Color Cathodoluminescence and minor element zonation of forsterite in Mukundpura chondrite

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Mukundpura is a carbonaceous chondrite (CM2) recently fell in Rajasthan, India (June 6, 2017). A typical fine-grained, clast-dominant matrix contains a few isolated forsterite and FeO-rich olivine grains. In this study, forsterite-rich olivines were investigated using color cathodoluminescence (CL) and Raman spectroscopy in order to explain the primitive stages of asteroidal aqueous alteration. Isolated forsterite (Fo99) in Mukundpura emits bright CL of varying color and shows CL zonation in different patterns accounting the structural defects and chemical inhomogeneity. Blue luminescence (also distinguished by enriched CaO and TiO2) is common in cores of the relict forsterite attributing refractory nature of the olivine. Electron Probe Micro Analyzer (EPMA) line scan across the CL-active forsterite grains shows minor elements zonation especially for activator elements and thus provides a correlation of color of the emitted luminescence with diffusible ions. The red CL zonation (also characterized by enriched FeO, Cr2O3, and MnO content) is common along the majority of forsterite rims suggesting aqueous activity in the parent asteroid. The strongest doublet Raman peaks corresponding to 821 and 854 cm$^{-1}$ are due to SiO$_4$ tetrahedral vibrational modes, and other peaks are often related to infer pure crystalline state of the forsterite. Thus, a combination of CL imaging and Raman spectroscopy is useful to explain the chemical-structural properties of luminescent pure forsterite and also helps in understanding the aqueous alteration of CM chondrite.

Keywords: Color Cathodoluminescence, Raman spectroscopy, Forsterite, CM chondrite, Aqueous alteration

INTRODUCTION

The primitive records of the solar system are registered in the Carbonaceous Chondrites (CC). Petrographic observations explain that the majority of carbonaceous chondrites have been processed either by low-temperature aqueous alteration or by thermal metamorphism (Nakamura, 2005; Brearley, 2006). Despite the imprints of various processing, the CCs remain the most important source of information available on early solar system evolution (McSween, 1979). The total falls and finds of CM (Carbonaceous Mighei type) chondrites accounts for nearly one-third population of carbonaceous chondrites and thus becomes the most abundant member (~ 30%) and accounts for ~ 4.4% of total chondritic falls and finds (Marocchi et al., 2014; Ray and Shukla, 2018).

Color CL imaging technique is unique to assess the growth structures like color zonation, crystal-chemical properties, and to elucidate the thermal history including the effect of asteroidal aqueous alteration process (Pack and Palme, 2003; Jones and Carey, 2006; Gucsik et al., 2013). The detailed observations of CL emissions from olivine and other phases of CCs can clarify the relationship between the CL images and the defects in crystals. Furthermore, the CL properties of the minerals and the dusts in the early solar system help us to understand the formation environment including the process of the hydrothermal alteration in the parent body (Gucsik et al., 2013).

The Mukundpura chondrite fell near Jaipur in Rajasthan, India on June 6, 2017 in the early morning (~ 5:15 IST). Preliminary mineralogical and petrological studies classified Mukundpura as CM2 (Ray and Shukla, 2018). Based on Mössbauer study and thermo-gravimetric analysis (TGA), bulk composition of Nitrogen, Carbon and their isotopic studies, Mukundpura resembles CM2.0 (Tripathi et al., 2018; Rudraswami et al., 2019). However,
One of the constituent minerals common in CC is Forsterite (Fo)-rich olivine (Dodd, 1981) that gives off visible light of emission in the form of cathodoluminescence (CL) subject to irradiation of the mineral by electron beam. CL study having high detection sensitivities helps to predict the thermal history through the detection of structural defects or impurity of the activator elements with high spatial resolution (Gucsik et al., 2013). The characteristic CL color of olivine due to presence of specific luminescence center could be a useful guide to unravel many significant textural features probably difficult to identify under routine optical microscope or in the Backscattered Electron (BSE) images.

