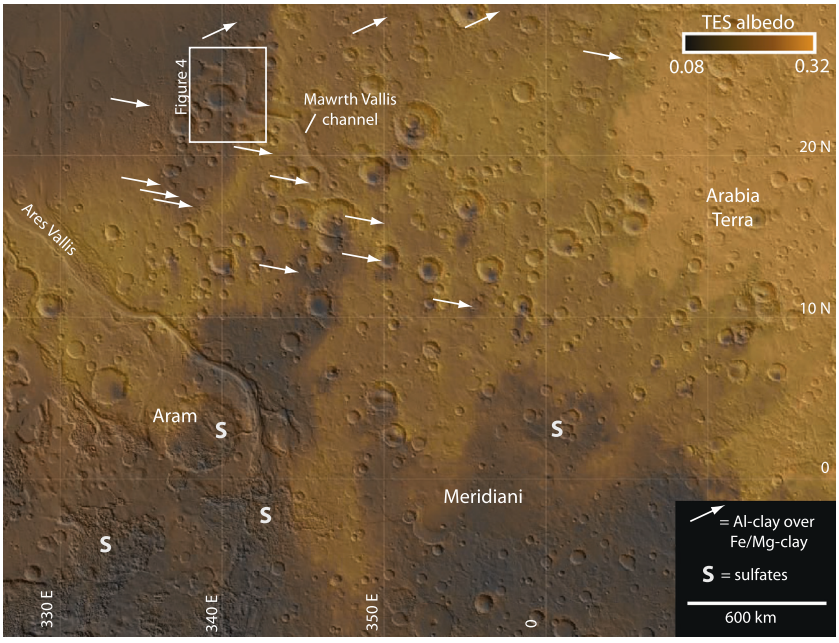

Fig. 1. Colorized TES albedo draped over MOLA shaded relief data show the regional context of the Mawrth Vallis region where the relatively low-dust surfaces contain spectral evidence for widespread, aluminous clay minerals that overly ferromagnesian clay mineral bearing rocks. Arrows point to areas where similar compositional stratigraphy was observed in small exposures from beneath the dust, throughout the western Arabia Terra region (Noe Dobrea et al., 2010). "S" marks areas where sulfates have been detected in younger rocks in Meridiani Planum, Iani Chaos, and Aram Chaos (Glotch and Rogers, 2007; Sefton-Nash et al., 2012). Aluminous clays are exposed in the ancient crust beneath sulfate deposits in at least one part of the Meridiani region (Wiseman et al., 2010), but in general, the stratigraphic relations between sulfates in the Meridiani area and phyllosilicate-dominated bedrock in the Mawrth Vallis area are masked by dust. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)