The distribution of olivine in the crater Aristarchus inferred from Clementine NIR data

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Abstract. Clementine imaged the Moon entirely at eleven wavelengths. This paper presents new results obtained on the crater Aristarchus using a heuristic method for the calibration of the near infrared (NIR) data set. We computed band ratios and we extracted spectra using a telescopic spectrum as reference. A new ~4×10 km olivine rich area has been identified on the southeastern rim of the crater, in addition to a smaller olivine rich area previously reported. The olivine to pyroxene ratio exceeds 6 in this new zone. This demonstrates the uniqueness of the Clementine NIR data set in discriminating olivine from pyroxene on the lunar surface, with implications for magmatic processes in the lunar mantle and crust.

Introduction

The Clementine spacecraft has acquired an almost global coverage of the lunar surface in eleven bandpasses with an average spatial resolution of about 250 m [*Nozette et al.*, 1994]. The UVVIS Camera had filters at 0.415, 0.75, 0.90, 0.95, 1.0 μm and the NIR camera had filters at 1.1, 1.25, 1.50, 2.0, 2.6, 2.78 μm. The analysis of the UVVIS data set has significantly improved our knowledge of the lunar mineralogy. A comprehensive analysis of the NIR data set has been delayed due to calibration problems. Independently of the calibration effort for the full NIR data set, which is the responsibility of the PI team, we developed a heuristic method to reduce NIR data in selected regions of the Moon.

The Aristarchus crater and more generally the Aristarchus plateau have been intensively studied in the past using earth-based remote sensing techniques and Clementine UVVIS data [*Lucey et al.*, 1986; *Hawke et al.*, 1995; *McEwen et al.*, 1994]. These previous studies revealed a global mineralogical heterogeneity, which makes the Aristarchus plateau one of the most interesting and also one of the most complex areas of the Moon. The impact event creating the crater Aristarchus, located at (23.7°N 313 °E) between Mare Imbrium and Oceanus Procellarum, has excavated highland and mare type material. The Clementine UVVIS bands allowed the discrimination between highland type materials and mare basalts on the Aristarchus plateau [*McEwen et al.*, 1994], their relative distribution and their preliminary stratigraphy [*Pinet et al.*, 1996]. Feldspar, clinopyroxene, olivine and Fe-bearing glass have been detected from telescopic spectra *Lucey et al.* [1986]. Olivine probably mixed with anorthite had previously been identified in a small area on the south rim of the crater [*Lucey et al.*, 1986; *Hawke et al.*, 1995]. A preliminary analysis of NIR images from orbit 186 confirmed the presence of a small zone dominated by olivine [*McEwen et al.*, 1994]. Our analysis of 3 consecutive NIR frames provides a comprehensive mapping of mafic minerals in the eastern part of the Aristarchus region. This is complemented by comparisons of spectra combining the UVVIS and the NIR data sets with laboratory measurements.

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Data Selection

The UVVIS data were calibrated using the algorithm developed by Brown university (C. M. Pieters et al., Clementine UVVIS data, calibration and processing, 1997, available at http://www.planetary.brown.edu/clementine/calibration.html). Bands at 900, 950, and 1000 nm, compared to the 750 nm continuum band, are indicative of the Fe^{2+} absorption of mafic minerals such as pyroxene and olivine. Absolute residual errors, partly due to scattered light, are estimated to be lower than ~4% on UVVIS data.

We have processed four bands in the NIR domain. The 1100 nm and 2000 nm bands discriminate olivine from pyroxene. Pyroxene has an absorption at 0.95 μm which depends on its Ca content, and another absorption at 2 μm. Olivine has a broad composite absorption from 1.0 μm to 1.3 μm. The 1250 nm band can be linked with a weak absorption feature of anorthite. The 1500 nm band is considered to be representative of the continuum.

Reduction Process for NIR Images

The reduction of the Clementine NIR data set is hampered by instrumental problems, in particular a large dark frame signal [*Lucey et al.*, 1998]. In addition, the actual gains and offsets cannot be reliably derived using only their respective values in the header. From the beginning to the end of a mapping orbit, the temperature of the optics increases by 25 degrees and the temperature of the cryocooler increases by 15 degrees. The dark frame signal is strongly dependent on these temperatures. All the NIR images used in this study have been obtained at midlatitudes (from 22 °N to 40 °N), which reduces the impact of temperature changes. The reduction method is described in *Le Mouélic et al.* [1998]. We use for the correction of each image a dark frame which has been acquired with the same filter, gain mode and exposure time, and the nearest instrument temperatures. When such a dark frame was not available (1500 nm band), we used a dark frame with the same conditions of time exposure and temperatures, but a different gain mode, and applied a multiplying factor which minimizes the instrumental high frequency pattern. We evaluated the offset of each NIR filter using the high correlation between NIR and UVVIS images. A set of flat fields has been derived from the data using a median filter on 40 homogeneous mare images

