

Chemical, isotopic and amino acid composition of Mukundpura CM2.0 (CM1) chondrite: Evidence of parent body aqueous alteration

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Abstract

The carbonaceous chondrites are intriguing and unique in the sense that they are the only rocks that provide pristine records of the early solar nebular processes. We report here results of a detailed mineralogical, chemical, amino acid and isotopic studies of a recently observed fall at Mukundpura, near Jaipur in Rajasthan, India. Abundance of olivines in this meteorite is low and of serpentine minerals is high. $\text{FeO}/\text{SiO}_2 = 1.05$ in its Poorly Characterised Phases (PCP) is similar to that observed in other CM2.0 chondrites. The water content of ~9.8 wt% is similar to that found in many other CM chondrites. Microscopic examination of matrix shows that its terrestrial weathering grade is W0 but aqueous parent body alteration is high, as reflected in low abundance of identifiable chondrules and abundant remnants of chondrules (~7%). Thus, most of the chondrules formed initially have been significantly altered or dissolved by aqueous alterations on their parent bodies. The measured bulk carbon (2.3%) and nitrogen content and their isotopic ($\delta^{13}\text{C} = -5.5\text{‰}$, $\delta^{15}\text{N} = 23.6\text{‰}$) composition is consistent with CM2.0 classification probably bordering CM1. Several amino acids such as Alanine, Serine, Proline, Valine, Threonine, Leucine, Isoleucine, Asparagine and Histamine are present. Tyrosine and Tryptophan may occur in trace amounts which could not be precisely determined. All these data show that Mukundpura chondrite lies at the boundary of CM2.0 and CM1 type carbonaceous chondrites making it one of the most primitive chondrites.

1. Introduction

The carbonaceous chondrites (CC) form a unique group of primitive extraterrestrial rocks in the sense that their analyses provides the best opportunity to understand the earliest processes and events such as time of origin of solar nebula, duration and formation of chondrules and refractory inclusions, heating due to short-lived radionuclides, accretion to form small planetesimals, evolution of the asteroid belt, thermal evolution, and aqueous alteration of minerals, which have occurred during evolutionary processes in the early solar system. They are known to retain their original chemical, isotopic and mineral characteristics since the time of formation of our solar system (Mcsween, 1979; Anders and Grevesse, 1989). Much of the understanding of the evolution of early solar nebula, primitive solar system composition and formation age of the solar system has been obtained from isotopic systematics of early condensates such as calcium–aluminium-rich inclusions (CAIs) and chondrules (Mcsween, 1979; Amelin et al., 2002). Origin of organic matter brought to the Earth, origin of water, accretion of planetary bodies, etc. have also been understood by the study of carbonaceous chondrites (Kvenvolden et al., 1970; Sephton, 2002; Brearley, 2006). These meteorites contain pre-solar grains from various stellar bodies that triggered the collapse of the solar molecular cloud (Zinner et al., 1989). Many CI and CM chondrites (e.g. Orgueil, Ivuna, Mighei, Murchison, Murray) with carbon content 2–5 wt% dominated by organic carbon have provided evidence of amino acids, expected to be precursors of life on Earth (Sephton, 2002). Besides, the carbonaceous chondrites are of specific significance as nearly 40,000 tons of extraterrestrial material that hit the Earth's upper atmosphere every year is principally contributed by CM chondrites, more than 90% of which gets ablated during transit through the Earth's atmosphere and less than 10% make it to the Earth's surface (e.g. Love and Brownlee, 1993; Kurat et al., 1994; Brownlee et al., 1997; Taylor et al., 1998; Rudraswami et al., 2012, 2015, 2016).

The relative frequency of fall of carbonaceous group of meteorites are only ~4 percent (Grady, 2000), and the last CM chondrite to fall in India was Erakot, Madhya Pradesh, 77 years ago. In spite of being rare, such a meteorite fell at Mukundpura (26°52'52.5" N, 75°39'53.7"E), near Jaipur in Rajasthan, India early in the morning, around 5:15 am (IST) on June 6, 2017 on a dry alluvial agriculture farm of Banshi Mehta. The rock broke into many pieces on impact and the fragments were recovered immediately, within hours, after the fall, eliminating the possibility of any significant terrestrial contamination. The meteorite accordingly has preserved the original pristineness. The conditions of fall and recovery of Mukundpura chondrite have been described by the Geological survey of India in their

internal report (<https://employee.gsi.gov.in/>) and by Tripathi et al., (2018). Briefly, the impact created a pit ~45 cm diameter and ~15 cm deep, and according to GSI, about 2.2 Kg of the fragments were recovered. Some relevant details related to Mukundpura chondrite are listed in Table 1. Many small fragments, a few cm to tens of cm in size were found in the pit, suggesting that meteorite experienced fragmentation when it impacted the ground and is very fragile. Various fragments show existence of fusion crust, ~1 mm thick, and probably the whole meteorite, before it impacted, was covered by fusion crust. The chondrite has been classified as a CM chondrite based on multiple techniques such as electron microscopy, Mössbauer spectroscopy, thermogravimetric analyses and laser Raman spectroscopy (Tripathi et al, 2018). In view of the scientific importance of this class of meteorites, we have now carried out a more detailed study to further refine its classification and to understand its textural and elemental characteristics, along with the isotopic composition of nitrogen and carbon to unravel its evolutionary history on the parent asteroid.

2. Sample description and analytical techniques

A chip weighing ~4 gm was collected by one of the authors (RPT), within a few hours of its fall from the impact crater (Fig. 1). Later on two of the authors (RPT and NB) visited the site and collected more information about condition of its fall. The external, exposed fusion crust of the chip was discarded and the unexposed interior portion has been used in this study. A part of the sample (~1.75 gm) was used for preparing a thick section for electron microscopy (Fig. 1). Microscopic examination of the section shows altered chondrules and mineral fragments. The remaining sample was crushed with a mortar to particle size less than 40 μm . This powder was used for Thermo Gravimetric, X-ray diffractometer, N and C isotope analyses, trace element and amino acid measurements. The experimental details for various techniques used are given below.

The thick polished section was initially mapped for back scattered electron (BSE) image using Scanning Electron Microscope (SEM: JOEL 5800 LV and JOEL 300 at National Institute of Oceanography, Goa, India). The Energy dispersive X-ray spectrometers (EDS) was used to characterize different mineral phases and were documented for further analyses using electron Probe Micro Analyzer (EPMA, Cameca SX-5 equipped with four spectrometers at National Institute of Oceanography, Goa, India). The electron microprobe analyses was made on various phases of the section using accelerating voltage of 15 kV and 12 nA with focused beam current of ~1–2 μm , and broad beam of ~5 and 20 μm (Rudraswami et al., 2011, 2012, 2015, 2016). The bulk elemental analyses of Poorly Characterized Phases (PCP) were measured using broad beam of ~5 μm , while the bulk

composition was evaluated using ~20 µm beam. Multiple analyses were made on several spots while very low total data due to voids, cracks, etc. were discarded. X ray mapping of Mg, Fe, Ca, Al, Mg, and S were carried out on the polished sections. The section used for BSE images and electron microprobe was also used for cathodoluminescence image using VEGA3 TESCAN SEM-CL to identify the thermal alteration in isolated mineral phases and chondrules. The sample was imaged at working distance of ~15 mm and accelerating voltage of ~15–20 kV. Tripathi et al (2018) have earlier carried out Mössbauer spectrometry, Thermo Gravimetric Analyses (TGA), and Raman spectrometry on this meteorite. Here we have carried out X-ray diffractometer (XRD) of its powder (~200 mg) using Philips PW 1840 XRD to determine its mineral composition.

