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Mapping of an ophiolite complex by high-resolution visible-infrared spectrometry

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[1] The Sumail massif of the Oman peridotite has been surveyed by the high spectral resolution imager HyMap. The field measurements have been taken simultaneously to the HyMap campaign with a GER 3700 spectrometer. To compare the two data sets, further calibration and atmospheric correction are made through empirical line corrections. A continuum removal by a modified Gaussian model on reflectance is then performed for each pixel to minimize atmospheric scattering and shadowing effects. Classification from spectral distance is established using field observations and comparisons at full spectral resolution to identify peridotite subunits (harzburgites and dunites) and to distinguish plagioclase-wehrlites from gabbros. Detections of hydrothermal transformations of olivine in serpentines and their alteration in carbonates along fracture networks, characterized by narrow spectral signatures, validate the classification. This demonstrates the utility of the high spectral resolution and the development of appropriate processing methods for geological identifications.

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1. Introduction

[2] The Oman ophiolite is a fragment of oceanic lithosphere which was obducted onto the Arabian continental margin during late cretaceous times (Maestrichtian, i.e., about 70 Ma) [e.g., *Coleman and Hopson*, 1981]. The two main lithological units are partially serpentinized mantle peridotites and gabbroic-basaltic rocks from the overlying crustal section.

[3] Because of the extent of the area (30,000 km²) and to the extremely rugged topography, with elevations between 0 and 2500 m, exhaustive sampling impossible. Remote sensing is able to provide more continuous lithological mapping and it is facilitated by the almost perfect rock exposure due to arid climate [*Pontual*, 1990].

[4] In addition, at smaller spatial scales, spectrometry can distinguish more subtle lithology variations [*Hunt*, 1977], essentially by absorption bands between 2100 and 2500 nm. Interpretations have been already possible using multispectral (less than 10 channels) satellite imagery. Landsat Thematic Mapper (TM) which has 1 channel covering the 2090–2350 nm range was first used by *Abrams et al.* [1988]. With the JERS-1 OPS instrument, which has 3 channels in the 2100–2500 nm range (130 nm resolution), *Denniss et al.* [1994] and *Pinet* [1999] describe a larger number of lithologies: harzburgite and dunite forming the mantle and various gabbros intruded by wehrlite in the crustal section.

[5] In imaging spectroscopy, high spectral resolution is the key toward advanced lithology discrimination based on mineral identifications including all transformations from the fresh rock to its weathered skin. This is expected with hyperspectral (hundreds of channels) airborne instruments like HyMap (16 nm resolution in the 2100–2500 nm domain) and AVIRIS (10 nm resolution) [e.g., *Cocks et al.*, 1998; *Bodechtel*, 2001; *Swayze et al.*, 2003; *Clark et al.*, 2003]. For peridotite fields, earlier hyperspectral investiga-

tions have been made with AVIRIS data [e.g., *Mustard*, 1993; *Chabrilat et al.*, 2000; *Launeau et al.*, 2002, 2004]. This work will focus on the interest of the Modified Gaussian Model (MGM) [*Sunshine et al.*, 1990] for an improved continuum removal [*Combe et al.*, 2005; *Pinet et al.*, 2006] to identify and map mineralogical zoning which could not be explained with classical remote sensing techniques.

2. Data: HyMap Hyperspectral Images and GER 3700 Field Spectra

[6] The Sumail massif of the Oman Ophiolite (Figures 1a and 1b) was surveyed with the imaging spectrometer HyMap on 4 and 6 December 2002 [*Pinet et al.*, 2003, 2006], covering approximately a 10 × 50 km area with a spatial resolution about 6 m. The total data set is mainly composed of strips oriented NE-SW. Six were acquired the first day and eight the second day. This work is a preliminary study of the Maqsad area, undertaken on a small subarea of the survey, using part of two HyMap NE-SW strips (Figure 1c) acquired the first day.

[7] HyMap has 126 discrete channels between 448 and 2478 nm regularly distributed among three grating devices avoiding most of the water vapor absorptions at 1400 and 1900 nm. Reflectance images and atmospheric correction with the atmosphere removal radiative transfer model (ATREM) [*Gao et al.*, 1993; *Cooperative Institute for Research in Environmental Sciences*, 1999] and the Empirical Flat Field Optimal Reflectance Transformation (EFFORT) [*Boardman*, 1998] were provided by the HyVista team.

[8] In situ measurements have been taken with a GER 3700 spectrometer between 3 and 7 December 2002 at various locations in order to spectrally document identified lithologies of interest and surface properties. The instrument has 640 channels between 315 and 2519 nm with a spectral sampling

Figure 1. (a) Location of the Oman ophiolite and (b) the survey area of the Sumail massif by HyMap. (c) Two portions of the total data set that are presented in this study: Mantle peridotites and gabbroic-basaltic crustal rocks are investigated in A, and recent alteration is investigated in B. The reference site of bright and dark surfaces chosen for calibration is located by the white arrow.

comprised between 1.5 and 12 nm. The ground field of view is about 100 cm².

