FeO and TiO_2 abundance analysis around Apollo-17 landing site using reflectance spectra from the HySI sensor on-board Chandrayaan-1

Disha Lal[1], Prakash Chauhan[2,*], R. D. Shah[1] and Ajai[2]

[1]M.G. Science Institute, Gujarat University, Ahmedabad 380 009, India
[2]Space Applications Centre (ISRO), Ahmedabad 380 015, India

The Hyperspectral Imager (HySI) on-board Chandrayaan-1 was used for mineralogical mapping of the lunar surface in the visible and near infrared spectral range. The objective of the present study is to investigate the lunar surface composition around the Apollo-17 landing site using the HySI-derived reflectance data and generate elemental abundance maps at higher spatial resolution. *In situ* data from returned samples along with spectral reflectance band ratios of 950 nm/750 nm and 450 nm/750 nm, normalized by 750 nm reflectance have been used for iron oxide (FeO) and titanium oxide (TiO_2) abundance mapping respectively. The HySI-generated FeO and TiO_2 maps were further compared with Clementine-derived FeO and TiO_2 maps and found to provide more details on the compositional variability. The regression equation derived using the HySI reflectance data can be used further to map the composition of the physically unsampled lunar surface.

Keywords: Hyperspectral Imager, lunar surface, mineralogical mapping, remote sensing.

THE primary scientific objective of the Chandrayaan-1 mission, launched by India, was to enhance our understanding about the origin and evolution of the moon based on simultaneous mineralogical, chemical and photo-geological studies of the lunar surface at resolutions (spectral and spatial) better than previous and contemporary lunar missions[1]. The Hyperspectral Imager (HySI), one of the scientific instruments of Chandrayaan-1, was used for mineralogical mapping in the visible and near-infrared spectral range with 64 contiguous bands of ~ 20 nm bandwidths[2] and swath of 20 km. It operates in the visible and near-infrared region of the electromagnetic spectrum ranging from 420 to 960 nm. The HySI with its high spatial (80 m) and spectral (~ 20 nm) resolution has enabled the study of minute compositional variations of the lunar surface and has been useful to determine the abundance, distribution and composition of minerals.

Rock and soil samples returned by the US Apollo and Soviet Luna missions have provided information about the detailed lunar surface composition, but restricted to a limited region on the equatorial nearside. The Clementine and Lunar Prospector missions acquired remote-sensing data of the entire moon surface, but at very low spectral and spatial resolution. The ultraviolet/visible camera (UV/Vis) of Clementine was designed to study the surface of the moon at five different wavelengths in the ultraviolet and visible spectrum at a spatial resolution of 100–350 m/pixel. The gamma ray spectrometer of the Lunar Prospector was designed to achieve global coverage from an altitude of approximately 100 km and with a surface resolution of 150 km (ref. 3).

Earlier, studies have been carried out for the Apollo-17 landing site using Clementine UV/Vis data[4,5] to map iron oxide (FeO) and titanium oxide (TiO_2) abundances using the methodology developed by Lucey *et al.*[6,7]. This methodology is based on the comparison of Clementine reflectance data for the Apollo and Luna landing sites with the measured FeO and TiO_2 concentrations of corresponding lunar samples. These relations to calculate the FeO (eq. (1)) and TiO_2 (eq. (2)) abundances also take into account the effect of sample maturity.

$$\text{wt\% FeO} = (17.427 \times \theta_{Fe}) - 7.565, \quad (1)$$

where $\theta_{Fe} = -\arctan\{[(R950/R750) - Y_{0Fe}]/[R750 - X_{0Fe}]\}$, and X_{0Fe} and Y_{0Fe} are the coordinates of the optimized origin on a plot of $R950/R750$ versus $R750$.

$$\text{wt\% TiO}_2 = 3.708 \times [\theta_{Ti}]^{5.979}, \quad (2)$$

where $\theta_{Ti} = \arctan\{[(R415/R750) - Y_{0Ti}]/[R750 - X_{0Ti}]\}$ and X_{0Fe} and Y_{0Fe} are the coordinates of the optimized origin on a plot of $R415/R750$ versus $R750$.