The samples were also analysed for obtaining total carbon and nitrogen (TC and TN) content, C/N ratios, along with stable carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotopic composition using Elemental Analyser (EA)–Flash EA1112 (Thermo) that is coupled to a Thermo Finnigan Delta V isotope ratio mass spectrometer in continuous-flow mode. Samples weighed precisely (15–18 mg) on a Sartorius ME-5 microbalance were tightly packed in pre-cleaned tin capsules. High purity helium (5.5 grade) was used as carrier gas and ultra-high pure oxygen was used for effective combustion of the samples. The gas produced in combustion column packed with chromium oxide and silver cobaltous-cobaltic oxide was passed through reduction column filled with reduced copper to convert the nitrogen oxide (NO_x) to N_2 . This gas is further passed through a trap of granular magnesium perchlorate ($\text{Mg}(\text{ClO}_4)_2$) for elimination of moisture and then through pre-packed gas chromatography (GC) column. For nitrogen analyses an additional CO_2 trap filled with ascarite was introduced for complete removal of CO_2 between the EA and the open split. Sample and standard bracketing was done during analyses to ensure the best measurement conditions and data quality. The stable isotopic ratios are expressed in per mil (‰) deviation relative to V-PDB (Pee Dee Belemnite) carbon standard for $\delta^{13}\text{C}_{\text{TC}}$ and relative to air-nitrogen standard for $\delta^{15}\text{N}_{\text{TN}}$. Replicate (n=4) analyses were made to understand sample heterogeneity; analytical precision of standards was observed to be better than $\pm 0.3\%$ for both $\delta^{13}\text{C}_{\text{TC}}$ and $\delta^{15}\text{N}_{\text{TN}}$. TC and TN were calculated from calibration curve made from four concentrations of ACA (6-Amino-n-Caproic acid, UMAST) working standard ranging from 3 to 24 µmoles for TC and 0.5 to 4 µmoles for TN.

Standard solutions of amino acids were prepared by dissolving 10 mg of each amino acid in 10 mL water comprising of 0.01 M hydrochloric acid. The analytes were further diluted to achieve concentration of 1–1000 ng/mL using 50% methanol containing 0.1%

formic acid. These solutions were used to construct standard linear calibration curve. A known amount (10 mg) of powdered Mukundpura chondrite was extracted from 1 mL of 50% methanol containing 0.01 M hydrochloric acid for 10 min using ultra-sonicator followed by 5 min of centrifuge at 15000 rpm. The residue was reconstituted in 200 μ L of 50% methanol containing 0.1% formic acid and underivatized extract was analyzed on LC-MS/MS system. This analyses was accomplished using 6420 Triple Quadrupole mass spectrometer (QQQ MS) coupled to 1290 pump, auto sampler and degasser (Agilent Technologies USA). The chromatographic separation was implemented with Sugar D column of length 250 mm, 2.1 mm internal diameter and 7 μ m particle size. The mobile phase is made of 30% acetonitrile containing 0.1% formic acid and the mobile phase was operated using isocratic mode at a flow rate of 600 μ L/min. The sample was ionized using electrospray ionization in positive mode with source temperature of 300°C and capillary voltage of 4000 V.

3. Results

We first describe the texture of Mukundpura section as revealed by scanning electron microscopy. A large section (~19 mm \times 14 mm) was examined for the presence of chondrules and other mineral phases. The chondrite seems to be a complex breccia with mineral phases showing different degrees of aqueous alteration. While the section (Fig. 1) shows fine-grained clastic matrix, the number of identifiable chondrules is ~7%, much less compared to the number expected in CM2 chondrites. The chondrule (CH-6) is type IA low-FeO porphyritic olivine chondrule that is rich in metal and has better preserved olivine phases compared to other chondrules which are found to have been altered (Fig. 2). We also found one glassy chondrule (CH-7) and one barred chondrule (CH-1) that has no preserved glass in between olivine bars indicating enhanced aqueous alteration (Fig. 2). Rest of the chondrules seems to be aqueously altered showing phyllosilicates inside chondrules with some evidence of mineral phases that are more resistant. However, most of the mineral phases present in the chondrules have been altered into phyllosilicates or fine-grained materials as seen in Fig. 2. Practically all the chondrules are surrounded by fine-grained phyllosilicate thick rims dominated by Fe-rich phases demonstrating abundant aqueous alteration. The carbonates and fosteritic minerals are plentiful and are spread throughout the matrix, while coarse-grained minerals of opaque phases, sulphides, Al-rich phases are rimmed by fine-grained matrix (Tables 2–4). The matrix consists largely of Fe-Mg serpentines as found in many other CM chondrites exhibiting a wide range of Fe/Mg ratios (Rubin et al., 2007). The matrix has Mg-rich serpentines in progressive stages of aqueous alteration (Tomeoka and Buseck, 1988). BSE image appears homogenous and no zoning was seen in the chondrules or individual

grains. CL intensity seems to be homogenous in chondrules, and olivine grains show small heterogeneity due to disequilibrium in the minor element distribution (Fig. 3).

The identified phases were further studied for chemical composition by electron microprobe. The bulk and mineral chemical composition are summarized in Tables 2–4. The bulk chemical composition of Mukundpura is close to CM2 chondrites. The X-ray image of element Mg, Ca, Al, S using electron microprobe from matrix were analyzed to understand the distribution of calcite, sulphate and other phases (Fig. 4). The green color in Fig. 4 gives an indication of the distribution of calcite in the Mukundpura chondrite. The calcite and sulfate concentration can be estimated by X-ray images of their respective elements. The combined X-ray elemental map of Mg (red), Ca (green) and Al (blue) can be used to obtain concentration of the calcite and sulphate phases in the chondrite. The abundance of the carbonates, having size range of ~10–80 μm , is estimated to be ~2.1 vol%.

Chemical composition of matrix, chondrules, PCP and various other phases like calcite, dolomite and olivines, based on electron microprobe analyses are given in Table 2. We also analyzed specific Fe-rich and Al-rich phases in detail as they are uncommon. The results on kamacite, pentlandite, taenite and pyrrothite are summarized in Table 3 and composition of Al rich phases is given in Table 4. The Mukundpura chondrite shows rare presence of framboidal magnetites which have considerably large proportion in CI chondrites. The mineralogy based on the bulk composition and XRD data show peaks of phyllosilicates with minor contribution from olivine and calcite (Fig. 5).

The mean carbon abundance is 2.3 wt%, while that of nitrogen is 0.10 wt% (Table 5). Multiple analyses were made to estimate reproducibility of C and N data. The multiple analyses of C and N lie within a narrow spread ($2\sigma = 0.4 \text{ ‰}$) with $\delta^{15}\text{N} = 23.6 \text{ ‰}$ and $\delta^{13}\text{C} = -5.5 \text{ ‰}$ (Table 5). Terrestrial weathering is generally severe in carbonaceous chondrites as they are easily prone to degradation of organic carbon, volatile elements, carbonates, reformation of phyllosilicates, etc. (Bland et al., 2006). The Mukundpura chondrite shows no visible signs of oxidation of metal and can be classified as W0 on weathering scale (Wlotzka, 1993). This is similar to weathering category A, defined by Meteorite Working Group of the NASA Johnson Space Center, Houston (Bland et al., 2006).

The Poorly Characterized Phases (PCP) in Mukundpura have mean $\text{FeO}/\text{SiO}_2 \sim 1.05$ which is slightly lower than that found in Cold Bokkeveld, QUE 93005, LAP 02277 ($\text{FeO}/\text{SiO}_2 \sim 1.2$) CM chondrites (Rubin et al., 2007). Some minor areas of the olivine fragments show light red luminescence, whereas the matrix has a blue luminescence as can be seen in Fig. 3. The porphyritic chondrule shows dull red color compared to the matrix

(Fig. 3a). The chondrules in these samples have size range of a few hundred μm (Fig. 2). This fits well within the size parameter of other CM chondrites. The Mukundpura chondrite has a few preserved chondrules but there is evidence of rounded features (Fig. 1), which seem to be remnants of chondrules that existed before they were altered, possibly due to aqueous processes at low temperature (Zolensky et al., 1997) and got converted into fine-grained phyllosilicates. Some well-defined rims, surrounded by additional fine grained rims, indicate that they were formed by accretion of fine-grained dust, probably during chondrule formation process (Metzler et al., 1992). Although one hibonite grain was identified along with some Al-rich phases, the CAIs have generally undergone much alteration so that it is difficult to recognise them in BSE images (Table 4). The near absence of refractory inclusions indicates severity of alteration.

