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MAPPING OF THE RONDA PERIDOTITE MASSIF (SPAIN) FROM AVIRIS SPECTRO-IMAGING SURVEY : A FIRST ATTEMPT

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1. INTRODUCTION

1.1. Ronda massif mineralogy

The Ronda peridotite massif is a large exposure (~300 km2) of upper mantle included in the earth's crust. From field observations, Obata (1980) showed that the massif displays a well-developed mineralogical zonation moving away from the basalt thrust contact : 1) garnet lherzolite, 2) ariegite subfacies of spinel lherzolite, 3) seiland subfacies of spinel lherzolite, and 4) plagioclase lherzolite are systematically encountered. Apart from these relatively smooth regional variations, peridotites display local but drastic variations in their modal composition, expressed mostly in their olivine / pyroxene and orthopyroxene (OPX) / clinopyroxene (CPX) ratio (peridotites range in composition from lherzolite to dunite), and in the local development of a pyroxenitic layering. These variations reflect phenomenons related to melt migration and/or partial melting. Although these last variations are small scale phenomenons, ranging from a few centimeters to a hundred meters, our preliminary field results have shown that their distribution at the scale of the massif is not random. The production of a global map of the distribution of such variations would be extremely useful to understand the petrological history of the massif (Suen and Frey, 1987), but achieving this task from field observations appears extremely difficult and no such map has been yet obtained by means of field geology work. Recent airborne spectro-imaging observations are currently being processed to achieve this objective.

1.2. Mapping by infrared spectro-imagery

Advances in remote sensing technology have led to the development of imaging or mapping spectrometry (Goetz et al., 1985). Mapping spectrometers measure both spatial and spectral information simultaneously with sufficient wavelength resolution such that, in principle, direct mineralogical information may be retrieved. In visible and near-infrared reflectance spectra, pyroxenes are readily identifiable in the laboratory from their characteristic Fe2+ electronic transition absorption bands located near 1 µm and 2 µm (e.g., Burns, 1970; Hunt and Salisbury, 1970; Adams, 1974), the center of the absorption band diagnostic of olivine being located at 1-1.05 µm. The spectra of OPX and CPX mixtures have been qualitatively described by previous researchers (Adams, 1974; Singer, 1981; Cloutis and Gaffey, 1991) as having properties that are intermediate to their end-members and estimating the modal abundances from the spectra appears possible (e.g., Sunshine and Pieters, 1993). The absorption band diagnostic of plagioclase is centered at 1.25 µm. Given the existence of discriminant absorption bands for each mineralogical species present in the Ronda massif, the production of a map of the variations in the mineralogical composition is a a priori reachable, though challenging objective.

1.3. Airborne campaigns : ARAT/ISM - AVIRIS/TMS

The airborne version of the imaging spectrometer ISM, developed for the Phobos-2 space mission, was operated over Ronda massif, during the July 91 campaign of the ARAT aircraft and about 20 separate ISM axes were flown over Sierra Bermeja on July, 5th, 9th, 10th and 11th. This ARAT/ISM campaign was coupled with an Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) flight over the same site during the European Multispectral Airborne Campaign (Mustard et al., 1992). Three cloud-free, hyperspectral images were acquired on 15th July 91.

Although not developed here, this is a unique opportunity for cross calibration between the two instruments, the main objective being to assess the consistency and the level of precision one can retrieve from independent spectral observations for the purpose of geological mapping and mineralogical interpretation (Chabrillat et al., 1993).

2. ANALYSIS

1.1 First order analysis

In this work, we use a simple linear mixing model (e.g., Gillespie et al., 1990) to evaluate the spatial distribution of spectroscopically distinct materials across the Aviris mapping of the Ronda massif from the mosaic of the three available images. The mosaic has been binned and is analyzed at the spatial resolution of 160x160m. Based on previous knowledge on the field and on statistical tests, small areas with both high internal spectral homogeneity and distinct respective spectral behavior, are selected to define an endmembers basis in the image.

In parallel with the ISM data analysis, the focus here is placed on the use of uncalibrated spectra for the purpose of mapping different geologic units and determining image endmembers (Smith et al., 1990) which will be later on, related to laboratory spectra and field spectroscopy (Mustard et al., 1992). After removal of the atmospheric absorption windows (0.92-0.98, 1.09-1.17, 1.33-1.5,1.75-2. micron), the Aviris spectra have been normalized to a standard area selected within the Ronda massif given its large surface proportion of well-exposed bedrock and the normalized relative reflectance values are scaled at 0.80 µm. Then, a spectro-mixing analysis is performed with a selection of endmembers representative of the main geological units previously mapped (Obata, 1980), in order to check whether the observed spectral variability agrees with the geological boundaries. Four endmembers are needed to account for nearly all the spectral variance. One endmember represents the vegetation, two endmembers are taken in the massif, corresponding to two locations within the peridotite massif based on previous knowledge of the area, the last endmember represents a non-peridotite field (sedimentary soil) without vegetation cover. Owing to the situation of the field of study (southern Spain: latitude 36¤30'), the period of observation close to the summer solstice, and the time of the observation near local solar noon, the shade effect appears very limited and probably included in what is considered to be our "Vegetation" endmember. A prevailing contribution of peridotite-like rocks is recognized within the whole Sierra Bermeja massif, combined locally with vegetation spots, in agreement with their locations on the ground. The contribution of the "sedimentary soil" endmember corresponds to the geological mapping of the peridotite massif and its surrounding rocks. In this analysis, the endmembers named peridotite, limestone.. are discriminated from their spectral variations in the albedo contrast, from their location on the imaging mapping with respect to the geological map, and from the regional groundtruth, but they are not mineralogically identified yet from the airborne spectral data, although rock samples collected in situ and analyzed with the RELAB facility at Brown University display unambiguous spectroscopic absorption features (Mustard et al., 1992).