The motivation of this study is to carry out a detailed observation of color CL characteristics of olivines from Mukundpura (CM2) chondrite – one of the primitive types of CCs. As the meteorite is a fresh fall, we presume the weathering grade is nil and also the meteorite apparently looks unshocked. This study was aimed to classify and characterize the forsterite and its relation to the aqueous alteration processes in its parent body. The CL study integrated with Raman spectroscopy was conducted to constrain the structural state of the forsterite.

SAMPLE AND ANALYTICAL TECHNIQUES

The Mukundpura meteorite was collected by PRL researchers immediately after the reported fall. The main mass was kept in the Repository unit of Geological Survey of India, Kolkata. Two thick sections prepared with epoxy resin were used for this study.

Color CL study was conducted using Color Cathodoluminescence (Chroma CL2, Gatan Inc.) Imaging system attached to the Electron Probe Micro Analyzer (EPMA) ( Cameca SX 100) at Physical Research Laboratory, Ahmedabad, India. RGB color filters were attached in front of the detector window to obtain color-filtered images. Light is collected with high efficiency by parabolic mirror. The wavelength of dominant sensitivity ranges from 300 to 800 nm. The balance of color has been achieved a number of ways to provide a flat response across the wavelength range. A 550 nm shortpass filter was used for signal detection. The CL measurement was performed using 15 kV accelerating voltage and 80 nA sample current. The advantage of attachment of Color CL with EPMA is precise elemental quantification. Quantitative elemental determination was performed using Wavelength Dispersive Spectroscopy (WDS) technique. The EPMA analyses were conducted with operating conditions at 15 kV of accelerating voltage, sample current of 80 nA, and 1 μm beam diameter. The longer counting times are preferred specially to improve the detection limits for the minor elements in olivine. The counting times are 20 s for Mg, 30 s for Si, Ti, Ca, Cr, and Fe, and 40 s for Al, Mn, and Ni. Natural mineral (Mg: Olivine, Si: Olivine, Ti: TiO2, Ca: Wollastonite, Cr: Cr2O3, Fe: Almandine, Al: Kyanite, Mn: Rhodonite, Ni: metallic Ni) standards were used for calibration, and the data were corrected for absorption, fluorescence, and atomic number effects using routine PAP procedure (a Phi-Rho-Z correction technique) (Pouchou and Pichoir, 1988). The detection limits of the analyses are as follows: Al2O3: 75 ppm, SiO2, CaO, MgO: 120 ppm, V2O3: 150 ppm, Cr2O3: 165 ppm, MnO, TiO2: 180 ppm, FeO: 220 ppm, and NiO: 260 ppm.

Ka X-ray imaging were carried out using 15 kV accelerating voltage and 50 nA sample current, and 1 μm beam diameter.

Raman analyses were carried out using Thermofischer Almega Xr Dispersive Raman spectrometer connected to an Olympus U–LH100–3 microscope equipped with a 532 nm Ar green laser as the excitation source at IIT Bombay, India. Single spectrum was acquired at a spectral range of 115–4260 cm−1 with a 50× objective lens, and the confocal pinhole diameter of 25 μm was used before the spectrometer entrance to ensure excitation area of 1.1 μm diameters. An irradiation power of 1–4 mW at the sample surface was found ideal for measurement taking into consideration noise reduction, peak broadening, and shift. Any shift in peak position, because of system drift was corrected prior to data analysis by comparing with the standard first order Raman peak position of quartz and a silicon wafer before and after each session. ‘Crystal–Sleuth’ software package is used to check the linear background corrections of raw data (Laetsch and Downs, 2006). Finally, ‘Fityk’ software is used to fit the individual corrected Raman band (Wojdyr, 2010). The spectrum obtained because of epoxy resin was disregarded from the sample spectrum during the Raman analyses.

