

## Analysis of Juventae Chasma Sulfate mound B using the Multiple-Endmember Linear Spectral Unmixing Model (MELSUM) on CRISM Data

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**Introduction:** Juventae Chasma, north of Valles Marineris on Mars contains several light-toned deposits (LTD). The four most prominent ones have been informally labeled A – D by [1]. They were interpreted as the result of sub-ice volcano eruptions [1]. More recently, [2] suggested a formation of these and other LTD's on Mars as spring deposits. This work focuses on the mineral composition of mound B, located at 297.7 E, -4.4 N. It has an extension of about 25km in length and 10 km in width. It rises from 2800 m to 266 m below datum. Two stratigraphic units can be identified in HRSC image data: a lower unit, consisting of an alteration of light and dark toned layers with thicknesses roughly ten meters, and an upper unit with layer thicknesses of approximately 100 m, estimated from an HRSC digital terrain model. The mineralogy of this outcrop was investigated by [3] based on IR data from the imaging spectrometer Observatoire pour l'Eau, les Glaces et l'Activité (OMEGA) on Mars Express. The authors identified the lower unit as monohydrated sulfate, most likely kieserite, and the upper unit as gypsum. This has been challenged by [4] who remarked that late-stage precipitation of gypsum after the precipitation of monohydrated sulfates is thermodynamically not favorable. Instead, they proposed polyhydrated sulfates as the main constituent of the upper unit of mound B. In this study, we assess the mineralogy of mound B based on NIR data from the imaging spectrometer CRISM on MRO, by using the Multiple-Endmember Linear Spectral Unmixing Model (MELSUM) developed by Combe et al. [5].

**The CRISM dataset:** The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) acquires in its targeting mode images in 544 channels by two sensors, a visible/near infrared sensor, sensitive between 362 and 1053 nm and an infrared sensor, sensitive at 1002 to 3920 nm [6]. It has a maximum spatial resolution of 18 m per pixel. We used CRISM data product FRT00009C0A in the range of 1 to 2.6  $\mu\text{m}$ , avoiding the deep, water-related absorption band at 3  $\mu\text{m}$  and beyond. The data was processed to remove instrumental effects and converted into reflectance data. A novel, time-dependent volcano-scan technique [7] was applied to remove absorption bands related to CO<sub>2</sub> much more effectively than the volcano-scan technique described by [8] that has been applied to CRISM and OMEGA data so far. This allows the interpretation of absorption features close to 2  $\mu\text{m}$ , which would other-

wise have been hidden by CO<sub>2</sub> artifacts. Absorption bands caused by H<sub>2</sub>O ice in the atmosphere are not removed by this correction algorithm, and thus have to be addressed during later processing steps.

**Overview of MELSUM:** Several strategies can be applied to analyze hyperspectral data. The most common method is to search for absorption features characteristic for specific minerals or groups of minerals, by defining appropriate spectral indices. A more elaborate method is the Spectral Mixture Analysis (SMA), which has been especially designed for mixtures of minerals [9], as pure mineral occurrences are expected to be rare at the spatial scale of spectral observations. The basic assumption is that the observed spectrum can be explained as a linear combination of a set of input spectra. This is the case if the individual components observed within the same pixel of the spectrometer are spatially separated from each other so that light interacting only with one surface mineral dominates over light interacting with different types of minerals at the same time, [10] as in an intimate mixture. The HiRISE scene PSP\_007126\_1755 of mound B with a spatial resolution two orders of magnitude higher than that of CRISM suggests that this assumption holds true: Dark material and light-toned material seem to cluster separately from each other in small topographic lows and little dunes, effectively limiting the surface where light can interact with both materials.

In the classic SMA, a solution for the measured spectrum is calculated by a linear combination of all input spectra (from a spectral library or from the image itself) at once. This can lead to negative coefficients, which have no physical meaning. MELSUM avoids this by calculating a solution for each possible combination of a subset of the reference spectra, with the maximum number of library spectra in the subset defined by the user. The solution with the lowest residual to the input spectrum is returned.