3. Methods

3.1. Calibration to Ground Reflectance

[9] In order to check the consistency of the calibration of the airborne data, field spectra have been acquired on the day and time of HyMap acquisition one bright and one dark spectrally homogeneous surfaces (arrow in Figure 1c). The bright one is a sebkha made of fine dust of peridotite while the dark one is a reg made of dark pebbles of peridotite covered by a thick crust of black desert varnish.

Both are easily located on the images. Despite the atmospheric correction provided by HyVista, airborne and field spectra (Figure 2) reveals that the bright surface levels are higher on HyMap spectra than on GER 3700 spectra (respectively 51 and 41 % reflectance at maximum). In Figure 2 a local overestimate (atmospheric residue, a), a drop between 1700 and 1800 nm (b), an unexpected peak at the place of the MgOH absorption feature of serpentine (c), and a drop beyond 2400 nm (d) are clearly identified as artifacts on HyMap spectra. These lead us to apply additional empirical line corrections [e.g., Secker *et al.*, 2001; Clark *et al.*, 2002].

Figure 2. Reflectance of homogeneous surfaces of sebkha (bright) and reg (dark). Atmospheric absorption at 1400 and 1800 nm have been masked. An empirical correction is applied to remove the artifacts (localized by the letters and noted in the text) observed in HyMap reflectances.

3.2. Continuum Removal Procedure

[10] Topography contributes significantly to the photometric variations controlling the continuum. Without a high spatial resolution digital elevation model, an absolute correction using radiative transfer equations cannot be performed. Moreover, strong deviations are also induced by the different spatial resolutions and the distances to the target between field measurements and remote acquisitions [Friedl *et al.*, 1995; Chen, 1999].

[11] For multiple data comparison and spectral analysis, continuum removal procedures are intensively used [Clark and Roush, 1984]. An improved method by way of the MGM was used successfully by Combe *et al.* [2005] to calculate a continuum insensitive to detector boundary's cut at both ends. The MGM fits the entire spectrum (reflectance R_k at channel number k) of an image by a set of n Gaussian curves defined by their position (center μ),

Figure 3. Importance of continuum removal. These synthetic spectra have different continuum shapes (1) despite having exactly the same absorption bands (2).

width (σ) and amplitude (strength s) and, according to Sunshine *et al.* [1990], the best continuum is assumed to be linear in wavelength λ (a and b are the slope and the intercept respectively). As a result, the continuum retrieved by MGM becomes independent from the absorptions [Sunshine and Pieters, 1993].

$$\ln(R_k) = (a\lambda_k^{-1} + b) + \sum_{i=1}^n s_i \cdot \exp \left[-\frac{(\lambda_k - \mu_i)^2}{2\sigma_i^2} \right] \quad (1)$$

[12] The algorithm starts with an initial solution allowing the best fit for the maximum number of pixels. The eight Gaussian curves (Table 1) have been chosen to provide an acceptable fit on the larger number of spectra with a minimum of absorption bands. Modifying these parameters may cause iterations to often stop prematurely, leading to a resulting continuum function not well constrained.

[13] Figure 3 demonstrates the importance of the continuum removal. This permits direct comparisons of spectra from various images [Combe *et al.*, 2005]. It consists of subtracting the continuum function $a\lambda_k^{-1} + b$ of equation (1) to spectra in logarithm reflectance space.

3.3. Geological Mapping

3.3.1. Classification by Spectral Distance

[14] A classification is performed with reference spectra chosen among the hyperspectral images. For each rock of interest, an average spectrum is calculated from several image pixels (Figure 4) at the location given by the geological map by Amri

Table 1. Initial Set of User-Defined Parameters for Eight Gaussian Absorption Bands

Center Position, nm	Width, nm
490	200
650	200
1000	150
1150	150
1500	120
1900	170
2100	40
2300	150

Figure 4. Spectra of the main lithologies measured by HyMap after continuum removal by MGM. Gabbros are the first five, and peridotites are the last five.

et al. [1994]. These pixels were chosen close to sampling locations to avoid large interpolations. Comparison uses a normalized spectral distance ID [Launeau *et al.*, 2002] by considering spectra as vectors $\vec{v}$ (image reference spectra) and $\vec{w}$ (image tested spectra):

$$ID(\vec{v}, \vec{w}) = \sqrt{\frac{1}{N} \sum_{\lambda} \left[\frac{R_v(\lambda) - R_w(\lambda)}{R_w(\lambda)} \right]^2} = \frac{\|\vec{v} - \vec{w}\|}{\|\vec{w}\|}, \quad (2)$$

where R is the reflectance, N the number of channels and λ the wavelengths. Spectral distance between each spectrum of the image and the reference spectra provide a relative quantification. Unlike the spectral angle mapping, this distance allows us to distinguish albedo variations as discussed by Combe *et al.* [2005].