Here θ_{Fe} and θ_{Ti} are iron and titanium-sensitive parameters respectively, and $R415$, $R750$, $R950$ correspond to reflectance values at wavelengths 415, 750 and 950 nm respectively.

This communication provides the results of an analysis of the HySI data for the Apollo-17 landing site. In this study, we have used the HySI-derived reflectance data along with sample-returned estimates of FeO and TiO_2 to map the FeO and TiO_2 contents in the Taurus–Littrow valley.

The area around the Apollo-17 landing site was selected for the present study. The Apollo-17 lunar module landed in the deep, narrow Taurus–Littrow (20.2°N, 30.8°E) on the moon. This valley is located in the mountainous highlands at the eastern rim of the Serenitatis basin. The soil samples retrieved from the selected study area contained a mixture of volcanic beads, impact glasses, agglutinates, highland lithic fragments and basalt fragments providing a wide range of composition[8]. The Apollo-17 site is in a dark deposit between massifs of the southwestern Taurus Mountains. During the Apollo-17 mission, soil samples were collected from 22 different sampling stations (including lunar rover vehicle stops),

*For correspondence. (e-mail: prakash@sac.isro.gov.in)

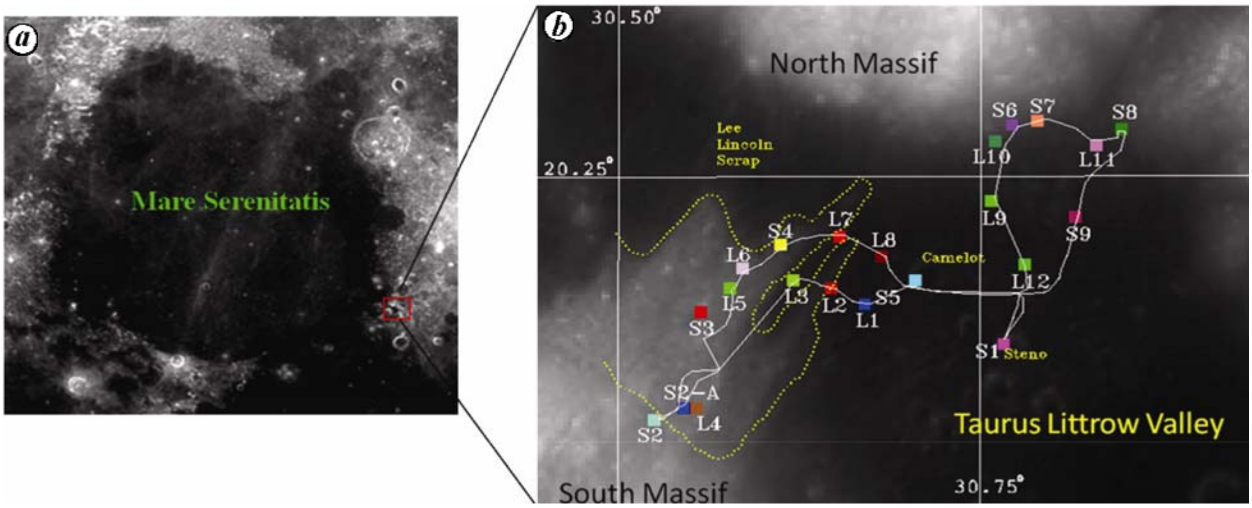

Figure 1. ***a***, Mare Serenitatis and the Taurus–Littrow valley shown in Clementine 750 nm albedo image. ***b***, Taurus–Littrow valley showing sampling stations and traverse during Apollo-17 mission mapped on the HySI image at 750 nm wavelength.

