The Meteoritical Society

Meteoritics & Planetary Science 43, Nr 4, 761–770 (2008)
Abstract available online at http://meteoritics.org

Ararki (L5) chondrite: The first meteorite find in Thar Desert of India

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(Received 10 February 2007; revision accepted 18 September 2007)

Abstract–We report here a chance find of a meteorite in the sand dunes of Ararki village of Hanumangarh district in the Rajasthan desert of northwest India. Chemical and petrological evidence in conjunction with isotopic composition of oxygen indicate that it is an L5 chondrite. The fayalite content of olivines is 26.3 mol%. The meteorite has some serpentinized olivines and 0.3% carbon having a terrestrial isotopic composition, indicating that it is moderately weathered. The absence of ^{22}Na indicate that the meteorite fell to Earth more than a decade ago. The cosmic-ray exposure age based on cosmogenic ^{21}Ne is 7.2 Ma. Low density of cosmic-ray heavy nuclei tracks, low ^{26}Al activity, the shielding parameter [$(^{22}Ne/^{21}Ne)_C = 1.094$] and absence of neutron capture effects indicate cosmic-ray shielding in a meteoroid having radius of about 16 cm, implying a meteoroid mass of about 60 kg and ablation of about 93%. The gas retention ages, based on U/Th-^4He and K-^{40}Ar are 1.1 and 0.58 Ga, respectively, suggesting a heating and degassing event late in the history of this meteorite.

INTRODUCTION

Thousands of meteorites have been found during the past several decades in hot deserts of the world, e.g., in Oman, North Africa and Australia (see e.g., Welten et al. 2004). Similar finds would be expected in the northwestern Thar Desert of Rajasthan, although no systematic search has been made so far. We report here the first find of a chondrite in the sand dunes of northern Rajasthan, suggesting the possibility of meteorites being preserved in this hot desert.

The Hanumangarh district in northern Rajasthan is a vast alluvial terrain devoid of any rocky hills and occurrence of hard rocks in the sandy farm lands is unusual. A stone, however, was found in 2001 near a recently excavated canal on a farm in Ararki village (29.06°N, 74.44°E; Fig. 1) by local residents Suman and Bhagirath Swami. After washing off the reddish black soil adhering to it, they found that the stone was magnetic. They contacted one of us (N. B.) and subsequently G. Lashkari of J. N. V. University visited the site and collected the sample. Further examination at Physical Research Laboratory confirmed it to be a meteorite.

VISUAL EXAMINATION AND PETROGRAPHIC STUDIES

The roundish meteorite has dimensions of $6 \times 8 \times 10$ cm and weighs 4.46 kg. It has a sandy surface with reddish, heavily weathered and oxidized fusion crust. Ablation features like regmaglypts are not recognizable, probably due to weathering. The interior appears black and is relatively less weathered, but some cracks are present throughout the rock. Figure 2 shows the surface and interior of the meteorite.

Thin sections of the meteorite (Fig. 3) show a large variety of abundant chondrules. These include barred, radial, fine grained, granular, and porphyritic olivines (about 40%), Ca-poor-pyroxenes (about 30%) types of chondrules of different shapes, sizes, and composition. Many chondrules are rusty and fractured. Their boundaries generally appear diffuse, sometimes barely discernible as they are intergrown with the granular matrix that largely consists of olivine, pyroxene, and opaque minerals (mostly nickel-iron and troilite). Olivines show simple twinning while pyroxenes generally display polysynthetic twinning. The meteorite is mildly shocked and also has veins

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Fig. 1. Location map of Ararki village in Hanumangarh district of Rajasthan, where the meteoritic stone was found.

filled with metal and graphite (Fig. 4) indicating that it belongs to high metamorphic grade, probably grade 5. Figure 4b shows that large apatite grains are also present.

Scanning electron microscopy (SEM) shows that the matrix has abundant fine-grained olivines with sizes in the range of 0.5 to 0.8 μm. There is some evidence of olivine associated with intergrowths of serpentine (odinite, Fig. 5) and phyllosilicates having dimensions of 50 to 500 nm. Presence of secondary minerals indicates weathering during the meteorite's residence on Earth (Zeigler et al. 2006). Energy dispersive (EDAX) and electron probe microanalysis (EPMA) were carried out to quantify the minerals. The measurements were made using an automated CAMECA SX-100 electron microprobe analyzer with an accelerating voltage of 15 kV, a beam current of 1.5 nA, and a beam diameter of ~1 micrometer. Table 1 shows some representative analysis of olivine and low-Ca pyroxene grains from Ararki meteorite. Olivine is 26.3 mol% fayalite indicating that the meteorite belongs to L group of chondrites. However, the abundance of olivines (about 40%), Ca-poor pyroxenes (30%, with Fs contents 23 mol%) and high metal content (5 to 8%) indicates that the meteorite lies at the boundary of L and H type (Hutchison 2004).

