Meteoritics & Planetary Science 40, Nr 4, 627–637 (2005)
Abstract available online at http://meteoritics.org

The Dergaon (H5) chondrite: Fall, classification, petrological and chemical characteristics, cosmogenic effects, and noble gas records

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(Received 08 September 2004; revision accepted 12 February 2005)

Abstract–A multiple fall of a stony meteorite occurred near the town of Dergaon in Assam, India, on March 2, 2001. Several fragments weighing <2 kg and a single large fragment weighing ~10 kg were recovered from the strewn field, which extended over several tens of square kilometers. Chemical, petrographic, and oxygen isotopic studies indicate it to be, in most aspects, a typical H5 chondrite, except the unusually low K content of ~340 ppm. A cosmic ray exposure of 9.7 Ma is inferred from the cosmogenic noble gas records. Activities of eleven cosmogenic radionuclides were measured. ^{26}Al and ^{22}Na activities as well as the ^{22}Na/^{26}Al activity ratio are close to the values expected on the basis of solar modulation of galactic cosmic rays. The low ^{60}Co activity (<1 dpm/kg) is indicative of a small preatmospheric size of the meteorite. Cosmic ray heavy nuclei track densities in olivine grains range from ~10^6 cm^{-2} in samples from the largest fragment to approximately (4–9) × 10^5 cm^{-2} in one of the smaller fragments. The combined track, radionuclide, and noble gas data suggest a preatmospheric radius of ~20 cm for the Dergaon meteorite.

INTRODUCTION

A multiple fall of a stony meteorite occurred in the eastern region of the state of Assam, India, on March 2, 2001, at 16:40 local time. The fall was visible over a distance of approximately 40 km, stretching from the river island of Majuli to west of the town of Dergaon (Fig. 1). The largest fragment, weighing 10.3 kg, was recovered in the village of Balidua (26°42′N, 93°51′E), a few kilometers west of Dergaon. Eyewitnesses observed a fireball accompanied by two loud detonations and mild tremor. The largest fragment fell in a sugarcane field, forming a crater approximately 40 cm in diameter and 60 cm deep. Additional smaller fragments were recovered in the village of Koilaghat (one piece weighing ~1.4 kg) and two fragments, each weighing <1 kg, were recovered in Majuli. It is possible that other fragments fell in the Brahmaputra River channels present in the area of the fall. Preliminary mineralogic and petrographic studies suggested that the meteorite belongs to the H5 group (Grossman and Zipfel 2001). In this paper, we present the results of a detailed study of the mineralogy, petrography, and chemical composition of this meteorite along with cosmogenic radioactivity, noble gases, and nuclear track records.

SAMPLES AND EXPERIMENTAL APPROACH

Nuclear track records were studied in several spot samples from the two largest fragments recovered in Balidua and Koilaghat. An additional sample from the Balidua fragment was analyzed for noble gas records. Broad physical characteristics of the meteorite were inferred from visual and microscopic observations of these fragments. Mineralogical and petrological characterizations are based on studies of polished thin sections made from several samples from the main fragment. Data on mineral chemistry was obtained using a JEOL JXA-8600M superprobe. Instrumental neutron activation analysis (INAA), inductively coupled plasma atomic emission spectroscopy (ICP-AES) and atomic absorption spectroscopy (AAS) techniques were used to obtain bulk composition of the meteorite. Clean fragments (~2.5 g) from the interior of the meteorite were crushed and powdered in an agate mortar. Two aliquots, each ~200 mg, were dissolved in HF-HCl for ICP-AES/AAS analysis.

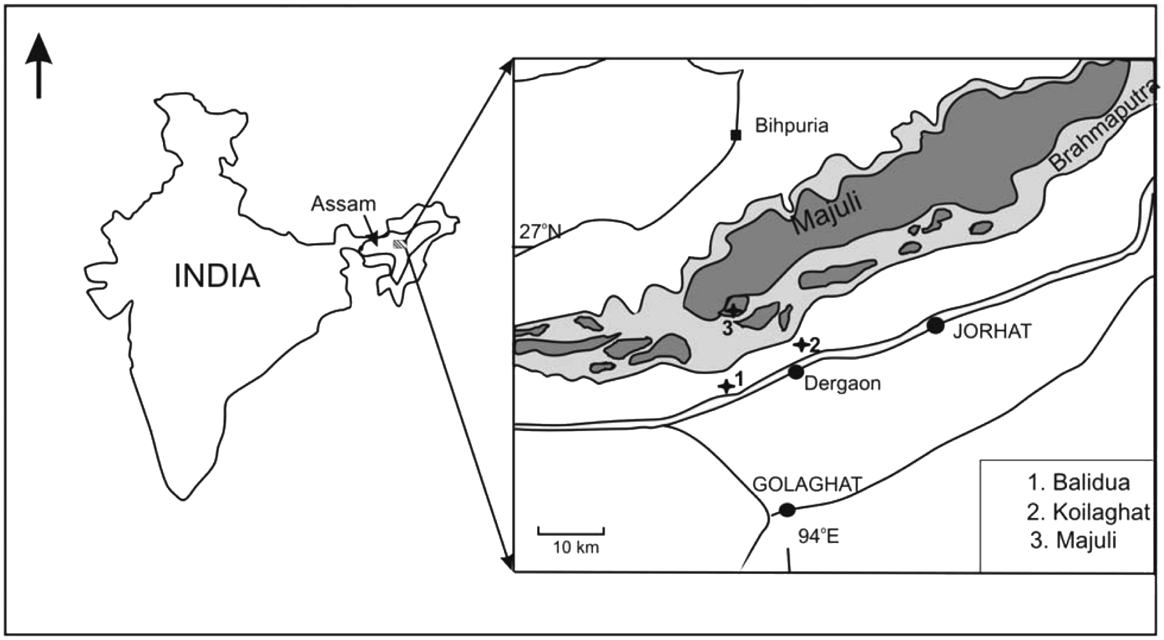

Fig. 1. A map showing the locations (the cross symbol) of three of the fragments recovered from the multiple fall of the Dergaon meteorite.

