Discovery of orthopyroxene–olivine–spinel assemblage from the lunar nearside using Chandrayaan-1 Moon Mineralogy Mapper data

Meteorite impacts on the Moon excavate materials from depth and redistribute them on the lunar surface[1], wherein the central peaks are supposed to have brought up materials from great depths as a result of the elastic rebound of the crust[2,3]. These morphological entities therefore act as windows into the lunar interior offering the simplest and easiest way to explore the lower crustal and/or upper mantle composition of the Moon. Previous studies based on samples brought from the Moon, lunar meteorites and remotely sensed data have established that the dominant mineralogy of the Moon comprises primarily of plagioclase, low- and high-Ca pyroxene and olivine[4].

Recent discovery of Mg-spinel-rich lithology in the inner ring of Mare Moscoviense[5] (a farside mare) based on the analysis of high-resolution Moon Mineralogy Mapper (M^3) data from Chandrayaan-1, has stimulated interest in studying and identifying such rock types more and more across the lunar surface. In Mare Moscoviense, Mg-spinel-rich lithology was associated with two separate and distinct rock types dominated by high concentrations of orthopyroxene and olivine[5]. Occurrences of orthopyroxene–olivine–spinel (OOS) lithological suite on the Moon are rare. Apart from the Moscoviense basin, occurrences of Mg-spinel-rich lithology have been reported at the central peaks of the crater Theophilus[6–9]. In this locality, the Mg-spinel-rich lithology occurs in association with mafic-free plagioclase and is associated with minor exposures of pyroxene and olivine-bearing materials. In a recent work[10], Mg-spinel-rich lithology has been identified at the floor of the crater Copernicus. Mg-spinel-rich lithology has also been reported in association with olivine, high-2 Ca pyroxenes and crystalline plagioclase from the central peak and faulted rims of the crater Tycho[11]. All these occurrences have restricted the spatial distribution.

In this note, we report the finding of Mg-spinel-rich lithology at the southern rim of crater Endymion situated in the northeast limb of the Moon on the nearside using high-resolution M^3 data. The Mg-spinel-rich lithology is found to occur in association with orthopyroxene–olivine-rich materials and perhaps represents the second discovery of the OOS lithological suite on the Moon after its discovery at the inner ring of Mare Moscoviense in the lunar farside and first on the lunar nearside.

OOS lithotype has been detected in the present study using the M^3 data from Chandrayaan-1 mission. The M^3 measures the reflected solar radiation from the lunar surface in the 460–3000 nm spectral range in 85 spectral bands with 20–40 nm spectral resolution (in its global coverage mode)[12]. It has a spatial resolution of 140 m from a 100-km orbit.

Spectra of Mg-spinel lack 1000-nm absorption feature and are characterized by a strong absorption near 2000 nm arising due to the small amounts of Fe^{2+} in the tetrahedral crystallographic site of the mineral[13]. Spectral signature of Mg-spinel-rich lithology as obtained from the southern rim of crater Endymion (Figure 1 *a*), shows this diagnostic absorption feature distinctly, as is depicted in Figure 1 *b*. It is found in association with mainly orthopyroxene–olivine-rich