Concentration of several elements was measured using different techniques. X-ray fluorescence (XRF) measurements were made using a Philips XRF analytical system. Three independent measurements were carried out on 3 different sets of powdered sample, using Dhajala (H3.8) chondrite as standard. Typical uncertainty is about 0.01 wt% in oxides. The carbon, hydrogen, nitrogen, and sulphur content was measured using a C-H-N-S- analyzer (Elementer-Vario- EL III). The trace and rare earth elements were measured using a Perkin Elmer ICP-MS system on 2 aliquots of the sample. About 50 mg of the samples and the standards were dissolved using the microwave acid-digestion technique following the procedure described by Balaram and Rao (2003). Concentrations of some elements (Fe, Ca, Ni, Co, Cr, Sc, Zn, As, Se, Eu, Ir, Os, and Au) were measured by instrumental neutron activation analysis (INAA). Allende (CV) and Dhajala (H3.8) meteorites were used as standards. The experimental set up and counting procedures are described in Murty et al. (2004). K, Th, and U were estimated by gamma counting with respect to our laboratory basalt standard (#107) of known concentrations (U = 5.69 ppm, Th = 14.5 ppm, and K = 2.63%). Concentrations of all these 3 elements are susceptible to terrestrial modification because U and Th are very high in soil compared to chondrites whereas K can be leached by rain. Concentrations of cobalt, chromium, and nickel determined by XRF and ICPMS are in agreement and results of INAA and XRF are also in agreement in most cases. Notable exceptions are Fe and Ni which are found to be higher in XRF analysis. We attribute this difference to sample inhomogeneity. Superior results or average values, where more than one technique was used, are given in Table 2. The results show Fe = 23%, Mg = 14.57%, Si = 15.8%, and Ni = 1.34% implying that Ararki belongs to L group of chondrites. Chondrite normalized profile of the 4 rare earth elements (Sm, Eu, Yb, and Lu) measured in Ararki is also flat as expected. Sulphur is abundant, measured to be about 2% even after a long terrestrial exposure, indicating little weathering of the meteorite. The abundance of carbon (0.32 wt%), is high for an L chondrite. The isotopic composition (Table 3) show $\delta^{13}C = -23‰$, similar to terrestrial organic carbon. Therefore, carbon in Ararki is likely to be terrestrial contamination. To confirm the L group classification, the isotopic composition of oxygen was measured at the Open University, U.K. These results are given in Table 3. Two aliquots gave good reproducibility and the isotopic composition is similar to that observed in L group chondrites. From the data, it appears that there is only slight, if at all, effect of weathering on oxygen isotopic composition.

MÖSSBAUER STUDIES

We have carried out Mössbauer studies to determine the behavior of iron minerals and to see if there is any effect of weathering (Bland et al. 1998). Ordinary chondrites primarily have 4 iron-bearing minerals, namely olivine $(Fe,Mg)_2SiO_4$, orthopyroxene $(Fe,Mg)SiO_3$, troilite (FeS), and kamacite (Fe-Ni alloy). Substitution of Ca and Al at different sites in the structure of some of these minerals in various proportions is also common. In each of these minerals, there are 2 unequivalent octahedral cation sites known as M1

Fig. 2. Surface features on the rounded sandy surface of the meteorite and the dark interior.

