Meteorite falls over India during 2003: Petrographic and chemical characterization and cosmogenic records

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Two meteorite falls observed over India in 2003 led to the recovery of surviving fragments. The Kasauli meteorite that fell in northern India is a single fall, while Kendrapara meteorite is a multiple fall that covered a large coastal region of Orissa. Data for petrographic characteristics and chemical composition suggest that the two meteorites belong to the H group of chondrites, with Kasuali suffering a lesser degree of thermal metamorphism than Kendrapara during their residence in their parent bodies. Cosmogenic records indicate a large size (≥ 1 m) for the Kendrapara meteoroid that has spent ~5 million years in interplanetary space following its ejection from its parent body until its fall on the Earth. On the other hand, the Kasauli meteoroid spent an unusually long time (~37 Ma) in interplanetary space before its fall and lost ~80% of its original mass during atmospheric ablation.

METEORITES are some of the oldest remnants of the solar system available for laboratory studies. Primitive meteorites contain in them microscopic refractory objects that are considered to be some of the first solids to form in the solar system. Studies of these objects provide us insight into the processes governing the very early evolution of the solar system and also the mode of its probable origin[1]. Meteorite studies in general provide clues to understand the evolution of their parent bodies, primarily the asteroids and occasionally Mars and the Moon. They also provide information about the energetic environment in the interplanetary space where they spend a considerable period of time, ranging from less than a million years to a few tens of million years after being ejected from their parent bodies until their eventual fall on the Earth[2]. Thus any new fall of meteorite is an important opportunity for planetary scientists to further our understanding of some or all of the above aspects related to solar-system studies. The global meteorite collection has increased several folds during the past 35 years, due mainly to collections of a large number of meteorites from cold and hot deserts, where they are accumulating over thousands of years[3]. However, fresh falls of meteorites that are unaffected by terrestrial weathering processes are often better for a variety of investigations.

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During the calendar year 2003, two meteorite falls were observed in India that led to recovery of the surviving fragments. Although additional falls were likely during the year, considering the expected number of falls over such a large area, they either fell in uninhabited areas and went unnoticed or there were no reports regarding attempts to recover the fragments. Here we provide a description of these two falls and also preliminary results obtained from studies of these two meteorites.

The first reported fall of the year was on 27 September 2003 that took place at around 18:30 h in the southeastern part of India. A brilliant fireball with intense greenish hue appeared in the northern sky and progressed towards the southern horizon and was observed by a large number of people in the southern part of West Bengal and coastal Orissa. The event led to multiple fall of meteorite fragments along coastal Orissa. Three of these pieces were retrieved by the Geological Survey of India (GSI) from Subarnapur village (20°32′22″N: 86°42′E), East Suniti village (20°27′30″N: 86°43′15″E) and West Suniti village (20°27′45″N: 86°42′10″E) in the Kendrapara district of Orissa; the weights of the recovered fragments are 490.2, 719 and 5460 g respectively. Photographs of a recovered fragment are shown in Figure 1. There are a large number of eyewitness reports of this fall. One such observation reported by an amateur astronomer notes that 'a greenish fireball appeared in the northern sky, streaked across the heavens towards southern horizon and got converted into a big lump of fire with golden yellow hue at 15° to 20° above the horizon that descended some way before getting extinguished'. He noted the duration of the event to be about 10 s, even though other observers claim it to be much longer. A detailed description of the nature of this fall as well as reconstruction of the orbit of this meteoroid based on various eyewitness accounts has been reported recently[4]. Given the nature of the fall, the recovery of fragments is obviously not complete. It is probable that a good number of fragments fell in the wet and marshy areas and are not retrievable. Further, the large area over which the fragments were scattered also led to possible collection of fragments by villagers and other individuals who visited the site and these remained untraced and undocumented. A newspaper report that a thatched house was 'ignited by the burning flare of the heavenly stone' at Surusuria village (21°29′50″N: 86°31′25″E), about 150 km from the actual site of fall of the main recovered fragment, was found to be unsubstantiated. A description of this meteorite was submitted to the International Meteorite Nomenclature Committee, and the meteorite fall was named Kendrapara[5], after the district where the three recovered fragments were found. Results obtained from a detailed study of several randomly collected small fragments of the Kendrapara fall have been reported recently[4]. Here we report results obtained from the study of the major fragments recovered and currently housed at the meteorite curatorial facility at GSI, Kolkata. Both the earlier and the present study led to similar conclusions about the nature and characteristics of the Kendrapara meteorite.