RESULTS

Microscopic observations

Under the microscope, Mukundpura appears as a clast bearing chondrite commonly characterized by a fine-grained matrix. Modal analyses suggest Mukundpura is matrix dominant (Mg serpentine ~ 65%, Tochilinite–Cronstedtite Intergrowths ~ 30%), the rest includes calcite ~ 2%, magnetite ~ 2%, olivine ~ 1%, and sulphide ~ 1%. Porphyritic olivine (PO) chondrules and their altered clasts containing nearly pure Mg-olivine (~ Fo90) are...
sparsely noted. Apart from chondrules, olivines generally occur as single euhedral/subhedral grains or as rounded to subrounded isolated grain or often as polycrystalline mineral clast aggregates within the matrix. Fine-grained accretionary rim is often visible surrounding the chondrule or mineral clasts. High-FeO olivines (~ Fo40–50) occur exclusively within the matrix and also as olivine bars in the barred chondrule (BO). A few diopside and spinel are recognized and appears to be component of the Calcium Aluminum-rich Inclusion (CAI). Fe–Ni metal (kamacite and taenite), sulphide (e.g., pentlandite and pyrrhotite), carbonates (mostly calcite), and magnetites occur as minor phases in the matrix. A few metal globules within the olivine clast are also noted.

**Electron Probe Micro-Analysis**

The olivine composition of Mukundpura chondrite is given in Table 1. Based on mode of occurrence, chemical composition and CL properties, the olivine can be grouped into the following types:

**Forsterite-rich chondrule olivine.** Chondrule olivines are mainly forsteritic (similar to type I chondrule) and shows a restricted compositional range Fo98.98-99.18 (Table 1 and Supplementary Table S1; Table S1 is available online from https://doi.org/10.2465/jmps.190610). Forsterite-rich chondrules are further characterized by low FeO (0.85–1.05 wt%), moderate CaO (0.1–0.26 wt%), and enriched Cr2O3 (0.36–0.48 wt%) content. Under Color CL, chondrule forsterite typically emits different shades of red luminescent color.

**Isolated Forsterite.** Isolated olivines are important constituent in matrix and are often forsteritic (Fo99.54–99.72) and characteristically give off blue luminescent at core. This represents the most refractory group with lowest FeO (0.28–0.48 wt%) and high Al2O3 (0.23–0.46 wt%), and CaO (0.54–0.74 wt%) content (Fig. 1 and Table 1). The core of isolated forsterite often gives off bluish violet luminescent with moderate Al2O3 (0.13–0.19 wt%) and CaO (0.4–0.55 wt%) content. The rim of the refractory forsterite gives off red luminescent color with increase of FeO (0.55–1.53 wt%), Cr2O3 (up to 0.57 wt%), and MnO (up to 0.28 wt%), respectively. Chemically isolated forsterites are similar to ‘refractory forsterite’ as previously described by Weinbruch et al. (2000) and Pack et al. (2004, 2005).

**High-FeO olivine.** High-FeO olivine (Fo90–62.04) mostly occur as isolated olivine grains in matrix or as barred olivine chondrule clast (Table 1).

![Figure 1. FeO versus CaO contents in isolated forsterite and chondrule forsterite from Mukundpura.](image-url)
electron images of isolated olivine (both forsterite and high-FeO olivine) grains, which are embedded in matrix, are apparently homogeneous. Under color CL, the isolated forsterite appears inhomogeneous; shows a wide range of behavior and exhibits zonation in CL intensity. The CL intensity is relatively subdued and in fact different shades of red are more common for altered, relict chondrules in Supplementary Figure S1 (available online from https://doi.org/10.2465/jmps.190610). The majority of isolated forsterite grains (Fig. 2) characteristically emit blue color in the core and red color along the margin. Figure 3 shows forsterite with varying intensity of red color from core to margin. The isolated high-FeO olivines are found to be CL negative.

