Petrography, classification, oxygen isotopes, noble gases, and cosmogenic records of Kamargaon (L6) meteorite: The latest fall in India

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Abstract—A single piece of meteorite fell on Kamargaon village in the state of Assam in India on November 13, 2015. Based on mineralogical, chemical, and oxygen isotope data, Kamargaon is classified as an L-chondrite. Homogeneous olivine (Fa: 25 ± 0.7) and low-Ca pyroxene (Fs: 21 ± 0.4) compositions with percent mean deviation of <2, further suggest that Kamargaon is a coarsely equilibrated, petrologic type 6 chondrite. Kamargaon is thermally metamorphosed with an estimated peak metamorphic temperature of ~800 °C as determined by two-pyroxene thermometry. Shock metamorphism studies suggest that this meteorite include portions of different shock stages, e.g., S3 and S4 (Stöffler et al. 1991); however, local presence of quenched metal-sulfide melt within shock veins/pockets suggest disequilibrium melting and relatively higher shock stage of up to S5 (Bennett and McSween 1996). Based on noble gas isotopes, the cosmic-ray exposure age is estimated as 7.03 ± 1.60 Ma and nitrogen isotopic composition (d15N = 18‰) also correspond well with the L-chondrite group. The He-U, Th, and K-Ar yield younger ages (170 ± 25 Ma 684 ± 93, respectively) and are discordant. A loss of He during the resetting event is implied by the lower He-U and Th age. Elemental ratios of trapped Ar, Kr, and Xe can be explained through the presence of a normal Q noble gas component. Relatively low activity of 26Al (39 dpm/kg) and the absence of 60Co activity suggest a likely low shielding depth and envisage a small preatmospheric size of the meteoroid (<10 cm in radius). The Kr isotopic ratios (82Kr/84Kr) further argue that the meteorite was derived from a shallow depth.

INTRODUCTION

India holds an exceptional record of eye-witnessed meteorite falls (~700 stones and irons falls, source: Geological Survey of India, Kolkata) since the earliest observed fall of Benares in 1798. Any new fall, whether a chondrite or an achondrite, not only adds to the meteorite database but also offers a unique opportunity to examine origin and formation history of asteroid belt.

In this study, we carried out detailed investigations on petrography, mineralogy, oxygen isotopes, cosmogenic records, and the noble gas isotopes including nitrogen of a new fall, the Kamargaon chondrite. We investigated the mineralogy and textures of the new fall, and its classification based on mineral chemistry, and textural studies led to a specific chemical grouping and assignment of petrologic types with a qualitative assessment of its rank in progressive shock metamorphism. The oxygen isotopic analyses further confirmed its group status and its relative position within that group.

CIRCUMSTANCES OF FALL AND MACROSCOPIC DESCRIPTION

A single stone weighing ~10 kg (~25 cm × 23 cm × 20 cm in size) fell on November 13, 2015 (12:00 hours, IST) at Bali Chappori village near Kamargaon town (lat: 26°39'N; long: 93°46'E) in the Golaghat district of
Assam, India (Meteoritical Bulletin 2016). The local villagers witnessed the meteorite fall during a bright sunny day and observed a trail from northwesterly direction. Eyewitnesses further explained that they heard a thunderous sound and observed an object fall on soft ground nearby in a wide-open area plowed for plantation of mustard oil seeds. The meteorite penetrated the ground and was finally buried inside a small hole of ~46 cm in diameter and ~90 cm in depth. Preliminary descriptions of this meteorite fall were reported by Goswami et al. (2016a, 2016b) and Ray et al. (2016a). This meteorite is the fourth fall in northeast India and the 20th fall in India during the last 25 years.