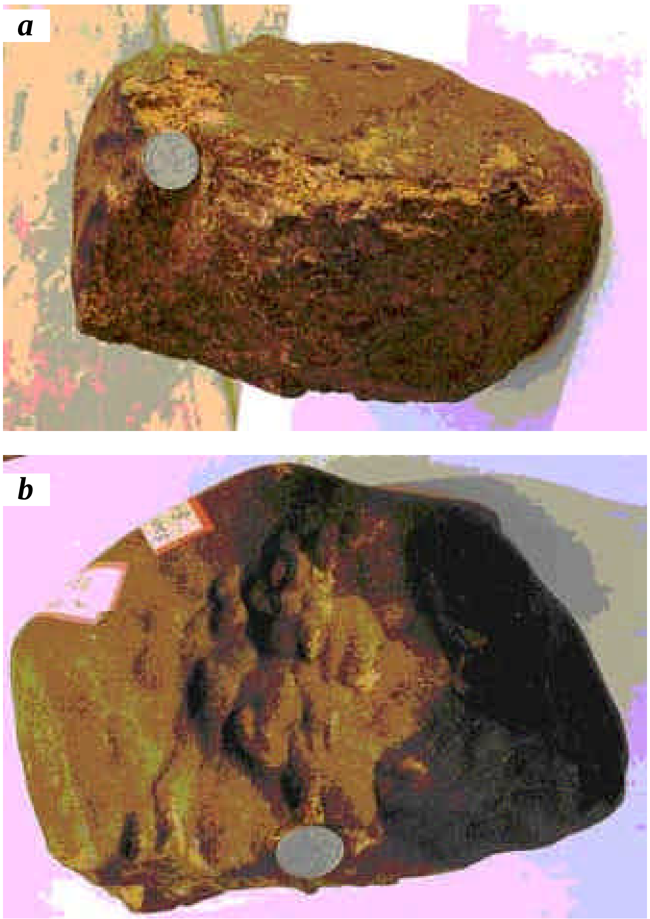

Figure 1. Recovered fragment of the Kendrapara meteorite with fractured surface (lateral) and thin-crusted (top and left side) third generation faces (***a***). Well ablated, closed textured first generation faces with regmaglypts (***b***).

The recovered fragments of the Kendrapara meteorite are dark on the unbroken surface and light coloured on the broken surface, with a good amount of visible metals (Figure 1). The meteorite is moderately magnetic in nature and its specific gravity is 3.5. Visible rusting is conspicuous, making the broken surface light brownish. The rusting is obviously caused by the wet environment of the area of fall. The main mass of the meteorite has incomplete tabular polyhedral shape (Figure 1 *a*) and measures 18.7 cm × 12 cm × 13 cm. The incomplete morphology indicates that a larger part got broken-off during the break-up event associated with the fall of the Kendrapara meteorite. Some of the surfaces are closed textured and smooth, indicating that they suffered a high degree of atmospheric ablation. Shallow-to-deep regmaglypts (Figure 1 *b*), which are mostly compound in nature, are also conspicuous on these faces; these faces are the probable first-generation surface that has not suffered pre- or post-ablation break-up. The second generation surface showing a few shallow regmaglypts, and a probable third generation surface, the basal face that is rough, knobby and darker than the other faces with shallow regmaglypts, could be inferred from our observations. The thickness of the fusion crust varies from 0.2 to 0.8 mm, being thinnest on the latest generation of surface. These morphological characteristics suggest the possibility that the Kendrapara meteoroid suffered at least two fragmentation events during its atmospheric transit[6].

Studies on thin sections of the Kendrapara meteorite show that it is essentially composed of olivine, pyroxene, abundant Fe–Ni metal, troilite and rare feldspar. A variety of well-defined chondrules of varying shape and size are present, even though these are few in number. The size of the chondrules ranges from 0.15 to 0.5 mm and they occur in a variety of textures. Overall metal proportion is high (about 30%), with minor amount of troilite. The metal part shows brownish iron-oxide staining due to alteration. The matrix is fine-grained and is moderately recrystallized. No major shock feature except loss of birefringence and a few minute cracks in olivine and pyroxene was noticed, indicating very low degree of shock metamorphism[7]. The abundance of metal is indicative of H group of the meteorite and the petrographic observations suggest that the Kendrapara meteorite[8] belongs to petrologic type 4–5.