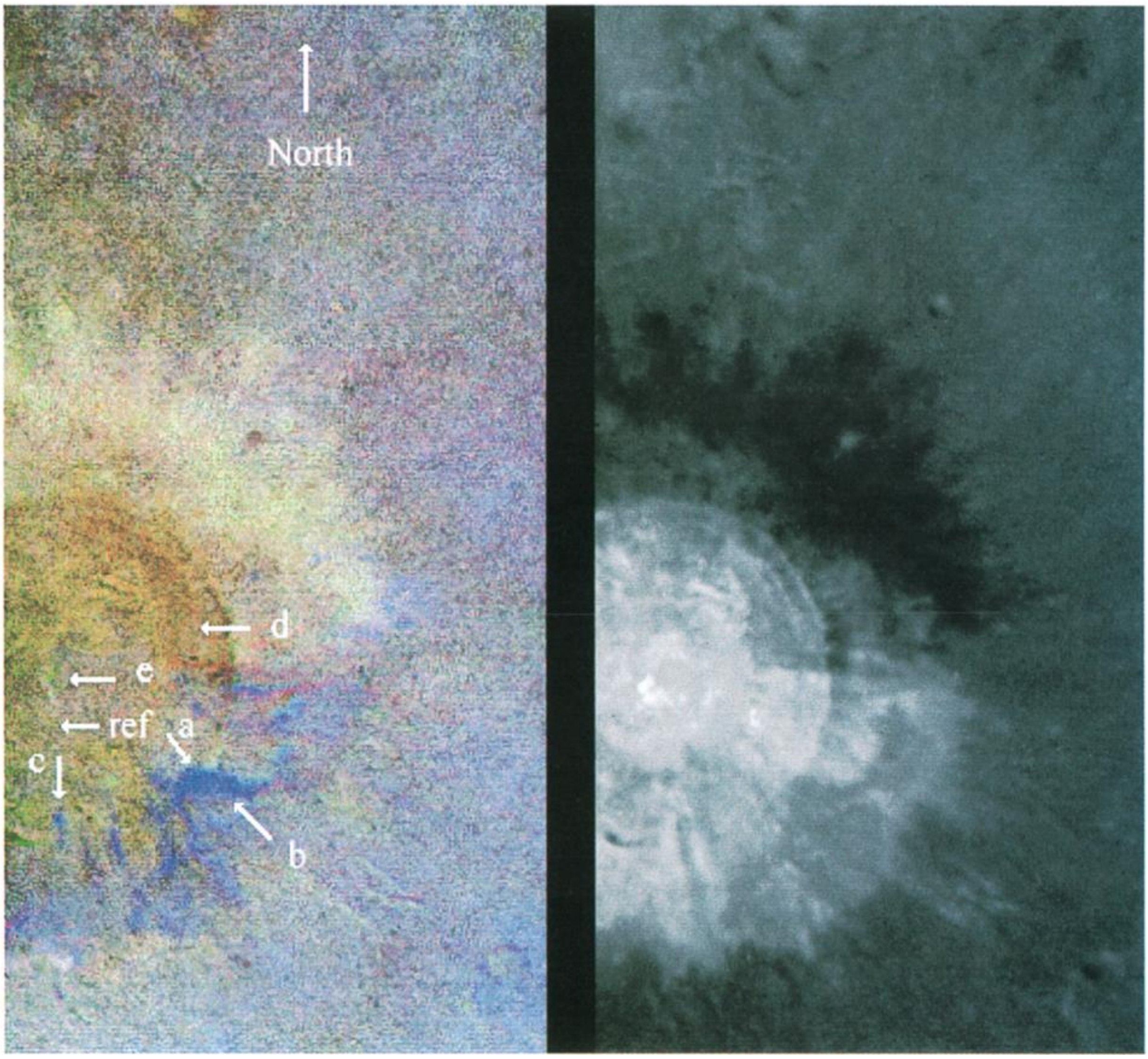

Figure 1. Right: mosaic of 3 gamma corrected images at 1500 nm. Left: Color ratio composite, where the 1100/1500 nm, 1250/1500 nm and 2000/1500 nm ratios are represented by the green, red and blue respectively on a scale from 0.8 to 1.2. Olivine rich units appear in blue (arrow a, b and c). A high pyroxene content appears in yellowish (arrow d). e is the anorthositic central peak. "ref" is the reference area for spectra.

of Oceanus Procellarum, following the approach described in *Le Mouélic et al.* [1998]. After subtracting the offset and dividing by the flat field, we corrected for viewing geometry effects using the phase function of *Shkuratov and Kreslavsky* [1998]. The 3 parameters of this model were derived from 10000 UVVIS images at 950 nm, which provide a first order photometric correction for our NIR filters. Only the spectral variation of the photometric function is not corrected. The overlap between two adjacent frames covers more than a third of each image. The consistency within overlapping regions has been used to check the validity of the reduction process. From this comparison, the conservative estimates of residual errors is ~4%.