The distribution of elemental enrichment can be confirmed by EPMA analyses in the different sectors of the isolated olivine grains (Figs. 2–4). The dark red sectors of olivine characteristically show higher MnO (~0.2 wt%), Cr$_2$O$_3$ (~0.5–0.7 wt%) and FeO (~1.5–1.6 wt%) content as compared to the sectors showing red CL emission in Supplementary Table S2–S4 (available online from https://doi.org/10.2465/jmps.190610). The discrepancies of elemental distribution are also evident in olivine showing bright violet CL emission. MnO, Cr$_2$O$_3$, and FeO content are comparatively low in region displaying violet emitted CL, whereas, these elements are intermediate in red region and gradually reaches at maximum in the dark red region. Variation plots of CaO, Al$_2$O$_3$, and TiO$_2$ show that their absolute content is relatively higher in the sector characteristically emitted with violet CL. However, CaO shows a restricted range both within violet region (0.40–0.55 wt%) and red region (0.02–0.03 wt%) (Table 1).

The presence of CL in forsterite is thought to be related to refractory nature with low FeO content (<1 wt%) and CaO range from 0.51–0.68 wt%. A detailed CL survey of Mukundpura chondrite reveals that highly forsteritic olivine (Fo ~ 99 mol%) emits bright CL, however high-FeO olivine (Fo ~ 50–60 mol%) lacks any luminescence and commonly appear as dark.

**Raman Spectra.** Raman spectrum of forsterite grain (Fig. 5a) is dominated by its signature doublet peak at 824 and 857 cm$^{-1}$. It also contains several weak peaks at 226, 304, 339, 390, 434, 545, 590, 608, 766 cm$^{-1}$, and two medium strong peaks at 921 and 963 cm$^{-1}$ respectively. A shoulder peak to the doublet is also observed at 879 cm$^{-1}$. Figure 5b shows major Raman peaks for FeO

**Figure 2.** (a) BSE image of an isolated forsteritic olivine grain. (b) Color Cathodoluminescence image of same grain showing a zoning pattern similar to type CLC (after Jones and Carey, 2006). (c) and (d) Variability of MnO, Cr$_2$O$_3$, FeO and CaO, TiO$_2$, Al$_2$O$_3$ in different sectors of CL-zoned sector as shown in forsteritic olivine. V, Violet; R, Red; DR, Dark Red. Analyzed positions in different sectors are along the line profiles A–A’ to E–E’. Color version is available online from https://doi.org/10.2465/jmps.190610.
rich olivine are 814 and 844 cm\(^{-1}\). Other weaker peaks in the high FeO olivine are 309, 529, 581, 910, and 947 cm\(^{-1}\) respectively. Primary Raman peaks for forsterite and high–FeO olivine appear similar except there is a systematic shift of peak position towards higher wave-numbers as Fo increases. Further, there are no noticeable differences in Raman spectra corresponding to core and rim of individual olivine grains.

**DISCUSSION**

Refractory forsterites are generally common in CM chondrites and rather sparse in CI chondrites (Steele, 1988). Refractory olivines are thought to be condensate from solar nebula (Steele, 1986a, 1986b; Weinbruch et al., 2000). However, evidence against the condensation hypothesis also exists in literature to explain their igneous origin (Jones, 1992). We found the forsterite–rich chondrule of Mukundpura chondrite chemically differs as compared to isolated forsterite in matrix. A plot of FeO versus CaO (Fig. 1) does not show any overlap in their composition and suggests isolated olivine has an independent mode of origin and cannot be related with chondrule olivine.