Electron probe analyses of different petrographic constituents of the Kendrapara meteorite were carried out by CAMECA SX-50 EPMA instrument at BRGM, Orleans, France. These data suggest that the Fa content in olivine varies between 18.2 and 19.6 ($n = 22$), with average Fa content being 18.8. The per cent mean deviation (pmd) of Fa content is 4.76. The proportion of olivine is higher in comparison with pyroxenes, while orthopyroxene is more abundant than clinopyroxenes. Fs content in Opx varies from 14.4 to 17.4 ($n = 17$), with an average of 16.4. The pmd of Fs content in Opx is 6.2. In clino-pyroxene, Wo varies from 32.3 to 48.4%, En ranges between 47.8 and 63%, and Fs content ranges from 4.7 to 9.1%. Metals and sulphides are abundant in Kendrapara. Both nickel poor (kamacite) and nickel-rich phases (taenite) are present. In kamacite Ni varies from 5 to 7%, whereas in taenite it ranges from 27 to 53%. Troilites are almost Ni-free, with concentration less than 0.05%. There is considerable uniformity in composition of olivine and pyroxene, both in matrix and chondrules.

Results obtained from bulk chemical analysis of a piece of Kendrapara meteorite carried out at GSI, Kolkata are given in Table 1. These data along with those obtained from mineralogic and petrographic study confirm Kendrapara to be a H-chondrite of higher metamorphic grade (H5). The earlier study of a smaller fragment of Kendrapara also led to a similar conclusion[4].

The two smaller fragments (~0.5 and 0.7 kg) of the Kendrapara multiple fall and a sample of the main (~5.5 kg) fragment were analysed at the Physical Research Laboratory, Ahmedabad for obtaining their bulk chemical composition, and deciphering the records of cosmic-ray produced radioactivity, noble gases and nuclear tracks in this meteorite. A variety of techniques such as radionuclide counting, mass spectroscopy and nuclear tracks were used for these studies.

A notable feature of the radionuclide counting data of the two Kendrapara fragments is the high activity of the short-lived nuclide ^{60}Co (45 and 63 disintegrations per minute per kg). ^{60}Co is produced by secondary neutrons that are generated within the meteoroid by interactions of high-energy galactic cosmic-ray protons during the exposure of the meteoroid in interplanetary space. The flux of secondary neutrons within a meteoroid increases with its size that allows for reaction cascades leading to neutron production to take place. Based on our data and those reported recently for several other smaller fragments of Kendrapara[4], the pre-atmospheric size of Kendrapara may be estimated to be ≥ 1 m. The noble gas data suggest a cosmic-ray exposure age of 4.5 ± 0.5 Ma for this meteorite. This duration may be considered as the time elapsed since the ejection of the Kendrapara meteorite from its parent asteroid until its time of fall on the Earth.

A single stone accompanied by a thundering sound fell on 2 November 2003 around 17:00 h in the field of Suresh Chandra Sharma in Kasauli village (29°35′N: 77°35′E) near Charthawal, Muuzaffarnagar district, Uttar Pradesh, India. The fall was witnessed by villagers of Kasauli and the meteorite was retrieved within half an hour of the fall. The impact of the meteorite created an oval-shaped crater with dimensions of 31 cm × 30 cm × 40 cm (Figure 2 *a*). The single mass of this meteorite, weighing 16.82 kg (Figure 2 *b*, *c*) and provisionally named Kasauli meteorite, is a nearly oriented one and has a plano-convex turtle-back shape with a truncated ellipsoidal outline. The meteorite is moderately magnetic and has a specific gravity of 3.6; some degree of weathering is visible as the meteorite was probably soaked in water by the villagers after retrieval. Rusting on exposed surface is distinct at a few places.

