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Mineral abundances at the final four curiosity study sites and implications for their formation

F. Poulet [a,*], J. Carter [b], J.L. Bishop [c], D. Loizeau [d], S.M. Murchie [e]

[a] Institut d'Astrophysique Spatiale, CNRS/Univ. Paris Sud, 91405 Orsay Cedex, France
[b] European Southern Observatory, Santiago 19, Chile
[c] SETI Institute and NASA Ames Research Center, Mountain View, CA 94043, USA
[d] LGLTPE, Université Claude Bernard, Lyon 1, 69622 Villeurbanne, France
[e] Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA

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ABSTRACT

A component of the landing site selection process for the Mars Science Laboratory (MSL) involved the presence of phyllosilicates as the main astrobiological targets. Gale crater was selected as the MSL landing site from among 4 down selected study sites (Gale, Eberswalde and Holden craters, Mawrth Vallis) that addressed the primary scientific goal of assessing the past habitability of Mars. A key constraint on the formation process of these phyllosilicate-bearing deposits is in the precise mineralogical composition. We present a reassessment of the mineralogy of the sites combined with a determination of the modal mineralogy of the major phyllosilicate-bearing deposits of the four final study sites from the modeling of near-infrared spectra using a radiative transfer model. The largest abundance of phyllosilicates (30–70%) is found in Mawrth Vallis, the lowest one in Eberswalde (<25%). Except for Mawrth Vallis, the anhydrous phases (plagioclase, pyroxenes and martian dust) are the dominant phases, suggesting formation conditions with a lower alteration grade and/or a post-formation mixing with anhydrous phases. The composition of Holden layered deposits (mixture of saponite and micas with a total abundance in the range of 25–45%) suggests transport and deposition of altered basalts of the Noachian crust without major chemical transformation. For Eberswalde, the modal mineralogy is also consistent with detrital clays, but the presence of opaline silica indicates that an authigenic formation occurred during the deposition. The overall composition including approximately 20–30% smectite detected by MSL in the rocks of Yellow-knife Bay area interpreted to be material deposited on the floor of Gale crater by channels (http://www.nasa.gov/mission_pages/msl/news/msl20130312.html) is consistent with the compositions modeled for the Eberswalde and Holden deltaic rocks. At Gale, the paucity, the small diversity and the low abundance of nontronite do not favor a complex and long drainage system. Localized aqueous processes in space and time environments could have produced both nontronites and sulfates. However, most materials in Gale are unfortunately dust covered, so that orbital data are limited by spatial resolution and surficial fines that could dilute and obscure the spectral influence of phyllosilicates in the rocks. Potential formation processes of diverse and abundant Mawrth Vallis deposits include low temperature hydrothermal alteration in marine environments and/or pedogenesis.

1. Introduction and objectives

Near-infraRed (NIR) imaging spectroscopy has contributed to a range of scientific and tactical objectives during the martian space missions, including major mineralogical and geochemical discoveries and unique investigations on the Mars Science Laboratory (MSL) landing site selection. The Gale crater landing site was selected for MSL/Curiosity by NASA headquarters in July 2011 after a selection process of over five years (Golombek et al., 2012). This site was chosen among 4 down selected study sites (Gale, Eberswalde and Holden craters, Mawrth Vallis) that all clearly addressed the primary scientific goal of assessing the past habitability of Mars with the phyllosilicate-bearing deposits as the main astrobiological targets. The identification and mapping of these minerals from orbital data has been successful at distinguishing between arid and aqueous environments, but a more quantitative approach will help to constrain the conditions of their formation(s). In this respect, a key constraint on the formation process of these targets, and thus on the past habitable environments and searching for biomarkers by future in situ investigations, is in their precise mineral assemblages. Near-infrared spectra provide the unique ability to

* Corresponding author.
E-mail address: francois.poulet@ias.u-psud.fr (F. Poulet).

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estimate the bulk mineralogy of these small-sized rocks from remote sensing observations. We present here the modal mineralogy of the major phyllosilicate-bearing deposits close to or inside the four MSL proposed ellipses derived from the modeling of Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) spectra using a radiative transfer model. The modeling method assumes an a priori choice of endmembers presumed to be present in the analyzed terrain (Poulet et al., 2002, 2008a). Thus, we first examine in Section 2 the mineralogy of the clay-bearing deposits, which will provide hints for the selection of potential endmembers by satisfying the characteristics of the spectra. We then explain our methodology for investigating the modal mineralogy (Section 3). Section 4 and its subsections contains the results of the last four study sites along with a discussion on the differences between the four candidate sites and the implications for their formation processes.