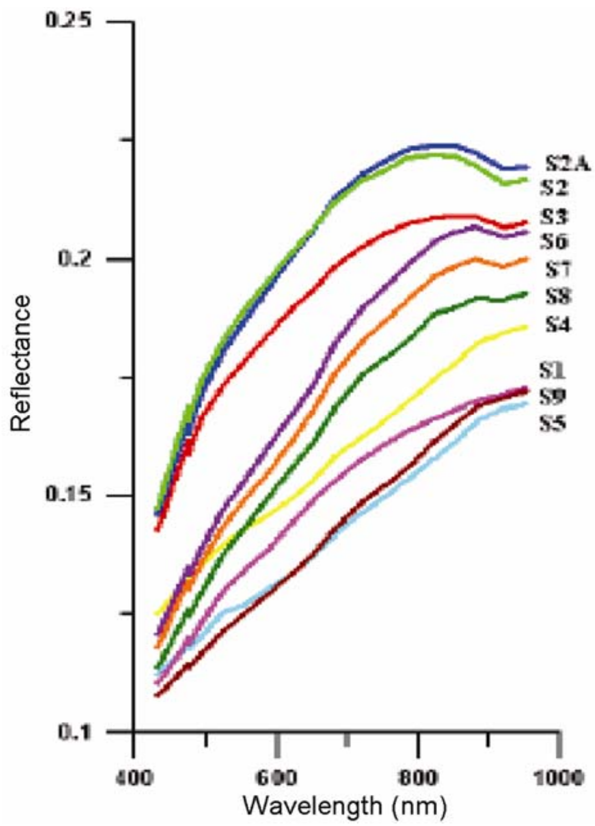

Figure 2. Reflectance spectra of the sampling stations derived from the HySI measured values.

which are widely spaced along 31 km of rover traverses, and their detailed compositional analysis was carried out[5,9]. The coupling of the Clementine data[4,5,9] with those from the return samples collected showed that highlands consist of complex impact melt breccias and pyroclastic debris of high Ti composition.

The scale of the traverse during the mission and the wide range of composition over the study area make this site suitable for the HySI calibration. Moreover, the geographical extent of the Apollo-17 site is quite appreciable in comparison with other Apollo missions, which augments the comparison with remote-sensing data.

The archive for Chandrayaan-1 science data is called ISRO Science Data Archive (ISDA). In the present study, we have used the HySI image pertaining to orbit number 722 acquired on 7 January 2009 over the Taurus–Littrow valley (www.issdc.gov.in). The locations of Apollo-17 sampling stations were identified on the HySI image (Figure 1 b; adapted from the map in a photograph extracted from the NASA panoramic camera: photograph AS17-2309), and spectral reflectance for these sampling stations was generated and analysed using spectral ratios.

Estimation of FeO concentration: In rocks and minerals, the presence of Fe is identified by a diagnostic absorption band centred at wavelength varying from 900 to 1000 nm, depending on their composition[10]. This fact was used in the algorithm developed by Lucey *et al.*[6,7] to estimate the FeO content using the spectral band ratio *R*950/*R*750.

The spectral reflectance for the lunar soil has been derived from the HySI data at each of the above-mentioned sampling stations for the compositional study (Figure 2). Spectral band ratio of 950/750 nm normalized by 750 nm was calculated for each of the 22 sampling stations from the spectral reflectance obtained from the HySI data and a spectral band image ratio was generated. Normalization of the spectral band ratio by reflectance at 750 nm was done to minimize the effect of lunar surface maturity on the spectral response to a certain extent. Regression analysis between the spectral band ratio (X) and the *in situ* FeO concentration from the return sample was carried out. The correlation coefficient between spectral