Dhajala (H3.8) and Diabase W-2 were used as standards. Neutron activation analysis was carried out in two separate irradiations. In the first batch of samples, four aliquots (40 to 60 mg) of the bulk meteorite were analyzed, while the second batch consisted of four aliquots (~60 mg) of the bulk sample on which the ICP-AES measurements were carried out. These samples together with standards (Allende [CV3], BCR-1 and AGV-1) were irradiated in the Dhruva reactor of Bhabha Atomic Research Center, Mumbai. The irradiated samples were counted using a high-purity Ge detector (148 cm^3) housed within 10 cm thick lead shield. The procedures are described by Laul (1979) and Shukla et al. (1997). Concentrations of Al, Mg, Ca, Mn, Fe, Ni, Na and K were determined using ICP-AES/AAS, while concentrations of other elements, such as, Co, Cr, Zn, Se, As, Sc, La, Sm, Eu, Yb, Ir, Os, and Au as well as Fe, Ni, and Na were determined using INAA procedures. Typical errors of measurements and reproducibility were within ~5% except for La, Yb (~15%) and Os (~20%). The activity of ^{40}K in a powdered box sample (~55 g) of the Balidua fragment and an internal standard of known K content (2.63%) were also measured to obtain an independent estimate of K content of the meteorite. Cosmogenic radioactivities were measured in a sub-sample of the Balidua fragment weighing 1.8 kg and in the powdered sample measured for ^{40}K activity as well as in the Koilaghat fragment (1.4 kg). The shortest half-life radioisotope that we could detect is ^{48}V ($t_{1/2}$ = 16 days). Activities of eleven cosmogenic radionuclides (^{26}Al, ^{60}Co, ^{22}Na, ^{54}Mn, ^{57}Co, ^{46}Sc, ^{56}Co, ^{58}Co, ^{7}Be, ^{51}Cr, and ^{48}V) were measured in the Balidua fragment. Activities of nine of these radionuclides (excluding ^{51}Cr and ^{48}V) could be determined in the Koilaghat fragment. ^{54}Mn, ^{22}Na and ^{26}Al activities were also measured in the powdered (box) sample of the Balidua fragment that was analyzed nine months after the fall. A low-background, 400 cm^3, high purity Ge detector housed within a 20 cm thick lead shield (Shukla et al. 2001) was used for measurement of cosmogenic radionuclide activities. ^{40}K activity and the independently measured K concentration served as an internal standard for estimating the cosmogenic activities following the procedure of Bhandari et al. (1989). For noble gas analysis, the sample was wrapped in an Al-foil and loaded into the extraction system of a VG-1200 noble gas mass spectrometer. Stepwise pyrolysis, following an initial combustion at 400 °C in 2 torr O_2, was carried out for analyzing the noble gases following procedures described previously (Murty 1997; Murty et al. 1998). Standard procedures were followed for study of nuclear tracks in olivine (Krishnaswami et al. 1971). Oxygen isotope analyses were performed on separate powdered samples of the Balidua and Koilaghat fragments. Approximately 1 mg aliquots of the samples were analyzed by the laser fluorination technique described by Miller et al (1999).

RESULTS

Macroscopic and Microscopic Features

The largest piece of the meteorite (Fig. 2) is dull brown grayish in color, rectangular, and has a thin fusion crust devoid of any distinctive surface features. The meteorite was soaked in water by the local people soon after its recovery that led to rusting of the fusion crust and of interior portions exposed due

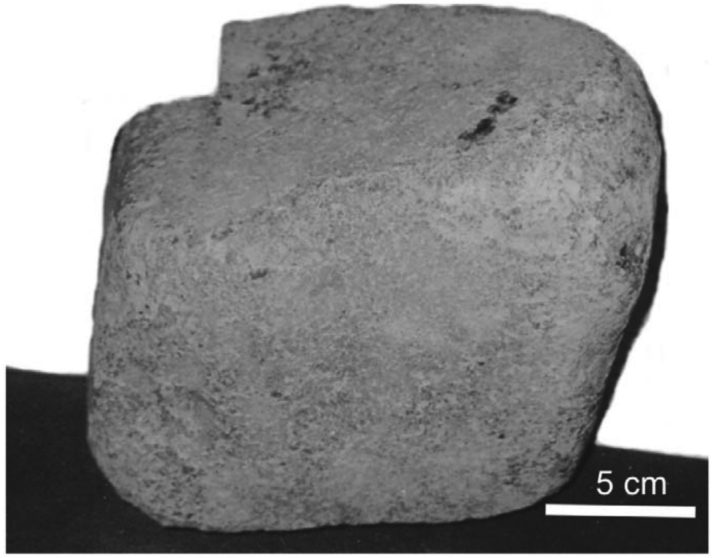

Fig. 2. The main fragment of the Dergaon meteorite (10.2 kg), which fell in Balidua.

to flaking off of the fusion crust prior to or at the time of impact. The meteorite is very fine-grained, and submilimeter-sized chondrules are visible on the exposed portions of both the Balidua and Koilaghat fragments. Studies of polished thin sections indicate a size range of 0.1–1 mm for the chondrules (Fig. 3), average size ~0.35 mm, typical of H chondrites. Chondrules representing various types and textures, such as porphyritic olivine, barred olivine, porphyritic olivine-pyroxene, radial, and cryptocrystalline or glassy are present. The chondrules show reaction rims as well as exsolution lamellae. The chondrule to matrix ratio measured in one polished thick section (1 cm × 0.8 cm) is 70:30.