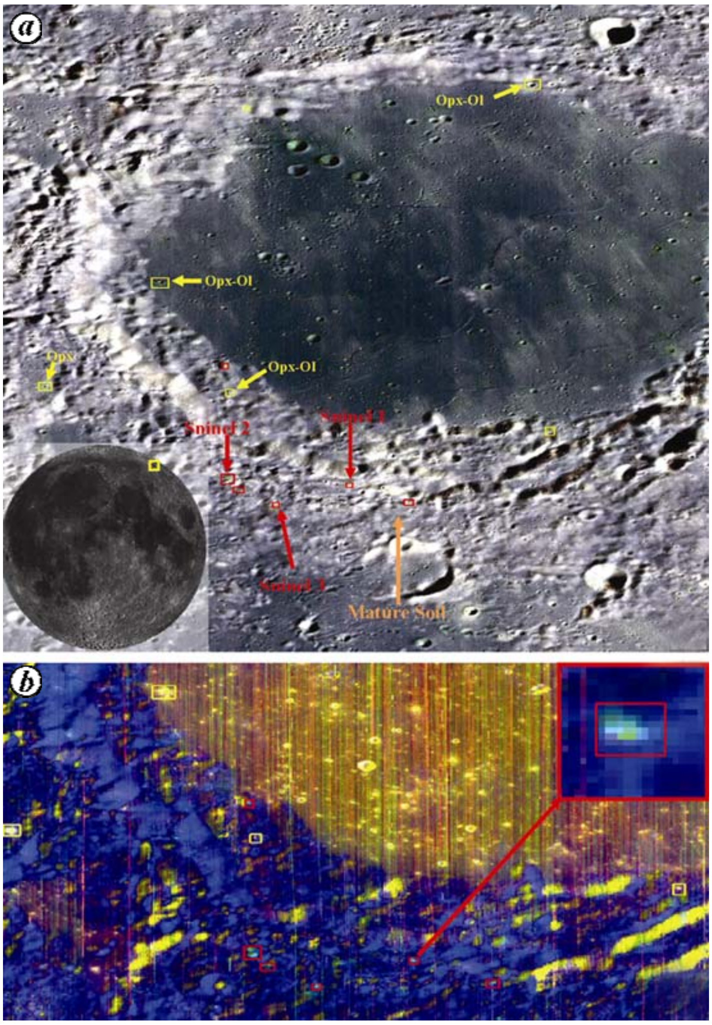

Figure 1. ***a***, Study area showing the locations of Mg-spinel-rich lithology (red box) and orthopyroxene–olivine-rich lithology (yellow box). Reflectance spectra have been obtained only from those boxes that have been numbered. ***b***, False colour composite prepared using integrated band depth (IBD)-1 as red channel, IBD-2 as green channel and 1.58-μm albedo as the blue channel. Mg-spinel-rich lithologies appear green, whereas orthopyroxene–olivine mixtures appear yellow in the IBD–albedo composite.

