Detection of Mg spinel lithologies on central peak of crater Theophilus using Moon Mineralogy Mapper (M³) data from Chandrayaan-1

D LAL¹, P CHAUHAN^{2,*}, R D SHAH¹, S BHATTACHARYA²,
AJAI² and A S KIRAN KUMAR²

¹*M.G. Science Institute, Gujarat University, Ahmedabad, India.*

²*Space Applications Centre, (ISRO), Ahmedabad, India.*

**Corresponding author. e-mail: prakash@sac.isro.gov.in*

Spectral reflectance data derived from Moon Mineralogy Mapper (M³) onboard India's Chandrayaan-1 has revealed Fe bearing Mg-spinel-rich lithology on central peaks of the crater Theophilus. These newly identified Fe bearing Mg-spinel-rich rock types are defined by their strong 2- μ m absorption and lack of 1- μ m absorptions in spectral reflectance response. Such lithology has been reported previously along the inner ring of Moscoviense Basin on the lunar far side. The Modified Gaussian Modeling (MGM) analysis of the Fe bearing Mg-spinel reflectance spectra has been done and the results of the analysis clearly bring out a strong spectral absorption at 1872 nm with no significant absorption around 1000 nm. The presence of spinel group of minerals in the Theophilus central peak and the fact that central peaks mostly represent uplifted mass of deep crustal material confirm that central peaks can be used as a window to study the deep crustal and/or upper mantle composition and may lead to a fresh perspective about the crustal composition of Moon.

1. Introduction

The Moon is the best preserved and most accessible laboratory for understanding impact cratering processes. Impacts are the most fundamental and important geologic processes in the Solar System and on the Moon, and are well preserved due to the lack of weathering agents on lunar surface. Complex craters are of particular interest. They have well defined central peaks and often a terraced rim. The central peaks are brought up from greater depths beneath the crater as the ground elastically rebounds after the relaxation of the shock and pressure of the impact (Melosh 1989; Pieters 1982). These complex impact structures are well-preserved, and the central peaks that have brought

up materials from great depth offer the easiest way to explore the composition of the Moon's lower crust and upper mantle, providing critical insights towards knowing more about the planets in Solar System.

This paper presents the result of compositional study of one such complex crater Theophilus with prominent central peak using Chandrayaan-1 Moon Mineralogy Mapper (M³) and SELENE/Kaguya Multiband Imager (MI) data. Theophilus (26.4°E, 11.4°S) is a very large crater ~100 km in diameter having very steep walls with prominent terrace systems, flat floor and imposing central peak as shown in figure 1. Previous remote sensing studies (Whitford-Stark 1981; Pieters 1986; Spudis *et al* 1989; Tompkins and Pieters 1999) have revealed

Keywords. Lunar surface; Mg-spinel; central peak; Theophilus; remote sensing.

Figure 1. (a) Theophilus crater shown on Clementine 750 nm albedo image. (b) Mosaic image of Theophilus crater using M³ data.

that Theophilus displays a rich mineralogical diversity. The compositional study has shown (Tompkins and Pieters 1999; Spudis *et al* 1989) that the central peak of the crater is dominated by anorthositic norites and noritic anorthosites with several exposures of pure anorthosites.

Here we report the results of compositional investigation done for the Theophilus Crater using hyperspectral data with high spatial and spectral resolution. Lithology having Fe-bearing Mg-rich spinel is identified on different units of the central peaks (Lal *et al* 2011; Dhingra *et al* 2011a, 2011b). Such spinel bearing rock types without any detectable mafic mineral are rare on lunar surface. It is reported only at one other place on the

far side of the Lunar surface at Mare Moscoviense along the inner basin ring and it is proposed that such Fe-bearing Mg-rich spinel bearing lithology are differentiation products of one or more plutonic events that intruded magmatic material into the lower part of the extensive feldspathic crust, itself derived from the magma ocean (Pieters *et al* 2011). The study of origin and occurrence of identified lithology at the central peak of the crater Theophilus will provide an aid in understanding the diversity of lunar surface composition.