**Cathodoluminescence and Raman Spectroscopy**

Our study shows forsterite grains in Mukundpura have different shades of luminescence (red/blue/violet). Earlier studies by Gucsik et al. (2013, 2016) described the CL properties of forsterite chondrule in Kaba CV3 chondrite and Tagish Lake CI/CM2 chondrite described different sheds of CL zoning. However, these studies were based on the CL properties of chondrule olivines. The inhomogeneous distribution of CL emission is clearly recognized in the CL image of Mukundpura isolated forsterite (Figs. 2–4), where intensity changes toward the outer edge from the central region of a particular grain. Negative CL in high–FeO olivine probably explains the quenching effects of divalent Fe ion. Red luminescent forsterite occasionally shows zoned texture (Fig. 2). Minor elements Mn, Cr, and Fe are characteristically enriched in red luminescent region whereas Ca, Al, and Ti in the blue luminescent areas in Table S2 suggesting relict olivine grains of different mode of origin as compared to forsterite chondrule. Therefore, CL color variation related to refractory elements is mostly intrinsic and likely to attribute structural defects. The reddish CL color is caused by small amounts of Mn (and/ or Cr) in forsterite whereas violet
CL is thought to be emitted from lattice defects (Steele, 1988; Benstock et al., 1997). A lack of luminescence in the fractures can be caused by the enrichment of Fe$^{2+}$ due to aqueous alteration in the parent body. The chemical inhomogeneity shown by the variation in luminescence intensity often relates to low degree of thermal metamorphism (Nishido et al., 2013). However, in CM chondrite, the complex CL zoning in associated with chemical inhomogeneity of Mukundpura forsterite suggests the role of thermal metamorphism is probably insignificant. In contrast, alteration of forsterite chondrule and numerous Tochilinite–Cronstedtite intergrowths in matrix suggest aqueous alteration were more efficient and conducive.

In the Raman spectra of olivine, the higher wave number modes are assigned to internal vibrations of SiO$_4$ tetrahedra (between 400 and 1000 cm$^{-1}$), whereas the lower side of the spectrum is involved to external SiO$_4$ vibrations [R(SiO$_4$) and T(SiO$_4$) vibrations] and M (2) cations translation motions (between 150 and 400 cm$^{-1}$) (Chopelas, 1991; Kolesov and Geiger, 2004). Although, the higher wave number region is further divided into sub regions of v2 (400-500 cm$^{-1}$) and v4 bending (500-610 cm$^{-1}$) and coupled v1–v3 stretching vibrations (800-1000 cm$^{-1}$). In our study, a minor peak at 226 cm$^{-1}$ is assigned to translation [T(SiO$_4$)] motion of SiO$_4$. Peak at 303 and 339 cm$^{-1}$ is assigned as M2 translation mode. The Mg–T (SiO$_4$) mixed modes lies below 250 cm$^{-1}$, and Mg–R (SiO$_4$) mixed modes lies within 300–400 cm$^{-1}$ in the low wave number region. A peak at 434 cm$^{-1}$ is a v2 (B$_1g$) + v2 (B$_2g$) vibrational mode and a vibration at 590 cm$^{-1}$ belongs to v4 (B$_1g$ + v2 (B$_2g$). Peaks at 545 and 608 cm$^{-1}$ are assigned to v4 stretching modes. The strongest peaks of forsterite yielded a doublet at 824 and 857 cm$^{-1}$, which can be assigned to SiO$_4$ tetrahedral symmetric and antisymmetric (v1 + v3) vibrational modes. A peak at 879 cm$^{-1}$ (B$_{2g}$ symmetry) and two weak bands at 921 (B$_{3g}$ symmetry) and 963 cm$^{-1}$ (A$_g$ mode) are assigned as v3 stretching vibrations (Chopelas, 1991; Gucsik et al., 2016). Spectral positions at 390 and 766 cm$^{-1}$ are not well identified. As magnesium content increases, peak–position shift is observed towards the high wavenumber side (Fig. 5). Highest peaks in high FeO olivine 814 (A$_g$ mode) and 844 (A$_g$) cm$^{-1}$ are assigned to (v1 + v3) vibrational modes. A peak at 309 cm$^{-1}$ (B$_{2g}$ symmetry) is assigned to SiO$_4$ rotation and at 947 cm$^{-1}$ (B$_{1g}$ mode) is assigned to v3 stretching vibra-
tion. Spectral positions at 529, 581, and 910 cm\(^{-1}\) for high FeO olivine are poorly understood.