The Mukundpura chondrite was studied using thermogravimetric analyses (TGA) to estimate their volatile and water content, and preliminary results of TGA have been reported by Tripathi et al (2018). The variation in wt% are related to loss of volatile components of which hydroxide and phyllosilicates are measures of intensity of alteration due to water (Fig. 6). The TGA analyses shows a total mass loss of $\sim 14\%$ in the temperature range of 30 to 1000°C . The mass loss in the temperature range of 30° to 200°C due to loss of molecular water is $\sim 2.05\%$, while between $200\text{--}400^\circ\text{C}$; the mass loss due to dehydroxylation of iron hydroxide is $\sim 2.03\%$. The phyllosilicates that release OH^- group in the range of 400° to 770°C show mass loss of $\sim 9.84\%$, while mass loss by calcium carbonate released CO_2 and sulfates in temperature range $770\text{--}900^\circ\text{C}$ leads to further reduction by $\sim 1.17\%$. This is not due to terrestrial alteration (Garenne et al., 2014) since the sample was picked up immediately after the fall on a dry day. The mass loss of $\sim 9.8\%$ due to loss of OH^- in phyllosilicates indicates presence of water resulting in aqueous alteration on the meteorite parent body.

Since Mukundpura meteorite was identified as CM chondrite, it was analyzed for the presence of Amino acids. The study has shown presence of Alanine (1011 ± 46 ppb), Serine (1532 ± 870 ppb), Proline (762 ± 107 ppb), Valine (1957 ± 125 ppb), Threonine (122 ± 17 ppb), Leucine (1198 ± 50 ppb), Isoleucine (1469 ± 75 ppb), Asparagine (539 ± 140 ppb), Glutamine (196 ± 39 ppb), Histamine (236 ± 78 ppb), Tyrosine ($<51 \pm 43$ ppb) and Tryptohan ($<6 \pm 21$ ppb). The uncertainties are standard deviation of the average value from five replicate measurements.

4. Discussion

The important chemical and isotopic analyses of Mukundpura chondrite obtained in this study are summarised in Table 6. We now compare these results with various types of carbonaceous chondrites to refine its classification that will be useful in distinguishing various types of hydrous asteroidal objects.

4.1. Classification of Mukundpura chondrite

Based mainly on Mossbauer spectra of iron rich phases, and other evidences this meteorite was classified by Tripathi et al, (2018) as CM carbonaceous chondrite. It must, however, be noted that CM chondrites have a complex aqueous alteration as the variation is distinct for different CM chondrites. The chondrules are largely pseudomorphed, serpentine replacing the chondrules, CAIs and other oxides, sulphides, etc. (Brearley, 2006). The bulk chemical composition of Mukundpura chondrite is analogous to CM chondrites. The bulk PCP chemical composition (Table 2) is only slightly different from previously studied CM2 chondrites. Specifically the SiO₂ content is relatively high in Mukundpura. Low “FeO/SiO₂” ratio of 1.05 in the bulk PCP places it in petrographic grade 2.0 (Rubin et al., 2007). This is similar to alteration observed in CI chondrites; although the texture and bulk chemistry of Mukundpura matches with CM group (Rubin et al., 2007). Based on the above data we classify the Mukundpura chondrite as belonging to petrographic grade CM2.0 which is analogous to CM1 as they epitomise a bridge between CI and CM chondrites. The FeO/SiO₂ value in Mukundpura chondrite is relatively lower than that compared to LAP 02277 (CM2.0) and MET 01070 (CM2.0) chondrites (Rubin et al., 2007). Apart from this, the metallic Fe-Ni abundance in the Mukundpura chondrite matrix is negligibly poor, similar to many CM2.0 chondrites. The uniqueness of PCP clump is rather uncertain due to complex accumulation of tochilinite and cronstedtite that look identical but differ in composition across chondrites (Trigo-Rodriguez et al., 2006). Hence, the current classification is supported by different types of analyses, discussed in the next section. Besides the textural features such as absence of Fe-Ni grains, phyllosilicates in the chondrules, reduced number of isolated silicate grains rich in carbonates, abundant chondrule pseudomorphs, etc. designate Mukundpura chondrite as highly altered CM chondrite of type 2.0 that are classified as CM1 chondrite (Rubin et al., 2007).

Earlier work reported by Tripathi (2018) using Mössbauer spectra reveals near absence (less than a few %) of olivine in this chondrite. This implies that olivine initially present has been converted to serpentine minerals due to alteration by water which must have been widespread on its parent body. The thermogravimetric analyses indicates ~9.8 wt%

mass loss in temperature range of 400°–770°C due to loss of hydroxyl group in phyllosilicates that can be ascribed to aqueous alteration. The loss of hydroxyl group in phyllosilicates is similar to that seen in many CM chondrites which vary between 5 to 12 wt% (Garenne et al., 2014).

4.2 Bulk carbon, nitrogen and their isotopic composition

Raman spectral analyses in Mukundpura chondrite exhibit D and G bands between 1200–1600 cm^{-1} that indicates the presence of large amount of organic matter consisting of disordered and aromatic (graphitic or polyaromatic) carbon (Tripathi et al., 2018). In addition, the bulk content of carbon and nitrogen and their isotopic composition provides good criterion for distinguishing between various classes of carbonaceous chondrites (Kerridge 1985; Pearson et al., 2006) and for determining degree of alteration on the parent body. Here, we have carried out study of elemental and isotopic composition of carbon and nitrogen, and compare them with the values reported in various CI and CM carbonaceous chondrites. Most of the CI chondrite has 4–5 wt% carbon and 0.2–0.5 wt% nitrogen which is higher than in other groups of carbonaceous chondrites, and indicates large abundance of C and N bearing minerals. The reduced C and N content with increasing petrologic grade in carbonaceous chondrites demonstrates alteration in parent body (Pearson et al., 2006). The $\delta^{15}\text{N}$ of CI1 chondrites ranges between +44 to +52 ‰ and $\delta^{13}\text{C}$ between –17 to –5 ‰, except in case of Tagish Lake CI2 which has $\delta^{15}\text{N}$ of +62 ‰ and $\delta^{13}\text{C}$ of +13 ‰ (Pearson et al., 2006). The CM2 chondrites of different types have bulk carbon content ranging between 2.1 to 2.7 wt%, while that of nitrogen between 0.08 to 0.14 wt%. The Mukundpura chondrite has nitrogen content similar to Nogoya or Murray CM2, while its C content is close to many other CM2 chondrites. Our measured value of $\delta^{15}\text{N}$ in Mukundpura is +23.6 ‰ which is close to that found in other CM2 chondrites e.g. Cold Bokkeveld (+27.0 ‰), Nogoya (+21.1 ‰) or Mighei (+28.3 ‰) (Pearson et al., 2006). The $\delta^{15}\text{N}$ is not comparable to CI chondrites, but lies within the range observed in CM2 chondrites. The CM2 have $\delta^{15}\text{N}$ value of +15 to +28 ‰, except for Murray and Murchison which show very high values (Pearson et al. 2006). The $\delta^{13}\text{C}$ in Mukundpura chondrite is –5.5 ‰. This falls within the values found in Alias CI1 chondrite, and differs by about –2 ‰ as compared to Cold Bokkeveld or Nogoya CM2 chondrites. The CM2 chondrite range for carbon and nitrogen bulk abundance is very narrow compared to other chondrites and Mukundpura chondrite safely fits into the classification of CM2.0.

It has been suggested by Pearson et al. (2002, 2006) that aqueous altered body accommodates larger quantity of C and N compared to thermally altered body. The C and N

in Mukundpura chondrite indicate that it has not been subjected to high temperature alteration. These C and N isotopes in Mukundpura have properties of both CI and CM chondrites and echo the primary material of its parent asteroid. Further, we would like to point out that the C and N-bearing phases are abundant in Mukundpura chondrite which is suitable for study of interstellar grains and organic constituents.