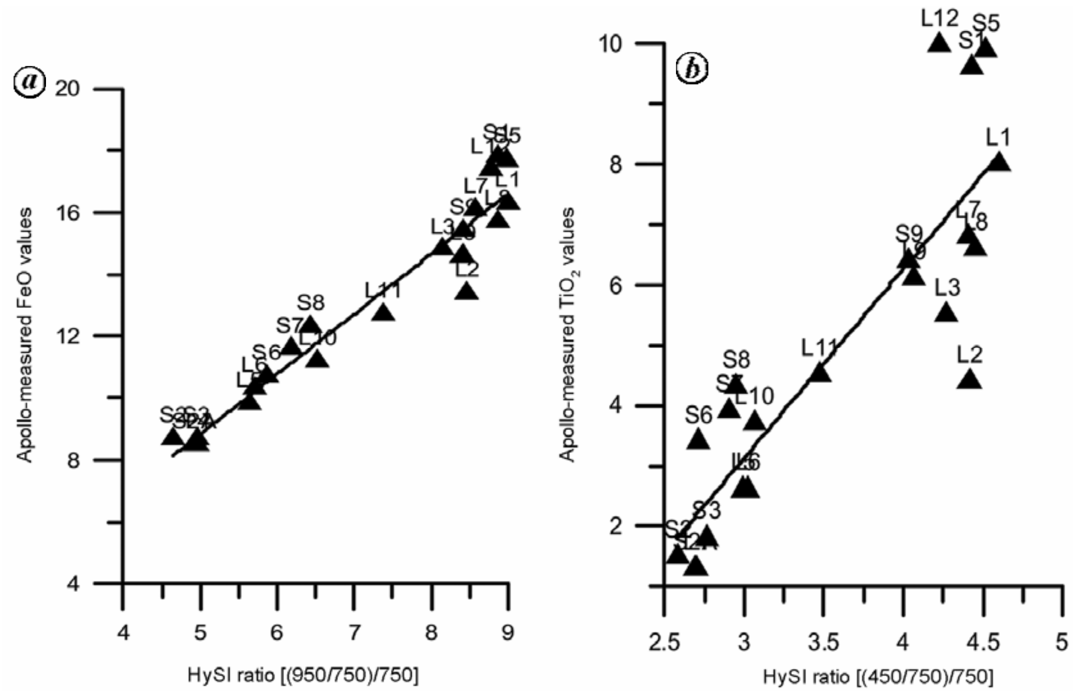

Figure 3. Correlation between ratios calculated using the HySI data and Apollo-17 measured FeO values (***a***) and TiO_2 values (***b***).

ratio (X) and FeO concentration was found to be 0.93 (Figure 3 *a*). The linear regression equation developed is given below

$$\text{FeO wt\%} = 1.945 * X - 0.90, \quad (3)$$

where $X = (R950/R750)/(R750)$.

Equation (3) was applied to each pixel of the HySI image and FeO abundance map for the study area was generated.

Estimation of TiO_2 concentration: Charette *et al.*[11] showed that Ti content is correlated with the telescopic measurements of UV/Vis ratio. It was found that there is a strong variation in colour between the UV and visible region, especially of the mare due to the principal compositional variable Ti. Further, new algorithms were developed for the estimation of TiO_2 using Clementine and Galileo multispectral data[6,7,12]. These methodologies relied on the plot of UV/Vis ratio versus Vis reflectance, and the titanium-sensitive parameter used spectral ratio 415/750 and reflectance at 750 nm (ref. 5). In order to study the Ti content in the lunar surface using the HySI data, we have used a wavelength of 450 nm instead of 415 nm, because of the limitation of the HySI in terms of spectral range. For HySI, the spectral range starts from 420 nm, but the first two bands are avoided in the study to reduce the effect of noise in the data. The spectral band ratio of 450/750 nm normalized by 750 nm was applied to derive the TiO_2 content from the HySI spectral reflectance data. The resultant values obtained are called parameter Y. The parameter Y, computed from the HySI image was correlated with the corresponding TiO_2 concentration derived from the analysis of the return samples. Linear regression between the parameter Y and the *in situ* TiO_2 concentration is given in Figure 3 *b*. The correlation coefficient R^2 was 0.78. The regression relation developed and used for the quantification of TiO_2 content in the soil is given below

$$TiO_2 \text{ wt\%} = 3.14 * Y - 6.31, \quad (4)$$

where $Y = (R450/R750)/R750$.

Applying eq. (4), TiO_2 abundance map showing spatial distribution of TiO_2 for the Taurus–Littrow valley was generated.

Figure 2 shows the reflectance spectra (derived from the HySI data) for the Apollo-17 sampling station sites. The sampling stations at the massifs have higher reflectance values compared to the valley soil. Most of the spectra have an absorption maximum between 920 and 950 nm, indicating mafic nature of the surface. The dominant mafic minerals found in the lunar surface are pyroxenes and olivines, which show absorption feature in the reflectance spectra between 920 and 1000 nm, according to the composition. The spectral range of HySI is 420–960 nm. Due the spectral range limitation of the HySI it is difficult to identify the exact mineral, but the mafic mineralogy of the lunar surface can be predicted[9]. The parameters (X and Y) defined for the estimation of FeO and TiO_2 were found to be linearly correlated with