Results

We obtained a mosaic of three adjacent frames from a north-south strip from orbit number 53, which covers the eastern part of Aristarchus crater. The spatial resolution is ~270 m/pixel. Before Clementine, the best previous digital images of Aristarchus had a resolution of ~2000 m/pixel [*Belton et al.*, 1994]. Band ratios are used to cancel out the effects of albedo and observation conditions, therefore highlighting variations due to mineralogy and maturity. Band ratios are normalized to unity. A color ratio composite is displayed in Figure 1, where the 1100/1500 nm, 1250/1500 nm, and 2000/1500 nm ratios are represented by the green, red and blue respectively. The consistency within overlapping areas and the low correlation with albedo (Figure 1) validate our reduction approach.

In order to extract spectra for the most interesting zones, we scaled our data using as a reference a telescopic spectrum obtained on the rather homogeneous crater floor by *Lucey et al.* [1986] ("ref" zone in Figure 1 and Figure 2). With this approach, we obtain an agreement better than 5% for the two other regions observed by Lucey et al. within the crater.

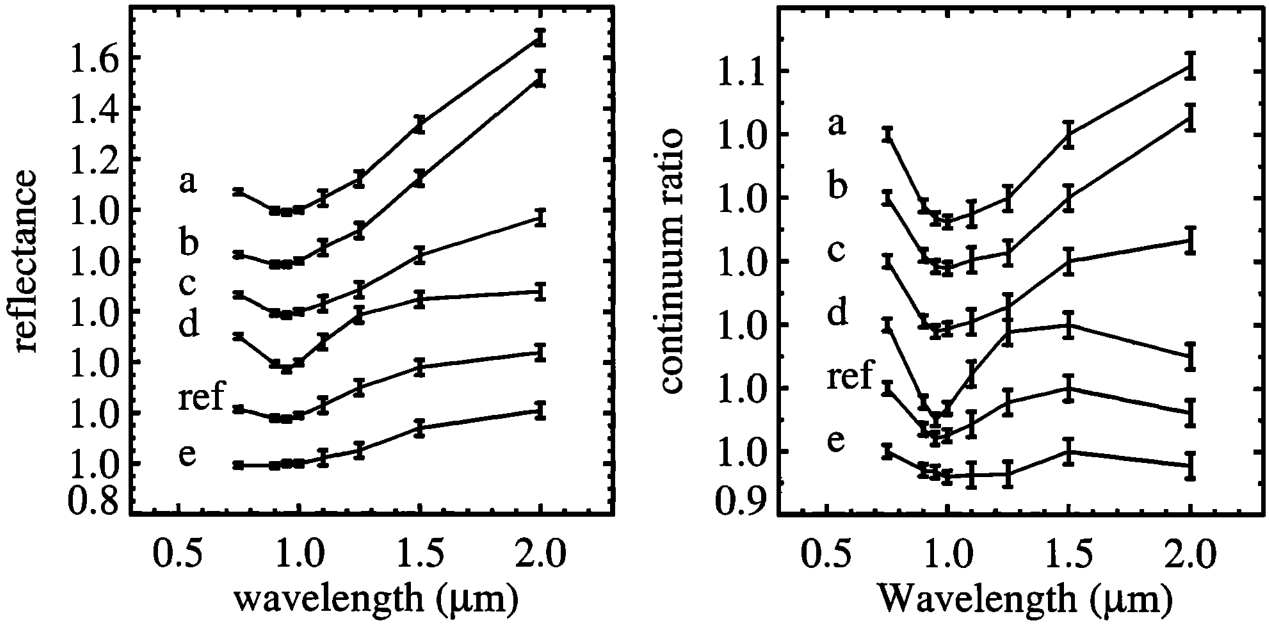

Figure 2. Reflectance spectra extracted from Aristarchus (see locations in Figure 1). Left: reflectance spectra scaled to unity at 1.0 μm. Right: spectra divided by a straight line fitting the spectrum at 0.75 and 1.5 μm, considered to be representative of the continuum. a, b and c: olivine rich units. d: pyroxene dominated areas. e: anorthositic central peak. ref: spectrum 2a from *Lucey et al.* [1986].

