

Compositional analysis of the Orientale basin using full resolution Clementine data: Some preliminary results

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Abstract: Clementine imaged the Moon globally in eleven different wavelengths. We used these data to construct a full resolution (250 m/pixel) multispectral image of the Orientale basin. Using this image in conjunction with other data sets, such as Earth-based spectra, we mapped the compositional units of the basin to obtain insights into its formation and evolution. The basin ejecta units are largely uniform in composition with the inner, Montes Rook Formation being slightly more mafic than the outer, Hevelius Formation. The Inner and Outer Rook mountains display many outcrops of pure anorthosite. These and other findings are consistent with a three layer model for the lunar crust consisting of a mixed zone (megaregolith) tens of kilometres thick overlying a layer of anorthosite above a basaltic layer.

Introduction

Orientele is a multi-ring impact basin, 930 km in diameter centred at 20°S 95°W. It is the youngest such basin on the Moon lending itself to study as an example of a relatively pristine impact feature (see Wilhelms, 1987, for a summary of basin geology). The rim is defined by the Cordillera mountains, 930 km in diameter. The Outer and Inner Rook mountains define two rings having diameters of 620 and 480 km respectively. A fourth innermost ring has been partly obscured by the basalt flooding that produced Mare Orientale. There are three principal geologic formations. The Maunder Formation lies within the Inner Rook mountains, is overlain in places by Mare Orientale and probably represents the impact melt sheet created during basin formation. The Montes Rook Formation is knobby and lies predominantly between the Outer Rook and the Cordillera ring (locally extending beyond the Cordillera ring). The Hevelius Formation, the main blanket of textured ejecta, lies beyond the Cordillera ring for a distance of about one basin diameter.

Spudis et al. (1984) used Apollo orbital geochemical and Earth-based spectral data to conclude that Orientale ejecta is uniformly feldspathic in composition (including pure anorthosite making up part of the inner ring of the basin), with no evidence for ultramafic components (Hawke et al., 1991). Belton et al. (1992) and Head et al. (1993) used Galileo image data to generally validate these inferences, with the additional observations that the Maunder Fm. is compositionally similar to the Hevelius Fm. and that the Montes Rook Fm. may be slightly more mafic than the Hevelius Fm.. Greeley et al. (1993) determined from the same

data set that Orientale mare deposits are a low-Ti variety. By creating a full resolution multispectral mosaic of the basin from Clementine data, we hope to better understand the detailed compositional relations among the geological units of the Orientale basin.

Procedure

Clementine mapped the moon at eleven wavelengths in the ultraviolet to the near infrared (Nozette et al., 1994). Figure 1 shows a mosaic of the basin made from 750 nm images, covering an area 40° by 40° and consisting of approximately 1500 frames. Similar co-registered mosaics were made at 415 and 950 nm. Figure 2 shows a colour mosaic constructed by making ratio images of these single wavelength mosaics: the red channel is controlled by the 750/415 nm ratio, green is 750/950 nm, and the blue channel is the 415/750 nm ratio. The red and blue channels indicate the steepness of the reflectance continuum (as well as titanium content in mare basalts) whilst the green is a function of the one micron absorption which increases with mafic content. Thus mature highlands are red/purple and fresh highlands are light blue. Mature mare regions are red and fresh outcrops of basalt are yellow (Pieters et al., 1993; McEwen et al., 1994). Clementine images were taken under a high sun angle, causing the morphology of a region to be washed out. We merged our