The macroscopic features of Kamargaon meteorite are consistent with an ordinary chondrite. The single mass is covered with fusion crusts of different textures and thickness. The fusion crust is relatively smooth, dull brown, thick (~1 mm), lacks well-developed regmaglypts and likely represents the rear surface during the flight through the atmosphere (Fig. 1a). On the other hand, the fusion crusts often appear as irregular surfaces with several shallow simple regmaglypts, black, thin, and slightly glossy with radiating flow lines. The face marked with the convergence of flow lines indicates the front side during its last stage of flight through Earth’s atmosphere (Fig. 1a). Tiny brownish spots in the grayish fractured surface are due to the oxidization of metal and sulfides present in the silicate matrix. A broken surface of the sample exposes the internal composition and texture. The chondrules are hardly discernible except for a few indistinct rounded outlines in the matrix are noticeable despite coarse chondrule-matrix recrystallization. Shock veins (dark brownish black), often bifurcating types, are rarely present (Fig. 1b). There are striations, resulted due to impact driven shear movement, apparently exposed on the melt-encrusted surface on silicate (Fig. 1b). On closer inspection, melt pockets appear to connect the numerous shock veinlets. Further details of shock veins are discussed later.

**METHODS**

Petrographic observations were carried out using a Zeiss polarizing microscope. Mineral compositions were determined using an electron microprobe (model Cameca SXfive) equipped with four wavelength dispersive spectrometers (WDS) at the CSIR-National Institute of Oceanography, Goa, India and electron microprobe (model Cameca SX 100) equipped with three WDS at the Physical Research Laboratory, Ahmedabad, India. Counting times for the elements were generally kept to 10–20 s except for Na, which was 7 s to reduce any volatilization effect. Operating conditions were 15 kV accelerating voltage, sample current 15 nA, and 1 μm beam diameter. Natural mineral (for silicates) and metal standards (for metallic Fe, Ni) were used for normalization and the data were corrected for absorption, fluorescence, and atomic number effects using routine PAP procedure (Pouchou and Pichoir 1988). Synthetic glass NIST 610 was run during certain intervals to check drift of the instrument. The 2σ error of most elements is better than ±5%. Estimation of modal mineralogy, chondrule-matrix ratio, and relative abundance of silicates, metal, and sulfides was conducted from four polished thin sections with the aid of manually operated routine point count device under optical microscope, mosaic of backscattered electron (BSE) images, and automated EPMA at 1 μm spacing, especially employed for the recrystallized matrix.

A fragment of Kamargaon meteorite (assigned as sample Kamargaon-z), weighing 331.23 mg, was
separated from the main mass and was analyzed at the Physical Research Laboratory, Ahmedabad, India for noble gases (He, Ne, Ar, Kr, and Xe) and nitrogen content and isotopic ratios using a Noblesse multicollector noble gas mass spectrometer following the procedures described by Mahajan (2015) and Mahajan et al. (2016). Gases were extracted in a low-blank vacuum furnace at temperatures 900 °C, 1200 °C, and 1700 °C using resistance heating method. Gases extracted from each step were split into two parts, one for noble gases and the second for nitrogen measurements. Noble gas fraction was cleaned of reactive gases using two getters (NP10, SAES). Heavy noble gases (Ar, Kr, and Xe) were separated from He and Ne using liquid nitrogen trap at charcoal for 10 min, and the He-Ne in gas phase was first introduced into the mass spectrometer for isotopic analysis. Afterwards, Ar, Kr, and Xe was desorbed from the cryotrap and measured by the mass spectrometer. The first line scan was performed on 200 g fragment using a 148 cc volume, 14 cm3STP, respectively, for 4He, 22Ne, 36Ar, 84Kr, and 5.3 ng for N2. The mass spectrometer was calibrated for sensitivity using noble gas from air standard reservoir. (The measured noble gas concentrations in the sample at different temperature steps are accurate to ±10% and are listed in Tables 2 and 3, respectively.) Data were corrected for blanks, interferences, and mass discrimination. Blank distribution is 5%, 2%, 10%, 2%, 2%, and 20% for He, Ne, Ar, Kr, Xe, and N, respectively. In the following discussion notations “c”, “t”, and “m” have been used for cosmogenic, trapped, and measured components, respectively. For He, we used \( (^{4}\text{He}/^{3}\text{He})_c = 5.6 \) (Leya and Masarik 2009), \( (^{36}\text{Ar}/^{38}\text{Ar}) = 1.53 \) (Wieler 2002), and \( (^{20}\text{Ne}/^{22}\text{Ne})_t = 0.8 \) and \( (^{21}\text{Ne}/^{22}\text{Ne})_m = 0.9 \) to obtain cosmogenic and trapped concentrations. For Kr and Xe, \( (^{83}\text{Kr}/^{84}\text{Kr})_c = 1.587 \), \( (^{128}\text{Xe}/^{132}\text{Xe})_t = 1.11 \) (Marti et al. 1966), and trapped components are assumed to be same as air, for deconvolution of cosmogenic and trapped components.