Mineral Composition

Various mineral phases identified in the Dergaon meteorite include olivine, orthopyroxene, calcic pyroxene, Na plagioclase, chromite, troilite, kamacite, and taenite. Representative analyses of olivine, orthopyroxene and clinopyroxene are given in Table 1. The olivine is fosterite (Fo_{80}) with MnO content 0.5% and low CaO (<0.03%). Al_2O_3 is ~0.03% in matrix olivine, while it is below detection level in olivine within chondrules. The orthopyroxene is bronzite with nearly uniform Fs content (17.6 to 18.6 mole percent). The CaO is generally low (0.19% to 0.45%) in the grains in contact with clinopyroxene. A few orthopyroxene grains show higher values of CaO up to 1.72%. The clinopyroxene shows nearly uniform composition with CaO (21 to 22%). Traces of Na, Al, Cr, and Mn are also present. The average chemical composition of the clinopyroxene may be approximated as: En:Fs:Wo = 0.51:0.06:0.43. The compositions of a few glassy phases within chondrules indicate them to be feldspathic but with higher Ca, Na, and Mg contents. Overall, the mineral chemistry data indicate no marked heterogeneity in the composition of the major mineral phases.

The metallic phase present in the meteorite is mostly kamacite, although rare occurrences of taenite are found as exsolved lamellae in the metallic phases. The Ni content of the kamacite is uniform and ranges between 6.3 to 6.8 wt%. Trace amounts of Co, Cu, As, and P are also present.

Bulk Composition of the Dergaon Meteorite

The concentrations of several major, minor, and trace elements in the Dergaon meteorite obtained by using INAA, AAS and ICP-AES techniques are given in Table 2. Our data for both major elements (Al, Mg, Ca) as well as siderophile elements (Fe, Ni, Co, Ir, Os, Au) are generally consistent with those reported for H group chondrites. The sole exception is K content of 352 ppm that is more than a factor of two below the mean H group abundance (786 ppm; Kallemeyn et al. 1989). The low K concentration was also confirmed by gamma ray spectrometry that yielded a value of 328 ppm making it an atypical H chondrite. Concentrations of REEs (La, Sm, Eu, and Yb) are also similar to those observed for H chondrites (Kallemeyn et al. 1989).

Noble Gases

The noble gas data based on stepwise pyrolysis of a fragment from the largest recovered piece of the Dergaon meteorite are given in Tables 3a–3c. The data are corrected for blanks, interferences, and instrumental mass discrimination following procedures outlined previously (Murty 1997; Murty et al. 1998). Blanks at all temperatures are <5% of the signal for all gases and have near atmospheric composition within the limits of uncertainty. The errors in

Table 1. Chemical composition of major mineral phases in the Dergaon meteorite.

	Olivine					Orthopyroxene						Clinopyroxene				
SiO_2	39.2	39.3	38.7	39.5	40.2	55.8	56.4	55.4	57.0	56.3	57.2	54.0	54.5	54.1	54.2	54.0
Al_2O_3	0.03	–	–	–	–	0.18	0.22	0.25	0.11	0.16	0.06	0.42	0.33	0.73	0.88	0.48
FeO	19.2	18.4	18.5	19.7	18.3	11.4	11.7	11.2	11.7	10.9	11.3	4.19	7.98	3.94	3.54	3.95
MgO	42.3	41.7	41.1	42.8	42.1	29.4	29.7	28.6	30.1	29.5	29.7	16.2	25.8	17.4	17.3	16.7
MnO	0.48	0.50	0.47	0.43	0.40	0.44	0.49	0.37	0.44	0.43	0.52	0.41	0.32	0.26	0.23	0.14
CaO	–	–	0.03	–	–	0.45	0.65	1.73	0.58	1.24	0.60	21.3	7.38	22.1	22.0	22.0
Na_2O	–	–	–	0.09	0.12	–	–	0.04	–	–	0.05	0.45	0.08	0.46	0.48	0.37
TiO_2	0.14	–	0.15	–	0.07	0.20	0.15	0.11	0.08	0.19	0.11	0.32	0.25	0.17	0.31	0.18
Cr_2O_3	–	0.04	–	–	–	0.67	0.25	0.59	0.19	0.13	0.21	0.63	0.98	0.62	0.69	0.62
NiO	–	0.05	–	0.08	–	0.52	0.44	–	–	–	–	–	0.04	–	–	–
Total	101.4	100.0	99.0	102.6	101.2	99.1	100.0	98.3	100.2	98.9	99.8	97.9	97.7	99.8	99.7	98.5

"–" indicates below detection limit.

Table 2. Chemical composition of the Dergaon meteorite.

Element	Concentration
Al (wt%)	1.09
Ca	1.08
Mg	13.6
Fe	27.3
Ni	1.82
Cr (ppm)	3705
Co	830
Na	7061
K	352[a], 328[b]
Mn	2329
As	2.24
Zn	48.5
Se	7.88
Sc	8.21
La	0.35
Sm	0.21
Eu	0.08
Yb	0.24
Ir (ppb)	764
Os	833
Au	188

[a]AAS.
[b]Gamma ray counting.

Table 3a. He, Ne, and Ar in the Dergaon meteorite.

Temperature (°C)	^{4}He	^{22}Ne (10^{-8}cm^{3}STP/g)	^{36}Ar	^{3}He/^{4}He (10^{-4})	^{20}Ne/^{22}Ne	^{21}Ne/^{22}Ne	^{38}Ar/^{36}Ar	^{40}Ar/^{36}Ar
400	34.3	0.044	<0.01	37.5	0.9614	0.8666	–	–
				±3.2	.0846	.0110		
1000	1597	1.444	0.137	52.6	0.9721	0.8281	0.9626	9229
				4.4	.0009	.0020	.0028	178
1600	142.8	1.590	1.146	103.0	0.9698	0.8627	0.3914	1555
				8.7	.0011	.0012	.0001	30
Total	1774	3.038	1.283	56.4	0.9709	0.8462	0.4528	2372
				4.8	.0012	.0016	.0004	46

Table 3b. Kr and Xe in the Dergaon meteorite.