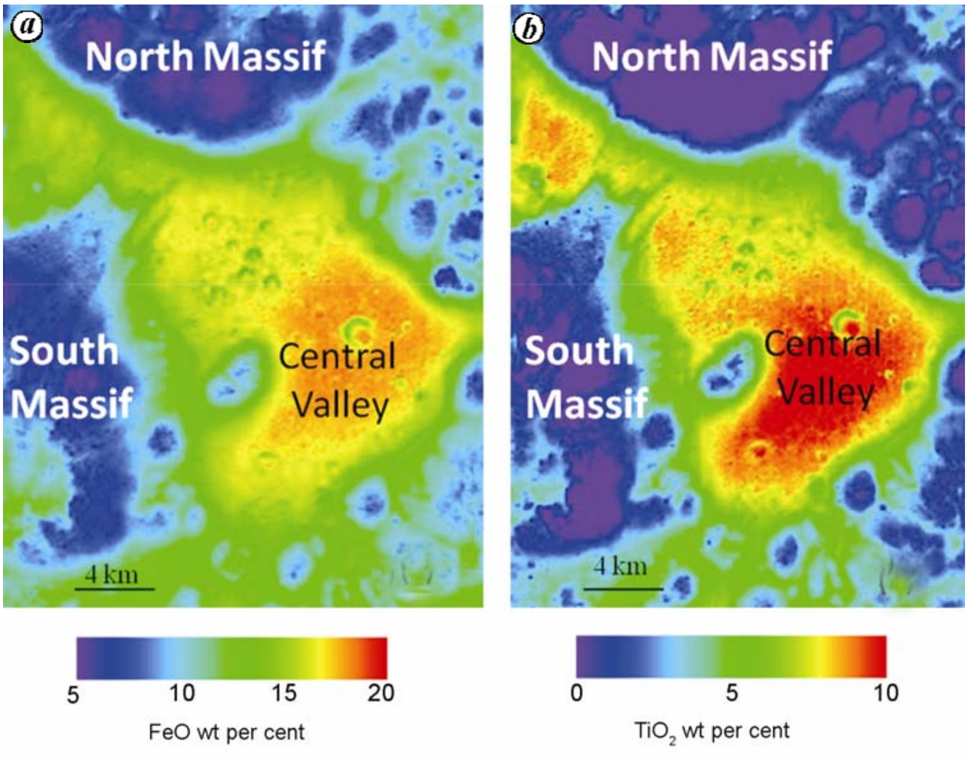

Figure 4. FeO abundance map (***a***) and TiO_2 abundance map (***b***) generated using the HySI data.

the *in situ* data, as shown in Figure 3. Correlation between the spectral ratio to estimate the TiO_2 content and the *in situ* data for the same was found to be weaker ($R^2 = 0.78$) in comparison to the correlation of spectral ratio ($R^2 = 0.93$) for FeO content with the respective *in situ* data. One of the reasons for this may be the use of the 450 nm spectral channel instead of the 415 nm channel in defining the Ti-sensitive parameter. The difference in the value calculated using the 415 nm spectral channel in case of the Clementine data and that calculated using the HySI data and the 450 nm channel is quite negligible (less than 1 wt%) and the mean percentage error is 3, which is also acceptable.

FeO and TiO_2 abundance maps for Apollo-17 landing sites generated from high spatial resolution HySI reflectance data are given in Figure 4. The abundance maps generated using HySI reflectance data were then compared with the corresponding Clementine-derived elemental abundance maps (Lucey *et al.* 2000, USGS) as shown in Figure 5. The high spatial resolution of HySI has enabled us to record the minute variations in the surface composition of the study area. In the abundance maps (Figure 4), the Fe and Ti contents of the ejecta material surrounding the crater are different compared to the central region. This was not observed in the case of the Clementine map (Figure 5). The Ti abundance map (Figure 4 *b*) shows a good gradation of the basaltic composition within the central valley and analysis of the region led to the classification of the basalts. The eastern region of the central valley is rich in Ti whereas the upper western region contains low Ti component admixed with non-mare material. The calculated elemental oxide concentration derived from the HySI data shows a deviation of not more than ~ 1% when compared to the *in situ* data. A comparative study of the Fe/Ti abundance map using the spectral band ratio measured by HySI and that obtained from the topographically corrected Clementine data analysis[4] shows good agreement. However, the elemental abundance map generated using the HySI reflectance data gives more detailed information.