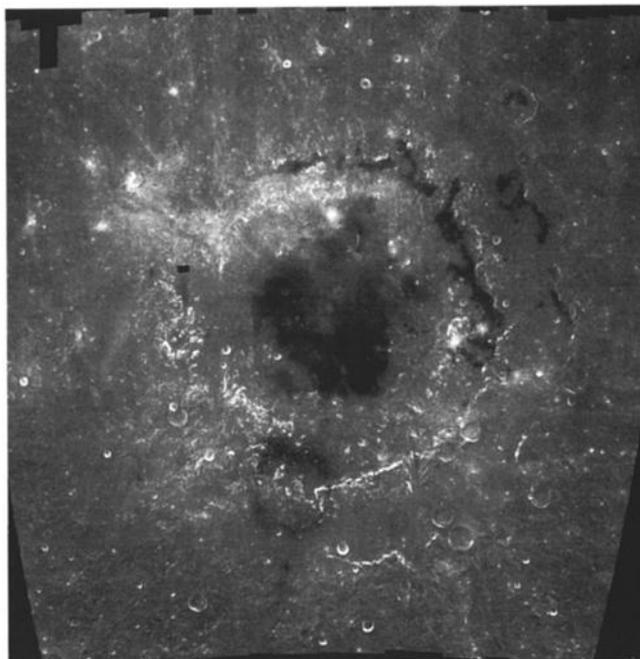


Figure 1. The 750 nm mosaic. This image covers an area 0-40°S and 75-115°W. It is made up of approximately 1500 Clementine images.

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Paper number 97GL00178.
0094-8534/97/97GL-00178\$05.00

multispectral image with an air brush relief map to aid the location of surface features.

Highlands

The basin ejecta units (Maunder, Montes Rook and Hevelius Fms.) are visible in Figure 2. Both the Maunder and Hevelius Fms. have similar, uniform compositions consisting of mature, iron-poor highlands material. The Montes Rook Fm. appears to be slightly more orange than the Hevelius Fm.; this colour difference is caused by small craters excavating fresh material with yellow floors, while fresh craters in the Hevelius Fm. tend to have blue floors. Figure 3 displays the 750/950 nm image (green channel) of the southwest portion of the basin showing the boundary between the Montes Rook (top) and Hevelius (bottom) Fms.. The top of the image shows many bright small craters, whilst craters in the lower part of

the image have dark floors. High values in the 750/950 nm image indicates the presence of mafic material. From these observations, we infer that the Montes Rook Fm. is more mafic than the Hevelius Fm., consistent with the findings of the Galileo team (Belton et al., 1992; Head et al., 1993) based on lower resolution data. This observation is concordant with the idea that the Montes Rook Fm. represents material excavated from deeper in the crust during the Orientale impact (McCauley, 1977), coming from a mafic layer lying below a anorthositic zone (Spudis and Davis, 1986). As the Montes Rook and Hevelius Fms. encircle the basin, it is necessary to explain the apparent inconsistency of the very blue region in the northwest portion of Figure 2. There is a calibration problem with the Clementine images, because the lunar phase function is not known well. The approximate phase function used is occasionally inaccurate close to the lunar equator, resulting in an over brightening of the 415 nm images and an