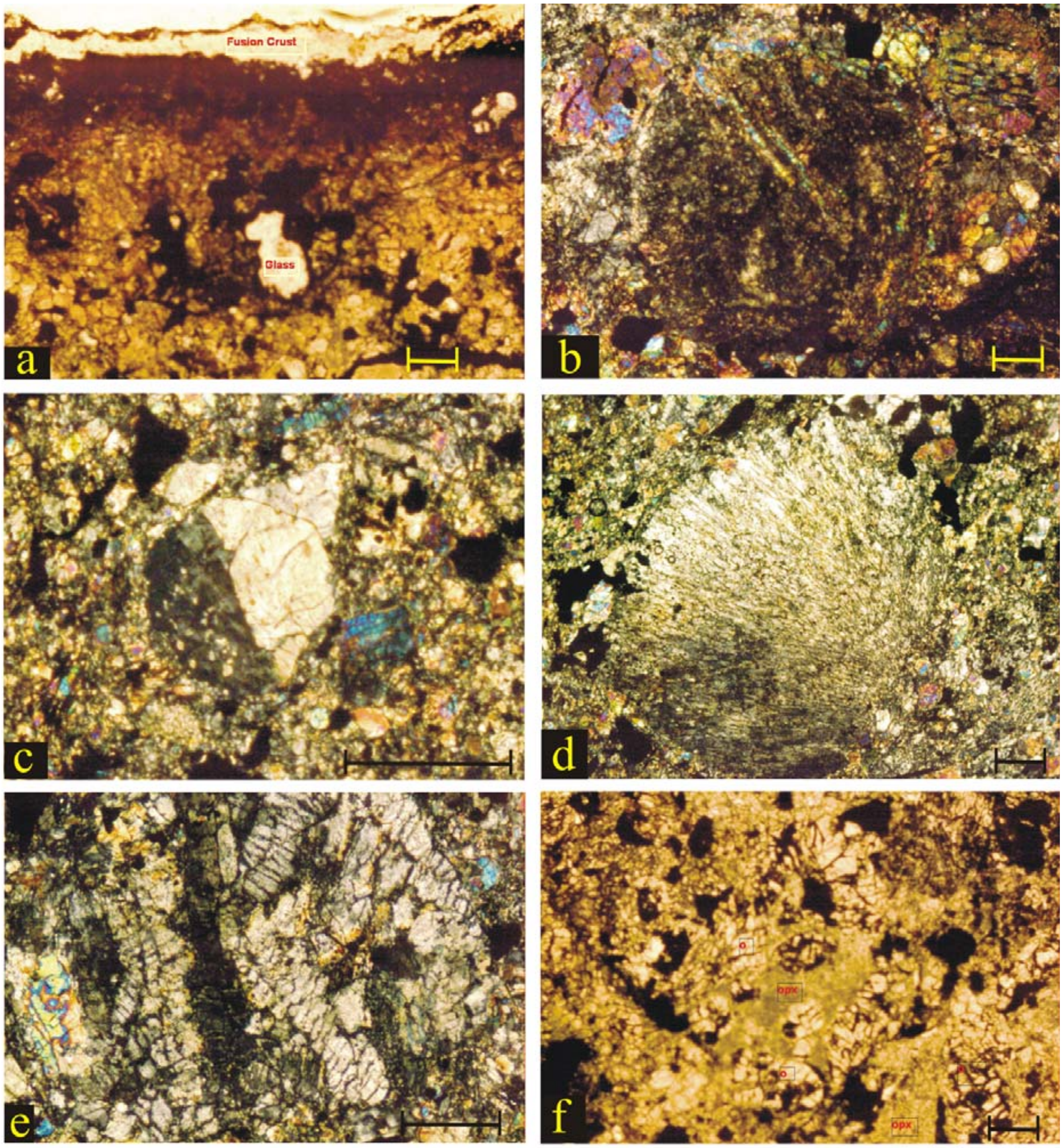
and M2. The Mössbauer spectrum for each of these iron environments is a quadrupole doublet. The Mössbauer parameters for iron in M1 and M2 sites of olivine are quite close and normally the 2 components remain unresolved. On the other hand, the 2 sites in pyroxene give somewhat different Mössbauer parameters. However, iron in meteoritic pyroxene preferentially occupies the more distorted M2 sites. Troilite is a magnetically ordered mineral and shows a 6-line component in the Mössbauer spectrum having a hyperfine field of about 31.6 T. The hyperfine magnetic field of kamacite which determines the splitting in the 6-line pattern, varies slightly with the Ni content but remains close to the pure iron value of 33 T.

The average Mössbauer parameters of these phases are well known (Verma et al. 2003). The Mössbauer parameters (quadrupole splitting [Qs], isomer shift [Is], magnetic hyperfine field [B_{hf}], and the absorption area) are given in Table 4. The Mössbauer spectrum of chondrites consists of 2 slightly overlapping strong doublets, each having a center shift of around 1.1 mm s^{-1}. The splitting of the outer doublet is around 3 mm s^{-1} and that of the inner one is around 2.0 mm s^{-1}. In addition to these, there are 2 sextets of small amplitudes corresponding to troilite and kamacite. On the negative velocity side, the outermost peaks of the 2 sextets are quite distinct, but on the positive velocity side, they often merge into a single broad peak.

The Mössbauer spectrum of the Ararki meteorite at room temperature is shown in Fig. 6. The spectrum consists of olivine, pyroxene, troilite and very little (~1% of total absorption area) kamacite; no other iron mineral is present in significant amount. The systematics of the Mössbauer absorption area for metallic phase versus silicate phase for ordinary chondrites is shown in Fig. 7 in which H and L/LL chondrites fall in different regions. There is a small region where there is an overlap of H and L chondrites. From this figure it can be seen that Ararki falls in the field of L/LL chondrites. However, the pyroxene abundance is unusually high for L chondrites and the olivine to pyroxene ratio in Ararki is close to the average value found in H-chondrites. This ratio depends on the geochemistry at the time of cooling/formation of minerals. The Sextet 1 indicates slightly altered troilite attributed to mild weathering. The hyperfine magnetic field at the nucleus (Bhf) in Ararki troilite is measured to be 28.7 T, which is only slightly lower than the average value of 31.1 T in meteoritic troilites. Such lowering may occur due to decomposition of troilite in smaller grains at early stages of weathering. Severe weathering and chemical alteration can be excluded on the basis of these results.

