

QUANTIFYING MINERAL ABUNDANCE THROUGH VSWIR MICROSPECTROSCOPY IN CARBONATE/SERPENTINE SYSTEMS. E. K. Leask¹ and B. L. Ehlmann^{1, 2, 1} Division of Geological and Planetary Sciences, California Institute of Technology, MC 100-23, Pasadena, CA, 91125. (Email:eleask@caltech.edu), ²Jet Propulsion Laboratory, Pasadena, CA.

Introduction: Visible to shortwave infrared (VSWIR) reflectance spectroscopy has been used for large-scale mineralogical mapping on Earth and Mars (e.g., (~20 m/pixel by CRISM—Compact Reconnaissance Imaging Spectrometer for Mars, [1]). The prototype ultra-compact imaging spectrometer (UCIS) [2], implemented for this work in microscopic mode, allows direct comparison between remote sensing data and microscale mineral identification and textures. VSWIR imaging spectroscopy is non-destructive, pre-

serves petrographic relationships, and requires minimal sample preparation. As each mineral has a different set of conditions under which it is stable, identifying multiple minerals (in context) allows for tighter constraints on geochemical conditions at the time of formation. It is not currently feasible to make and study thin sections on Martian rocks *in situ*; UCIS is proposed as an alternative method to obtain a similar level of petrographic information.

Samples from the Semail Ophiolite (Oman) are used as an analogue for Martian carbonate and serpentine deposits [3] to evaluate the capabilities of VSWIR spectroscopy to discriminate between carbonate minerals, distinguish carbonates from minerals with absorptions at similar wavelength positions, and to quantify their abundances. This work is part of a project to establish methods of identifying and quantifying carbonate content at many spatial scales using VSWIR reflectance spectroscopy.

Methods: Data Collection. Rock samples were cut ~ 2x3 cm, polished (required only for later SEM work), and imaged with the prototype UCIS instrument in its micro-spectroscopy mode [2]. The UCIS instrument is a reflectance imaging spectrometer covering the wavelength range 0.5–2.5 μm , with 10 nm spectral resolution and a pixel footprint of ~ 81x81 μm . Samples are mounted onto a translating stage; each sample takes about 3 minutes to image. Afterwards, the samples were carbon coated and imaged on a scanning electron microscope (SEM). Energy-dispersive spectroscopy (EDS) maps were obtained over the area of the sample, providing elemental abundance data for direct comparison with the UCIS images. Different subsamples of each rock were sent to Actlabs for x-ray diffraction (XRD) analysis, to provide independent mineral identification and abundance estimates.

Linear Unmixing. At this scale, many pixels consist of a single mineral phase. As a first-order approximation, we use linear spectral unmixing to estimate the abundance of phases present in the image. This assumes most mixed spectra result from areal ‘checkerboard’ mixtures. Spectral endmembers are chosen from within the scene, and best-fit abundance estimates are obtained using a non-negative linear least squares algo-

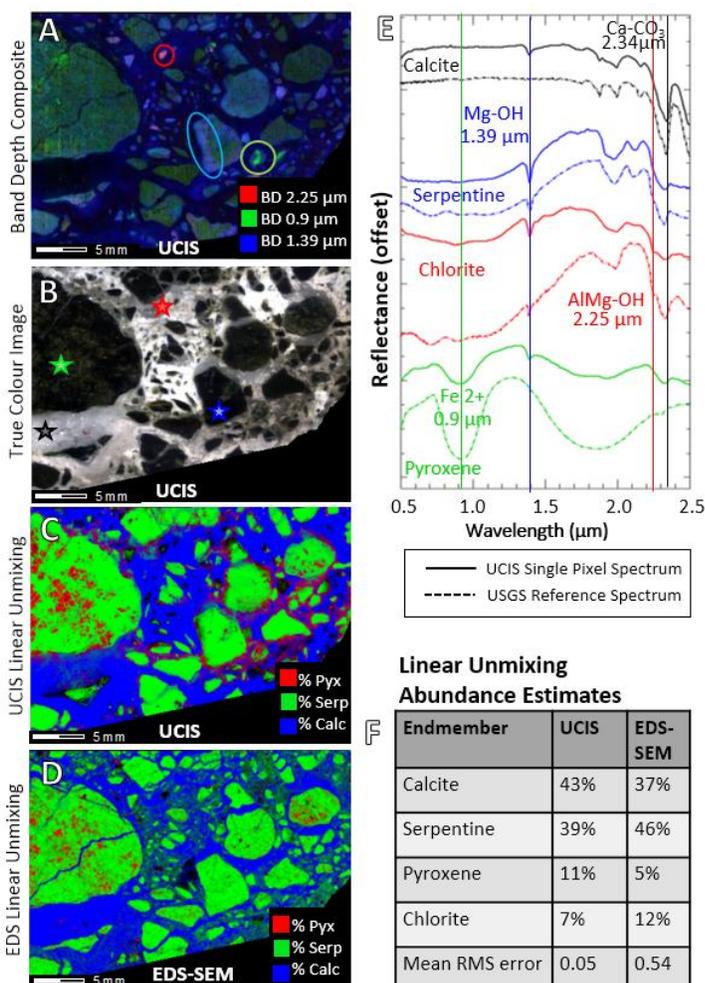


Figure 1: Mineral identification, petrographic textures, and unmixing results for a travertine conglomerate. A) Band depth colour composite, highlighting rare (pink) clasts with Al/Mg-OH and alteration around the outside of clasts (blue) but not the interior (green). B) True colour image showing location of single-pixel spectra in E). C, D) Results of linear unmixing with UCIS and EDS data. E) Endmember spectra used in unmixing. F) Linear unmixing results using UCIS spectra and EDS element abundances.

