WHAT CAN TERRESTRIAL SAND-TEXTURED SOILS REVEAL ABOUT THE COMPOSITION OF CORE MATERIALS FORMING MARTIAN REGOLITH?

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ABSTRACT

Reliable interpretations of remote sensing data obtained from Mars, notably in the visible and near-infrared spectral domains, need to correctly account for variations on the reflectance of the sand-textured regolith covering its surface. These variations, in turn, are directly associated not only with the presence of iron oxides, which are also found in dune fields and coastal landscapes on Earth, but also with the composition of the core (parent) material forming different types of Martian regolith. While the core materials of terrestrial sand-textured soils can be clearly identified, the same cannot be said about the core materials of Martian regolith. The difficulties to solve this open question are mainly prompted by the relatively restricted range of experiments that can be performed using equipment deployed on Mars. In fact, missions have been proposed to overcome these restrictions by collecting and bringing samples of Martian soils to Earth. In the meantime, the pairing of remote sensing technology with *in silico* experiments continues to play a key role in investigations of Martian geomorphology, mineralogy and weathering history. Following this trend, we have compared the effects of different types of core materials on the reflectance of Martian regolith in order to add to the current knowledge about its composition. The core material candidates were selected based on remote and *in situ* observations of terrestrial and Martian sand-textured soils. Our *in silico* experiments were performed using a first-principles simulation framework in conjunction with measured reflectance data obtained from different regions on Mars. Besides contributing to the elucidation of the problem at hand, our findings enable an original and predictive assessment of the impact of different core materials on the spectral signatures of terrestrial and non-terrestrial sand-textured soils.

***Index Terms*—** Sand, regolith, core material, quartz, basalt, silica-rich basaltic composition, reflectance.

1. INTRODUCTION

Sand-textured soils are primarily composed of particles (grains) of weathered rocks immersed in a pore space. These rocks correspond to the parent (core) material of these soils. In terrestrial landscapes, this is typically a silicate mineral such as quartz (the most common form of crystalline silica), gypsum or calcite, with quartz being the most abundant [1]. While these minerals are colourless in pure form, trace amounts of contaminants may substantially affect their spectral appearance. Depending on the weathering process, the core material may occur as pure particles, coated particles or mixed with contaminants [2]. The particle coatings correspond to a mineral (*e.g.*, kaolinite or illite) matrix [1]. The contaminants often include iron oxides (*e.g.*, hematite, goethite and magnetite), which may also occur as pure particles or embedded in the particle coating [2].

Relevant investigations of Martian geomorphology, mineralogy and weathering history rely on spectral data obtained through orbitral sensors [3] as well as Earth-based telescopes [4] and equipment deployed on the red planet's surface [5]. Since Mars is largely covered by sand-sized regolith, in order to accurately interpret this data, it is essential to have a clear picture about its impact on the overall reflectance of the underlying Martian soils, notably in the visible (Vis) and near-infrared (NIR) domains [6, 7]. This, in turn, would require a detailed knowledge about the composition and optical properties of the covering regolith.

It has been indicated that basalt is a prevalent rock type on Mars [3] and low-reflectance Martian terrains, which are characterized by sand-sized particulates [3], may be dominated by basaltic lithologies [8]. Hence, one might expect that the regolith covering these terrains may predominantly have basalt as its core material. We note, however, that the presence of silica-rich deposits on Mars, including areas with relatively low reflectance [3], has also been the object of extensive investigations [7]. In fact, tangible evidence of nearly pure silica deposits was provided by Spirit rover's inoperative right front wheel excavation of light-toned soil while traversing the Gusev crater [6, 9]. These observations also raised the possibility that regoliths covering certain Martian landscapes might have silica as their core material like certain terrestrial sand-textured soils.