NOBLE GASES

A clean chip of the meteorite, part of which was used for chemical analysis, was taken for noble gas studies. The sample was wrapped in Al foil and loaded into the extraction system of the noble gas mass spectrometer. All noble gases were analyzed by stepwise pyrolysis, after an initial combustion at 400 °C in 2 torr O_2 using standard procedures described earlier (Murty 1997; Murty et al. 1998). The data reported here have been corrected for blanks, interferences, and



Scale bar 200μm

Fig. 3. a) Photomicrograph of thin section of the meteorite close to the fusion crust (polarized light). The outer margin of the stone is generally stained red due to weathering. Occasional glassy patches are also seen in the granular matrix as marked; b) Chondritic structure. The boundary of most of the chondrules tends to merge with the granular matrix (crossed Nicols); c) Euhedral olivine crystal (twinned, simple) in a fine-grained matrix of olivine and pyroxene (crossed Nicols); d) Radiating chondrule showing partial integration with granular matrix (crossed Nicols); e) A large chondrule composed of pyroxene with some olivine grains in between. The pyroxene shows undulose extinction. The margin of the chondrule integrates partially with the granular matrix (crossed Nicols); f) Granular matrix of olivine and pyroxene with minor amount of opaques (polarized light). Scale bar in all the photographs is 200 μm.

instrumental mass discrimination. Blanks at all temperatures are ≤5% of the signal and have near atmospheric isotopic composition within errors. The noble gas concentrations are given in Table 5. Helium consists of almost pure cosmogenic and radiogenic (^{4}He) components, but Ne isotopic composition suggests the presence of a small amount of trapped Ne component. Ar is a mixture of trapped, cosmogenic, and radiogenic components. Using the end member compositions suggested by Eugster (1988) for trapped and cosmogenic components in ordinary chondrites, we derive cosmogenic ^{3}He, ^{21}Ne, ^{38}Ar, and radiogenic (^{4}He, ^{40}Ar, ^{129}Xe) components. These are given in Table 6.

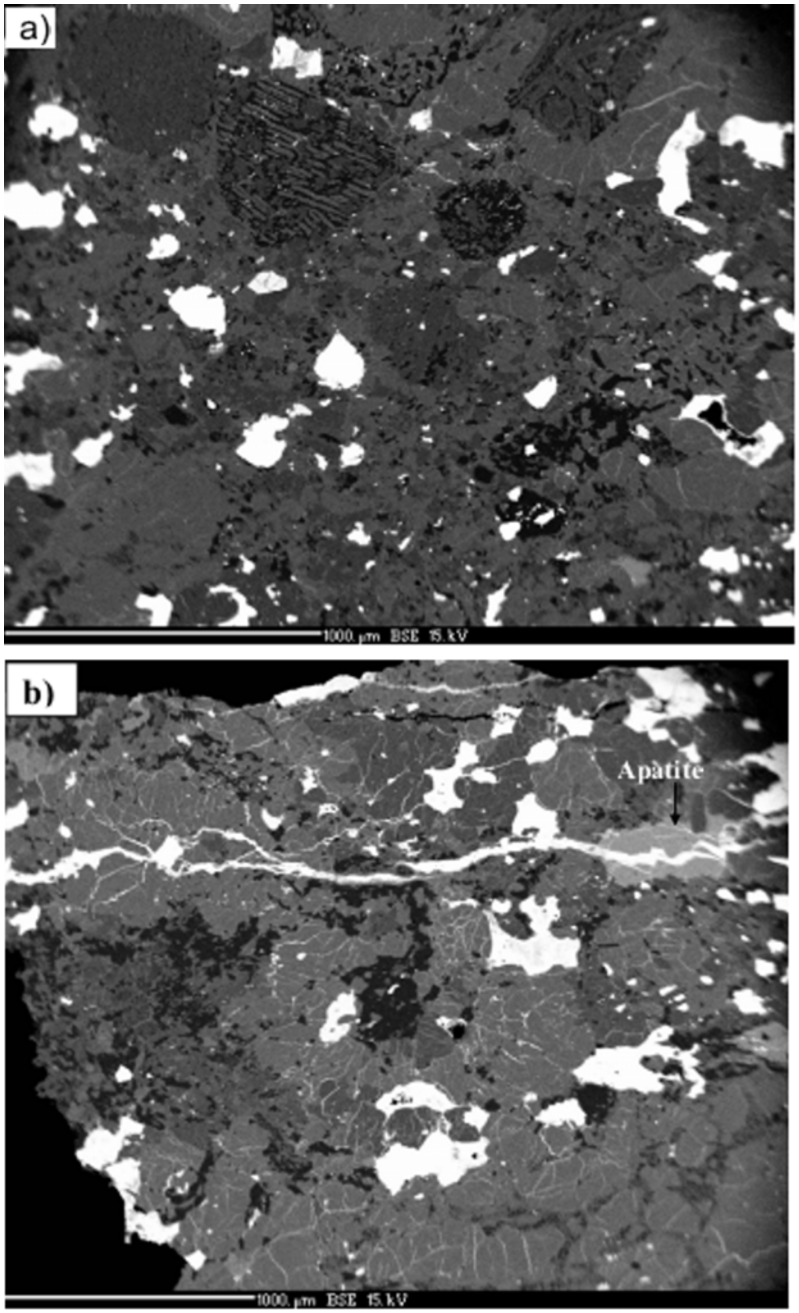


Fig. 4. a) The general texture of Ararki chondrite as seen in the back scattered electron image of a polish thick section. Various types of chondrules showing diffused/distorted chondrule boundaries, large crystals of olivine, low-Ca pyroxenes within the chondrule and large metal grains depicting high petrological class; and b) a metal vein flowing through a large apatite grain (~400 μm).