The recovered meteorite measures 29 cm × 25.5 cm × 10.25 cm. The bottom face is almost flat; two smaller side faces are rectangular in shape and flat-to-slightly de-

Table 1. Chemical composition of Kendrapara and Kasauli meteorites

Element	Abundance (%) Kendrapara	Kasauli	H-Chondrite (mean)[9]
Ti	0.066	0.066	0.06
Al	1.29	1.15	1.22
Cr	0.34	0.34	0.29
Fe	26.52	28.00	27.81
Mn	0.26	0.26	0.26
Mg	14.41	14.42	14.1
Ca	1.30	1.27	1.26
Na	0.70	0.66	0.64
K	0.11	0.09	0.08
P	0.12	0.11	0.15
Ni	1.57	1.73	1.64
Co	0.07	0.08	0.09
S	2.75	2.59	1.91

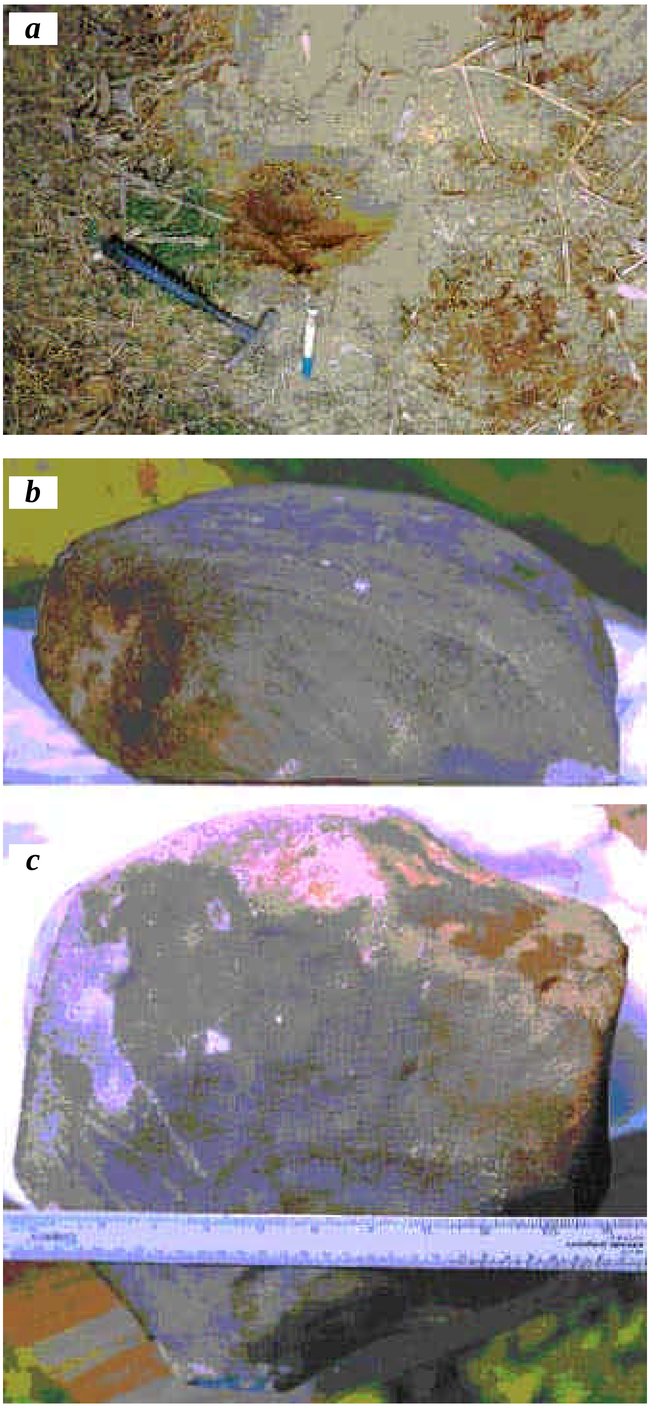

Figure 2. Elliptical impact crater created by the Kasauli meteorite (***a***). Top convex face with flow lines (***b***) and bottom flat face with shallow regmaglypts (***c***).

pressed in nature. The convex, oval face opposite to the flat bottom side is the largest and has distinct flowage lines that diverge out on the convex surface (Figure 2 *b*), indicating this as the stagnation point. This meteorite is fully covered by fusion crust with a thickness of about 0.2 to 0.5 mm. The crust is greyish in colour and netted in nature. Shallow elliptical, compound regmaglypts are present only on the bottom flat surface (Figure 2 *c*). It appears that the two side faces represent the frontal side during the last phase of the flight, whereas the large convex side was the lateral side. Minute shiny metallic knobs are observed on the surface of the meteorite.