^{84}Kr (10^{-12}cm^{3}STP/g)	^{132}Xe	^{84}Kr ≡ 100 ^{82}Kr	^{83}Kr	^{86}Kr	^{132}Xe ≡ 100 ^{86}Kr	^{130}Xe	^{131}Xe	^{134}Xe	^{136}Xe
126.9	265.5	21.46	21.44	30.50	142.9	16.48	82.33	37.85	31.84
		±.03	.08	.07	.3	.06	.24	.08	.10

Table 3c. Cosmogenic, radiogenic, and trapped noble gas components (10^{-8} cm^{3} STP/g) in the Dergaon meteorite.

Cosmogenic			Radiogenic		Trapped		
^{3}He	^{21}Ne	^{38}Ar	^{4}He	^{40}Ar	^{36}Ar	^{84}Kr	^{132}Xe
10.0	2.56	0.388	1722	3043	1.02	0.0126	0.0265

abundances are ±10% (for He, Ne, Ar) and ±15% (for Kr, Xe). Errors in isotopic compositions represent 95% confidence limits. Kr and Xe in the 400 °C step are at blank level and the 1000 °C and 1600 °C fractions were combined for analysis. Concentrations and isotopic ratios of major isotopes of Kr and Xe are reported in Table 3b. Among the light noble gases, He and Ne are dominated by cosmogenic and radiogenic (^{4}He) components, while Ar is a mixture of trapped, cosmogenic and radiogenic components and ^{84}Kr and ^{132}Xe are of trapped origin.

Cosmogenic Radionuclides and Nuclear Tracks

The measured activities of eleven cosmic ray produced radionuclides with half-life varying from 16 d (^{48}V) to 0.73 Ma (^{26}Al) in a sample of the largest (Balidua) fragment of the Dergaon meteorite are given in Table 4. Negligible activity of ^{60}Co (<1 dpm/kg) suggests that, in spite of being a multiple fall, the pre-atmospheric size of the Dergaon meteoroid was rather small and no significant production of secondary thermal neutrons took place within the meteoroid during its recent cosmic ray exposure in space. The measured ^{26}Al activity (54.9 ± 0.9 dpm/kg) is consistent with that expected for a moderate-size H chondrite (Leya et al. 2000). Data for several of the longer-lived nuclides in the smaller (Koilaghat) fragment of the Dergaon meteorite are also included in Table 4. The data obtained from direct counting of both the fragments as well as from a smaller box sample from the larger Balidua fragment are consistent with each other.

Track densities in olivine isolated from several near surface samples of the large fragment of the Dergaon meteorite collected at Balidua, the size of which is approximately 18 cm × 10 cm × 17 cm, range between 1.5 × 10^{6} cm^{-2} to 8 × 10^{5} cm^{-2}. Samples of the smaller Koilaghat fragment yielded lower track densities in the range of (3–9) × 10^{5} cm^{-2}; the track data are presented in Table 5.

DISCUSSION

Classification of the Dergaon Meteorite

Petrographic and mineralogical data as well as bulk chemical composition indicate that the Dergaon meteorite is an H chondrite. The only deviation that is readily evident (see Fig. 4) is the distinctly lower K content (328 to 352 ppm) compared to the mean value of 786 ppm in H chondrites (Kallemeyn et al. 1989). The lower value of K makes Dergaon a unique meteorite amongst the H chondrites. The possibility that potassium was lost during the higher degree of metamorphism experienced by the Dergaon meteorite may be ruled out in the absence of any significant depletion of other volatile element (e.g. Na, Zn, Se; Fig. 4) relative to H chondrites (see, e.g., Patzer et al. 2004). We also explored the possibility of this meteorite belonging to some other groups such as the acapulcoites or lodranites that have some chemical similarities to ordinary chondrites but have suffered higher degree of metamorphism and differentiation. However, as noted above the relative depletion of other volatile elements such as Zn and Se seen in these groups of meteorites is absent in the Dergaon meteorite. Further, the measured oxygen isotopic compositions (Table 6) in samples of both Balidua and Koilaghat fragments of the Dergaon meteorite show that