COSMOGENIC COMPONENTS AND EXPOSURE AGES

Cosmogenic $(^{22}Ne/^{21}Ne)_c$ has a value of 1.094 ± 0.003, indicating several centimeters of shielding for the sample analyzed for noble gases. For the chemical composition of Ararki and the shielding parameter as given by $(^{22}Ne/^{21}Ne)_c$, production rates for ^{3}He and ^{21}Ne are calculated following the procedure suggested by Eugster (1988). In case of ^{38}Ar the modified procedure of Marti and Graf (1992) has been used. The exposure ages obtained from various cosmogenic components (Table 6) are (in Ma) $T_3 = 4.6$, $T_{21} = 7.2$, $T_{38} = 5.3$ (Table 7). The lower value of T_3 could be due to partial loss of ^{3}He, most probably during interplanetary transit. Lower T_{38} on the other hand could be either due to uncertainty in production rates or due to terrestrial weathering involving preferential loss of a Ca-rich phase.

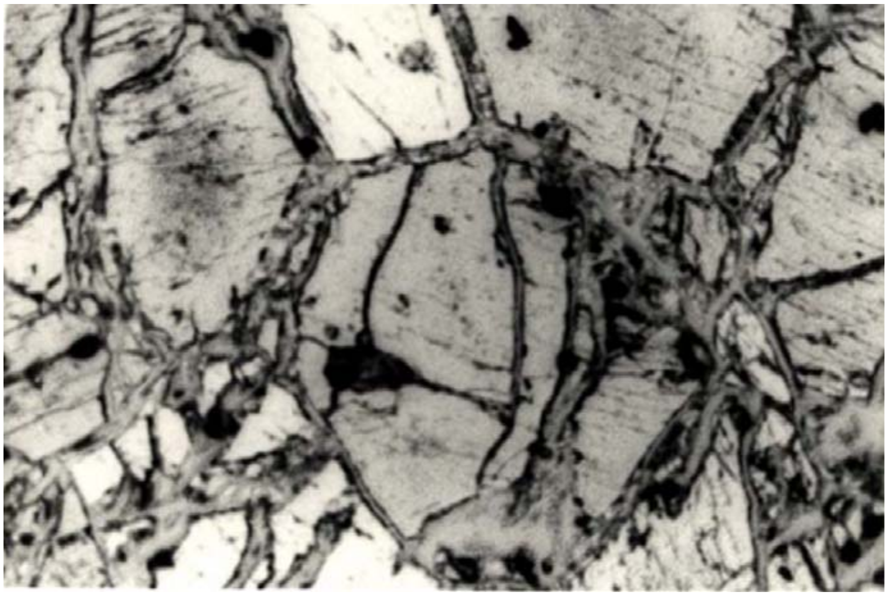


Fig. 5. Evidence of serpentinized olivine. The section is 200 µm wide.

Table 1. Composition of olivine and low-Ca pyroxenes in Ararki chondrite.

Oxide	Olivine						Low-Ca pyroxenes				
(wt%)	Chondrule	Matrix					Chondrule		Matrix		
SiO_2	37.34	37.75	37.32	37.38	37.64	37.01	53.39	54.00	54.83	54.78	54.61
Al_2O_3	0.31	0.04	–	–	0.00	0.08	0.58	0.28	0.16	0.12	0.13
FeO	24.58	22.51	23.76	24.61	22.93	25.07	15.69	15.09	15.11	14.52	15.07
MgO	36.04	38.52	37.99	38.26	38.32	36.81	27.58	28.17	28.97	28.59	28.34
MnO	0.33	0.36	0.45	0.39	0.55	0.41	0.38	0.48	0.38	0.58	0.40
CaO	0.07	0.01	0.01	0.04	0.02	0.04	0.67	0.65	0.66	0.56	0.60
K_2O	0.01	–	0.01	–	0.02	0.01	0.01	–	0.02	–	0.02
Na_2O	0.01	0.00	–	–	0.04	0.01	0.02	0.04	0.03	0.03	0.00
TiO_2	0.02	0.03	0.00	–	0.01	–	0.23	0.28	0.14	0.13	0.13
Cr_2O_3	0.07	–	0.07	0.06	–	0.10	0.86	0.09	0.20	0.01	0.06
NiO	–	0.03	–	0.10	0.13	0.21	0.17	0.17	0.18	0.03	0.00
Total	98.8	99.3	99.6	100.8	99.7	99.7	99.6	99.3	100.7	99.4	99.4
Fa (mol%)	27.7	24.7	26.0	26.5	25.1	27.7					
Fs (mol%)							23.9	22.8	22.4	21.2	22.1
En (mol%)							74.8	75.9	76.4	74.5	74.0
Wo (mol%)							1.30	1.26	1.25	1.05	1.12