rithm [4]. Endmember selection was refined until average root-mean-square errors were under 0.05. Occasional fine-grained mixtures and boundaries where large crystals provide a window to phases below (see Fig. 1C, D) do not combine linearly. Such areas can be identified by petrographic textures, and the abundance of a mixed phase can be estimated as a separate endmember. UCIS images were coregistered with EDS elemental abundance maps. Areas corresponding to the same endmember pixels chosen above were used to unmix the elemental abundance data independently via the same algorithm.

Results and Analysis: Mineral Identification. Carbonates of different compositions (calcite, magnesite, and dolomite) are identifiable through ~ 10 nm shifts in the position of the $2.3 \mu\text{m}$ cation-carbonate vibrational absorption overtone (Figs. 1E, 2C) [5]. Rare clasts, such as the chlorites identified by an Al,Mg-OH absorption at $2.25 \mu\text{m}$ (pink in Fig. 1A) [6], are readily identifiable in UCIS and EDS data but fall below the detection threshold of powder XRD analysis.

Alteration Textures. Alteration fronts are seen in both figures; in Fig. 1A, the edges of some clasts show deeper $1.4 \mu\text{m}$ (OH) absorptions, and the relatively-intact pyroxene centre of another clast is highlighted in green. In Fig. 2B, zones of intense serpentinization (green) are focused around carbonate veins (blue), while the rock interior has relatively pure pyroxene signatures. Intermediate spectra with both pyroxene (0.9 and $1.8 \mu\text{m}$) and serpentine (1.4 and $2.3 \mu\text{m}$) ab-

sorptions track the progress of alteration, may represent relatively poorly crystalline materials, and may contribute to the ‘amorphous’ component of XRD analyses.

Mineral Quantification. Linear unmixing results can yield abundance estimates that are within ~ 5 -7% of other methods (XRD and EDS maps). Spectral unmixing results for each phase are spatially coherent, even when similar spectral endmembers are included (e.g. antigorite and chlorite). Elemental unmixing results using EDS data are able to track the same phases, although compositionally similar pyroxenes and serpentines may be misidentified. However, EDS data can clearly track the abundances of endmembers within a fine-grained matrix; the current best practice with UCIS data is to classify a separate ‘mixed’ phase. A sensitivity analysis to investigate the effects of endmember choice (including the use of reference spectra and ‘dark’ endmembers) is in progress.

Conclusions: Linear spectral unmixing of VSWIR reflectance spectra provides a good approximation of mineral abundance within a sample, consistent with abundance estimates from XRD (weight %) and EDS (area %). The UCIS instrument demonstrated the ability to differentiate between carbonate minerals (~ 10 nm difference in band position) and other minerals like serpentines with similarly positioned major absorptions. UCIS is especially well suited to identify spatially coherent rare phases that would be missed by traditional techniques such as XRD, and is a rapid method to survey a set of samples with minimal preparation.

Future Work: The degree of spectral variability of a given phase in a natural sample will be assessed, including the role of grain size and overall albedo. A second field campaign at the Semail Ophiolite will focus on VSWIR imaging at the outcrop scale; airborne HyMap data of the region will provide a third spatial scale [7], more similar to orbital data available at Mars. Ideally, we will be able to robustly constrain the carbonate content of a large area, using our ground-truthing at smaller spatial scales.

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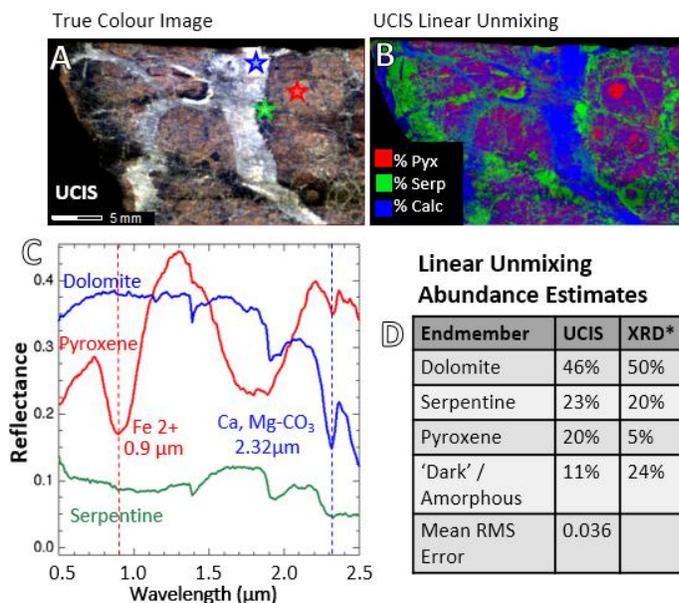


Figure 2: Mineral textures and abundances in a veined serpentinite. A) True colour image shows location of endmember spectra. B) UCIS linear unmixing result shows petrographic relationship between phases. C) Endmember spectra. D) Linear unmixing results using UCIS spectra and XRD mineral abundances.