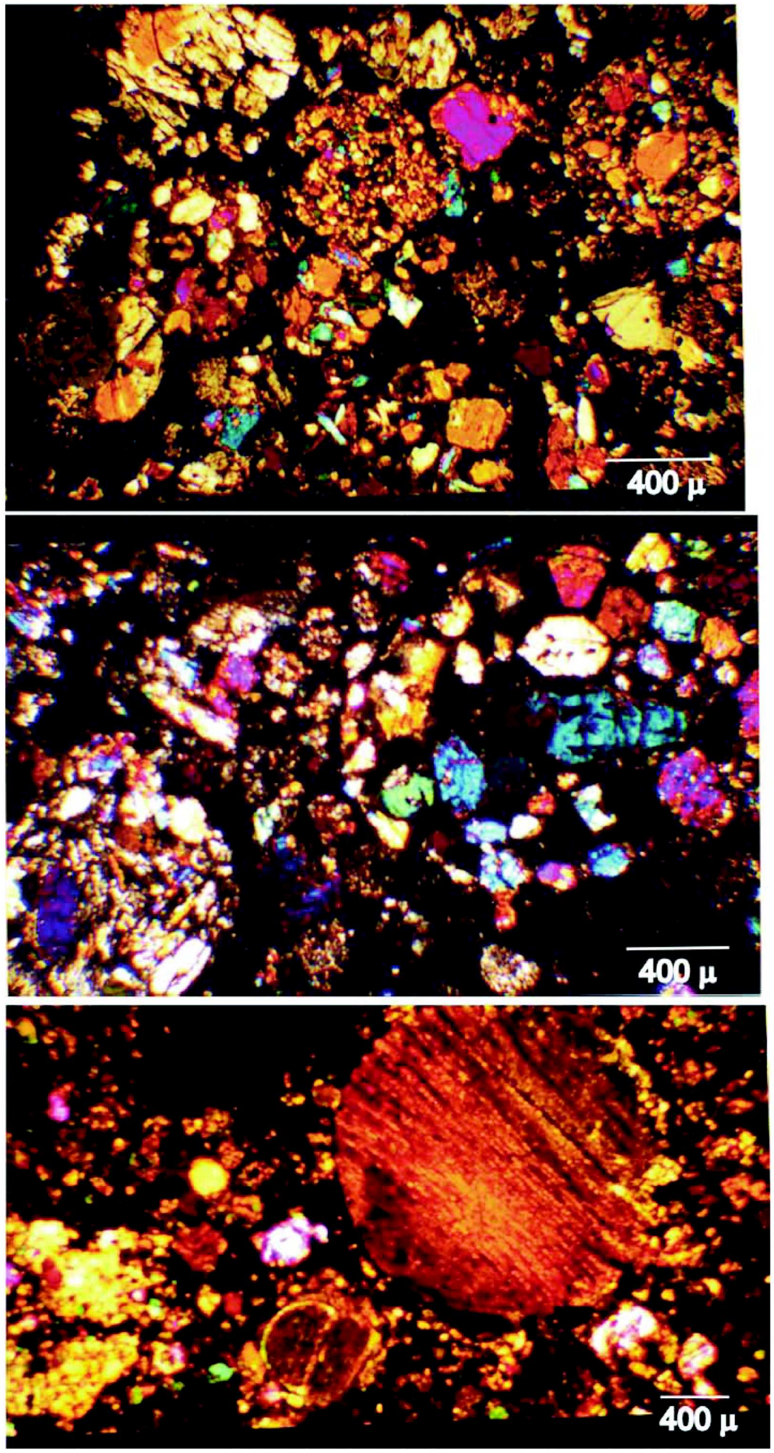

Fig. 3. Representative photomicrographs of several sections of the Dergaon meteorite showing chondrules of various types.

the oxygen isotope composition ($\Delta^{17}O$ values of +0.80‰ and +0.67‰, respectively) falls within the range for H chondrite (0.77 ± 0.04)‰ (Folco et al. 2004). Even though the intra-sample difference in the $\Delta^{17}O$ values is quite significant and may represent sample heterogeneity given the precision of such measurement (±0.02‰), these values are far removed from the average $\Delta^{17}O$ values for acapulcoites and lodranites (–1.04‰ and –1.10‰, respectively; Clayton and Mayeda 1996). It has been shown recently that Dar al Gani (DaG) 896 is a surface sample of a differentiated melt body originating from the floor of an impact crater on a H type asteroid, based on perfect match of its oxygen isotopic composition with H chondrites, although chemical composition indicated severe depletion of sidereophile elements (Folco et al. 2004).

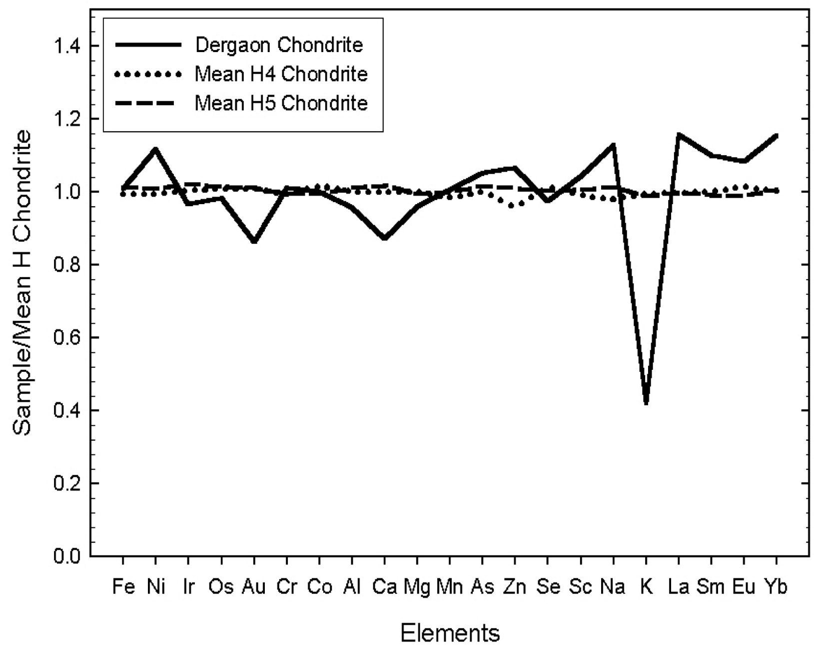

Fig. 4. Chemical composition of the Dergaon meteorite normalized to the mean H chondrite composition (Wasson and Kallemeyn 1988). Also shown are the average H4 and H5 compositions.

Table 4. Activity of cosmogenic radioisotopes at the time of fall (March 2, 2001) of the Dergaon meteorite.