RADIOGENIC COMPONENTS AND GAS RETENTION AGES

The radiogenic ages are determined from the radiogenic ^{4}He and ^{40}Ar (Table 6). Although U, Th, and K have been measured in this meteorite, because of the possibility of their alteration due to weathering, as discussed earlier, we prefer to use the average L group concentrations (Wasson and Kallemeyn 1988) of U (18 ppb), Th (42 ppb), and K (920 ppm). We thus obtain U, Th-^{4}He (T_4) and K-Ar (T_{40}) ages of 1.1 and 0.58 Ga, respectively (see Table 7). Lower T_{40} (than T_4) indicates loss of radiogenic ^{40}Ar carrier phase due to terrestrial weathering. The measured ratio $^{129}Xe/^{132}Xe$ (1.296 ± 0.006) is higher than the trapped chondritic value and indicates presence of $^{129}Xe^*$ (from decay of ^{129}I). Lower amount of $^{129}Xe^*$ (7×10^{-12} ccSTP/g) could also be due to selective loss of gases from an iodine carrying phase.

TRAPPED COMPONENT

Trapped helium in Ararki is negligible. About 55% of ^{20}Ne is of trapped origin. About 60% of this trapped Ne gets released at or below 800 °C, and the remaining comes mostly in 1600 °C step and hence cannot be dismissed as

Table 2. Bulk chemical composition[a] of the Ararki meteorite.

Major elements	Concentration (%)	Trace elements	Concentration (ppm)
Si	15.81	V	94.5[2]
Fe	23.0	Sc	8.65
Mg	14.57	Zn	97.5[2]
Al	1.44	Ga	7.75[2]
Ca	1.64	Ge	22.5[2]
Ni	1.34	As	2.06[2]
Mn	0.169	Se	7.7
Na	0.5	Ru	1.04
K	0.0749[5]	Sm	0.239[2]
P	0.126	Ir	0.517
Co	0.0642	Os	(0.606)
Ti	0.08	Au	0.157
Cr	0.372	Eu	0.08[4]
S	2.02[3]	Yb	0.287[2]
		Lu	0.042[2]
C	0.34[3]	Th	(0.080)[5]
		U	(0.040)[5]

[a]Average or the most reliable values based on (1) X-ray fluorescence, (2) ICPMS, (3) CHNS analyzer, (4) INAA, and (5) gamma counting methods. The values within parentheses have higher errors ranging between 15 to 23%.

Table 3. Isotopic composition of carbon and oxygen.

$\delta^{13}C$	$\delta^{17}O$	$\delta^{18}O$	$\Delta^{17}O$
−23‰	3.58	4.92	1.03
	3.69	5.04	1.07

atmospheric contamination. About 70% of ^{36}Ar and >95% of ^{84}Kr and ^{132}Xe are of trapped origin (Table 8). The amounts of these trapped gases are similar to the reported values among the ordinary chondrites (Eugster et al. 1993). Trapped ^{84}Kr and ^{132}Xe fall in the range of values expected for petrologic type 5/6 (Schultz et al. 1990). The elemental ratios ($^{36}Ar/^{132}Xe$) = 147 and ($^{84}Kr/^{132}Xe$) = 1.39 are higher than expected for Q component (Ott 2002) in ordinary chondrites. It may be noted that noble gas component with higher elemental ratios is generally observed in CO, CV, and CK carbonaceous chondrites.

COSMIC-RAY TRACKS

Two spot samples of the meteorite taken from diagonally opposite corners were processed for cosmic-ray heavy nuclei tracks. The samples were etched in boiling WN etchant of Krishnaswami et al. (1971) for 6 h to reveal tracks in olivine grains, but no tracks could be found, setting an upper limit of $10^5/cm^2$ for the track density. Taking the exposure age of 7.4 Ma and following the procedure of Bhandari et al. (1980) we estimate that the meteorite has been ablated at least 9 cm on both the locations, consistent with cosmogenic $^{22}Ne/^{21}Ne$ ratio.

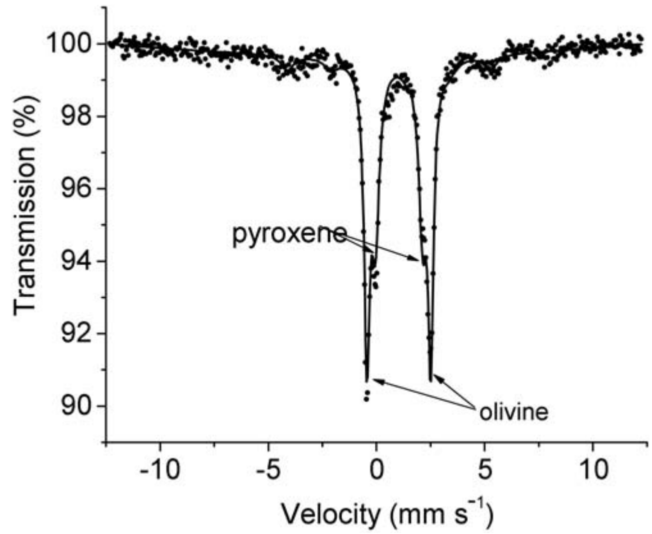


Fig. 6. Mössbauer spectrum of the Ararki meteorite showing olivine and pyroxene absorption bands.