4.3. Chondrules, minerals, matrix and amino acids

The CI chondrites show no evidence of chondrules and, even if they once existed in their parent body (ies), they would have got destroyed during their evolution on the parent body. The Mukundpura CM2.0 chondrite has many chondrules which are pseudomorphs with their rims barely visible (Fig. 2), as is typical of CM1 chondrites. This indicates that chondrules have undergone alteration after accretion on the parent body. The reaction, along with mild heating, possibly due to short-lived radionuclides, has galvanized the alteration from anhydrous mineral phases to fine-grained clay minerals (Miyamoto, 1991). Perhaps, it depends on the temperature and the duration of the heating process since water content is vital in determining the extent of aqueous alteration (Garenne et al. 2014). The presence of carbonates, low Fe content of olivines, low abundance of preserved Fe-Ni phases in matrix and presence of magnetite indicate that alteration was significant. The effect of alteration due to water is also seen in aqueous mineral phases such as serpentines, carbonates, sulphates, etc. which are quite extensive (Brearley, 2006). Only the rims in most of the chondrules have survived, except one chondrule CH-6 which is slightly better preserved (Fig. 2). The CM chondrites that are classified as type 1 are extremely rare and essentially have widespread alteration, not only in matrix, but also in the chondrules and refractory inclusions. All chondrules in CM1 type chondrites are dominated by serpentine minerals (Brearley, 1995; Zolensky et al., 1997). Almost all chondrules in the Mukundpura chondrite have altered to fine-grained serpentine minerals similar to that of CM1 chondrites (Fig. 2). Most of the chondrules have a thick fine-grained rim as seen in many CM chondrites. Water plays a significant role in the evolution of the CM-chondrite parent body and is responsible for alterations in the chondrules and matrix (Tomeoka and Buseck, 1988). Aqueous alteration of CM chondrites showing varied degree of alteration from fully altered as seen in many CM chondrites (such as MET 01070 (CM2.0), LAP 02277 (CM2.0), QUE 93005 (CM2.1), Cold Bokkeveld (CM2.2), Nogoya (CM2.2)) to the least altered Paris CM2.7–2.9 chondrite that have been much debated (Hewins et al., 2014). The aqueous alteration has probably changed the mineral composition, though the bulk chemical composition has remained intact, indicating that the transformation occurred in closed system. The majority of the chondrules

show evidence of aqueous alteration and this is also the case for CAIs. Both these types of objects have been altered to phyllosilicates as also seen in many other CM chondrites. The percentage of chondrules in CM chondrites is highly variable but majority of them are close to ~20 percent (Weisberg et al., 2006); in contrast, the Mukundpura chondrite has lower chondrule population of only ~7%. From the above considerations we conclude that lack of chondrules is probably due to severe aqueous alteration, which transformed silicate phases present in the chondrules into serpentine minerals.

The carbonate minerals are spread throughout the matrix and occupy around 2.1 vol% and provide information about some parent body processes. The carbonates are embedded in matrix, dominated by calcite, followed by dolomite. Dolomite found in Mukundpura chondrite, as in other CM2.0 chondrites, is also possible evidence of parent body alteration (Rubin et al., 2007; Lee et al., 2014). Dolomite is rare in the least altered CM chondrites. Along with calcite, the Mukundpura chondrite contains some individual mineral phases largely dominated by forsteritic olivine, Fe-Ni metals, magnetite, troilite, pentlandite and some Al-rich phases (Table 2–4). The forsteritic olivines are thought to be product of primary solar nebula condensates and the hydrous minerals are suspected to have been formed before accretion of the parent body (Metzler et al., 1992). Thus we have evidence of very early alteration of minerals in the Mukundpura CM chondrite.

In view of the high carbon content, presence of abundant water and low thermal activity to which this meteorite was subjected, we have looked for amino acids in Mukundpura chondrite. The results show presence of high concentration of Alanine, Serine, Proline, Valine, Threonine, Leucine, Isoleucine, Asparagine and Histamine, as given in the previous section. Tyrosine and Tryptophan are present in trace amounts which could not be determined precisely. Their concentrations in Mukundpura are similar to those found in other primitive CM carbonaceous chondrites (Cronin et al., 1988; Sephton, 2002). As various amino acids are sensitive to temperature, their presence confirms the mild nature of metamorphic events the body has undergone. High temperature metamorphism would have definitely destroyed the amino acids (Cronin et al., 1974). This observation suggests that Mukundpura chondrite experienced similar metamorphic events as other primitive CM chondrites. Amino acids are related to the origin of life and most of the CM chondrites have shown their presence in significant amounts. Further detailed studies related to amino acids will be taken up when more samples become available.

4.4. Implications of CM chondrites to interplanetary dust

Every year the Earth receives nearly 40,000 ($\pm 20,000$) tons of extraterrestrial dust particles in the size range tens of μm to mm of which more than 90% get totally ablated during their transit through the Earth's atmosphere (Love and Brownlee, 1993; Taylor et al., 1998). The surviving ten percent is considerably more in comparison to the material brought in as meteorite falls, making these small dust particles the largest contributor of extraterrestrial material reaching the Earth's surface. Collection of uncontaminated tiny extraterrestrial material is difficult (e.g. Maurette et al., 1991; Love and Brownlee, 1993; Taylor and Brownlee, 1991; Taylor et al., 1998; Prasad et al., 2015). On the other hand, meteorites, because of their large size, ranging between a few cm to tens of meters, are well suited for a detailed scientific study. Although the carbonaceous chondrites represent only a small fraction of the falls, they are of particular interest due to many reasons cited above. Among the various carbonaceous chondrite groups, CM falls are the highest, just over a percent of the total meteorite, and their chemical and isotopic characteristics are similar to the cosmic dust (see e.g. Kurat et al. 1994; Brownlee et al. 1997; Engrand et al., 1999; Rudraswami et al., 2012, 2015, 2016; Imae et al., 2013). The chondrites have preserved interiors unlike the micrometeorites that get severely heated, losing their original characteristics. Since most of the micrometeorites are chemically similar to CM type chondrites, Mukundpura chondrite becomes very relevant for getting better insight in characterizing cosmic dust. Various CM chondrites have undergone dissimilar degrees of aqueous alteration (McSween, 1979; Brearley, 1995; Browning et al., 1996; Rubin et al., 2007; Beck et al., 2014). The Mukundpura CM2.0 chondrite represents a large body with aqueous alteration that has poor chondrule to matrix ratio (7 to 93 %) in comparison to other carbonaceous chondrites. The Mukundpura chondrite also seems to have the porosity, physical and chemical features that will generate grains seen in interplanetary dust particles (IDPs) and micrometeorites. The study of CM chondrites and their relation with the extraterrestrial dust can thus lead to significant understanding of their major sources in the asteroidal belt. Further evaluation of this primitive CM chondrite with cosmic dust will be of significance.

5. Conclusions

Chondrite fall is not uncommon, but Mukundpura has turned out to be quite a unique CM chondrite in the sense that, based on its chemical composition, texture, mineralogy, water content, N and C bulk content, N and C carbon isotope ratios, trace elements, and amino acids, it can be considered as one of the most primitive meteorites. The bulk composition of

Mukundpura is largely dominated by phyllosilicates, followed by olivine, calcite, and magnetite as minor components. Based on the bulk C, N and their isotopic composition along with chemical composition and mineral characteristics, we can classify Mukundpura as CM2.0 (CM1) chondrite, as one of the rarest observed falls of its type. The Mukundpura chondrite has the least chondrule to matrix ratio indicative of large aqueous alteration on its parent body. The evidence of large quantity of organic matter also supports the primitiveness of this chondrite. The Mukundpura chondrite is an extremely interesting object since this type of material may be the precursor of a large number of IDPs and micrometeorites, falling on the Earth.

Acknowledgements

We express our appreciation to Mr. Banshi Mehta, in whose farm the meteorite had fallen, for cooperation and useful information. This work was carried out with the support of MOES-PMN and PLANEX (Physical Research Laboratory, Ahmedabad) programs. Skilful assistance of Vijay Khedekar and Areef Sardar during the electron microscopy work is gratefully acknowledged. The support from Girish Prabhu during XRD analyses is appreciated. This is NIO contribution Number: xxxx.

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Figure captions

Figure 1.