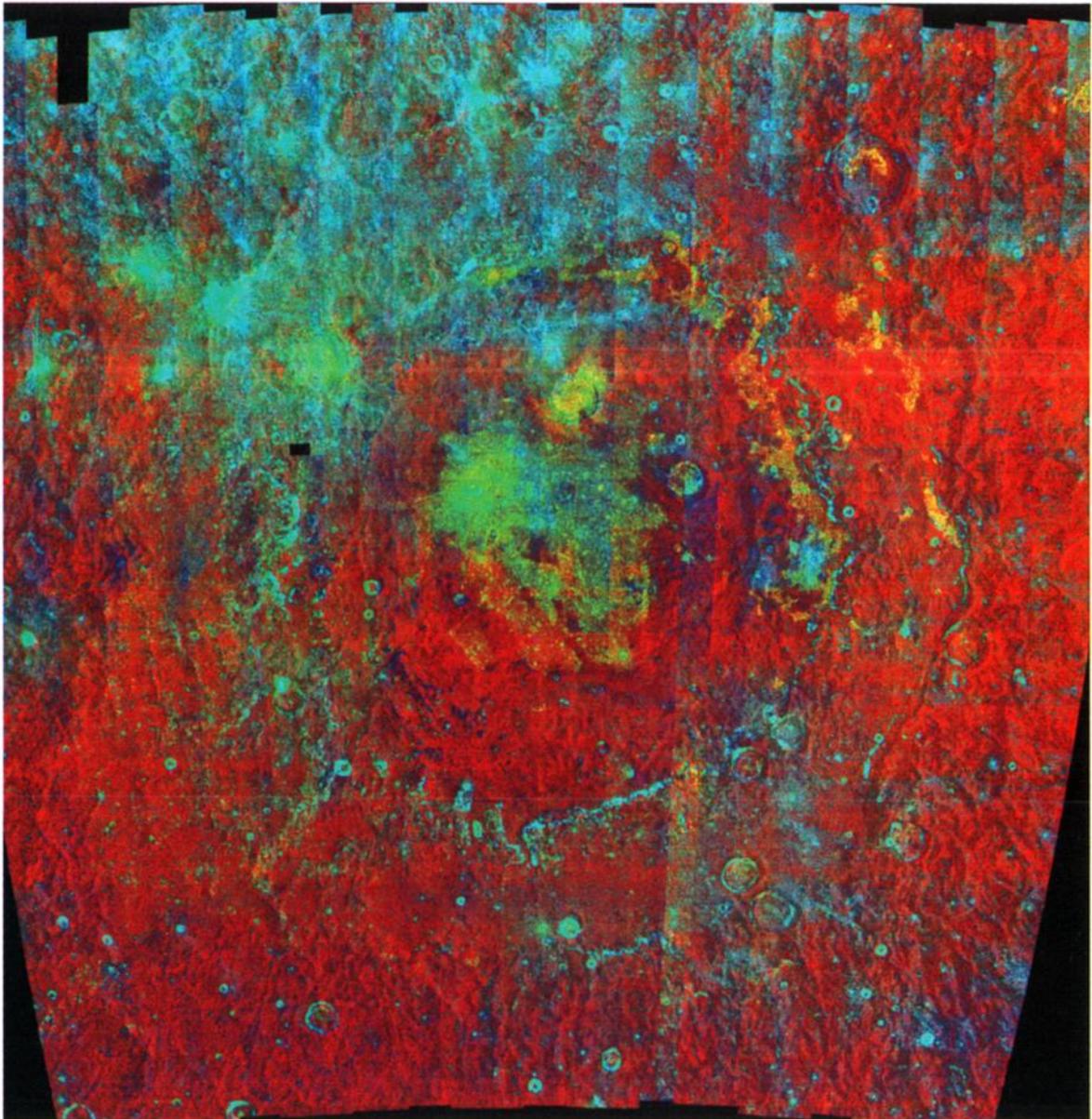


Figure 2. In this colour mosaic the red channel is determined by the value of the 750/415 nm ratio, green is 750/950 nm and the blue channel is 415/750 nm. Mature highland areas appear red/purple, exposures of fresh highland material are light blue. Mature mare regions are red and fresh outcrops of basalt are yellow.