The measurement of cosmogenic radionuclides was performed on 200 g fragment using a 148 cc volume, ultralow background high purity germanium (HPGe) detector housed inside a 10 cm thick lead shield.

Another small fragment ~20 mg was analyzed at the University of California, San Diego, by a CO2-laser fluorination technique (Bao and Thiemens 2000; Chakraborty et al. 2013). The powdered meteorite samples weighing 8.18, 7.26, and 4.12 mg (in a batch of three) were loaded in a stainless steel boat along with a couple of NBS-28 samples. The fluorination chamber was pumped overnight to high vacuum and while heating the chamber at 100 °C. Before lasing, the chamber (with sample) was pre-etched with 30 torr of BrF5 for an hour to remove any remaining absorbed water. Subsequently, the samples were lased with an IR laser (CO2 laser) in the presence of 30 torr of precleaned (by pumping an aliquot of BrF5 while frozen in ~90 °C ethanol slush) BrF5. After lasing, the evolved oxygen was collected on a molecular sieve through two U-traps at LN2 temperature and the yields were measured by a capacitance manometer. Oxygen isotopic compositions were measured off-line by a Finnigan MAT 253 mass spectrometer.

**PETROGRAPHY AND MINERAL CHEMISTRY**

The mineral modes were determined using point count methods by optical microscopy and on BSE mosaic using 1 μm line scan by auto-mode EPMA. The modal abundances include ~43% olivine, ~30% orthopyroxene, 8% feldspar (maskelynite/plagioclase glass), 3% clinopyroxene, 8% metal, 4% troilite, and 2% accessories like chromites and merrillite. The BSE image shows the matrix is coarsely recrystallized; however, we note a few relict barred olivine (BO) chondrule and cryptocrystalline chondrule in the form of a coarsely recrystallized state (Fig. 2a). Moreover, chondrules with diffused outlines were more common but hard to identify due to coarse chondrule-matrix recrystallization of similar mineralogical composition (Fig. 2b). Both low- and high-Ca pyroxenes are noticeable; however, the dominant phase is low-Ca types, next to olivine. Coarsely recrystallized feldspar (>100 μm in size) is common both within the chondrule as well as in the matrix. In fact, the coarsely recrystallized nature of matrix is further understood from equigranularity olivine grains meeting at triple points.

Feldspars in recrystallized chondrules are mostly interstitial. In contrast, feldspars (commonly transformed to maskelynite) in the matrix include two different sizes and textures. The most dominant mode includes highly irregular shaped (as large as 500 μm in size) and appear as solid-state transformed maskelynite (isotropic under crossed polarized light). In contrast, the second mode is smaller in size (<100 μm) and comparatively less common and also resembling as shock-melted plagioclase glass (compositionally often deviates from usual stoichiometry). The latter often occurs as fracture fillings to the adjacent silicates (olivines and pyroxenes) as rapidly quenched glass.