In this paper, we assess this possibility using a first-principles simulation framework and measured reflectance data obtained from different regions on Mars. More specif-

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ically, we examine the impact of different core materials on the reflectance of these regions. In our controlled *in silico* experiments, we considered three alternatives (labelled A, B and C) to represent the core materials forming the regolith covering these regions. In alternative A, we considered basalt as the core material occurring in the pure, mixed and coated (within an illite matrix [10]) particles. This alternative was motivated by the previously mentioned abundance of basalt on the Martian surface. In alternative B, we considered quartz as the core material occurring in the three types of particles. This alternative was triggered by the qualitative similarities between the spectral signatures of Martian regions believed to have large silica deposits (*e.g.*, Gusev crater [6, 10]) and that of terrestrial sand-textured soils (*e.g.*, red dune fields found in the Australian outback and in the Arabian desert [1]) that have quartz as their core material. Finally, in alternative C, we considered basalt as the core material occurring in pure and coated particles, and a silica-rich basaltic composition occurring in the mixed particles. This alternative was prompted by results serendipitously obtained in previous experiments [10], as well as studies indicating that silica-rich deposits occurring on Mars were formed from the remnants of basaltic precursor materials after extensive weathering processes involving hydrothermal fluids [6, 9].

2. MATERIALS AND METHODS

In our investigation, we considered the regoliths covering five areas located in three different regions on Mars, namely the Olympus-Amazonis [4], the Oxia Palus [4] and the Gusev crater [5]. In order to characterize the regolith covering these regions, we have employed data specific to Martian sand-textured soils whenever such data was available (*e.g.*, porosity (60%) [10]), and average data describing terrestrial sand-textured soils (*e.g.*, grain roundness (0.482) and sphericity (0.798) [1]) otherwise. The dimensions for the sand-sized and silt-sized particles were obtained from data provided in the literature [1, 2], and the presence of clay-sized particles was assumed to be negligible. The remaining parameter values used to obtain the modeled reflectance data are given in Table 1.

Using measured reflectance data [4, 5, 10] obtained from the selected areas as reference, we have computed a set of directional-hemispherical reflectance curves for each of these areas. These sets, in turn, consisted of three curves, one for each of the three alternatives (A, B and C) employed to represent the core materials forming the regolith covering these regions. Due to the estimated high silica content of the basaltic composition considered in alternative C, we assumed that its extinction coefficient is negligible like in the quartz case [1]. However, since this composition is likely to have a higher density than that of quartz (2.65 kg/L [1]) due to the presence of the basaltic precursor materials with a density closer to that of basalt (3 kg/L [10]), it is also expected that it may have a higher refractive index than that of quartz. Since the actual spectral values for this refractive index are unknown at this time, we have assigned to them the spectral values employed for basalt [10], which may be regarded as upper bounds for this spectral quantity. Although our choice of values for the basaltic composition's refractive index and extinction coefficient may not find an exact correspondence in materials commonly found on Earth, it is important to note that, as experimentally inferred by Rice *et al.* [6], the optical properties of silica-rich materials on Mars may not be the same as those obtained in terrestrial settings under ambient conditions.

Set	sand	silt	μ_p	μ_m	μ_c	r_{hg}	ϑ_{hg}	ϑ_m
I	85	15	0	90	10	0.75	0.005	0.00
II	95	5	0	100	0	0.15	0.070	0.00
III	85	15	0	100	0	0.25	0.030	0.00
IV	95	5	0	100	0	0.20	0.030	0.00
V	85	15	10	80	10	0.50	0.030	0.01

Table 1. Input data sets I, II, III, IV and V used to obtain modeled reflectance curves for areas located on distinct regions of Mars: the Olympus-Amazonis (I), the Oxia Palus (II) and the Gusev crater (sites D-green (IV), E-red (IV) and E-green (V)), respectively. The texture of the samples is described by the percentages (%) of sand and silt. The particle type distributions considered in the simulations are given in terms of the percentages (%) of pure (μ_p), mixed (μ_m) and coated (μ_c) grains. The parameter r_{hg} corresponds to the ratio between the mass fraction of hematite to ϑ_{hg} (the total mass fraction of hematite and goethite). The parameter ϑ_m represents the mass fraction of magnetite, which is assumed to appear as pure particles [2].