Photographs of two recovered pieces of the Mukundpura fragments, weighting ~1.04 and 1.75 g (left). The smaller piece is used for thermogravimetric, trace element, amino acids, and isotopic analyses. Thick section was prepared using large piece of Mukundpura chondrite for petrographic studies using scanning electron microscope. Further, electron microprobe and cathodoluminescence studies were made on this section (right). The scale bar shown is 2 mm.

Figure 2.

Backscattered electron (BSE) images of some representative chondrules from Mukundpura chondrite showing various degrees of aqueous alterations in (a) metal rich porphyritic chondrule (CH-6), (c) barred olivine chondrule (CH-1). Some chondrules (d, g, h), are surrounded by silica rich rims indicating aqueous alteration. CH-7 (f) is a unique glass chondrule. CH-91 (i) is the altered chondrule with some olivine phenocrysts and thick rim. CH-9 (b) and CH-84 (e) are isolated FeO-poor olivine phases from fragments of chondrules.

Figure 3.

The cathodoluminescence (CL) image of various chondrules and fragmented olivine cluster grains from Mukundpura chondrite. The SEM image is given in Figure 2, except for image e and f. CL intensity essentially seems to be homogenous in chondrules and olivine grains, except in isolated olivine grains (d-f). Scale bars are given in the figures.

Figure 4.

Backscattered electron (BSE) image of matrix from the Mukundpura chondrite along with X-ray mapping for different elements such as Al, Ca, Mg and S, respectively. The combined X-ray elemental maps of Mg (red), Ca (green) and Al (blue) in the same region of matrix shows the distribution of calcite grains.

Figure 5.

X ray Diffraction curve for Mukundpura chondrites. The identified phases such calcite, olivine, Fe-cronstedtite and Mg-serpentine is marked.

Figure 6.

Thermal Gravimetric Analyses (TGA) curve of Mukundpura chondrite (Tripathi et al., 2018). The vertical lines show temperature ranges related to loss of molecular water, hydroxides, phyllosilicates and carbonates. (Garenne et al., 2014). Their percentages are shown in the figure.

Fig. 1

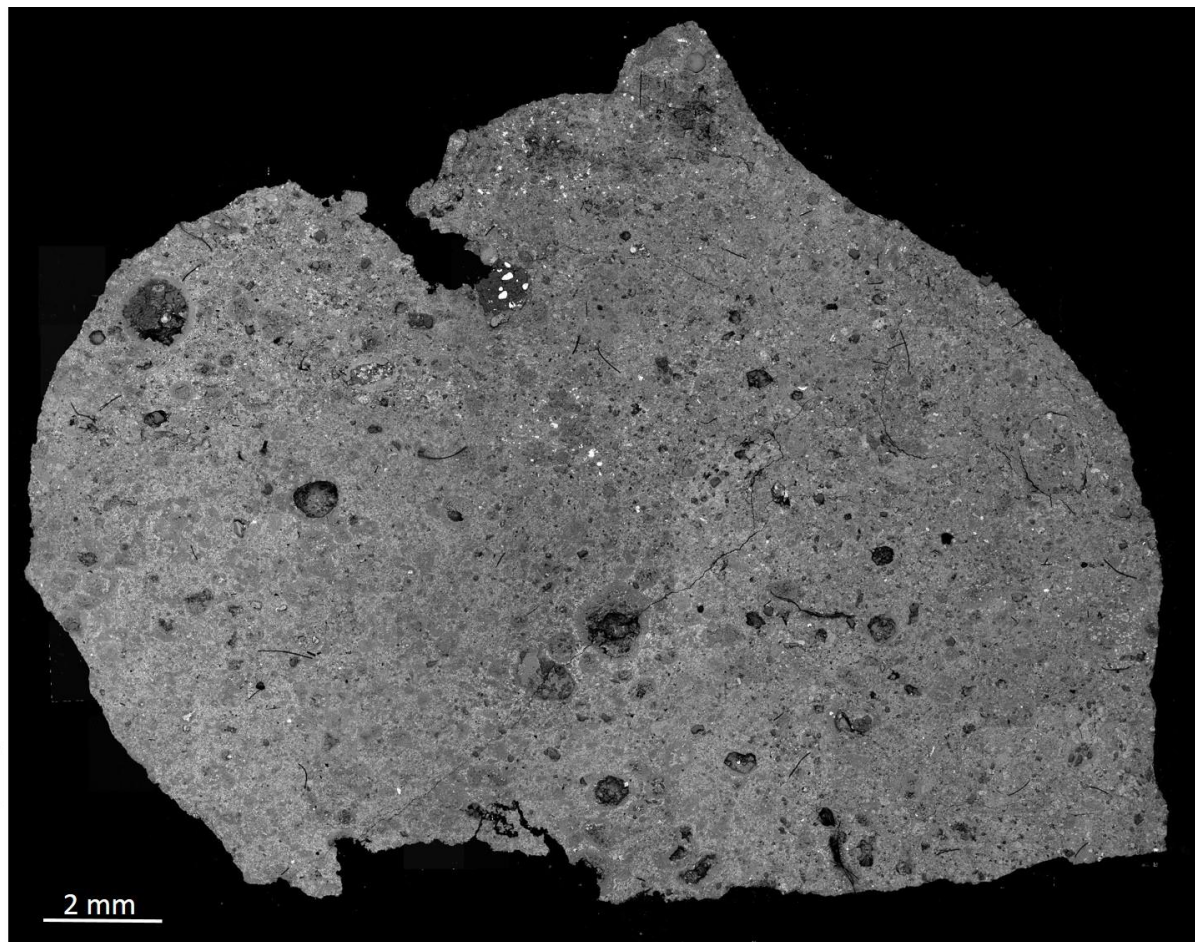
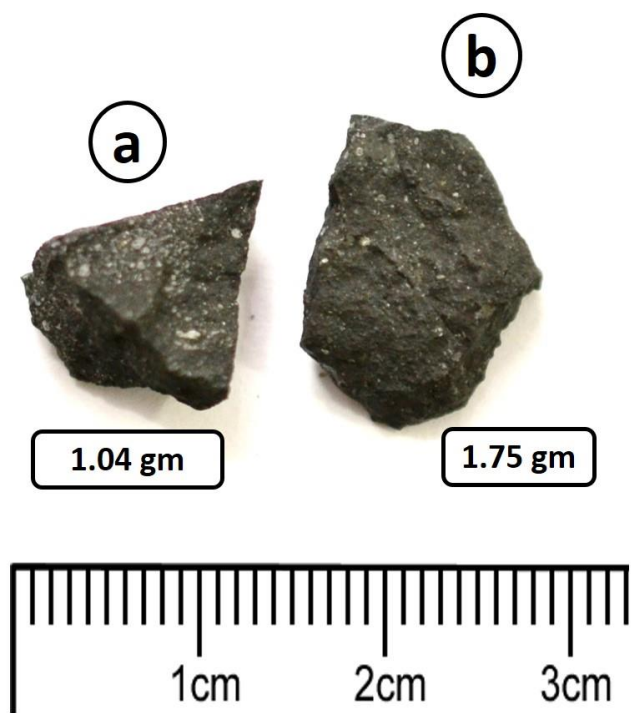