The lunar spectral reflectance data with high spatial resolution acquired by HySI were used to attain the compositional information of the lunar surface at Apollo-17 landing site. An algorithm was developed for the estimation of FeO and TiO_2 contents on the lunar surface using spectral reflectance data from HySI. The results showed that the spectral band ratios 950/750 nm and 450/750 nm normalized by 750 nm give a good estimation of FeO and TiO_2 using the HySI data. The regression equations thus generated can be used to estimate the FeO and TiO_2 contents of other regions. One of the advantages of using the HySI data for mapping the elemental abundance is that the compositional variability of the lunar surface could be mapped with greater details. This study has shown that the spectral band ratio to obtain TiO_2 abundance exhibits a linear correlation with the TiO_2

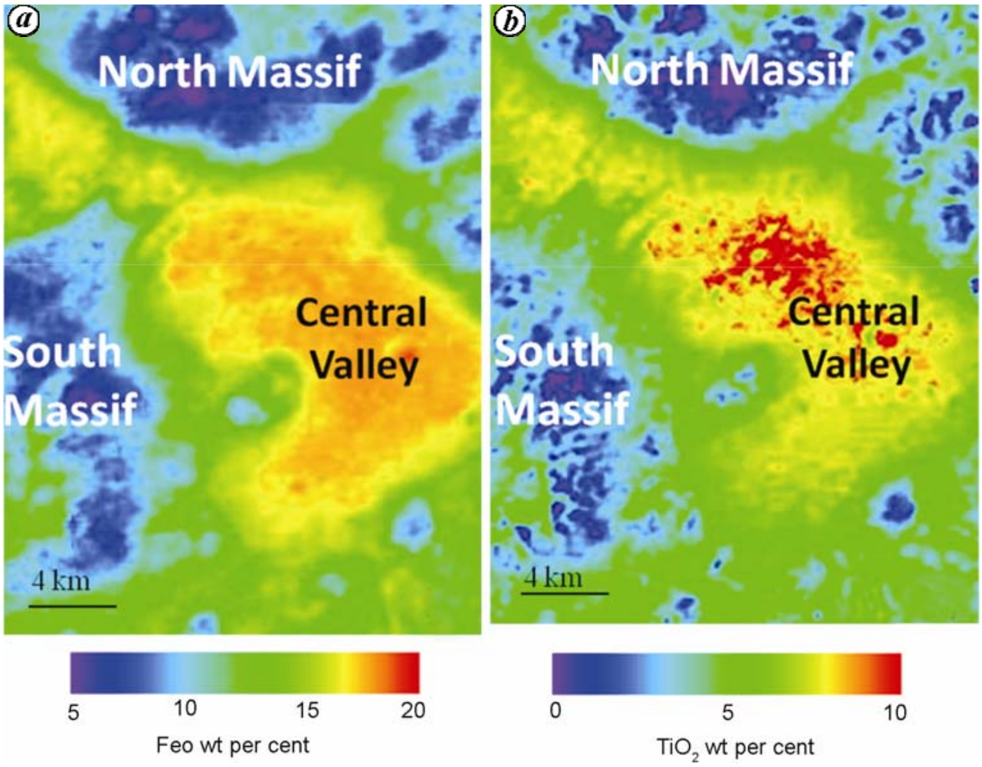

Figure 5. FeO abundance map (***a***) and TiO_2 abundance map (***b***) using the Clementine data.

values obtained from the Apollo-17 return-sample analysis, and suggests the possibility of estimating the mentioned elemental oxide (TiO_2) by means of the reflectance spectral band ratio derived from the HySI data. The regression equations obtained for the estimation of the mentioned elemental oxide (FeO and TiO_2) were based on the study around Apollo-17 landing site, and its correlation with the return-sample data and comparison with Clementine data. However, the robustness of the algorithm developed here to estimate FeO and TiO_2 also needs to be tested for different regions of the lunar surface.

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