Troilite and Fe, Ni metals commonly occur within the matrix; however, few metal globules are likely to occur as inclusions within the relict, the recrystallized chondrule. Troilites occur as discrete grains or patches, conjoined with Fe, Ni metal and localized melt pockets. Discrete troilites (size ranges up to 400 μm) are studded with numerous fine pits and are often polycrystalline in
nature. Conjugate troilite-taenite grains are more common as compared to troilite-kamacite conjugate pairs. Fe, Ni metal grains (taenite>>kamacite) vary from euhedral to subhedral outline, irregular blebs, and globules within the matrix. Chromite (max up to 50 µm in size) and merrillite (10–20 µm in size) occur as accessory phases within the matrix. A few chromites are also found to coexist with olivine grains, while merrillite occurs as discrete grains. Average mineral phase compositions of Kamargaon chondrite are given in Table 1. The olivine compositions of chondrule and matrix show a restricted range (Fa: 24.9 ± 0.7). The low-Ca pyroxene and high-Ca pyroxene composition appear uniform with mean composition of Wo4.3 ± 0.7En47.7 ± 0.6Fs8.1 ± 0.9 vs. Wo1.5 ± 0.3En77.4 ± 0.5Fs21.1 ± 0.4 and respectively. The average compositions of Fa (mol%) and Fs (mol%) fall under L-group, after Van Schmus and Wood (1967) (Fig. S1 in supporting information). Kamacite shows almost uniform composition (Ni ranges from 6.2 to 6.5 wt%), while Ni in taenite ranges between 14 to 28 wt%. Cr# (= molCr/mol[Cr+Al]) and Fe# (= molFe/mol [Mg+Fe]) of chromite are 0.85 and 0.86, respectively, while CaO and P2O5 of merrillite vary from 50 to 52 wt% and 40 to 42 wt%, respectively. We estimated the equilibration temperature of the Kamargaon meteorite using coexisting olivine-chromite thermometry (Wlotzka 2005) based on Fe/Mg equilibrium between olivine and chromite. We further adopted the two-pyroxene thermometer as the meteorite exhibits the highest degree of textural recrystallization and homogeneous silicate composition (Lindsley 1983). The mean temperature calculated from olivine–chromite yields a value of ~700 °C (Fig. S2 in supporting information). Similar temperature range was also found in Dar al Gani (L6) chondrite. Lindsley’s two-pyroxene thermometers using Fe-Mg distribution coefficient provide a mean equilibration temperature ~800 °C. The temperature difference between these two thermometers is ~100 °C, which probably reflects the effect of postshock reheating. Fracturing of silicate phases is common. Shock melt veins with quenched metal-sulfide melt texture (commonly occur as troilite-metal globules or blebs) are rarely noticed within the glassy matrix (Fig. 2c). Globules/blebs basically comprise the metal-troilite intergrowth textures with kamacite guest and troilite host. This feature suggests rapid cooling resulted due to late impact event probably after the equilibration of chondrite. The injection of Fe-Ni-S liquid (temperature higher than metal-troilite eutectic) within the colder silicates is further held responsible for
quenched metal-sulfide melt texture. Composition of metal of quenched textures are commonly kamacite (Ni < 6.5 wt%), while the host troilite composition ranges Fe ~ 63 to 64 wt% and S ~ 35 to 36%, respectively.

Based on the mean olivine and pyroxene compositions and the textural-chemical homogeneity (<2% PMD), Kamargaon chondrite can be classified to the L-group and feldspar with >100 μm in size corresponds to petrologic type 6 following the scheme of Van Schmus and Wood (1967).

The most common features of shock metamorphism in the Kamargaon meteorite include well-developed planar fractures (PF) within olivine and pyroxene grains. Optical evidence of weak mosaicism in olivine and presence of maskelynite (solid-state transformation of feldspar) and shocked plagioclase glass further suggests shock stage belong to S3 and S4 (Stöffler et al. 1991). Following the shock classification scheme of troilite-metal as discussed by Bennett and McSween (1996), the presence of melt pockets, polycrystalline troilite, and quenched metal-sulfide melt textures suggests local disequilibrium shock melting corresponding to the shock stage up to S5.

**OXYGEN ISOTOPES**

The values observed for δ18O and Δ17O0.528 are 4.37‰ and 0.67‰, respectively (the 2σ errors for δ18O and Δ17O measurements are 0.2‰ based on control analyses of NBS-28 standard), which are in the range of L-chondrite and match the petrological classification derived using the mineral composition.

**NOBLE GASES AND NITROGEN ISOTOPES**

The measured concentrations and isotopic ratios of noble gases and nitrogen are given in Table 2 (He, Ne, Ar, Kr, and N) and Table 3 (xenon). We use the concentrations of 21Ne and 38Ar, the 22Ne/21Ne ratio as shielding parameter and L-chondrite production rates given by Dalcher et al. (2013) to calculate cosmic-ray exposure (CRE) ages. For 3He, 83Kr, and 126Xe, production rates of L-chondrites provided by Eugster (1988) were used to derive the CRE age. The CRE ages for noble gases T3, T21, T38, T83, and T126 are listed in Table 4. The mean exposure age of Ne, Ar, Kr, and Xe (T21, T38, T83, T126), 7.03 ± 1.6 (Ma), gives a realistic CRE age of Kamargaon meteorite. However, the CRE age 7.03 ± 1.6 Ma, is less indicating loss of helium. The CRE age of ordinary chondrites (L-type) commonly range between 1 and 50 Ma (Alexeev 2005). Although there is no distinct peak in CRE age distribution of L-type ordinary chondrites, the exposure age of Kamargaon, 7.03 ± 1.6 (Ma), coincides with the 7 Ma peak of H-type ordinary chondrites in CRE age histogram (Wieler 2002).