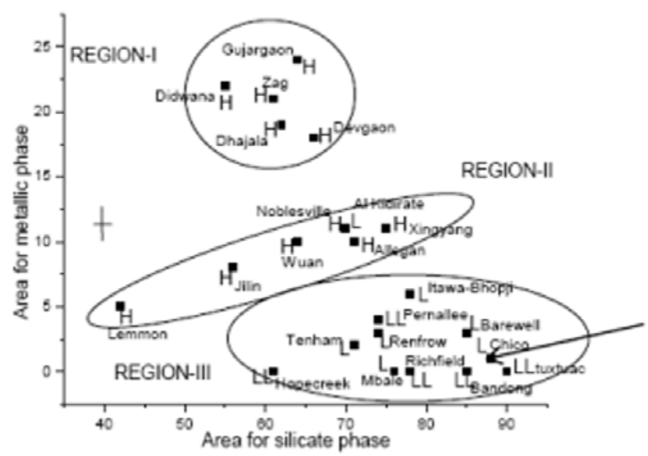


Fig. 7. Olivine/pyroxene absorption ratios in H and L/LL chondrite types falling in 2 distinct regions (I, III). Some L chondrites overlap in the field of H chondrites, marked by region II. The Ararki value, shown by an arrow, falls in region III.

GAMMA ACTIVITY

A sample weighing 62.119 g, taken from the interior of the Ararki meteorite, was counted on a large volume gamma ray spectrometer for 38,054 min during October 2003. The gamma ray spectrometer consists of a large volume hyper pure germanium detector having 115% efficiency relative to 7.5 cm NaI(Tl) scintillator (Shukla et al. 2001). Using a sediment standard (#107, 50.424 g containing U = 5.69 ppm, Th = 14.5 ppm and K = 2.63%), the concentrations of K (749 ± 12 ppm), Th (80 ± 28 ppb) and U (40 ± 7 ppb) were determined using their standard gamma ray energy peaks. In addition, the cosmogenic ^{26}Al could also be determined by its 1809 keV gamma ray to be 35 ± 1.6 dpm/kg meteorite. The counting rates and the

Table 4. Mössbauer parameters of the Ararki meteorite.

Spectrum	IS (mm s^{-1})	QS (mm s^{-1})	B (Tesla)	Area (%)	Assigned mineral
Doublet 1	1.14	2.98	–	48.57	Olivine
Doublet 2	1.14	2.14	–	35.62	Pyroxene
Sextet 1	0.57	–0.16	28.7	11.43	Troilite altered
Sextet 2	0.69	–0.19	31.3	4.3	Pure troilite

Table 5. He, Ne, and Ar data for the Ararki chondrite.

Temp. (°C)	^{4}He	^{22}Ne (10^{-8} ccSTP/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	67.78	0.094	0.027	188	4.314	0.5364	0.3661	883
				15	.021	0.0016	0.0048	7
800	252.3	0.702	0.093	1787	2.553	0.7404	0.4584	1086
				151	.005	0.0019	0.0037	10
1200	82.25	1.327	0.209	2026	1.020	0.9064	0.6116	307
				171	.001	0.0019	0.0008	3
1600	39.78	0.999	0.209	1622	1.684	0.8307	0.5663	277
				14	.003	0.0023	0.0010	3
Total	442.2	3.123	0.537	1701	1.676	0.8337	0.5554	458
				144	.003	0.0021	0.0016	4

Errors in concentrations are ±10%. Errors in isotopic composition represent 95% C.L and are given below the values.

Table 6. Cosmogenic, radiogenic, and trapped components (cm^3STP/g) in the Ararki chondrite.

Cosmogenic			Radiogenic			Trapped		
^{3}He	^{21}Ne	^{38}Ar	^{4}He	^{40}Ar	^{129}Xe	^{36}Ar	^{84}Kr	^{132}Xe
---------10^{-8}---------			-----10^{-8}----		10^{-12}	10^{-8}	-----10^{-12}-----	
7.52	2.59	0.23	403	246	7.0	0.387	35.3	26.0

Table 7. Cosmic-ray exposure ages (Ma) and gas retention ages (Ga) of the Ararki chondrite (errors in ages are ±15%).

Cosmic-ray exposure ages			Gas retention ages	
T_3	T_{21}	T_{38}	T_4	T_{40}
4.6	7.2	5.3	1.1	0.58

Table 8. Some Kr and Xe isotopic data (amounts in 10^{-12} cm^3STP/g).

^{84}Kr	^{132}Xe	$^{82}Kr/^{84}Kr$	$^{83}Kr/^{84}Kr$	$^{128}Xe/^{132}Xe$	$^{129}Xe/^{132}Xe$
36.8	26.4	0.2433 ± 0.0020	0.2643 ± 0.0035	0.1031 ± 0.0041	1.296 ± 0.006

Table 9. Counting rates of Ararki (62.1186 g) counted for 38054.4 min.