Olivine-rich Units in the Aristarchus Region

Since olivine is thought to be associated with the lunar mantle or with Mg-rich plutons, the finding of olivine in extensive surface areas provides valuable clues about the subsurface composition [*Pieters and Tompkins*, 1999]. The color ratio composite (Figure 1) provides for the first time in the Aristarchus region the spatial distribution of the olivine dominated zones, which appear in blue (high absorption at 1100 and 1250 nm, no absorption at 2000 nm). We confirm the presence of the small olivine rich region extending over a few km^2 previously identified by *McEwen et al.* [1994] (arrow c Figure 1 and spectrum c in Figure 2). The most striking result is a much larger olivine rich area (see a and b) which extends over 4×10 km^2. Other small olivine rich units can also be identified. There is no strong correlation between the color ratios and albedo, which favors an interpretation of these features in terms of mineralogical content as opposed to maturity variations [*Fischers and Pieters*, 1996]. However, spectrum (b) is clearly more mature than spectrum (a) (25% shallower olivine absorption feature and steeper continuum). Spectrum (a) corresponds to the inner edge of the rim, where downslope transportation is likely to expose fresh material. The comparison of spectrum (a) with laboratory spectra of olivine mixed with pyroxene [*Singer*, 1981] suggests that the pyroxene content is extremely low compared to olivine. This is consistent with a troctolitic or dunitic composition. The pyroxene content in area (c) is markedly higher ($\sim$ 25%) from the comparison with laboratory spectra.

Distribution of Pyroxene

The northern inner part of the crater rim shows spectral characteristics of pyroxene (see spectrum (d) on Figure 2 and arrow (d) on the color composite). A composition dominated by high-calcium clinopyroxene augite mixed with plagioclase was proposed by *Lucey et al.,* [1986] from previous telescopic observations of the crater. The pyroxene-rich regions appear yellowish to brownish on the color ratio composite.

The Central Peak

The central peak of Aristarchus has been previously reported by *McEwen et al.* [1994] as mainly dominated by anorthosite. This conclusion was partly based on very low values of the central peak on the 1250/1500 nm ratio from orbit 186. However, very high raw values (of the same order as the fixed pattern of hot pixels) were obtained at 1250 nm, suggesting that the camera was saturated in this area. Saturation seems to have produced an artefact in the band ratio similar to a plagioclase feature. Indeed, the central peak complex can no longer be identified on the 1250/1500 nm ratio from orbit 53, acquired with different gain and offset settings for the 1250 nm image (Figure 3). However, the spectrum extracted from the central peak (spectrum (e) Figure 2) still exhibits weak mafic absorption features, which is consistent with a dominant anorthositic component. The high albedo of the peak and its immediate surroundings are also consistent with a major feldspatic content.

Conclusion

Our analysis of the Aristarchus area shows that the Clementine NIR data set provides essential complementary information to the UVVIS data set in discriminating between major mineral species on the lunar surface at a resolution of a few 100 m. In particular, the NIR data set is essential for discriminating between olivine and pyroxene.

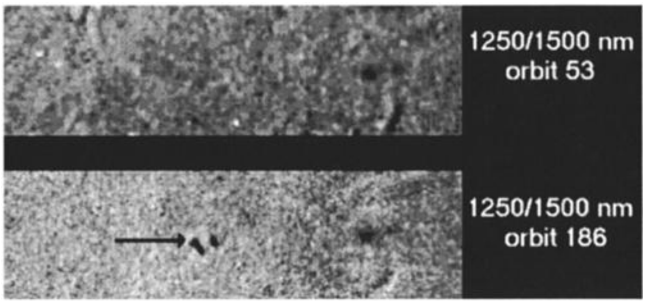

Figure 3. 1250/1500 nm ratios from orbit 186 [*McEwen at al.*, 1994] and orbit 53. North is on the left. The low values in the central peak for orbit 186 result from saturation of the 1250 nm image.

Using this data set, we have characterized the distribution of mafic minerals in the Aristarchus region, confirming the presence of small olivine rich areas on the south outer slope. The most striking result is the identification of a ~4×10 km^2 region close to the southeastern rim of the crater, which exhibits a very strong signature of olivine without any significant admixture of clinopyroxene (troctolite or dunite). Telescopic observations of this relatively large area with a much improved spectral resolution should provide additional constraints on its actual mineralogical composition. The central peaks of Copernicus present similar characteristics [*Pieters*, 1982; *Lucey et al.*, 1991; *Pinet et al.*, 1993]. The outer rim of Aristarchus is expected to be composed of material from shallow depths, contrarily to the central peak. Our results support a wide vertical distribution of plutons or other types of magmatic intrusions in the lunar crust in the Oceanus Procellarum region. The NIR data set is also useful for identifying anorthositic regions from the low level of absorption of mafic minerals.

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