Thin-section study shows that the Kasauli meteorite is composed of olivine, pyroxene, abundant Fe–Ni metal, troilite and devitrified glass. Olivine occurs in higher abundance than pyroxene. A variety of well-defined chondrules of varying shape and size are present. The size of the chondrules ranges from 0.1 to 0.6 mm. Presence of well-defined chondrules and sharp chondrule–matrix boundary indicates a lower petrologic group for this meteorite. Overall metal proportion is quite high (about 25 to 30%) with minor amount of troilite that generally occurs in association with metals. The matrix is fine-grained and moderately recrystallized and the meteorite had suffered low degree of shock metamorphism[7]. The abundance of metal suggests Kasauli to be a H-group chondrite, while the petrographic observations suggest that it experienced a lesser degree of metamorphism than Kendrapara and belongs[8] to petrologic type 4.

Electron probe analyses of different petrographic constituents of the Kasauli meteorite were carried out using CAMECA SX-100 and Cameca SX-51 EPMA at Kolkata and Faridabad respectively. The Fa content in olivine generally varies between 16 and 22 ($n = 26$), with an average Fa content of 21.3; the pmd of Fa content is 4.76. However, a few olivines with much different Fa values (Fa-31, Fa-8) were also found. Orthopyroxene is more abundant than clinopyroxenes and the average Fs content in Opx is 16 ($n = 20$), with pmd value of 5.2. As in the case of olivine, few opx with much higher and lower Fs values (Fs-4.7 and Fs-31.6) were also found. Two phases of clinopyroxenes are present. Clinopyroxenes with high Ca content have an average composition of $Wo_{35.2}En_{50.53}Fs_{14.25}$. A low calcic phase of cpx has an average composition $Wo_{10.91}En_{87.4}Fs_{1.68}$. Metals and sulphides occur in considerable amount in Kasauli and both nickel-poor (kamacite) and nickel-rich (taenite) phases are present. In kamacite Ni varies from 5.3 to 6.4%, whereas in taenite it ranges from 48 to 52%. Troilites are almost Ni-free, with a concentration less than 0.1%.

Results obtained from bulk chemical analysis of a piece of Kasauli meteorite carried out at GSI, Kolkata are given in Table 1. These data along with those obtained from mineralogic and petrographic study confirm Kasauli to be a H-chondrite of low metamorphic group (H4).

A cut fragment of the Kausauli meteorite along with documented spot samples from six locations from different faces of this meteorite were analysed at PRL for obtaining its bulk chemical composition, and deciphering the cosmic-ray exposure records following procedures similar to those adopted for Kendrapara. The preliminary results obtained from the compositional studies confirm Kasauli to be a H-group of chondrite. The noble gas data suggest an exposure age of ~37 million years for this meteorite, a rather long space exposure considering that a majority of H-chondrites have nominal cosmic-ray space exposure age of ~8 million years. The measured activities of the different cosmic-ray produced radionuclides (^{7}Be, ^{56,58}Co, ^{46}Sc, ^{57}Co, ^{54}Mn, ^{22}Na, ^{60}Co and ^{26}Al) with half lives varying from 53.3 days to 0.7 million years are at saturation level, which is expected because of the very long space exposure duration of the meteorites. Combining noble gas data and observed records of galactic cosmic-ray produced nuclear tracks in the six spot samples analysed by us, it is possible to infer the degree of atmospheric ablation suffered by the Kasauli meteorite during its atmospheric transit. Our preliminary data suggest this to be ~78%, which is within the typical range (70–85%) inferred for most single-meteorite falls.

Note added in the proof: Following the submission of the paper, two reports appeared describing the Orissa fall (Mohanty, M. *et al.*, *Curr. Sci.*, 2004, **87**, 428–429) and chemical composition of a fragment of this fall that confirms its extra-terrestrial origin (Nair, A. C. C. *et al.*, *Curr. Sci.*, 2004, **87**, 654–657). In these reports various fragments of this multiple fall have been given informal names such as Subarnapur, West Suniti, East Suniti and Jagannath. As noted in the present paper, the name approved for this multiple fall by the Meteorite Nomenclature Committee of the International Meteoritical Society is Kendrapara (ref. 5). Thus all fragments of this multiple fall, including those reported in the above two papers, should be referred to as fragments of Kendrapara meteorite.

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