The modeled directional-hemispherical reflectance curves were computed using a first-principles light transport model, SPLITS (*Sp*ectral *Li*ght *T*ransport Model for *S*and) [1], that accounts for the morphological and mineralogical characteristics of the constituent particles of sand-textured soils, as well as their distribution in the pore medium [2]. These curves were obtained by casting 10^6 rays (per sampled wavelength) from an angle of incidence equal to $0°$, and collecting all rays reflected into the upper hemisphere using a virtual spectrophotometer [1]. To enable the full reproduction of our experimental results, we have made SPLITS available on online [11] along with the supporting spectral data sets (*e.g.*, refractive index and extinction coefficient curves [2]) associated with various minerals considered in our investigation.

3. RESULTS AND DISCUSSION

In our first round of experiments, we computed modeled reflectance curves for the Olympus-Amazonis and Oxia Palus regions, and compared them with measured reflectance curves provided by Mustard and Bell [4]. The latter correspond to composite spectra obtained by merging data acquired through the ISM (Imaging Spectrometer for Mars) experiment (on the 1989 Soviet Phobos-2 mission) with Earth-based telescopic observations, and removing atmospheric attenuation [4, 10]. As it can be observed in the graphs depicted in Fig. 1, alternative A (having basalt as the core material) resulted in reflectance curves markedly lower than the measured reference curves. Alternative B (having quartz as the core material) resulted in reflectance curves higher than the measured reference curves, especially when we considered the presence of quartz-coated particles (Fig. 1 top). The closest approximations were obtained employing alternative C (having basalt as the core material of pure and coated particles, and a silica-rich basaltic composition as the core material of mixed particles).

We remark that the measured curves presented in Fig. 1 correspond to merged data obtained for large areas using distinct strategies: one using a scanning imaging spectrometer from the orbit altitude of 6300 km, and the other using Earth-based telescopic observations [4]. Consequently, these data incorporate a certain degree of spatial and temporal variabilities [10]. Such variabilities need to be taken into account when one compares the measured curves with their modeled counterparts, which were computed considering light interactions taking place at a specific location and at a given instant of time.

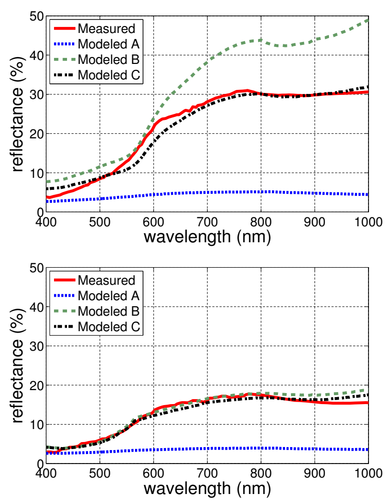

Fig. 1. Comparisons of measured [4] and modeled reflectance data for the Olympus-Amazonis (top) and Oxia Palus (bottom) regions. The modeled curves were computed considering the three alternatives (A, B and C) employed to represent the core materials forming the regoliths covering these regions, as well as the input data sets I (Olympus-Amazonis) and II (Oxia Palus) provided in Table 1.

In our second round of experiments, we computed modeled reflectance curves for sites located at the Gusev crater and compared them with measured reflectance curves provided by Bell *et al.* [5]. The measured curves were obtained