3.3.2. Serpentine Index

[15] Because of common hydration of their primary minerals, peridotites show spectral features of the hydroxyl group (OH) in the range 2200–2400 nm [King and Clark, 1989; Swayze, 2004]. On the other hand, serpentine does not preserve the main absorption bands of the minerals from which it has been formed (Figure 4), thus the occurrence of serpentine might hamper the detection of the absorption bands of olivine and pyroxenes around 1000 nm.

[16] Serpentinized minerals have several absorption bands in spectra between 2100 and 2500 nm. The strongest absorptions are around 2300 nm as can be seen in Figure 5a, but they are not a

diagnostic of serpentinized minerals because other absorption processes occur at these wavelengths (e.g., Figure 5b). The small absorption isolated near 2130 nm due to Mg-OH and giving a M shape to spectra is more reliable to presence of serpentine. When narrow absorptions features like these are available, the absorption band depth can be calculated using the ratio between the average reflectance of the shoulders at 2077 and 2166 nm and the reflectance of the minimum at 2130 nm. To have zero values when serpentinization is low, we have defined the following index:

$$\frac{R_{2077} + R_{2166}}{2 \times R_{2131}} - 1. \quad (3)$$

3.3.3. Mapping Alteration and Magnesite

[17] The weathering is commonly seen as a complication of the lithology discrimination by remote sensing. However, it may also map the extension of some processes of low-grade metamorphism which would have been missed without such high spectral resolution images. For example the magnesite is locally an abundant alteration product of serpentine related to low-grade metamorphism and recent water circulations that have concentrated it along faults. Like other carbonates, it shows useful narrow absorptions features due to C-O bonds [Hunt, 1977]. Two of them vary from 2305 nm to 2335 nm and from 2449 nm to 2453 nm, from MgCO_3 (magnesite) and $\text{MgCa}(\text{CO}_3)_2$ (dolomite) to CaCO_3 (calcite) end-members. Dolomites most enriched in Mg are in effect not distinguishable from magnesite on HyMap data. However, like for calcite and dolomite [Launeau *et al.*, 2004], low concentrations

Figure 5. USGS spectra of (a) serpentines and (b) carbonates used to build appropriate index and color composite for mapping.

of magnesite can be deduced from an appropriate color composition centered on the narrow peak of reflectance at 2384 nm constrained between the two absorptions bands of the magnesite (or dolomite) at 2305 nm and 2447 nm (Figure 5b).

4. Results

4.1. Lithological Mapping

[18] Reflectance images in Figure 6a are dominated by topographic effects. Moreover, diversity of the surface composition is not sufficient to provide a good contrast because all petrologic units present similar spectra with absorption bands mainly due to Fe^{2+} electronic processes in the range 700–1300 nm (Figure 4).

[19] Removing a continuum by MGM (Figure 6b) minimizes spatial variations of apparent reflectance

due to differences of illumination conditions when strong effects of rough topography occur (Figure 6a). Main lithological identifications (gabbros, harzburgite, dunite) are then obtained by a simple color composition at 789 nm (green), 983 nm (red) and 2304 nm (blue), chosen along weak variations around the 1000 nm absorption feature (Figure 6b). They are deduced from direct ground observations and from control point on the geological map of *Amri et al.* [1994]. It reveals harzburgite in green and dunite in yellow. Since gabbros and the plagioclase-wehrlite do not have deep narrow absorption feature at 2304 nm they appear blue (Figure 6b).

[20] The boundary between peridotites and crustal lithologies is very sharp and is always underlined by a dunitic horizon. These cartographic results agree with the conclusions drawn from the global mapping of the massif established by means of

Figure 6. Lithological identifications: (a) Color composite of reflectances. Purple, gabbros; yellow, peridotites and vegetation; dark: shadow. (b) Color composite of reflectance after continuum removal by MGM. Yellow, dunites; green, harzburgite; blue, gabbros; red, vegetation. (c) Gabbroic rocks classification by spectral distance. G, layered gabbros; LG, laminated gabbros; W, wehrlite. (d) Serpentine. Bright corresponds to high serpentinization.

various color composites derived from scaled reflectance data [Pinet *et al.*, 2003, 2005].