2. Datasets

A variety of datasets were used for this study, including the M³ onboard Chandrayaan-1, Multi-band Imager (MI) of Selene and high spatial resolution data of Narrow Angle Camera (NAC) onboard Lunar Reconnaissance Orbiter (LRO). The combination of these datasets allowed detailed analysis of the diversity of the crater Theophilus as well as independent verification of the results.

2.1 M³ hyperspectral data

M³ is guest instrument onboard Chandrayaan-1, India's first mission to the Moon (Goswami and Annadurai 2009; Pieters *et al* 2009). M³ is an imaging spectrometer operating in the wavelength range of 0.5–3 μm with spectral resolutions of 20 and 40 nm. Most of the M³ data were acquired in spatial resolution of 140–280 m and with 85 spectral bands in global mode (Green *et al* 2011). Level 1B data (Pieters *et al* 2009) was downloaded from the NASA Planetary Data System website (<http://img.pds.nasa.gov/>).

2.2 NAC data

In order to investigate morphological details we used datasets of the Narrow Angle Camera (NAC) onboard Lunar Reconnaissance Orbiter (LRO) which captured images with a spatial resolution as high as 0.50 m/pixel (Robinson *et al* 2010). These datasets from NAC are available in the public domain from <http://lroc.sese.asu.edu/>.

2.3 MI data

The MI is a high-resolution multiband imaging camera consisting of two visible and near-infrared sensors. It takes push-broom imaging data by using selected lines of area arrays. The spectral band assignments are 415, 750, 900, 950 and 1000 nm for visible and 1000, 1050, 1250 and 1550 nm for near-infrared. The spatial resolution of visible bands is

20 m, and that of near infrared bands is 62 m from the 100 km SELENE orbital altitude (Ohtake *et al* 2008). The datasets of MI for Theophilus region were downloaded from <https://www.soac.selene.isas.jaxa.jp/archive/>. We have used both VIS and NIR spectral channels for the investigation.

2.3.1 Reflectance data generation

Apparent reflectance (ρ_λ) was generated using spectral band convolved solar flux $E_{0\lambda i}$ which is provided along with the radiance data. Following formula was used to obtain the apparent reflectance:

$$\rho_\lambda = \frac{(\pi \times d^2 \times L_\lambda)}{(E_{0\lambda i} \times \cos \theta_s)}$$

where d is Moon–Sun distance correction, θ_s is solar zenith angle, L_λ is radiance as a function of wavelength. $E_{0\lambda i}$ is spectral band convolved solar flux. The M^3 data is used only up to 2500 nm as beyond this spectral range the signal is contaminated by thermal effect.

2.3.2 Analysis technique

In order to study the variability of the minerals in the Lunar surface a false colour composite (FCC) has been generated by assigning red, green and blue colour to 950, 1250 and 2000 nm channels, respectively (figure 2a) to M^3 reflectance data and similarly 950, 1250 and 1550 nm channels were assigned to red, green and blue colour, respectively (figure 2b) to generate FCC using MI data. This band combination will allow spatial variations of the broad mineralogical classification to be examined. We applied linear stretch to the image between zero and 255 digital number values without stretching any particular band strongly.

Modified Gaussian Model (MGM) has proven to be one of the most powerful tools for deconvolution of reflectance spectrum of binary or ternary mixtures as well as overlapping absorption features. The deconvolution of the spectra into the individual absorption bands will help to establish relationships between spectral information and physical properties of the surface. The model has also been applied to Martian meteorites and even remote data from Mars (Sunshine and McFadden 1993; Mustard and Sunshine 1995). We have applied MGM to resolve the spectral bands from the composite spectra which provides information on band centers, full wave half maxima and band strengths (Sunshine *et al* 1990). The exact position of different band absorption depth will enable to identify the minerals present in the lunar surface.

Figure 2. (a) FCC generated using M^3 data by assigning Red, Green and Blue to 950, 1250 and 2000 nm spectral channels and (b) FCC generated using MI data with Red, Green and Blue as 950, 1250 and 1550 nm spectral channels. The arrows show compositionally varying areas.