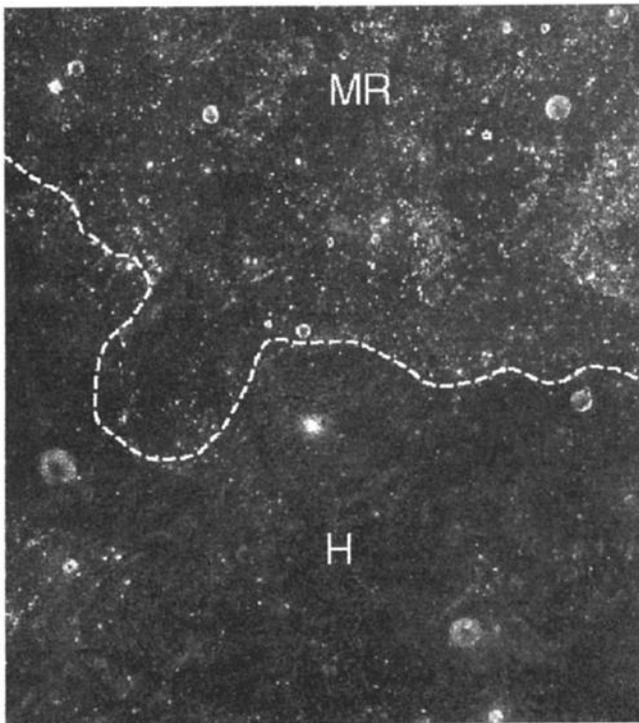


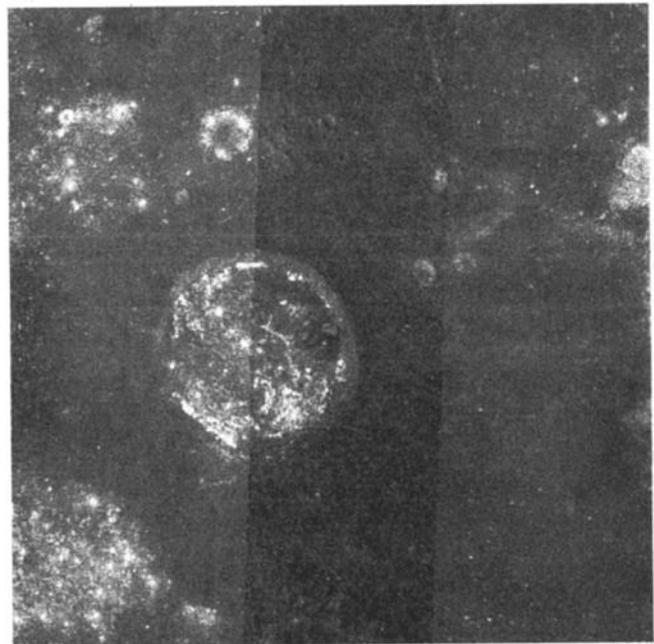
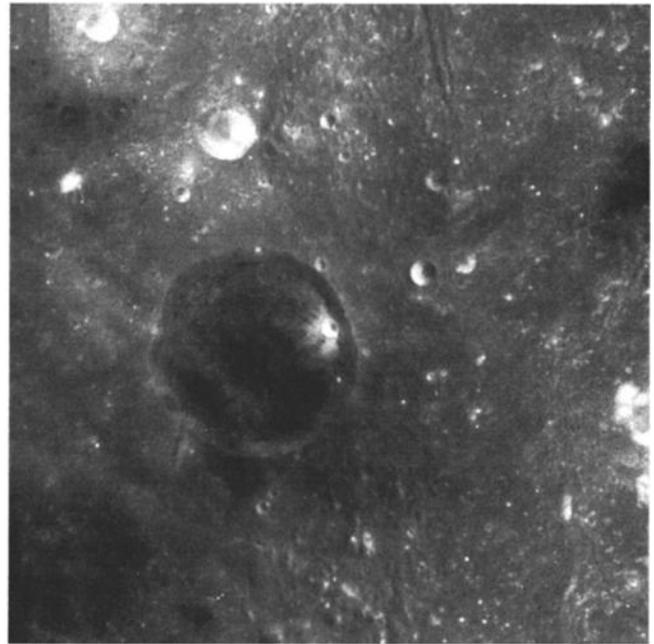
Figure 3. Part of the green channel (750/950 nm) image showing the southwest part of the basin. The top of the image shows many more bright (relatively high mafic content) craters compared to the lower part of the image. This represents a mafic compositional difference between the Montes Rook (MR) and Hevelius (H) Formations.

extra blueness in multi-spectral images. However, some of this blue is "real". There is fresh highland material in this region in the form of ejecta from a few Copernican craters.

Analysis of the Inner Rook mountain ring revealed dark blue-purple areas which appeared to correlate to the topographic highs and fresh scree slopes on the mountains. Dark blue in the multispectral image represents very low mafic content. These units correspond to areas that had previously been determined to be made of anorthosite from Earth based spectra (Spudis et al., 1984) and to have very low iron content (< 1.0 wt. % Fe) as shown in the global iron map made from Clementine data (Lucey et al., 1995). Our mosaic shows that outcrops of anorthosite are even more common than previously thought. The anorthosite has been exposed by uplift of the primordial crust; such uplift probably occurred during the formation of the inner basin rings, which may be caused by oscillatory vertical motions during the basin modification stage (Grieve et al., 1981), or by structural uplift and collapse (Spudis, 1993).