The concentrations of radiogenic 4He and 40Ar and radiogenic ages are given in Table 4. Gas retention ages...
Table 2. Noble gases in Kamargaon meteorite (sample Kamargaon-z); concentrations are 4He, 22Ne, and 36Ar in 10\(^{-8}\) cm\(^3\)STP/g, and 84Kr in 10\(^{-12}\) cm\(^3\)STP/g.

| Temp. (°C) | 4He (ppm) | 22Ne (ppm) | 36Ar (ppm) | 3He/4He | 20Ne/22Ne | 21Ne/22Ne | 38Ar/36Ar | 40Ar/36Ar | N\(_2\) (ppm) | δ\(^{13}\)N (‰) | 82Kr/84Kr | 83Kr/84Kr | 86Kr/84Kr | 900  | 12.4  | 0.03  | 0.005 | 0.0937 ± 0.0041 | 0.8788 ± 0.0029 | 0.8611 ± 0.0037 | 0.995 ± 0.002 | 3971 ± 2 | 0.12 | 23.8 ± 0.1 | b.l. | b.l. | 900  | 77.3  | 1.25  | 0.111 | 124.0 | 0.0806 ± 0.0005 | 0.8011 ± 0.0007 | 0.8500 ± 0.0005 | 1.043 ± 0.001 | 1251 ± 1 | 0.17 | 16.7 ± 0.2 | 0.2260 ± 0.0006 | 0.2256 ± 0.0013 | 0.2998 ± 0.0010 | 1700 | 2.5   | 0.81  | 0.269 | 25.9 | 0.1470 ± 0.0064 | 0.8084 ± 0.0003 | 0.8554 ± 0.0005 | 0.608 ± 0.001 | 180 ± 1 | 0.08 | 11.8 ± 0.2 | 0.2149 ± 0.0004 | 0.2136 ± 0.0001 | 0.2985 ± 0.0008 | Total | 92.1  | 2.09  | 0.385 | 38.3 | 0.0841 ± 0.0038 | 0.8051 ± 0.0006 | 0.8523 ± 0.0006 | 0.739 ± 0.001 | 537 ± 1 | 0.38 | 18.1 ± 0.2 | 0.2185 ± 0.0005 | 0.2175 ± 0.0005 | 0.2990 ± 0.0009 |

b.l. = blank level.

Table 3. Xenon data in Kamargaon meteorite (sample Kamargaon-z). 132Xe in 10\(^{-12}\) cm\(^3\)STP/g.

| Temperature (°C) | 132Xe (ppm) | 124Xe/132Xe | 126Xe/132Xe | 128Xe/132Xe | 129Xe/132Xe | 130Xe/132Xe | 131Xe/132Xe | 134Xe/132Xe | 136Xe/132Xe |
|------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 1200             | 8.69        | 0.0057 ± 0.0001 | 0.0056 ± 0.0001 | 0.0832 ± 0.0001 | 1.254 ± 0.004 | 0.1609 ± 0.0003 | 0.8099 ± 0.0016 | 0.3941 ± 0.0003 | 0.3367 ± 0.0010 |
| 1700             | 16.23       | 0.0051 ± 0.0001 | 0.0048 ± 0.0001 | 0.0842 ± 0.0002 | 1.332 ± 0.002 | 0.1631 ± 0.0005 | 0.8206 ± 0.0004 | 0.3785 ± 0.0003 | 0.3150 ± 0.0006 |
| Total            | 24.9        | 0.0053 ± 0.0001 | 0.0051 ± 0.0001 | 0.0839 ± 0.0002 | 1.305 ± 0.003 | 0.1623 ± 0.0004 | 0.8169 ± 0.0008 | 0.3839 ± 0.0003 | 0.3226 ± 0.0007 |
based on $^4$He and $^{40}$Ar were calculated as follows. In the absence of trapped neon, $^{20}$Ne/$^{22}$Ne < 1, He is assumed to be a mixture of radiogenic and cosmogenic components. Using $(^{4}\text{He}/^{3}\text{He})_c = 5.6$, cosmogenic $^{4}$He was subtracted from the measured $^{4}$He. We calculate the U-Th-$^4$He radiogenic age $T_4 = 170 \pm 25$ Ma for Kamargaon, assuming average U and Th of L-chondrites. $^{40}$Ar is assumed to be entirely of radiogenic origin. Kamargaon has 640 ppm K, using this we calculate the $^{40}$Ar radiogenic age $T_{40}$ = $126\pm 4$ Ma.