Isotope	Energy (keV)	Net count rate (cpm)	Background (cpm)	Activity (dpm/kg)
^{26}Al	1808.6	0.0553 ± 0.0024	0.00214 ± 0.00004	35.0 ± 1.6
^{60}Co	1173.24	0.0061 ± 0.0025	0.0120 ± 0.00005	<2.73
	1332.5	0.0118 ± 0.0023	0.0226 ± 0.00005	<5.27
K(^{40}K)	1460.75	0.3384 ± 0.0042	0.0494 ± 0.00004	749 ± 12 ppm

background details are given in Table 9. The activity of cosmogenic radionuclides depends on size of the meteoroid and shielding depth. The activity also decays with terrestrial residence time since its production ceases when the meteorite falls on earth. Since the terrestrial age of Ararki is <<10^5 yr, inferred by only slight alteration seen in minerals, as discussed above, the low value of ^{26}Al activity cannot be attributed to its decay after the fall of the meteorite on earth. Absence of ^{22}Na (half-life 2.6 yr), expected to be ~40 to 60 dpm/kg depending on the phase of the solar cycle on the basis of the observed range of $^{22}Na/^{26}Al$ ratios of 1.1–1.7 in many fresh falls (Bhandari et al. 2002), implies terrestrial age of a decade or more. Measurements of longer lived radionuclides, e.g., ^{14}C (Welten et al. 2004) may be useful in better estimates of the terrestrial age of the meteorite.

PRE-ATMOSPHERIC SIZE AND TERRESTRIAL AGE

There are many cosmogenic indicators such as heavy nuclei tracks, spallation produced radioactivity (due to, e.g., ^{26}Al), $[^{22}Ne/^{21}Ne]_c$, neutron capture rare gas isotopes ^{82}Kr and ^{128}Xe and radioactive ^{60}Co which are sensitive to shielding and can be used to determine the preatmospheric size of the meteoroid in space. We discuss these one by one in order to estimate the size of the meteoroid. The most sensitive shielding parameter is cosmic-ray tracks. Their absence, corresponding to production rate of $<1.3 \times 10^4$ cm^{-2} Ma^{-1}, provides a lower limit of about 16 cm for the preatmospheric radius, under the assumption of spherical geometry of the meteoroid. Absence of excess ^{82}Kr and ^{128}Xe produced from (n, γ) reactions on Br and I, respectively, also indicate that the preatmospheric radius of the meteoroid is <22 cm (Eugster et al. 2002) since, for a body bigger than r = 22 cm, the n-capture produced stable isotope ^{82}Kr starts building up (Eugster et al. 2002; Murty et al. 2004). If the preatmospheric radius of Ararki is <22 cm, we neither expect much n-capture produced ^{82}Kr, nor a measurable density of nuclear tracks on the surface of the recovered piece of 4.46 kg (equivalent to recovered radius of ~7 cm). Some thermal neutron produced ^{60}Co can be expected, but with half-life of 5.2 yr it decays quickly with terrestrial age. Its observed limit is therefore consistent with small size of the meteoroid or terrestrial age of a decade or more. Cosmogenic (^{22}Ne/^{21}Ne) = 1.094 also suggest a small body, ≤20 cm. The observed ^{26}Al activity, when compared with the production rates given by Bhandari et al. (1993) puts severe constraint on the size of the meteoroid. The ^{26}Al activity of 35 dpm/kg is consistent with meteoroid radius of ~15 cm and ablation of ~5 cm. Thus, based on all the shielding indicators measured in Ararki, we come to the conclusion that the meteoroid radius was 16 ± 3 cm, implying a pre-atmospheric mass of about 60 kg. Considering that the recovered mass is ~4.5 kg, it is estimated that nearly 93% of the meteorite was ablated during the atmospheric transit.

SUMMARY

Identification of a well-preserved meteorite find in Ararki village of the Indian Thar Desert shows that searches for old meteorites in this region, as in other deserts in the world, can be fruitful. Mössbauer spectrum of troilite, occurrence of serpentinized olivine, and possible loss of ^{40}Ar carrier phase indicate that the Ararki meteorite is slightly weathered. Petrographic and chemical analysis shows that it belongs to L5 group of chondrites. The preatmospheric mass is estimated to be about 60 kg, indicating that about 93% of the mass was ablated when the meteoroid passed through the Earth's atmosphere. A late heating or degassing event is documented based on short (0.6–1.1 Ga) radiogenic ages.

Acknowledgments–We appreciate the insight of Suman Swami who recognized this meteorite and are grateful to Bhagirath Swami for making this meteorite available for our study. The conditions under which this meteorite was found is based on his description. We are grateful to Dr. S. K. Bhattacharya for the carbon isotopic composition of this meteorite and PLANEX National facility at PRL for allowing us to use EPMA. We thank Marc Caffee for thoughtful comments and Harold Connolly Jr. for critically examining the mineral data. N.B. thanks Indian National Science Academy for an Honorary Scientist grant.

Editorial Handling—Dr. A. J. Timothy Jull

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