3. Results and discussion

3.1 Spectral analysis

The mafic minerals (pyroxenes and Olivines) exhibit a diagnostic absorption bands (Burns 1993) centered at wavelength varying from 900 to 1000 nm depending on their composition. Pyroxenes show second absorption band near 2000 nm (Adams 1974; Cloutis and Gaffey 1991; Klima *et al* 2007, 2010). Plagioclase exhibit a feature near 1250 nm, if it contains a few tenths of a percent of FeO in its structure (Adams and Goulland 1978; Pieters *et al* 2009) which gets diminished or lost entirely by shock processes (Adams *et al* 1979). In

order to study the variability of these minerals in the Lunar surface we generated a false colour composite using M³ and MI bands as discussed in the methodology section (figure 2a). The different compositional units in the study area based upon the spectral variabilities as seen in the FCC were identified and the reflectance spectra for these regions were generated as shown in figure 3.

The reflectance spectra collected from the crater walls (figure 3: S1) exhibits two absorption features occurring around 920–950 nm and 1930–1970 nm suggesting the presence of low-Ca pyroxene bearing lithology (Adams 1974; Cloutis and Gaffey 1991; Klima *et al* 2007, 2010) which is in consistency with the previous results obtained using telescopic spectra (Tompkins and Pieters 1999). At some of the

widely separated regions along the walls, on the crater floor and on the central peak, spectral signatures suggesting Olivine were obtained (figure 3: S2) which were also mentioned in previous studies (Tompkins and Pieters 1999). Some regions on the central peak (figure 3: S3) show a possible plagioclase dominant lithology. The reflectance spectra collected from these regions has absorption depth maxima at 1.24 μm indicating the probable presence of plagioclase with very smaller amount of FeO. These results are consistent with the recent analysis of Dhingra *et al* (2011a, 2011b).

3.2 Mg-bearing spinel rich mineralogical exposures on the central peak

Figure 3(a) shows the anomalous regions in yellow colour on different units of the central peaks indicating a different surface composition in comparison to the crater walls as well as the crater floor. The reflectance spectra measured from these units of the central peak shows a prominent absorption at 2- μm and lacks 1- μm absorption feature (figure 3: S4, S5). The explanation of these spectra can be that the surfaces represent a rock type dominated by Fe-bearing Mg-rich spinel with no detectable other mafic minerals (Pieters *et al* 2010, 2011; Dhingra *et al* 2011a, 2011b). The central peak has several small such exposures indicating the presence of Fe bearing Mg-spinel-rich rock type on its different units. Also some freshly exposed craters on the floor of Theophilus indicates the presence of this unique rock type with Fe-bearing Mg-rich spinel. High spatial resolution (~ 20 m/pixel) multispectral images of Selene (MI) data were used to evaluate the absence of any mafic mineral absorption feature at around 1000 nm in the reflectance spectra of these spinel rich units. The reflectance spectra as obtained from the MI data are shown in figure 4. The spectra for the identified Fe-bearing Mg-rich spinel region (S4) show no peculiar absorption near 1 micron indicating the lack of mafic minerals such as olivine and pyroxene in this lithology.

Figure 5 shows the results of the MGM deconvolution for the reflectance spectra obtained from the identified Fe-bearing Mg-spinel rich lunar surface. Table 1 describes the details of the band centers obtained for the absorptions present in the reflectance spectra along with the absorption strength. The MGM deconvolved band centers show the presence of absorption at around 1800 nm and absence of any absorption in the wavelength ranges from 500 to 1500 nm. These results also confirms the absence of any type of mafic mineralogy in the identified units of the central peak except for spinel.

Figure 3. (a) Different locations and (b) reflectance spectra as obtained from M³ data for crater Theophilus. The S4 and S5 represent the reflectance spectra obtained from the identified Fe-bearing Mg-rich spinel lithology. It lacks the 1 μm absorption feature of mafic silicates.

Figure 4. (a) FCC generated using MI with $R = 950$ nm, $G = 1250$ nm and $B = 1550$ nm. (b) Reflectance spectra collected for different regions of the central peak. The spectra S4 for the identified Fe-bearing Mg spinel rich surface shows no absorption feature at around 1000 nm.