Cosmogenic $^{3}$He, $^{21}$Ne, $^{38}$Ar, $^{83}$Kr, $^{126}$Xe, $^{22}$Ne/$^{21}$Ne, $T_3$, $T_{21}$, $T_{38}$ Ma

|       | $^{3}$He | $^{21}$Ne | $^{38}$Ar | $^{83}$Kr | $^{126}$Xe | $^{22}$Ne/$^{21}$Ne | $T_3$ | $T_{21}$ | $T_{38}$ |
|-------|---------|----------|----------|----------|----------|---------------------|------|---------|---------|
|       | 7.74 ± 0.86 | 1.78 ± 0.18 | 0.24 ± 0.03 | 71 ± 0.70 | 454 ± 48 | 1.17 ± 0.62 | 4.82 ± 0.07 | 7.09 ± 0.80 | 6.79 ± 0.34 |

The shortest half-life radionuclide measured was $^{7}$Be (53.3 days). Other cosmogenic radionuclides studied include $^{26}$Al, $^{22}$Na, $^{54}$Mn, and $^{57}$Co. The measurement of activities of various radionuclides was carried out using average K concentration (800 ppm) for L-chondrite (Wasson and Kallemeyn 1988). We adopt the

**Table 4. Cosmogenic, radiogenic, and trapped noble gas components in Kamargaon meteorite (sample Kamargaon-z). T_{average} is average of $T_{21}$, $T_{38}$, $T_{84}$, and $T_{126}$ CRE ages. $^4$He, $^{21}$Ne, and $^{38}$Ar in $10^{-8}$ cm$^3$STP/g, and $^{83}$Kr and $^{126}$Xe in $10^{-14}$ cm$^3$STP/g.**
same calculation procedure as described by Bhandari et al. (1989). The calculated activities of the detected cosmogenic nuclides are given in Table 5.

The measured activity of $^{26}$Al ($39 \pm 3$ dpm/kg) is low and matches with the production rate depth profile for chondritic meteorite with a radius of $<10$ cm (Bhandari et al. 1993; Leya et al. 2000). We were not able to detect any measurable activity of the neutron-capture isotope $^{60}$Co in Kamargaon meteorite. We can compare results on the Kamargaon meteorite with our earlier observations on cosmogenic radionuclides activity of Itawa Bhopji (L3–5) chondrite, which fell around peak activity of the solar cycle 23 on May 30, 2000 in the western part of India (Bhandari et al. 2002). We note both Itawa Bhopji and Kamargaon meteorites are chemically similar and fell during the peak of the two consecutive solar cycles 23 and 24, respectively. The role of solar activity and its modulation in the cosmogenic radioisotopes in various chondritic meteorites has been already discussed elsewhere (Bhandari et al. 2002). We found a good match with comparable level of activities and the activity ratio of pair of isotopes with comparable half-life, i.e., $^{57}$Co/$^{54}$Mn, which is due to the similarity of chemical composition (i.e., target atoms of Fe) and fall condition. This was consistent in view of the low shielding depth estimated based on nuclear track data which led to infer a small meteoroid ($R < 10$ cm) in interstellar space (Bhandari et al. 2002). The production of $^{60}$Co is due to thermal neutrons. Thus, the negligible activity of $^{60}$Co in Kamargaon, which is similar in chemical composition to the Itawa Bhopji meteorite, suggests that low flux of thermal neutrons resulted due to the small size of the meteoroid and hence neutrons were not thermalized. This further implies that the meteoroid had a small preatmospheric size ($\leq$10 cm) in interplanetary space.