**MELSUM as similarity measure:** Depending on the number of library spectra and the chosen number of spectra in each subset, MELSUM can lead to a very high number of combinations, and thus a very high computation time for an entire CRISM observation. Therefore, we identified the spectral variability existing in the data set in a first step. Visual analysis of the data suggested the presence of three different spectral units in the dataset: A light-toned lower unit (kieserite in [3]) a light-toned upper unit (gypsum in [3]), and a

dark toned unit. To verify this, we used MELSUM as a similarity measure within the image. We first averaged spectra for each of these units over several tens of pixels to reduce noise. We then used those averaged spectra as input to MELSUM. This analysis showed that these three spectral units are enough to describe the variability in the data to first order, as the residuals were dominated by noise. However, we noticed variations within the lower light-toned unit. We finally proceeded with the analysis of each of the three units individually.

#### MELSUM as mineral detector:

We chose 34 laboratory spectra of sulfates, mafic minerals and iron oxides plus a spectrum for H<sub>2</sub>O ice as reference spectra for the unmixing of averaged spectra for each of the identified spectral regions. The best fit found for the dark material was a combination of olivine, pyroxene and ice (an effect of ice aerosol and not present at the surface). The lower light-toned unit was best modeled by a mix of szomolnokite, kieserite, olivine and ice. The upper light-toned unit fits best with a combination of romerite, rozenite, olivine and ice. A combination similar to kieserite-szomolnokite would be rozenite-starkeyite, which both have four water molecules in their crystals. A fit of this combination could not be checked as we did not have access to a starkeyite spectrum. Starkeyite, is a polyhydrated magnesium sulfate that also fits well to the observed spectra [11,12].

*Application to the entire image:* Finally, we used MELSUM on each spectrum of the image, using the reduced input spectral library with only the endmembers that had been chosen in the previous tests on average spectra. Atmospheric scattering has a major additive contribution that is modeled by a straight line with a negative slope. The result of MELSUM is a set of images displaying the mixing coefficients of each library spectrum at each image pixel. Coefficient values vary mainly to adjust the amplitude of spectral features, which depend on a variety of parameters, including grain size, and can therefore not be translated directly into abundance maps. The direct comparison of coefficients for different library spectra is difficult, but

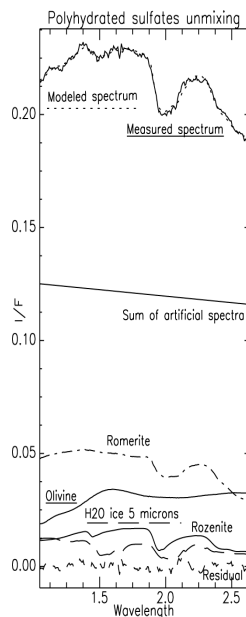


Figure 1: Spectral unmixing of a polyhydrated sulfate spectrum. Note the good fit between modeled and measured spectra.

each coefficient alone can act as an indicator for the relative distribution of that component within the analyzed image. The results show that the lower, thinly layered part of the mound is dominated by szomolnokite, but kieserite locally plays a role. The thickly layered section has been modeled exclusively by the two ferric polyhydrated sulfates romerite and rozenite. This could suggest that the combination of these two endmember spectra replaces a mineral spectrum that was not available in the spectral library.

**Conclusions:** The very good fit between measured and modeled spectra demonstrates the effectiveness of MELSUM as a tool to analyze spectral data from CRISM. It can be applied either to assess the intrinsic variability of the hyperspectral data set, or as a tool to infer the mineralogy of the substances contributing to a given spectrum. MELSUM correctly detected monohydrated sulfates in the lower unit, szomolnokite and kieserite, and polyhydrated sulfates in the upper unit, with a combination of romerite and rozenite being the best match. In contrary to findings of [3], gypsum is not present. Mafic, olivine rich material is found in both units.

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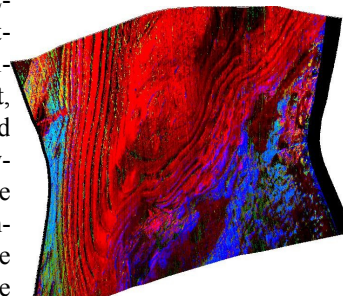


Figure 2: RGB image with the coefficients of romerite (red), kieserite (green) and szomolnokite (blue). MELSUM detects monohydrated sulfate in the lower part and polyhydrated sulfate in the upper part of the mound.