The frequency of Raman-active translations in forsterite and high Fe olivine is typically dependent on stretching vibrational modes (symmetric/asymmetric) of SiO\(_4\) and reduced mass and polyhedral volume at M\(_2\) octahedral site (Kolesov and Tanskaya, 1996, Kuebler et al., 2006).

Relationship between CL zoning and Chemical composition

Several earlier studies described that CL intensity correlates with minor elements Ca, Al, and Ti content (Steele, 1986a, 1986b, 1995; Pack and Palme, 2003; Pack et al., 2004; Jones and Carey, 2006). Even, in our study we find a strong correlation of CaO and Al\(_2\)O\(_3\) when Al\(_2\)O\(_3\) and CaO contents within the forsterite are relatively higher (0.1–0.4 and 0.4–0.7 wt%\) in Supplementary Figure S5 (available online from https://doi.org/10.2465/jmps.190610). This suggests CaO correlates well with Al\(_2\)O\(_3\) within refractory forsterite region (Fig. S5). However, the correlation between CaO and TiO\(_2\) is apparently poor (Fig. S5). The strong correlation between FeO and Cr\(_2\)O\(_3\) and MnO attributing red and dark red luminescence and the increasing trend of FeO is always accompanied by increasing contents of Cr\(_2\)O\(_3\) and MnO in Supplementary Figure S6 (available online from https://doi.org/10.2465/jmps.190610). This clearly suggests mixing of Fe, Cr, and Mn-rich component due to secondary process. However, Steele (1995) did not discuss any significant relation between CL intensity with the elemental concentrations of Al, V, Ti, and Sc. Pack and Palme (2003) further suggested that in experimentally grown forsterite, the CL intensity increases with Ca, Al, and Ti concentrations. Based on the studies of Kaba and Tagish Lake meteorites, Gucsik et al. (2013, 2016) discussed that CL intensity decreases towards the rim of the olivine of chondrule forsterite. Our studies suggest that refractory forsterites are sensitive to Al-Ti blue CL emission, while the Fe, Mn enrichments are related to different sheds of red CL emission. Our results on Mukundpura are partially comparable with the earlier studies by Pack and Palme (2003) and Gucsik et al. (2013, 2016). However, it is difficult to constrain and compare the CL emission from different studies unless we have specific information on wavelength of CL emission.

Additionally, Jones and Carey (2006) described four different CL zoning patterns that would be useful for discussing the evolution of minor element distribution patterns. The four types are: Type CLA (homogeneous), Type CLB (slightly varying), Type CLC (oscillatory), and Type CLD (heterogeneous). Based on this classification scheme, forsterite as shown in Figure 4 falls under the category CLB, whereas grains shown in Figures 2 and 3 corresponding to type CLC.

Olivine zonation and aqueous alteration

High TiO\(_2\) content of forsteritic olivine corresponds to refractory nature. Two possibilities for the origin of this refractory forsterite are consistent with its formation mechanism (Gucsik et al., 2013). First, these forsterite grains represent refractory condensates from the solar nebula and secondly, as crystallized from a melt. There is a possibility that refractory forsterite could have crystalized within chondrule. However, chondrule forsterite is chemically dissimilar from the isolated forsterite (Fig. 1). In fact, high Ca, Al, and Ti contents may not be compatible with bulk chondrule compositions. Additionally, low MnO content (<0.04 wt%), occurrences of fine-grained rim around the isolated forsterite in many instances may suggest an independent origin, appears incompatible to
suggest di
refractory forsterite with elevated Al, Ca, and Ti contents
igneous origin or may be considered as a relict phase sur-
vived the chondrule melting event. The pristine core of
refractory forsterite with elevated Al, Ca, and Ti contents
suggest diffusion of these elements had occurred before
the Mg–Fe inter-diffusion. The latter is also responsible
for Cr and Mn enrichments.