Fig. 2

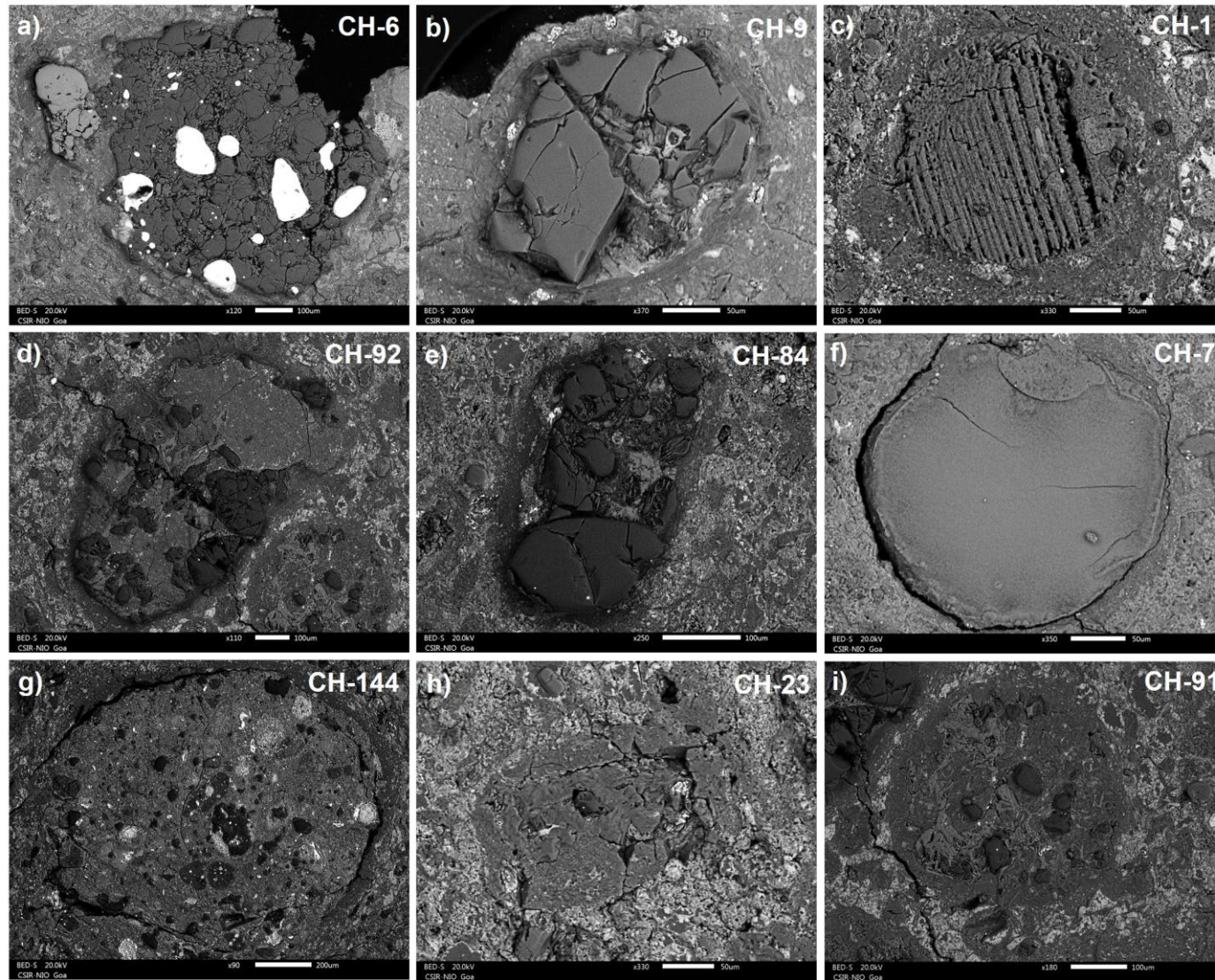


Fig. 3

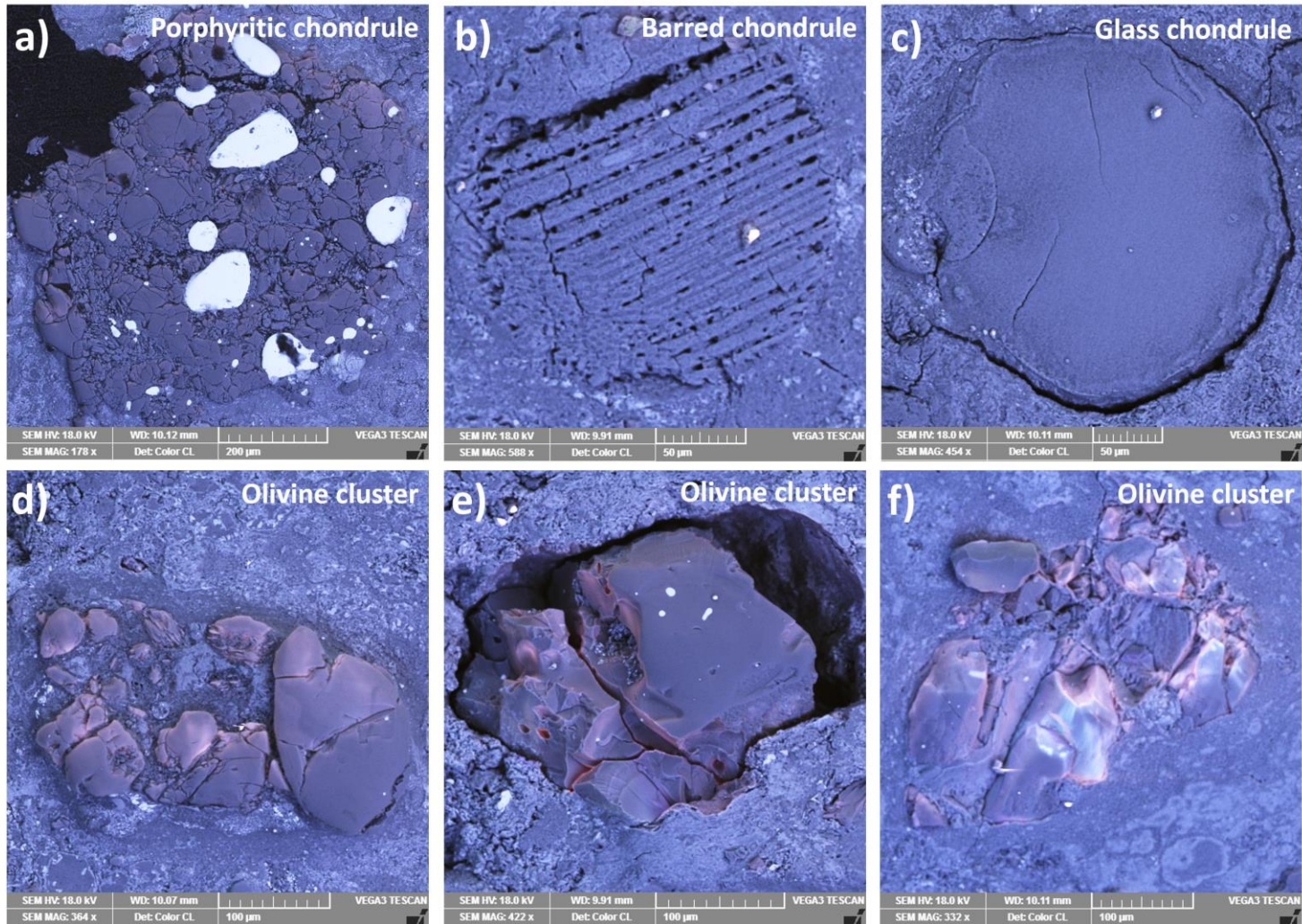


Fig. 4

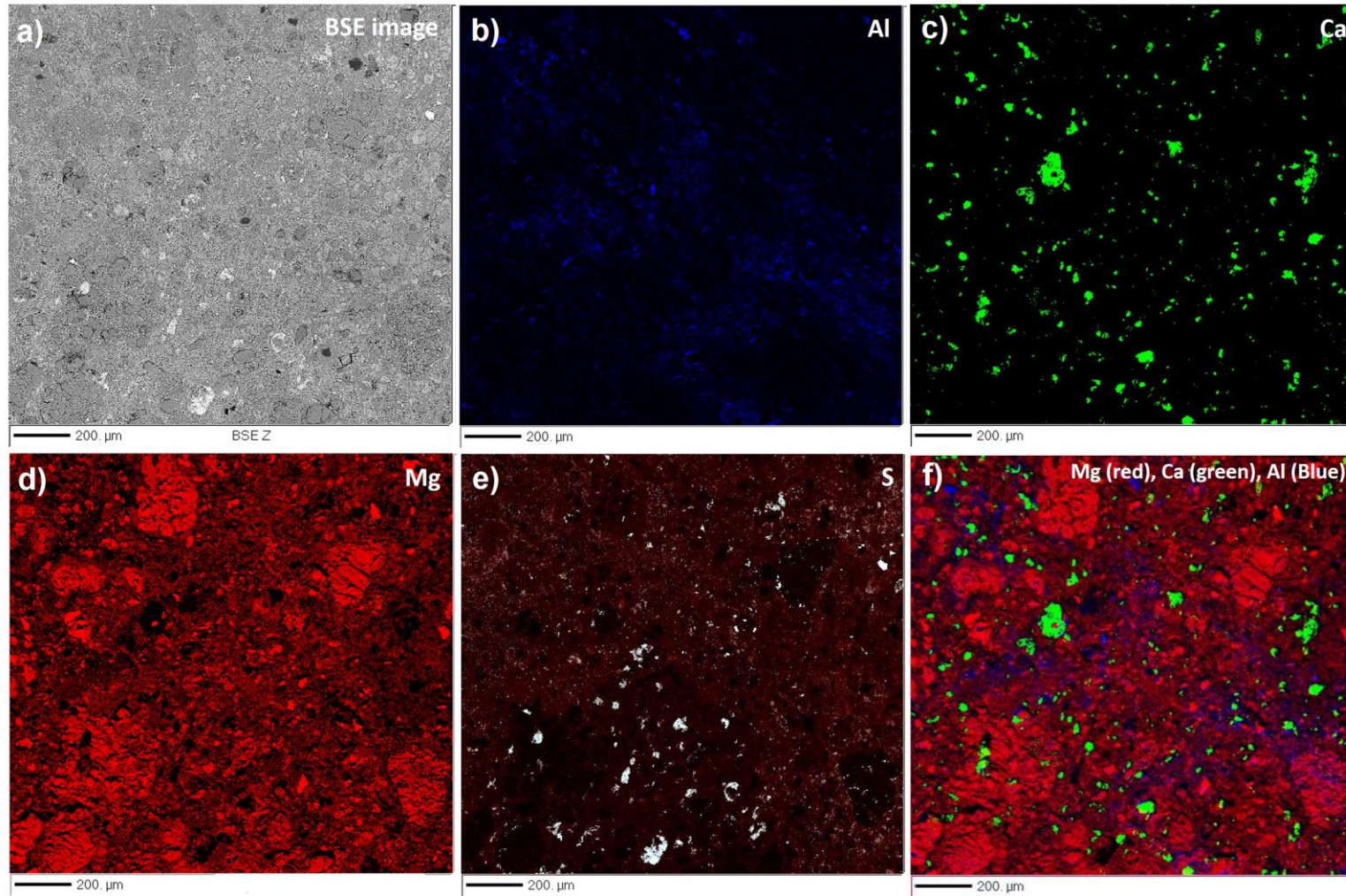


Fig. 5

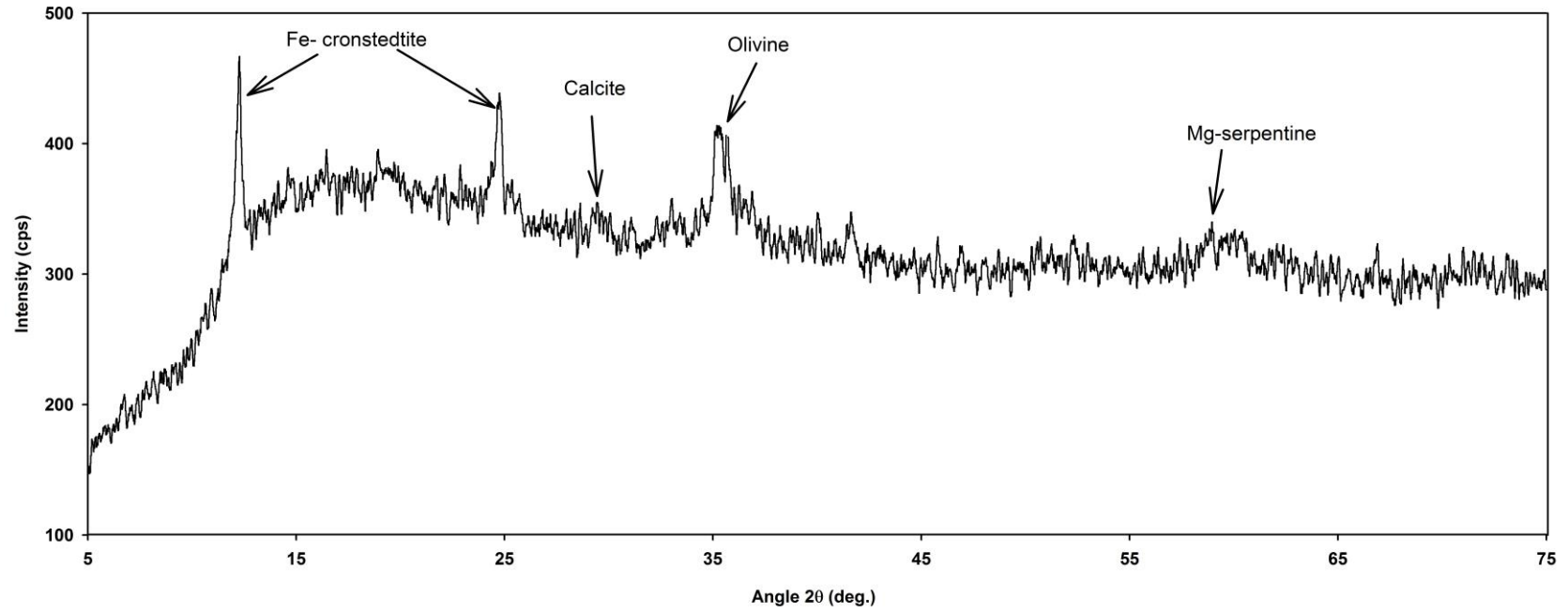


Fig. 6

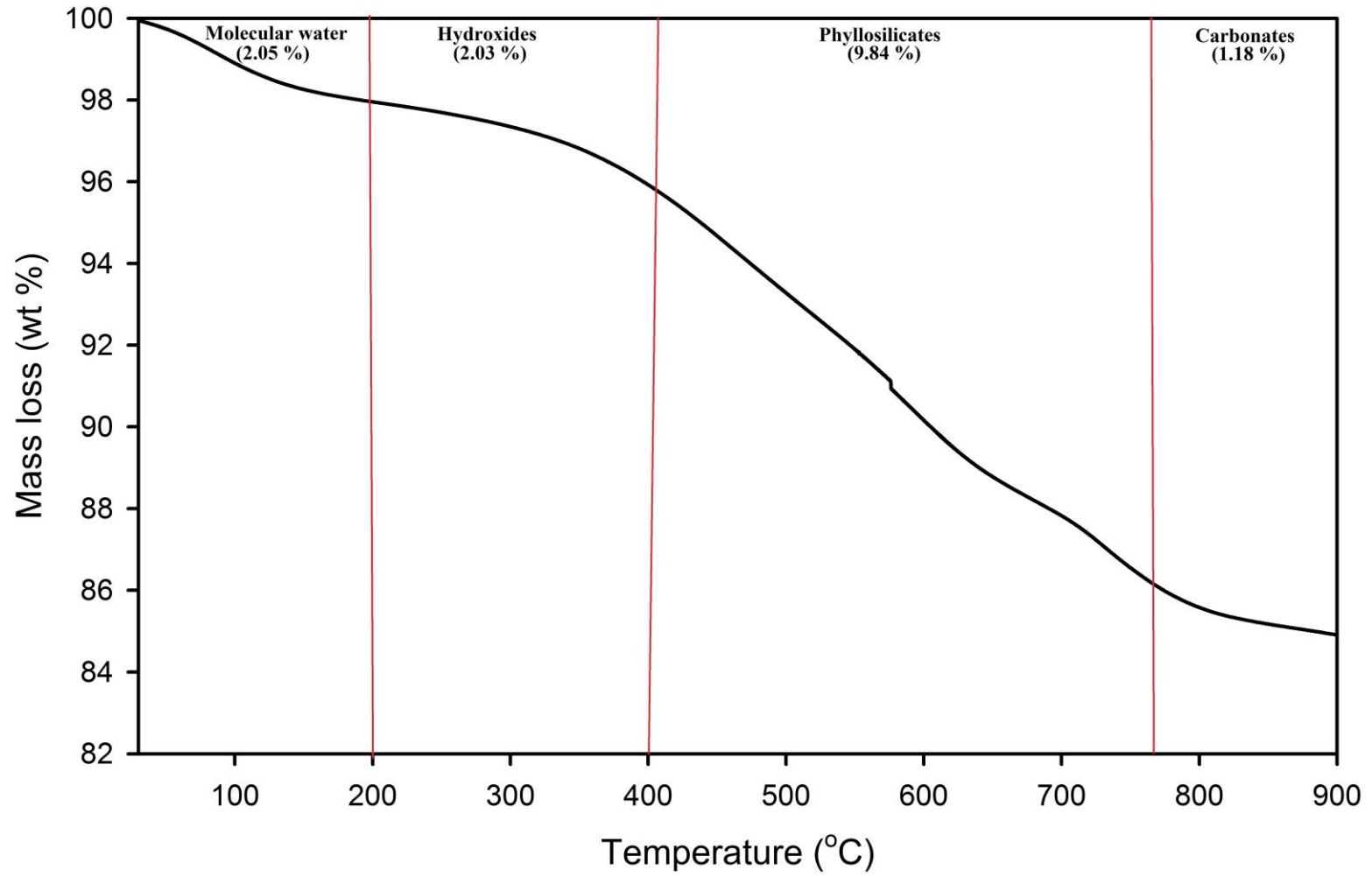


Table 1. Detail of the fall of the Mukundpura chondrite.

Parameters	Details
Place of fall	Mukundpura, Rajasthan, India
Co-ordinate	26°52'52.5" N, 75°39'53.7"E
Date of fall	6 th June 2017
Time of fall	0515 am (IST)
Recovered mass	~2.2 kg

Table 2. Chemical compositions (wt%) and standard deviations for electron microprobe analyses of different components in Mukundpura chondrite.

	Matrix bulk		PCP		Chondrule rim		Calcite		Dolomite		Olivine I		Olivine II		Pyroxene		Magnetite	
	N=742		N=54		N=68		N=43		N=8		N=76		N=53		N=13		N=10	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
SiO ₂	25.16	3.17	28.74	3.18	29.21	2.07	–	–	–	–	40.39	1.74	34.23	1.97	53.77	2.99	0.37	0.24
Al ₂ O ₃	3.47	2.02	3.09	0.94	3.00	1.14	–	–	–	–	0.79	1.77	1.05	1.96	2.80	1.50	0.14	0.29
TiO ₂	0.10	0.03	0.13	0.13	0.11	0.02	–	–	–	–	0.05	0.03	0.04	0.07	0.29	0.32	0.01	0.02
Cr ₂ O ₃	0.34	0.48	0.31	0.24	0.62	0.25	–	–	–	–	0.31	0.14	0.36	0.15	0.81	0.40	0.07	0.04
FeO	29.39	3.75	30.10	5.32	22.09	2.61	0.81	0.20	4.34	0.54	1.14	0.53	29.82	6.20	3.79	1.98	71.31	3.20
MnO	0.20	0.05	0.21	0.05	0.22	0.04	0.04	0.07	2.12	0.73	0.11	0.12	0.30	0.09	0.22	0.15	0.01	0.03