Table 1. Deconvolution result for the reflectance spectra (S4 in figure 3).

Band center (nm)	FWHM (nm)	Absorption strength
394.9	835.1	-0.26
406.2	848.1	-0.20
377.0	883.0	-0.53
1617.4	237.5	-0.04
1872.7	589.2	-0.32

High spatial resolution NAC images were used to investigate the morphology of the study area. The regions showing the spectral signatures of Fe-bearing Mg-spinel rich rocks (figure 6a, b, c in M³ Image) were identified on NAC images (figure 7a, b, c) showing more details due to high spatial resolution. When these regions were compared, it was found that morphologically there is no recent crater or any new surface disturbance observed which may lead to the anomalous spectral signature. This suggests that these regions are not the result of any recent cratering event. The analysis of high spatial resolution images provides evidence that Fe-bearing Mg-spinel rich lithology is not derived from a cratering event that occurred after the formation of Theophilus crater, and is thus material exposed by Theophilus itself.

3.3 Possible origin

The spinel rich regions are mainly observed on the slopes of different units of the central peak except at one or two places where it is identified on the floor of the Theophilus crater. One possible origin can be that it may be a component of deeper crust

Figure 5. Deconvolved reflectance spectra (S4 in figure 3) using MGM and the table shows the details of the absorption centers with its strength.

Figure 6. Different regions on the central peak identified with Fe-bearing Mg-spinel lithology marked on M³ image.

Figure 7. Showing the same identified regions, as on M³ images in figure 6, at higher spatial resolution using NAC images.

uplifted and exposed in the form of central peak after the impact event.

4. Conclusions

The characterization of the Theophilus crater on the basis of spectral signatures as obtained using M³ data from Chandrayaan-1 mission presents new

results in terms of mineralogy of the central peak. The compositional investigation confirms the presence of rock type that is rich in Fe-bearing Mg-rich spinel on different units of the central peak of the Theophilus crater. Both the deconvolution results and the spectral analysis indicate that the lithology has Fe-bearing Mg-rich spinel. The morphological analysis indicates that these exposures are not material re-excavated by recent cratering events

but have remained relatively undisturbed since the formation of Theophilus crater and represent a component of the lunar surface which is brought up from the lower crust/upper mantle during the crater formation.

The global distribution of the Fe-bearing Mg-spinel needs to be studied using global M³ data. The detection of spinel bearing lithology at these scales merits a better understanding of the origin of these lithologies and their stratigraphic position in the geological evolution of the Moon.