Isotope	Half-life	γ-energy (keV)	Koilaghat fragment 1.4 kg cpm	Koilaghat fragment 1.4 kg dpm/kg	Balidua fragment 1.8 kg cpm	Balidua fragment 1.8 kg dpm/kg	Balidua box 55.5 g cpm	Balidua box 55.5 g dpm/kg
^{48}V	16 d	983.5			0.37 ± 0.03	14.4 ± 1.2		
		1311.6			0.29 ± 0.02	15.4 ± 1.1		
^{51}Cr	27.7 d	320.07			0.18 ± 0.03	46 ± 7.7		
^{7}Be	53.3 d	477.56	0.15 ± 0.02	56.1 ± 7.5	0.17 ± 0.01	47 ± 2.8		
^{58}Co	70.78 d	810.75	0.11 ± 0.01	5.3 ± 0.5	0.15 ± 0.01	5.3 ± 0.4		
^{56}Co	78.8 d	846.75	0.11 ± 0.01	5.5 ± 0.5	0.14 ± 0.01	5.1 ± 0.4		
^{46}Sc	83.9 d	889.26	0.11 ± 0.01	5.5 ± 0.5	0.15 ± 0.01	5.5 ± 0.4		
^{57}Co	271.35 d	122.07	0.26 ± 0.01	9.1 ± 0.4	0.28 ± 0.02	7.2 ± 0.5		
^{54}Mn	312.2 d	834.8	1.59 ± 0.01	76.5 ± 0.9	1.92 ± 0.02	68.2 ± 0.9	0.24 ± 0.01	84.7 ± 3.5
^{22}Na	2.6 y	1274.54	1.02 ± 0.01	71.6 ± 1.0	1.39 ± 0.01	72.0 ± 0.8	0.11 ± 0.01	56.6 ± 5.1
^{60}Co	5.27 y	1173.23	0.02	<1.4				
		1332.51	0.003	<0.2	0.02 ± 0.01	<1.0		
^{26}Al	7.3×10^5 y	1808.65	0.52 ± 0.004	52.2 ± 0.7	0.74 ± 0.01	54.9 ± 0.9	0.06 ± 0.003	44.2 ± 2.2
^{40}K (K = 340 ppm)[a]	1.28×10^9 y	1460.75	0.96 ± 0.01		1.30 ± 0.01		0.15 ± 0.006	
^{22}Na/^{26}Al				1.37		1.31		1.28

[a]Mean of AAS and gamma ray counting (Table 2).

Note: Errors are 1 σ (statistical). Additional error due to variation in K content is ~4%.

Nevertheless, DaG 896 showed an increased K content and not a deficit as in Dergaon. Hence, rather than attributing the K loss in Dergaon to metamorphic processes, it can be classified as anomalous H chondrite having low K content. In light of the above discussion, we conclude that Dergaon belongs to the H group of chondrite with a unique K composition. The presence of degraded boundaries around chondrules (Fig. 5a) as well as metal segregation and the presence of devitrified chondrules suggest that the Dergaon meteorite suffered a high degree of thermal metamorphism. Granoblastic texture and development of xenoblastic grain at the contact of chondrule margin also supports this view. A higher degree of metamorphism of the Dergaon chondrite can also be inferred from the texture showing enclosure of plagioclase laths with large pyroxene grains along with segregation of metallic phases (Fig. 5b) along the common boundaries of plagioclase and pyroxene grains. Further, the uniform composition of orthopyroxene and also of co-existing orthopyroxene-clinopyroxene pairs suggest attainment of metamorphic equilibrium during thermal

Table 5. Measured track densities in spot samples from two fragments of the Dergaon multiple fall.

Sample number	Track density (no. of tracks/cm^2)	Shielding depth (cm)
Balidua-1	$(1.2 \pm 0.04) \times 10^6$	4.7
Balidua-2	$(1.0 \pm 0.04) \times 10^6$	5.3
Balidua-3	$(1.1 \pm 0.04) \times 10^6$	5.0
Balidua-4	$(0.9 \pm 0.05) \times 10^6$	5.7
Balidua-5[a]	$(1.5 \pm 0.05) \times 10^6$	4.0
Balidua-6[a]	$(0.8 \pm 0.04) \times 10^6$	6.0
Balidua-7	$(1.3 \pm 0.06) \times 10^6$	4.5
Koilaghat-1	$(0.4 \pm 0.04) \times 10^6$	8.5
Koilaghat-2	$(0.9 \pm 0.06) \times 10^6$	5.7
Koilaghat-3	$(0.3 \pm 0.04) \times 10^6$	9.0

[a]Random samples (location unknown).

Table 6. Oxygen isotope data for two fragments of the Dergaon multiple fall.

Sample	δ^{17}O‰	δ^{18}O‰	Δ^{17}O‰
Balidua	3.15	4.53	0.80
Koilaghat	3.17	4.82	0.67

metamorphism. We have inferred the equilibration temperature using a numerical model ("QUILF" [Andersen et al. 1993]) and the composition of coexisting orthopyroxene and clinopyroxene pairs and obtained values between 660 °C and 820 °C and the mean value of 760 °C is close to the value suggested for the H5 group (Dodd 1981). These observations confirm that the Dergaon meteorite belongs to the H5 group. Features characteristic of a high degree of shock level are absent in Dergaon. Occasional irregular and fluid flow like features and planar fractures and undulatory extinction of olivine seen in thin sections studies are indicative of a low shock level (S2-S3) experienced by this meteorite.

Cosmogenic Records in the Dergaon Meteorite

Noble Gases

The amount of cosmogenic ^{3}He, ^{21}Ne and ^{38}Ar present in the Dergaon meteorite was derived using the end-member compositions suggested by Eugster (1988); these values along with the values for radiogenic ^{4}He, ^{40}Ar and trapped ^{36}Ar, ^{84}Kr and ^{132}Xe are given in Table 3. Using the value of $(^{22}\mathrm{Ne}/^{21}\mathrm{Ne})_c = 1.160 \pm 0.002$ and the chemical composition of the Dergaon meteorite, we have estimated the production rates of cosmogenic ^{3}He, ^{21}Ne (Eugster 1988), and ^{38}Ar (Marti and Graf 1992) and calculated the exposure age of this meteorite (Table 3a). We obtain values of 10.2 Ma and 9.2 Ma, respectively, based on ^{21}Ne and ^{38}Ar data and adopt the average value of 9.7 Ma as the cosmic ray exposure duration of Dergaon. A lower value of T_3 = 6.4 Ma is indicative of partial ^{3}He loss.