| Isotope | Half-life | $\gamma$-Energy (kev) | Kamargaon (L6) Activity (dpm/kg) |
|---------|-----------|----------------------|----------------------------------|
| $^7$Be  | 53.1 d    | 477.5                | $81.0 \pm 9.0$                   |
| $^{55}$Co | 271.3 d  | 122.5                | $2.70 \pm 0.7$                   |
| $^{54}$Mn | 312 d    | 834.5                | $39.0 \pm 1$                     |
| $^{26}$Na | 949 d    | 1274.5               | $48.1 \pm 2$                     |
| $^{26}$Al | 0.73 Ma  | 1808.6               | $39.0 \pm 3$                     |

The three isotope plots of $^{130}$Xe/$^{132}$Xe versus $^{136}$Xe/$^{132}$Xe and $^{82}$Kr/$^{84}$Kr versus $^{83}$Kr/$^{84}$Kr for Kamargaon are shown in Fig. 3. Individual temperature steps data are plotted. Trapped components like SW, Q, and HL are shown (see text for references).

Table 5. Cosmogenic radionuclides activity (dpm/kg) at the time of fall of Kamargaon meteorite.

| Isotope | Half-life | $\gamma$-Energy (kev) | Kamargaon (L6) Activity (dpm/kg) |
|---------|-----------|----------------------|----------------------------------|
| $^7$Be  | 53.1 d    | 477.5                | $81.0 \pm 9.0$                   |
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| $^{26}$Na | 949 d    | 1274.5               | $48.1 \pm 2$                     |
| $^{26}$Al | 0.73 Ma  | 1808.6               | $39.0 \pm 3$                     |
SUMMARY

Based on mineral chemical studies, in particular chemical compositions of major minerals, olivine and low-Ca pyroxene, Kamargaon has been assigned as a typical L-chondrite. Oxygen isotope studies further support this conclusion. Based on well-equilibrated silicate phase compositions, the majority of chondrules merge into the bulk rock due to high degree of recrystallization and metamorphism that correspond to coarsely equilibrated type, i.e., petrologic type 6 (olivine and low-Ca pyroxene PMD <2%). The temperature of peak thermal metamorphism was estimated ~800 °C (two-pyroxene thermometer), which falls well within the range of L6. Evidences of shock metamorphism include mainly fracturing of olivines and PF (S3/S4; Stöffler et al. 1991); however, the presence of maskelynite, a few shock melt veins with quenched metal-sulfide melt textures, is attributed due to hot injection of Fe-Ni-S into the colder silicates resulting in rapid cooling (Ray et al. 2016b). It is therefore argued that shock stage was reached locally up to S5 (based on the metal-troilite shock classification scheme of Bennett and McSween 1996).

The trapped ratios of heavy noble gases (Ar, Kr, and Xe) and trapped isotopic signature δ15N = −17.8 ‰ suggest the presence of Q gas. Nitrogen abundance is 0.38 ppm. The radiogenic ages T40 = 684 ± 93 Ma and T4 = 170 ± 25 Ma for Kamargaon probably explains gas loss during an event. The CRE age derived from noble gas data is ~7.0 Ma.

All cosmogenic radionuclide suggests a smaller pre-atmospheric size (<10 cm in radius) for the parent meteoroid.

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**SUPPORTING INFORMATION**

Additional supporting information may be found in the online version of this article:

**Fig. S1.** Mole% Fs in orthopyroxene versus mol% Fa in olivine from ordinary chondrites of different groups (after Brearley and Jones 1998, their fig. 181). Kamargaon data plot into the field of L-group chondrites. Outliers include Bo Xian (BX), Roosevelt County 078 (RC 078), Kramer Creek (KC), Kendleton (K), and Cerro los Calvos (CLC). Olivine data from Rubin (1990) are shown along the x-axis.

**Fig. S2.** Isotherm diagram for chrome spinel (filled circles) and chromite (open circles) for Dar al Gani 952 (a L6 chondrite, after Wlotzka 2005). Kamargaon chromite fall under typical L6 range. Chrome spinel and chromite data of H and LL groups are also shown for comparison. Data source: Wlotzka (2005).