Guesik et al. (2013) in their study of Kaba CV3 sug-
gested that metasomatic reactions play a major role in mi-
gration of diffusible ions. However, imprint of any high
temperature alteration probably is not important for Mu-
kundpura CM2. In fact, abundance of phyllosilicates and
presence of carbonate (mainly calcite), TCIs (Tochilinite-
Cronstedtite intergrowths) in matrix suggested low tem-
perature aqueous alteration which not only promoted the
leaching of movable ions also induced incorporation of
Fe, Cr, and Mn. The relatively lower chondrule proportion
(~ 7%) in earlier study also suggests Mukundpura expe-
rienced substantial aqueous activities (Rudraswami et al.,
2019). However, the possible role of hydrothermal alter-
ation is not completely ruled out, especially Mukundpura
CM2 has various TCI clast (~ 30%) in the matrix and
presence of TC1 is often correlated to hydrothermal altera-
tion (~ 170°C, Zolensky, 1984) in Supplementary Figure
S2 (available online from https://doi.org/10.2465/jmps.
190610). Therefore, the reasonable explanation provides
low temperature hydrothermal alteration induces migra-
tion of diffusible ions Fe, Cr, and Mn occurred along
the margins of forsterite, while core of the refractory for-
sterite remains undisturbed and thus resulting relative en-
richment of Ca, Al, and Ti. Thus, the blue CL emission
can be correlated with primary process (either condensa-
tion or melt-crystallized process), while secondary aster-
oidal process (low temperature aqueous process) caused
trace element zonation and corresponding red CL emis-
sion. However, the exact mechanism driving the diffusion
of Fe, Cr, and Mn are still least understood. The elemental
enrichment is also understood in X-ray mapping where
Ca is characteristically enriched in core while margin of
the grain shows enrichment of Fe and Cr in Supplementary
Figure S3 (available online from https://doi.org/10.
2465/jmps.190610). The Al distribution in X-ray map-
pers to be fracture controlled in Supplementary Figure
S4 (available online from https://doi.org/10.2465/jmps.
190610). Based on homogeneous alteration of accretion-
ary rim and fine-grained matrix in Mukundpura CM2, our
study, further, indicates that aqueous alteration occurred
after the mixing and incorporation of different clasts.
However, a few outliers exist in the form of TCI-rich clasts attributing an independent history of aqueous alter-
ation. The fine-grained nature of the matrix of Mukund-
pura also promotes pervasive aqueous alteration. Our
result highlights that lack of complex carbonates and
chondrules in matrix and transformation of majority of
phases to secondary minerals suggest both clasts and ma-
trix experienced similar degree of aqueous alteration. The
undisturbed records of fine-grained rim around the few
mineral clasts suggest their pristine nature and possibly
nebular origin, although experienced secondary alteration
concurrently with the matrix during asteroidal aqueous
alteration.

CONCLUSIONS

The isolated forsterite in Mukundpura CM2 is characte-
erized using EPMA, color CL imaging and micro–Raman
spectroscopy in order to understand the minor element
distribution and structural imprint of olivine. The Raman
spectra of Mukundpura forsterite correspond to typical
crystalline nature with characteristic doublets peaks. This
observation well corresponds to the CL zoning thus pre-
serving the structural defects in the grain cores, and char-
acteristic blue luminescent resulted due to refractory na-
ture of forsterite grain. Migration of activator elements in
the forsterite grain plausibly indicates hydrothermal alter-
ations by fluid processes in the parent asteroid as a sec-
ondary process. Furthermore, the integrated color CL and
micro–Raman technique would be useful to provide val-
able information corresponding to the crystal chemistry
of the minerals occurring in terrestrial and extraterrestrial
materials and also can be a powerful exploratory tool for
future planetary and asteroidal missions.

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SUPPLEMENTARY MATERIALS

Color version of Figures 2–4, Supplementary Figures S1–
S6 and Tables S1–S4 are available online from https://
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