[21] Since we are looking at subtle differences between almost similar spectra, *ID* tend to be zero and we rather display the inverse of *ID* which increases strongly when spectra become closer. The spectral distance to three average spectra of

identified units are presented in Figure 6c: they are laminated gabbros, layered gabbros and plagioclase-wehrlite. Layered gabbros (rocks formed in a magma chamber) form well-delimited units while a petrologic continuity is found between plagioclase-wehrlite and laminated gabbros (interpreted as intrusive rocks). This petrological continuity is

Figure 7. Spectra of carbonates and serpentinized minerals. (a) Collected from the HyMap image. (b) Alteration and magnesite mapping. Pure magnesite appears medium green along the wadi (bottom right). The dolomite (blue arrow) is carried from the Jabal al Akhdar massif on the northwest, invisible on the image.

in agreement with formation conditions characterized by a magmatic origin drastically contrasted with harzburgites and dunites which are residual peridotites [Girardeau and Francheteau, 1993]. In the western part of the image, all gabbroic rocks are present on steep slopes of mountains and found in quaternary deposits made of rubbles and gravels well contrasted with the surrounding peridotites.

4.2. Serpentine Mapping

[22] The serpentine index (Figure 6d) reveals higher amounts of serpentine in harzburgite and dunite areas. This might indicate that the main peridotites are deeply affected by hydrothermal processes and serpentine formations. Gabbro areas and more surprisingly late intrusive body of wehr-lite are relatively poor in serpentine: they probably never get altered by such strong circulation of water which was not mapped before this work.

[23] The presence of olivine in dunite and harzburgite areas (Figure 6b) is confirmed by the detection of its common product of hydrothermal transformation: serpentine (narrow Mg-OH absorption feature). Uncertain zonings of the NE [Denniss et al., 1994] are now well identified and attributed to

a late low-grade metamorphism detected by narrow (30 nm width) absorption features of magnesite, alteration product of serpentine. This kind of validation by the mineralogical transformation path is possible with HyMap because its spectral resolution of 16 nm is a fraction of the absorption bands of interest.

4.3. Alteration Mapping

[24] In Figure 7, some dolomite (white to pale green) appears in the valley on the western border of the peridotite as pebbles of sedimentary rocks coming from the Jabal al Akhdar massif. The magnesite can be fully identified in the harzburgite along wadis (medium green color) where it forms large concretions, probably where the water table is close to the surface. In the surrounding harzburgite, the spectral signature of magnesite is quite weak but highlights areas of low-grade metamorphism. By contrast, the southern harzburgite (Figure 7) are very dark, indicating that no such low-grade metamorphism was superimposed on the first serpentine transformation. The detection of that low content in magnesite is possible after continuum removal by MGM (Figure 8a) because the two absorption bands of carbonates near 2300 and 2500 nm are

Figure 8. Spectral signatures of two carbonates (calcite and magnesite) and gabbros extracted from the HyMap data set. (a) After continuum removal by MGM, carbonates show two deep absorption bands near 2300 and 2450. (b) Classical continuum removal erases any absorption band near the limit of the spectra at 2470 nm and enhances the local minimum near 2300 nm for every spectra.

well preserved and are different of gabbro spectra (negative slope toward longer wavelengths). This would not be possible with a classical continuum removal modeled by straight lines that are tangential to the spectra [e.g., *Clark and Roush*, 1984], like the one that is implemented in the ENVI software, because at the edge of the spectra, this continuum is sensitive to shape of the absorption bands. Indeed, in Figure 8b, both carbonate and gabbro spectra show a minimum near 2300 nm resulting in an ambiguity which prevents from the use of reference points for defining a classical continuum. The shape of spectra at 2385 nm indicates a systematic artifact, but its amplitude is about the same over the whole image. Thus it does not lead to an error on the magnesite index as it is only used to map relative variations.

5. Conclusion

[25] Mapping lithologies of the Oman ophiolite emphasizes that high spectral resolution images are well appropriate in geology and that the increase in information demands the implementation of new processing methods.

[26] Like previous works using multispectral data (JERS OPS by *Denniss et al.* [1994] and Landsat TM by *Dromard* [1999] and *Pinet* [1999]), the main lithological units (gabbros and peridotites) are mapped. However, unlike those works, direct identification of lithologies having narrow absorption bands is made possible from hyperspectral observation data. Moreover, that determination is enhanced by MGM continuum removal which minimizes illumination condition variations and facilitates the interpixel comparison by means of straight spectral distance measurements.

[27] From a geological viewpoint, the ability to map serpentines in great detail can improve the knowledge of earlier hydrothermalism while maps of ultimate product of alteration, like the magnesite in peridotite, can outline various rate of massif exhumation.

[28] This work also contributes to a better definition of spectral resolution requirements for geological applications. In this preliminary analysis of HyMap data acquired over the ophiolitic Sumail massif, geological classification by spectral distance is performed on the whole spectral domain while spectral analysis of secondary minerals is mainly focused on a restricted spectral range between 2000 and 2500 nm. This demonstrates that the same hyperspectral image can be used for

multiple objectives and analyzed through different approaches requiring high spectral resolution on the whole spectral domain.

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