The cosmogenic ^{82}Kr/^{83}Kr ratio of 1.07 estimated from the Kr isotope data, for a trapped composition of Kr-Q (Busemann et al. 2000), is much higher than the pure spallation value expected for chondritic composition (0.77 ± 0.04, Lavielle and Marti 1988). This suggests the presence of excess ^{82}Kr (^{82}Kr$_n$) from ^{81}Br (n, $\gamma\beta$) ^{82}Kr reaction. The absence of thermal neutron produced ^{36}Ar$_n$ from ^{35}Cl (n, $\gamma\beta$) ^{36}Ar reaction as well as the very low activity of ^{60}Co clearly suggest that the thermal neutron fluence experienced by the Dergaon meteorite over its entire cosmic ray exposure duration, including the very recent past (over a few half-lives of ^{60}Co), is negligible. Taken together, these observations suggest that the size of the meteoroid was large enough to generate epithermal neutrons to produce ^{82}Kr$_n$ (Göbel et al. 1982), but not sufficiently large to generate thermal neutrons. We can put a limit of ~20 cm as the radius of the meteoroid to explain these observations (Eberhardt et al. 1963).

If we consider the data obtained for radiogenic ^{4}He and ^{40}Ar in Dergaon (Table 3a) and the average U (12 ppb) and Th (42 ppb) contents of H chondrites (Wasson and Kallemeyn 1988) as well as the measured K content of 340 ppm, we obtain U, Th-^{4}He age (T_4) = 4.18 Ga and K-Ar age (T_{40}) = 4.7 Ga. Although the precision is low, the values of T_4 and T_{40} are similar within experimental uncertainty (±10%) and the relatively lower value of T_4 is also consistent with partial ^{4}He loss.

Trapped Ne compnents contribute little to the measured Ne inventory. On the other hand, about 80% of ^{36}Ar and >99% of ^{84}Kr and ^{132}Xe are of trapped origin. The trapped ^{84}Kr and ^{132}Xe amounts suggest a high degree of metamorphism, close to grade 5 (Schultz et al. 1990), for this meteorite. The elemental ratios ^{36}Ar/^{132}Xe = 38.4 and ^{84}Kr/^{132}Xe = 0.47 are somewhat lower and are suggestive of partial loss of trapped noble gases, leading to enrichment of heavier gases. The absence of any appreciable gas loss in the cosmogenic (^{21}Ne, ^{38}Ar) and radiogenic (^{40}Ar) components, as well as the presence of ^{129}Xe (106×10^{-12} cm^{3}STP/g) from the decay of extinct radionuclide ^{129}I, suggest that the event that led to the loss of trapped gases must have occurred early on the parent body of the Dergaon meteorite and not during the breakup event that liberated the meteoroid ~9.7 Ma ago.

Cosmogenic Radioactivity

The measured ^{26}Al activity (54.9 ± 0.9 dpm/kg) in this meteorite is similar to those generally found in H chondrites. The slightly lower value for the powdered box sample (Table 4) taken from the near surface region of the Balidua fragment can be attributed to its lower effective shielding depth (see Table 5). If we consider the production depth profiles of ^{26}Al for spherical H type meteoroids of various sizes (Bhandari et al. 1993; Leya et al. 2000), the preatmospheric radius of the Dergaon meteoroid is estimated to be ≥20cm. On the other hand, the negligible activity of ^{60}Co (<1.0 dpm/kg), which is produced by thermal neutron capture, indicates that the preatmospheric size of the Dergaon meteorite was not large enough to thermalize secondary