2. Examination of the mineralogy of phyllosilicate-bearing deposits

We use data from the CRISM imaging spectrometer, taken over and/or at proximity of the ellipse of each study site as defined by the selection process that combined major scientific objectives and safety of the entry, descent and landing scenario (Golombek et al., 2012). This instrument acquires reflectance 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. For each landing site, we select the data cubes that have the strongest signatures of clay minerals. The atmospheric gas absorptions are corrected empirically using atmospheric transmittance spectra of Mars generated by rationing reflectance spectra at the base and summit of Olympus Mons (Langevin et al., 2007; McGuire et al., 2009). CRISM cube with the presence of icy aerosols is systematically excluded. No dust aerosol correction is applied. Despite the significant effect of the aerosols on the overall shape of near-infrared spectra (e.g., Vincendon et al., 2007). Poulet et al. (2009) have shown that the modeling method can be confidently used on the spectra uncorrected for the aerosols. Spectral parameter maps are built by measuring the strengths of specific metal-OH vibration bands that allow discriminating between various hydrous minerals (Bishop et al., 2008a; Carter et al., 2013a). In particular, a band near 2.2 μm indicates the presence of Al-rich clays and Si-OH species, while a band in the 2.3 μm region indicates Fe/Mg-rich clays. Spectral parameter maps are filtered for observational biases and thresholds are applied to remove noise as extensively discussed in Carter et al. (2013a). For CRISM observations over Holden and Gale craters that are strongly disturbed by strong aerosol opacity and long atmospheric path length respectively, an alternative method to correct the atmosphere has been used. This empirical method is a sky-dip correction that samples the CO_2 absorption bands at different atmospheric path lengths as governed by variations in topography within each observation. Using a simple atmospheric model, the sky-dips are converted into a transmittance spectrum adapted to each pixel according to its path length. A similar method described in detail in Noe Dobrea et al. (2009) was also successfully applied to the atmospheric correction of OMEGA spectra.

2.1. Eberswalde crater

At Eberswalde crater, the stratigraphy and geomorphology, and mineralogy recorded a complex hydrological system resulting in the formation of a fluvial–deltaic system (Moore et al., 2003; Malin and Edgett, 2003; Lewis and Aharanson, 2006; Pondrelli et al., 2008). The delta-like feature consists of bright and dark interlayered deposits interpreted to display a cyclic depositional pattern. There is also the presence of an extensive polygonal pattern similar to patterned ground on Earth where sandstones with an evaporate-encrusted surface are subjected to thermal contraction. Some channels display geological characteristics similar to terrestrial braided channels that result from channel abandonment related to lateral migration or avulsion and subsequent infill of the channel by finer sediments. Clay minerals whose distribution is associated with different outcrop characteristics located in Eberswalde delta as well as in the basin, have been observed with the strongest signature near the bottom of the delta front (Milliken and Bish, 2010; Fig. 1). These spectral signatures are however very weak. For the purpose of our modeling, two CRISM images were analysed covering both the basin and the delta, and an average of more than one hundred ratioed spectra are necessary to emphasize absorption bands smaller than 1% at 1.92 μm and 2.30 μm indicative of the presence of Mg/Fe-smectite. Additional spectral analyses are performed in Section 4.1 to map more subtle signatures.

2.2. Gale crater

Gale crater exposes a thick sequence of alternating bedded deposits of phyllosilicate-bearing rocks and sulfate-bearing rocks (Milliken et al., 2010). Uncertainty remains about the depositional formation scenarios of these deposits. Their geological characteristics could be explained by lacustrine (sourced from either groundwater or overland flow), eolian deposition in a paleo-polar or high obliquity environment (Thomson et al., 2011; Wray, 2013). Observations within the ellipse and the mounds are encumbered by surface dust, which complicates the determination of the precise composition. Fig. 2A shows that the 2.3 μm band map (red unit) has the strongest signatures well associated to beds of the lower mound beneath sulfate-bearing rocks (Milliken et al., 2010; purple unit in Fig. 2A). The position and shape of the 2.29 μm band in this lower formation is spectrally consistent with iron-rich clay (likely nontronite) (spectrum #2 in Fig. 2B; Wray, 2013). A shoulder at 2.23 μm could indicate the presence of a substitution of Al^{3+} for Fe^{3+} in nontronite (spectrum #1 in Fig. 2B; Bishop et al., 2002). Additionally, weaker signatures of Al-rich clays and opaline silica are reported at close association to the nontronite-rich deposits (dark blue unit of Fig. 2A and spectrum #3). It is important to note that even the spectral ratios have weak signatures. Without the ratioing technique, it is difficult to separate the atmospheric contribution from the surface one, especially in this region where

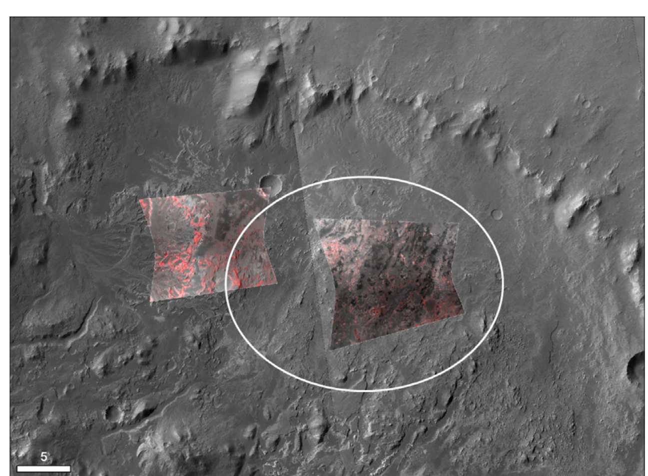

Fig. 1. Eberswalde crater. MSL landing site ellipse over Eberswalde and 2.30 μm band mineral maps from CRISM FRT000060DD and FRT00008038 images over a CTX composite image.