Maria

The basin mare deposits, both the central Mare Orientale as well as Lacus Veris and Lacus Autumni located inside the outer rings in the northeast section of the basin, appear uniformly red-orange in colour, indicating that they consist of low-titanium mare basalts (a small region of blue in central Mare Orientale, associated with two first month orbits, is probably a photometry effect). Maunder, a post-mare impact crater, 55 km in diameter, has excavated material with a green-yellow signature, indicating that its ejecta is largely made up of mare



Figures 4a,b. 750 nm and green channel images of the crater Kopff. Note how the small crater that impacted on the eastern floor of Kopff is bright in 4a but dark in 4b which is consistent with an anorthositic composition.

basalt. Thus, Maunder failed to penetrate through the mare to excavate the underlying basin floor (highlands) material. As a crater of this size might be expected to excavate as deeply as 3-4 km (Grieve et al., 1981), this observation suggests that Mare Orientale may be locally fairly thick, at least in the northern portion of the basin floor.

A low albedo circular deposit is located in the southern part of the basin, straddling the Outer Rook ring. This dark feature mantles basin topography and has been interpreted as a deposit of pyroclastic glass (Schultz and Spudis, 1978). Although obvious in the 750 nm albedo image and as a high-Fe unit on the global maps based on Clementine images

(Lucey et al., 1995), this feature is not evident in the colour mosaic (Figure 2). This glass is probably rich in Fe, and may have its analogue in the sample collection in certain ultramafic volcanic glasses, such as the Apollo 15 emerald green glass (Delano, 1979).

Craters

Many of the craters which lie outside of the Rook mountains show mature, highlands compositions. Some have relatively mafic interiors (e.g., Eichstadt, which appears to be similar to the Montes Rook Fm. material) or are filled with mare basalt (e.g., Schlüter). Mauser crater has a bright yellow ejecta blanket indicating that it has excavated fresh basalt. The pre-mare crater Kopff is particularly useful in helping us to probe the subsurface. Its ejecta blanket displays a dark blue material, indicating that anorthosite lies at shallow depths below the basin floor. During the epoch of mare flooding, Kopff was also filled by basalt, creating the dark floor material of the crater. A subsequent impact into the eastern side of Kopff's floor has exposed material of very high albedo and this crater has excavated dark blue material. This unit shows that the original floor of Kopff may well have been extremely rich in anorthosite (Figures 4a,b).

Observations

The uniformity of the spectral signature of the Mauser Fm. in the inner basin supports the idea that it represents the remnants of an homogeneous impact melt sheet, created by large scale melting of upper crustal rocks during basin formation. The melt sheet appears a uniform red colour indicating it to be a mature, iron-poor highlands unit. This signature corresponds to a feldspathic, "upper" crustal rock type, such as anorthositic norite or noritic anorthosite (Spudis et al., 1984; Hawke et al., 1991). Thus, unlike several near side basins, the Orientale basin melt sheet is *not* that of LKFM, or highlands basalt (Spudis, 1993). This relatively aluminous composition could reflect the formation of this basin in a target of thick crust of relatively feldspathic make-up, as suggested by the Clementine compositional (Lucey et al., 1995) and geophysical data (Zuber et al., 1994).

Our results support the view that the inner rings of basins are composed of uplifted target rocks, in this case primordial crust made up of anorthosite that lies beneath a more mafic highlands megaregolith, but above a largely basaltic lower crust (Grieve et al., 1981; Spudis and Davis, 1986; Spudis, 1993). This concept is illustrated by the abundant anorthosite-rich, "blue" massifs that make up parts of the inner and outer Rook mountains. These massifs correlate with previous observations of anorthosite in Earth-based spectra (Spudis et al., 1984; Hawke et al., 1991) and regions of extreme iron depletion (Lucey et al., 1995).

Conclusions

On the basis of the new multispectral mosaic, we conclude the following:

- Ejecta units of Orientale basin display general uniformity of composition, with some important variations, namely the more mafic nature of the Montes Rook Formation.