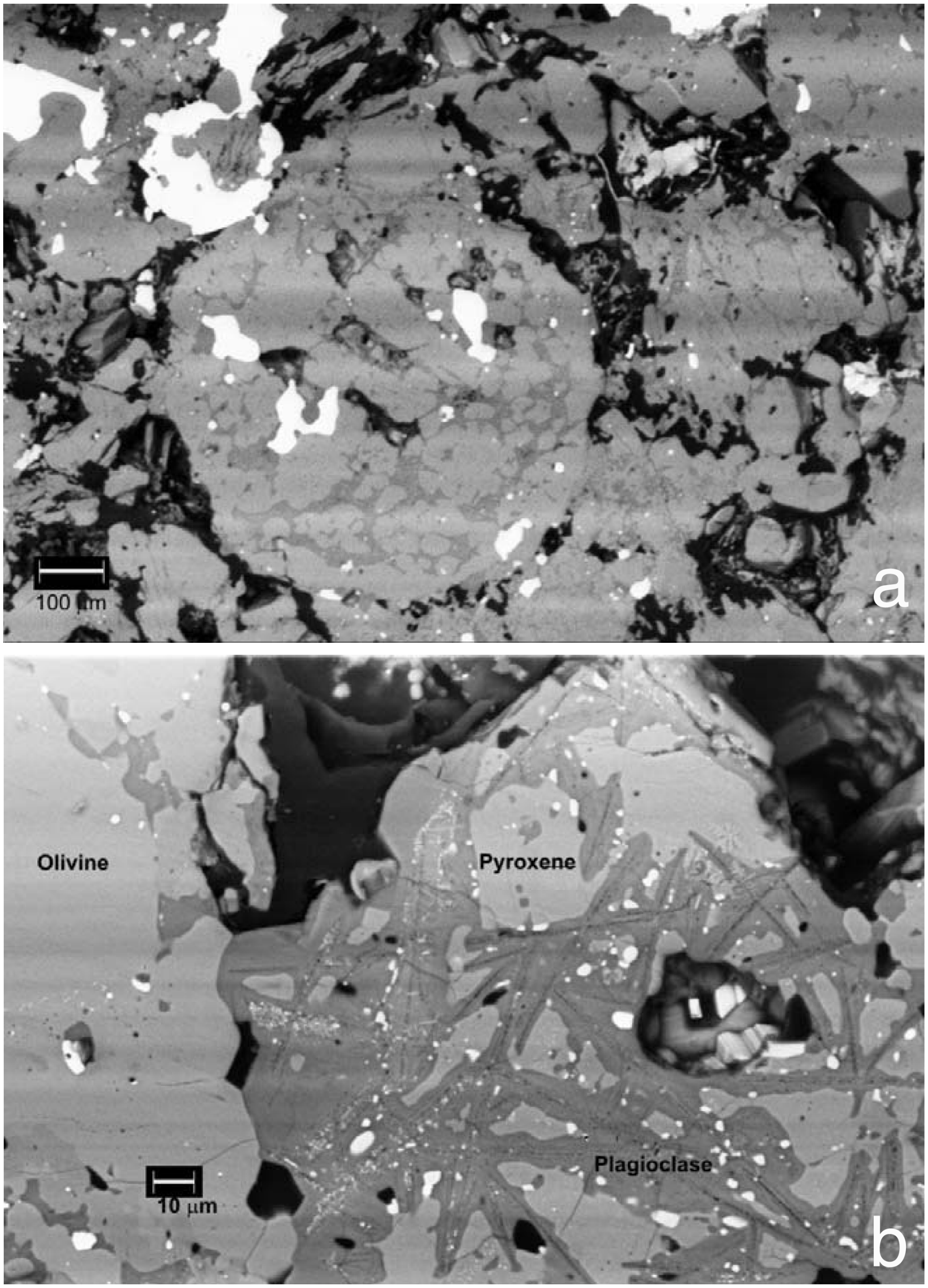

Fig. 5. Backscattered scanning electron microscope images of a large chondrule with degraded boundaries (top) and intergrowth of pyroxene and plagioclase, with metallic phases around the plagioclase (bottom).

neutrons produced within the meteoroid by high energy galactic cosmic ray proton induced interactions during its space exposure. This puts a limit of about 20 cm for the preatmospheric size considering the production depth profile given by Eberherdt et al. (1963). We shall consider the above constraints in conjunction with the nuclear track and noble gas data (see next section) to infer a plausible size of the Dergaon meteoroid. The $^{22}Na/^{26}Al$ activity ratio is an indicator of the average flux of GCR for a few years prior to the fall of a meteorite (see, e.g. Bhandari et al. 2002). The observed $^{22}Na/^{26}Al$ activity ratio (1.31 ± 0.03) in Dergaon is consistent with the value calculated on the basis of sunspot numbers during solar cycles 22 and 23 following the procedure of Bhandari et al. (1989).

Nuclear Track Record and Preatmospheric Size of the Dergaon Meteorite

It is possible to estimate the shielding depth of a sample from the recovered meteorite within the original meteoroid by combining nuclear track data and cosmic ray exposure age following the procedure of Bhattacharya et al. (1973). The track data presented in Table 5 combined with the exposure age of 9.7 Ma derived from ^{21}Ne and ^{38}Ar data indicate shielding depths of ~4.0 to 6.0 cm for the various samples analyzed from different diametrically opposite locations of the largest fragment of the Dergaon meteorite recovered at Balidua. Measured track densities for several samples from the smaller fragment recovered at Koilaghat suggest somewhat higher shielding depths of ~6 to 9 cm. We have considered a value of ~25 kg for the total mass of the Dergaon fall (assuming the recovered mass to represent ~50% of the total fall) in obtaining these values. It may be noted here that the estimated shielding depths are only slightly sensitive to this parameter (see, e.g., Bhattacharya et al. 1973) and even for a recovery efficiency of 10% for this multiple fall, the shielding depths in Table 5 will be lower by only a few millimeter to about a centimeter. Reconstruction of the preatmospheric size of a meteorite is rather straightforward in the case of a single fall when samples from various faces of the recovered meteorite are analyzed. However, for a multiple fall, as is the case for the Dergaon meteorite, the same approach may be applied only if the center of the original meteoroid is contained within the analyzed fragment. Fortunately, this is the case for the largest fragment of the Dergaon meteorite where samples located on diametrically opposite surfaces in three orthogonal directions and separated by more than 10 cm within the recovered fragment yielded low values of shielding depth (4 to 6 cm) in the original meteoroid suggesting that the center of the Dergaon meteoroid is located within this fragment. We have used the track data for this fragment to arrive at a preatmospheric radius of ~20 cm for the Dergaon meteorite. Combining this value with the limits inferred from ^{26}Al activity and Kr isotopic ratio (≥20 cm) and ^{60}Co activity (≤20 cm) we consider a value of 20 cm to be the most plausible preatmospheric radius of the Dergaon meteorite.

SUMMARY AND CONCLUSIONS

Major, minor, and trace elemental composition as well as oxygen isotopic ratio show that the Dergaon meteorite belongs to the H group of chondrites with a unique exception of K whose abundance is lower by a factor of about two than expected for H chondrites. Petrographic records as well as trapped noble gas data suggest that this meteorite experienced a high degree of thermal metamorphism and may be classified as an H5 chondrite. A cosmic ray exposure age of 9.7 Ma is estimated from the cosmogenic noble gas data. Activities of cosmogenic radionuclides are at saturated level, and the $^{22}Na/^{26}Al$ activity ratio is similar to that expected based on solar modulation of galactic cosmic rays during the rising phase of the solar cycle 23. The combined noble gas, radioactivity, and nuclear track data suggest a preatmospheric radius of ~20 cm for this meteorite.

Acknowledgments–We acknowledge technical help provided by K. M. Suthar in obtaining the track data reported in this paper. We appreciate helpful reviews by Kees Welten and an anonymous reviewer. This work was partially supported by the PLANEX program of the Indian Space Research Organization (ACM, PP, and KD).

Editorial Handling—Dr. Marc Caffee

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