MgO	15.65	2.78	18.25	3.95	18.36	1.99	0.07	0.11	17.09	1.50	55.53	2.55	29.95	5.38	34.41	6.37	0.27	0.25
CaO	1.16	1.27	0.18	0.17	0.78	0.65	54.46	3.06	27.57	1.94	0.29	0.14	0.23	0.11	3.59	6.03	0.24	0.26
Na ₂ O	2.23	1.71	0.67	0.23	2.09	0.76	–	–	–	–	0.05	0.09	0.13	0.26	0.10	0.11	0.87	0.50
K ₂ O	0.06	0.03	0.04	0.02	0.08	0.02	–	–	–	–	0.00	0.01	0.00	0.02	0.00	0.01	0.03	0.02
P ₂ O ₅	0.14	0.29	0.05	0.06	0.21	0.39	–	–	–	–	0.01	0.02	0.05	0.06	0.01	0.04	0.05	0.07
S	3.41	1.19	1.01	0.35	3.19	0.53	–	–	–	–	0.04	0.06	0.29	0.76	0.16	0.04	1.25	0.45
Ni	1.03	0.51	0.34	0.22	1.71	0.40	–	–	–	–	0.03	0.03	0.13	0.28	0.04	0.07	1.37	0.54
CO ₂	–	–	–	–	–	–	43.16	2.19	44.00	2.12	–	–	–	–	–	–	–	–
Total	82.33	3.80	83.12	4.23	81.67	2.09	98.37	4.97	95.11	4.57	98.73	3.44	96.58	4.69	99.99	3.76	75.99	3.19

SD = Standard deviation.

N = Number of analyses.

Olivine I and II are two different composition of olivine.

Table 3. Chemical composition (wt%) of FeNi rich phases in Mukundpura chondrite.

Metal Phases	Kamasite		Pentlandite		Taenite	Pyrrhotite	
	N=6		N=11			N=5	
	Mean	SD	Mean	SD		Mean	SD
S	-	-	31.06	2.59	-	36.81	1.38
Fe	79.48	2.04	29.84	2.20	66.21	50.15	3.39
Ni	6.93	1.46	29.03	3.16	19.92	-	-
Total	86.41	2.80	89.93	5.78	86.13	86.96	4.59

SD = Standard deviation.

N = Number of analyses.

Table 4. Chemical composition (wt%) of some Al-rich phases identified in Mukundpura chondrite.

Sr. No.	SiO ₂	Al ₂ O ₃	TiO ₂	Cr ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	S	Ni	Total