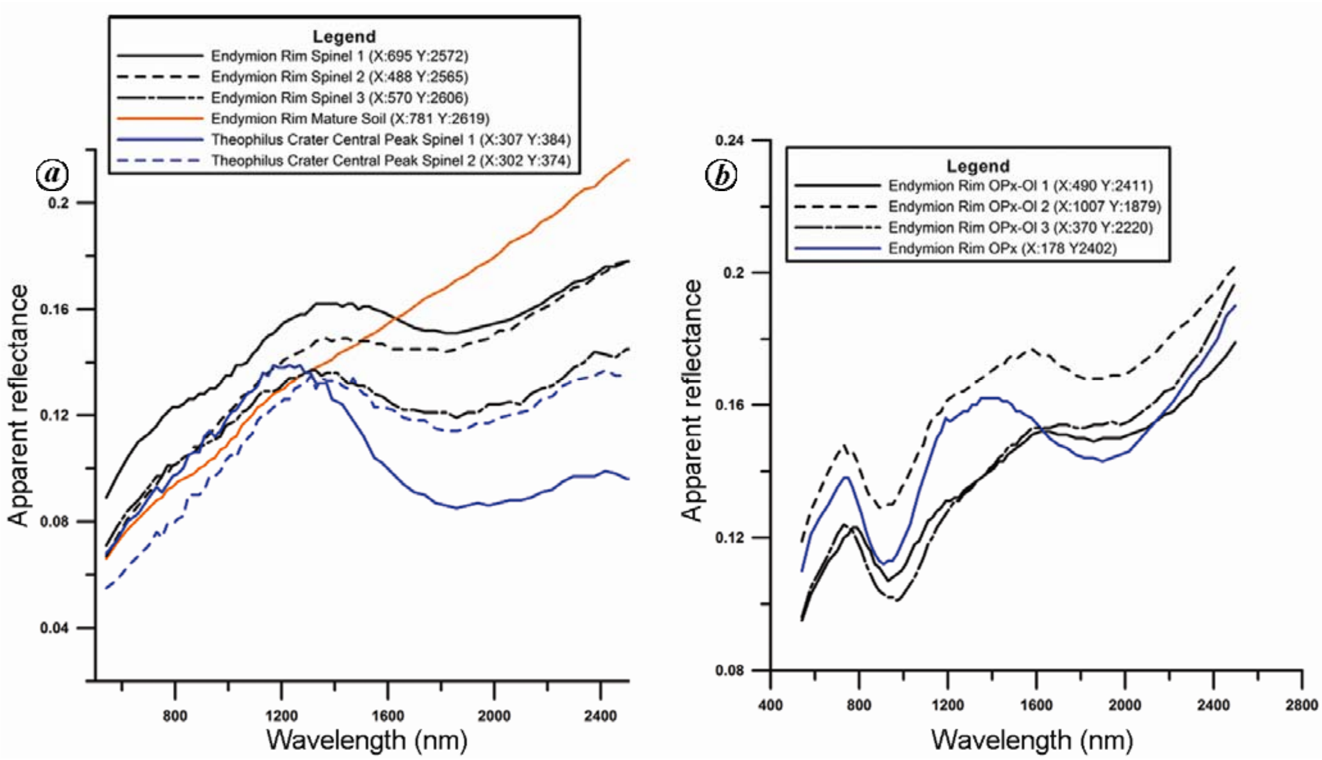

Figure 2. ***a***, Apparent reflectance of Mg-spinel-rich lithology as observed along the southern rim of crater Endymion (numbered boxes in Figure 1 *a*) and at the central peak of crater Theophilus for comparison. ***b***, Apparent reflectance of orthopyroxene–olivine-rich lithology (numbered boxes in Figure 1 *a*).

lithology (Figure 2). Olivine mostly occurs as a mixture with orthopyroxene and/or spinel as olivine spectra show a prominent absorption near 2000 nm, which is typical of pyroxene and/or spinel. Exposure sizes of Mg-spinel-rich lithology and OOS, in general, are very small and comprise of maximum 6–10 M^3 pixels.

Endymion is a 125-km diameter crater situated in the northeast limb of the Moon and is characterized by concentric faulted rim structure. It is located to the east of Mare Frigoris and north of Lacus Temporis. The crater floor has been flooded by low-albedo basaltic lava. The floor appears smooth and featureless, having very few tiny craterlets located within the rim. OOS rock types are mostly concentrated along the southern rim of crater Endymion and mostly occur within the base of the faulted rims, as shown in Figure 1 *a*. Integrated band depth (IBD) images have been generated to analyse the relative strength of the absorption features near 1000 and 2000 nm respectively. In the IBD-2000 image, Mg-spinel-rich lithology appears as a bright spot in an otherwise dark surrounding.

The OOS suite of rocks in the crater Endymion is similar to those reported from the Mare Moscoviense in terms of geological setting. However, unlike the Moscoviense Basin, no separate and distinct exposure of olivine has been observed from the present study area. From the spectral analysis, it is evident that olivine occurs as a mixture with either orthopyroxene or spinel. But several pure exposures of Mg-spinel-rich lithology and orthopyroxene-rich lithology have been observed in the study area.

The study of crater models and geological analyses predicts that basin ring represents a zone of deepest crustal excavation associated with the enormous basin-forming impact event[14,15]. The geological setting associated with the OOS assemblage at crater Endymion therefore points towards the deep-seated origin for this Mg-spinel-rich lithology. The identification of OOS lithology, in general, and Mg-spinel-rich lithology, in particular, at the rim of crater Endymion provides a new set of clues for understanding the occurrence of this rock type on the Moon.

Future studies involving very high-resolution data from LRO will help in studying the morphology of the OOS exposures. Detailed mineralogical analysis is required to draw inferences about the chemistry of this OOS suite of rocks on the Moon.