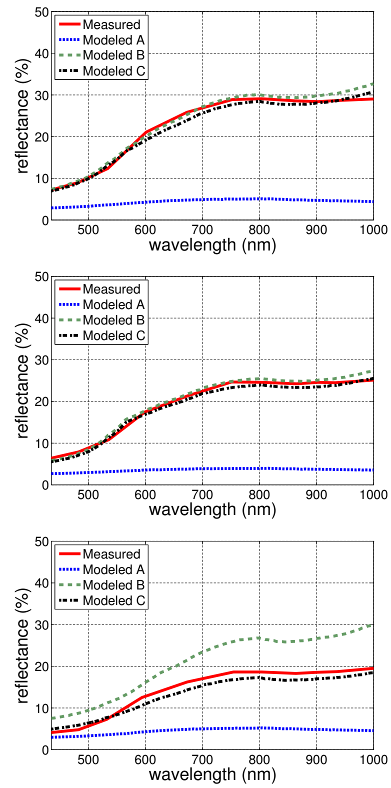

Fig. 2. Comparisons of measured [5] and modeled reflectance data for three sites located in the Gusev crater: D-green (top), E-red (middle) and E-green (bottom). The modeled curves were computed considering the three alternatives (A, B and C) employed to represent the core materials forming the regoliths covering these sites, as well as the input data sets III (D-green), IV (E-red) and V (E-green) provided in Table 1.

from multispectral images acquired using a digital imaging system (panoramic camera) onboard the Mars exploration rover Spirit [5, 10]. Again, as it can be observed in the graphs depicted in Fig. 2, alternative A resulted in reflectance curves markedly lower than the measured reference curves, while alternative B resulted in close approximations when we considered only the presence of mixed particles (Fig. 2 top and middle). The closest approximations, notably when we considered the presence of pure and coated particles (Fig. 2 bottom), were obtained employing alternative C.

Our findings indicate that the sand-textured Martian regoliths, notably in the regions considered in our investigations, may not be characterized by a dominant presence of basalt as their core material. Furthermore, despite the spectral and morphological similarities between regolith found on Mars and quartz-sand found on Earth, it is not likely that the Martian particulate materials have silica as their exclusive core material like their terrestrial analogues. Instead, our findings indicate that the core materials of the selected samples of Martian regolith are likely to be characterized by a small, albeit spectrally influential, presence of basalt and a prevalent presence of silica-rich basaltic compositions.

It is worth noting that the occurrence of regolith having a silica-rich basaltic composition as its core material would represent a strong indication of the presence of underlying silica-rich deposits. Besides aiding the search for water on Mars [6] and shedding new light on the red planet's evolutionary history [7], the detection of these deposits also have an astrobiological significance. This aspect has been prompted by studies relating the precipitation of silica from fluids to a mechanism for the preservation of microbes [6, 7]. Not surprisingly, areas that may contain silica-rich deposits are considered primary candidates for examination by future landed missions aimed at the collection of samples to be returned and analysed at Earth-based laboratories [9].

4. CONCLUSION

It has been often assumed that basalt is the prevailing mineral forming the core of Martian regoliths. Although this may be plausible for the regoliths covering certain regions, the evidence pointing to the presence of silica-rich deposits on Mars raised another possibility. More specifically, like certain terrestrial sand-textured soils, these regoliths could have silica as their parent constituent. Our findings demonstrate this may be indeed the case for regolith covering those silica-rich deposits. However, they also indicate that silica occurring in the core of mixed regolith particles is more likely to be found forming compositions with basaltic precursor materials. Moreover, they suggest that a relatively smaller occurrence of pure and/or coated regolith particles having basalt as their parent material can still have a noticeable influence on the spectral responses of Martian regoliths, including those covering regions bearing silica-rich soil deposits.

Contaminants, like hematite and goethite, have a strong influence on the Vis-NIR responses of terrestrial and non-terrestrial sand-textured soils. Accordingly, they have been the focal point of many studies involving the interpretation of these signatures. However, our investigation shows that the core composition of these particulate materials may have a more significant impact on these responses than it has been previously expected. Thus, by overlooking this impact, one might inadvertently hinder the predictive capabilities of remote sensing observations of regions covered by these soils.

To increase the accuracy/cost ratio of interpretations of remote sensing data obtained from the Martian surface, particularly by missions aimed at the location of new silica-rich deposits, it is essential to strengthen the current understanding about the composition and optical properties of their covering regoliths. We believe that our findings contribute to this goal.

As future work, we intend to investigate the light transmission profiles of Martian regoliths, which may also significantly affect the interpretation of the spectral responses of soil deposits located underneath them.

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