Three tests on three different spectral domains are performed :

1- throughout all the useful spectral domain available for AVIRIS, i.e. 0.4-1.8 micron,

2- on the 0.8-1.8 µm domain, in an attempt to reproduce the ISM spectral sampling interval. Geological boundaries of the peridotite massif are identified, and highly vegetated areas and vegetated areas within the massif are discriminated. These two tests lead basically to the same results, with a higher average rms residual over the first spectral domain (1.7%) than over the second one (0.8%). Indeed, after having removed the 0.4-0.8 µm bands, the high rms values in the variance image, which were located over vegetation spots, have disappeared. This means that a great deal of the observed variance arises from the spectral variability associated to the visible domain, with little related to mineralogical information. When we compare the second test with the same analysis applied to the ISM axes, these results are in complet agreement (Chabrillat et al., 1993).

3- Finally, the spectral domain analysis is restricted to 0.7-1.3 micron, which is a significant spectral domain for the mineralogical caracterisation of mafic minerals. This corresponds to a residual analysis approach while the previous tests correspond to continuum analyses (see Sabol et al., 1992). The atmospheric absorption windows (0.80-0.84, 0.92-0.97, 1.10-1.17 µm) are removed from the test. This analysis shows similar results than the two previous ones, with a still lower average rms residual 0.6% and is in favor of a mineralogical contribution in the observed variations between the spectra of the two endmembers located within the massif, although it may also arise from topographic effects and/or vegetation differential contributions.

At this stage of analysis, one sees that, through the spectro-mixing approach undertaken, it is possible for the purpose of mapping geology to discriminate from uncalibrated spectra, vegetated and non-peridotite areas from the peridotitic massif itself. It is very likely that the observed spectral variations are at least partially controlled by the soil and bedrock lithologies. This preliminary conclusion agrees with a recent independent evaluation of AVIRIS data (Mustard, 1993). To go further in the geological understanding and the spatial organisation of the Ronda massif, a "second order" analysis is needed, with the goal of examining whether or not spectrally detectable mineralogical variations may exist within the peridotite massif.

2.2 Second step analysis

The approach consists in building up a numerical mask which allows to reject the pixels in the image in which vegetation and mineralogical effects unrelated to the peridotite massif are present in a significant proportion. We then repeat the mixing analysis on the remaining part of the image. Although one cannot completely exclude that there may be little residual vegetation and/or topographic effects, they should be significantly reduced. Consequently, the results derived from this "second order" mixing should be prevailing related to mineralogical variations occurring within the peridotite massif only. The reason of these two steps approach is that the spectral contribution resulting from the mineralogical variations within the peridotite massif has a much more subtle effect upon the spectrum than first order reflectance variations resulting from : i- the vegetation cover, and ii- the large mineralogical contrast between the massif itself and the surrounding geological units.

With the criteria of rejection that we have chosen (pixels with fractions of vegetation or non-peridotite field higher than 20%), based on the test over the 0.7-1.3 spectral domain described previously, 18% of the Aviris image mosaic over the Sierra Bermeja massif (i.e., ~2200 spectra) is kept with a sufficient spatial connectivity between the pixels for the purpose of geological mapping. A check with the fieldwork observations shows that it corresponds to the well-exposed bedrock and soil areas distributed across the massif. Within these areas, four endmembers are requested, the level of the average rms residual being 0.43%. One identifies a well-exposed area where land denudation occurred due to a forest fire; another maps the summit and northern part of Mount Reales but also the south part of the top of a well-exposed bedrock elongated crest located in the eastern side of the massif. The third endmember fraction image reveals an encircling pattern around Mount Reales, and the last one mainly maps out the north part of the previously described eastern exposed crest. As suggested by the variations between the relative reflectance spectra, this distribution might be related to different content and/or type of pyroxene in the lithology of the well-exposed bedrock and soil areas.

3. CONCLUSION

In both AVIRIS and ISM data, through the use of mixing models, geological boundaries of the Ronda massif are identified with respect to the surrounding rocks. We can also yield first-order vegetation maps. ISM and AVIRIS instruments give consistent results. On the basis of endmember fraction images, it is then possible to discard areas highly vegetated or not belonging to the peridotite massif. Within the remaining part of the mosaic, spectro-mixing analysis reveals spectral variations in the peridotite massif between the well-exposed areas. Spatially organized units are depicted, related to differences in the relative depth of the absorption band at 1 micron, and it may be due to a different pyroxene content. At this stage, it is worth noting that, although mineralogical variations observed in the rocks are at a sub-pixel scale for the airborne analysis, we see an emerging spatial pattern in the distribution of spectral variations across the massif which might be prevailingly related to mineralogy. Although it is known from fieldwork that the Ronda peridotite massif exhibits mineralogical variations at local scale in the content of pyroxene, and at regional scale in different mineral facies, ranging from garnet-, to spinel-to plagioclase- lherzolites, no attempt has been done yet to produce a synoptic map relating the two scales of analysis. The present work is a first attempt to reach this objective, though a lot more work is still required. In particular, for the purpose of mineralogical interpretation, it is critical to relate the airborne observation to field work and laboratory spectra of Ronda rocks already obtained, with the use of image endmembers and associated reference endmembers (e.g., Smith et al., 1990). Also, the pretty rough linear mixing model used here is taken as a "black-box" process which does not necessarily apply correctly to the physical situation at the sub-pixel level (see Sabol et al., 1992). One may think of using the ground-truth observations bearing on the sub-pixel statistical characteristics (texture, structural pattern, surface distribution and vegetation contribution (grass, ...)) to produce a more advanced mixing model, physically appropriate to the geologic and environmental contexts.

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