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Occurrence of gold mineralization in rocks of Proterozoic Delhi Supergroup around Ambaji, Banaskantha District, Gujarat

We report here the occurrence of gold in a polymetallic (copper–lead–zinc) sulphide deposit of the Ambaji mining area in Gujarat, India. The Ambaji mine (24°34′53″ : 72°84′49″) is located at village Ambaji, Taluka Danta, Banaskantha District, Gujarat (Figure 1) at the southern termination of the Ambaji–Deri–Banaskantha polymetallic sulphide mineralized southern Delhi fold belt. The rock formations of Ambaji area belong to the Proterozoic Basantgarh Formation of Kumbhalgarh Group of Delhi Supergroup and form a part of the main Delhi synclinorium of Heron[1]. They consist of metasediments and metavolcanics. Metasediments are represented by calc–silicate rocks, dolomite, marble, biotite–schist, quartz–sericite-schist, talc–tremolite–chlorite schist and biotite–hornblende gneiss. Metavolcanics comprise of epidiorite and amphibolite. Metarhyolits have also been found in the Deri–Ambaji mine area[2]. These rocks have undergone upper greenschist to lower amphibolite facies regional metamorphism and are intruded by 990 Ma Ambaji granites[3].

About 5.5 million tonnes (mt) of measured and indicated reserves of polymetallic sulphide deposits have been reported from Ambaji area. Chief ore minerals are galena, sphalerite, chalcopyrite and pyrite. The sulphide mineralization is mainly hosted by hydrothermally altered felsic metavolcanic rocks now represented by quartz–biotite–sericite schist, phylite–chlorite schist, talc–tremolite schist, biotite–amphibolite-gneiss/schist and amphibolites[4].

Surface indications of mineralization in the area are mainly limonitization and development of malachite and azurite. Both massive and stratiform types of mineralization are observed. The promising mineralization zone is highly sheared and folded. The general trend of amphibolite and hornblende–biotite schist is N64°W–S64°E and dip 30° northeasterly. The general trend of shear zone is E–W. Many workers have suggested that the mineralization in the area is of volcanogenic massive sulphide type[5].

It is well known that silver is associated with the lead–zinc ores of Ambaji–Deri–Banaskantha belt. There are no reports of platinum group elements (PGE) and gold in the Ambaji deposit. Gold, platinum and palladium associated with sulphide minerals are reported here.

Nine grab samples were collected from the bedrock of amphibolite, limonitized sulphide ores, quartz–biotite–sericitie schist and biotite–hornblende gneiss/schist exposed in the Ambaji mines area. The samples were analysed for PGE and gold by fire assay combined with ICP–AES technique at the Central Chemical

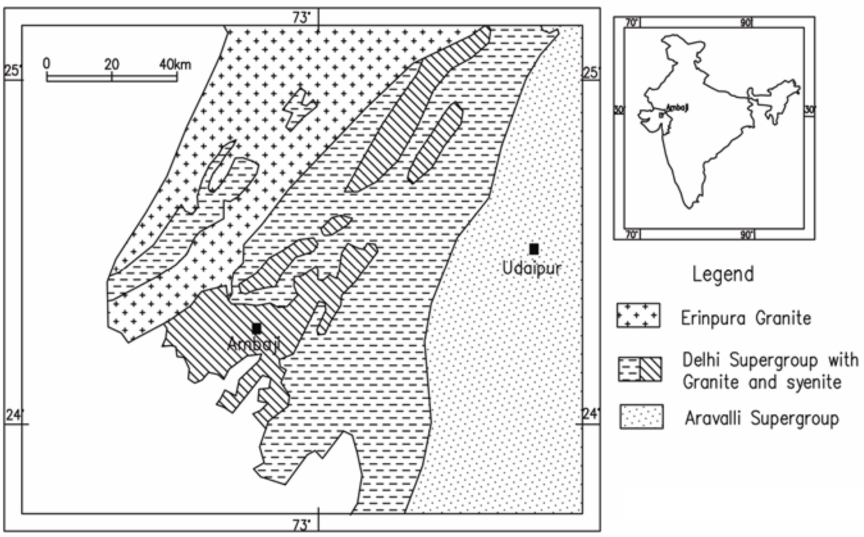

Figure 1. Map showing the location of Ambaji mine in Gujarat. (Modified after GSI, 1980.)