1	3.27	43.57	0.20	0.21	5.06	0.00	17.39	0.19	0.11	–	0.05	1.58	0.06	71.69
2	14.46	35.23	2.13	0.13	9.44	0.20	21.95	0.13	0.28	–	0.07	1.01	0.06	85.09
3	20.87	27.35	0.32	0.09	13.64	0.04	9.44	3.46	2.40	0.08	0.17	6.72	1.61	86.19
4	12.30	54.65	0.06	0.09	5.93	0.04	9.93	2.22	4.84	0.07	0.06	3.61	0.19	93.99
5	16.10	44.28	0.03	0.08	6.39	0.07	11.03	4.82	6.69	0.05	0.09	3.89	0.29	93.81
6	26.52	26.27	0.37	0.25	8.07	0.09	12.02	6.93	2.75	0.03	0.10	1.86	0.28	85.53
7	26.92	34.54	0.09	1.01	4.01	0.38	15.98	1.04	0.97	0.06	0.07	0.82	0.09	85.99

Table 5. Carbon and nitrogen abundances (%) and isotopic compositions (‰) obtained for Mukundpura chondrite.

Element	Wt in mg	C%	δ ¹³ C ‰
Carbon	11.30	2.3	-6.1
	9.91	2.3	-5.5
	9.44	2.3	-5.3
	10.35	2.2	-5.3
	Average	2.3	-5.5
	2σ	0.0	0.4
	Wt in mg	N%	δ ¹⁵ N ‰
Nitrogen	10.08	0.10	23.6
	15.05	0.10	24.1
	17.94	0.09	23.1
	16.69	0.10	23.5
	Average	0.10	23.6
	2σ	0.01	0.4

Table 6. Summary of results of analyses of Mukundpura chondrite

Analyses	Results
Matrix percent	93%
Chondrule percent	7%
Terrestrial weathering grade	W0
Nitrogen content	0.10 wt%
Nitrogen isotope $\delta^{15}\text{N}$	$23.6 \text{ ‰} \pm 0.4 \text{ ‰}$
Carbon content	2.3 wt%
Carbon isotope $\delta^{13}\text{C}$	$-5.5 \text{ ‰} \pm 0.4 \text{ ‰}$
Loss of OH^- from phyllosilicates	9.80%
Fe-Ni metals	Trace
Olivine	<1%
Pyroxene	Trace
Al-rich phases	Trace
Calcite content	2.1 vol%
FeO/SiO ₂ in PCP	~1.05
Amino acid	Present
Classification	CM2.0 (CM1) chondrite