- Mare basalts in Orientale are of the low titanium variety and relatively uniform in composition. Dark pyroclastics are high in Fe.
- Inner and Outer Rook mountain rings show many peaks of pure anorthosite.
- Post-basin craters have exposed a variety of compositional units, showing that the subsurface is highly variable in composition.

Currently the Clementine data is largely qualitative in nature. When the fully calibrated data become available, it will be possible to produce a detailed geological/compositional map of the basin which will be an extremely valuable tool in helping us to better understand the process of basin formation and evolution.

Acknowledgements. We thank USGS Flagstaff for their invaluable help with ISIS, particularly Tammy Becker, Mark Robinson and Kay Edwards. This is Lunar and Planetary Institute Contribution 908.

References

- Belton M.J.S. and 18 others, Lunar impact basins and crustal heterogeneity: New western limb and far side data from Galileo, *Science* 255, 570-576, 1992.
- Delano J.W., Apollo 15 green glass: Chemistry and possible origin, *Proc. Lunar Planet. sci. Conf.* 10, 275-300, 1979.
- Greeley R. and 12 others, Galileo imaging observations of lunar maria and related deposits, *J. Geophys. Res.* 98, 17183-17205, 1993.
- Grieve R.A.F., Robertson P.B., and Dence M.R., Constraints on the formation of ring impact structures, based on terrestrial data, *Multi-ring Basins*, Proc. Lunar Planet. Sci. 12A, 37-57, 1981.
- Hawke B.R., Lucey P.G., Taylor G.J., Bell J.F., Peterson C.A., Blewett D.T., Horton K., Smith G.A., and Spudis P.D. (1991) Remote sensing studies of the Orientale region of the Moon: A pre-Galileo view. *Geophys. Res. Letters* 18, 11, 2141-2144.
- Head J.W. and 8 others, Lunar impact basins. New data for the western limb and far side (Orientale and South Pole-Aitken basins) from the first Galileo flyby, *J. Geophys. Res.* 98, 17149-17181, 1993.
- Lucey P.G., Taylor G.J., and Malaret E., Abundance and distribution of iron on the Moon. *Science* 268, 1150-1153, 1995.
- McCauley J.F., Orientale and Caloris, *Phys. Earth Planet. Interiors* 15, 220-250, 1977.
- McEwen A.S., M.S. Robinson, E.M. Eliason, P.G. Lucey, T.C. Duxbury, P.D. Spudis, Clementine Observations of the Aristarchus Region of the Moon, *Science* 266, 1858-1862, 1994.
- Nozette S. and 33 others, The Clementine Mission to the Moon: Scientific Overview, *Science* 266, 1835-1839, 1994.
- Pieters C. and 11 others, Crustal Diversity of the Moon: Compositional analyses of Galileo solid state imaging data. *J. Geophys. Res.* 98, 17127-17148, 1993.
- Schultz P.H. and Spudis P.D. (1978) The dark ring of Orientale. implications for pre-basin mare volcanism and a clue to the identification of the transient cavity rim, *Lunar and Planetary Science IX*, 1033-1035.
- Spudis P.D., Hawke B.R., and Lucey P., Composition of Orientale basin deposits and implications for the lunar basin-forming process. *Proceedings Lunar and Planetary Science Conference 15, Journal of Geophysical Research* 89, p. C197-C210, 1984.
- Spudis P.D. and Davis P.A., A chemical and petrological model of the lunar crust and implications for lunar crustal origin. *Proceedings Lunar and Planetary Science Conference 17, Journal of Geophysical Research* 91, no. B13, p. E84-E90, 1986.
- Spudis P.D., *The Geology of Multi-ring Basins: The Moon and Other Planets* Cambridge University Press, New York and Cambridge, 263 pp, 1993.
- Wilhelms D.E., The Geologic History of the Moon, *U. S. Geological Survey Prof. Paper* 1348, 302 pp., 1987.
- Zuber M.T., Smith D.E., Lemoine F.G., and Neumann G.A., The shape and internal structure of the Moon from the Clementine mission, *Science* 266, 1839-1843, 1994.

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(Received: July 1, 1996; revised January 14, 1997; accepted: January 15, 1997)