References

- Adams J B 1974 Visible and near-infrared diffuse reflectance spectra of pyroxenes as applied to remote sensing of solid objects in the solar system; *J. Geophys. Res.* **79** 4829–4836.
- Adams J B and Goulland L H 1978 Plagioclase Feldspar: Visible and near infrared diffuse reflectance spectra as applied to remote sensing; 9th LPSC, pp. 2901–2909.
- Adams J B, Horz F and Gibbons R V 1979 Effects of shock loading on the reflectance spectra of plagioclase, pyroxene and glass (abstract); *Lunar Planet Sci.* **10** 1–3.
- Burns R G 1993 Mineralogical Applications of Crystal Field Theory; Cambridge University Press, Cambridge, UK.
- Cloutis E A and Gaffey M J 1991 Pyroxene spectroscopy revisited: Spectral-compositional correlations and relationships to geothermometry; *JGR* **96** 22,809–22,826.
- Dhingra D *et al* 2011a Compositional diversity at Theophilus Crater: Understanding the geological context of Mg-spinel bearing central peaks; *Geophys. Res. Lett.* **38** L11201, doi: 10.1029/2011GL047314.
- Dhingra D *et al* 2011b Non-linear spectral un-mixing using Hapke Modeling: Application to remotely acquired M³ spectra of spinel bearing lithologies on the moon, LPSC XXXXII, Abstract # 2431.
- Goswami J N and Annadurai M 2009 An overview of the Chandrayaan-1 Mission; *Curr. Sci.* **96**(4) 486–491.
- Green R O, Pieters C M, Mouroulis P, Eastwood M, Boardman J, Glavich T, Isaacson P J, Annadurai M, Besse S, Barr D, Buratti B J, Cate D, Chatterjee A, Clark R, Cheek L, Combe J P, Dhingra D, Essandoh V, Geier S, Goswami J N, Green R, Haemmerle V, Head J W III, Hovland L, Hyman S, Klima R L, Koch T, Kramer G Y, Kumar A S K, Lee K, Lundeen S, Malaret E, McCord T B, McLaughlin S, Mustard J F, Nettles J W, Petro N E, Plourde K, Racho C, Rodriguez J, Runyon C, Sellar G, Smith C, Sobel H, Staid M I, Sunshine J M, Taylor L A, Thaisen K, Tompkins S, Tseng H, Vane G, Varanasi P, White M and Wilson D 2011 The Moon Mineralogy Mapper (M³) Imaging spectrometer for lunar science: Instrument description, calibration, on-orbit measurements, science data calibration and on-orbit validation; *J. Geophys. Res.* **116** E00G19, doi: 10.1029/2011JE003797.
- Klima R L, Pieters C M and Dyar M D 2007 Spectroscopy of synthetic Mg–Fe pyroxenes I: Spin-allowed and spin-forbidden crystal field bands in the visible and near-infrared; *Meteorit. Planet. Sci.* **42** 235–253.
- Klima R L, Dyar M D and Pieters C M 2010 Near-infrared spectra of clinopyroxenes: Effects of calcium content and crystal structure; *Meteorit. Planet. Sci.* **46**(3) 379–395.
- Lal D *et al* 2011 Identification of spinel group of minerals on central peak of crater Theophilus using Moon Mineralogy Mapper (M³) data from Chandrayaan-1 mission, LPSC XXXXII, Abstract # 1339.
- Melosh H J 1989 Impact cratering: A geologic process (New York, Oxford: Oxford University Press).
- Mustard J F and Sunshine J M 1995 Seeing through the dust: Martian crustal heterogeneity and links to the SNC meteorites; *Science* **267** 1623–1626.
- Ohtake M *et al* 2008 Scientific objectives and specification of Selene multiband imager; *Adv. Space Res.* **42**(2) 301–304.
- Pieters C M 1982 Copernicus crater central peak: Lunar mountain of unique composition; *Science* **215** 59–61.
- Pieters C M 1986 Composition of the lunar highland crust from near-infrared spectroscopy; *Rev. Geophys.* **24** 557–578.
- Pieters C M *et al* 2009 The Moon Mineralogy Mapper (M) on Chandrayaan-1; *Curr. Sci.* **96**(4) 500–505.
- Pieters C M *et al* 2010 Identification of a new spinel-rich lunar rock type by the Moon Mineralogy Mapper (M³), LPSC XXXXI, Abstract #1854.
- Pieters C M *et al* 2011 Mg-spinel lithology: A new rock type on the lunar farside; *J. Geophys. Res.* **116** E00G08, doi: 10.1029/2010JE003727.
- Robinson M S *et al* 2010 Exploring the Moon at High-Resolution: First results from the lunar reconnaissance orbiter camera (LROC), 38th COSPAR Scientific Assembly, 18–15 July 2010, Bremen, Germany, p. 11.
- Spudis P D, Hawke B R and Lucey P G 1989 Geology and deposits of the lunar Nectaris basin 19th LPSC, pp. 51–59.
- Sunshine J M and McFadden L A 1993 Reflectance spectra of the Elephant Moraine A79,001 meteorite: Implications for remote sensing of planetary bodies; *Icarus* **105** 79–91.
- Sunshine J M *et al* 1990 Deconvolution of mineral absorption bands: An improved approach; *J. Geophys. Res.* **95**(B5) 6955–6966.
- Tompkins S and Carle P 1999 Mineralogy of the lunar crust: Results from Clementine; *Meteor. Planet. Sci.* **34** 25–41.
- Whitford-Stark J L 1981 The evolution of the Nectaris multi-ring basin; *Icarus* **48** 393–427.