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Characterization of a newly fallen Nigerian meteorite

Abbasher Gismelssed[1] · Olugbenga Okunlola[2] · Ahmed Al-Rawas[1] · Ali Yousif[1] · Matthew Oyedokun[2] · Jacob Adetunji[3] · Hisham Widatallah[1] · Mohamed Elzai[1]

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X-ray diffraction (XRD), Fields Emission Scanning Electron Microscope (FE-SEM) with EDS and Mössbauer Spectroscopy (MS), were applied to investigate a newly fallen solid piece of debris named the Aba Panu meteorite, after a city in south western Nigeria (Lat: N 08° 14′ 25.7″ and Long: E 003° 33′ 47.0″). Matching X-ray diffraction results, together with the FE-SEM analysis confirms the presence of four kinds of iron-bearing minerals, namely olivine, pyroxene, kamacite (Fe-Ni alloys) and troilite (FeS). The Mössbauer spectra recorded at 295 K and 78 K consist of two strong paramagnetic doublets emanating from olivine of quadrupole splitting 2.9 mm/s and pyroxene of quadrupole splitting 2.1 mm/s. These are superimposed on two magnetic sub-spectra attributed to kamacite and troilite phases. From the Mössbauer sub-spectra absorption area, the ratio of the olivine absorption area to the pyroxene absorption area indicates that the meteorite can be classified as an L-ordinary chondrite. The mole fraction of the Fe end-member of olivine (fayalite) and the orthopyroxene (ferrosilite) calculated from the EDS data will be used to identify the petrographic type of the meteorite.

Keywords Meteorites · Ordinary chondrite · Kamacite · Mössbauer · FE-SEM · Petrologic type

1 Introduction

Outer Interplanetary space in the solar system contains a number of stars, planets, asteroids, and gaseous clouds. These are continuously subjected to collisions with each other. Some of their fragments then travel through space, and, due to Earth's gravity field, could reach the Earth's surface as meteorites.

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✉ Abbasher Gismelssed
abbasher@squ.edu.om

[1] Physics Department, College of Science, Sultan Qaboos university, Muscat, Sultanate of Oman

[2] Department of Geology University of Ibadan, Ibadan, Nigeria

[3] School of Environmental Sciences, University of Derby, Kedleston Road, Derby DE22 1GB, UK

Meteorites impacts have been recorded frequently in the far north and south of Africa, but less so in West Africa. The meteorite-fall of very significant size (a super bolide), the closest to Nigeria happened in Ghana 1.07 million years ago, resulting in the only circular lake in Ghana. The resulting Lake Bosumtwi, is situated within the meteorite impact crater, with a diameter of about 10.5 km and outer ridge of 20 km [1–3]. Nigeria has recorded many meteorite falls as recorded by the Geological Surveys of Nigeria in the last 50 years. Most had been recorded in the Northern part of the country. This fall is one of the few that have been recorded in the southwestern Nigeria.

On Thursday, April 19, 2018, a large fire ball (or bolide) originating from the planetary orbit survived its way through the atmosphere detonated at an altitude 30 km. Fragment of the meteorite hit surface of the Earth at villages near Ipapo in South Western Nigeria in Itesiwaju LGA [*Anberee Isale* (Lat: N 08° 14′ 25.7″ & Long: E 003° 33′ 47.0″), *Aba Leke* (Lat: N 08° 19′ 48.9″ & Long: E 003° 33′ 53.9″), *Anberee Oke* and *Owode*] and Tede in Atisbo LGA (Aba Ajebandele, with coordinates; Lat: N 08° 21′ 48.7″ & Long: E 003° 34′ 34.6″) [4, 5]. This was accompanied by a series of reverberating and disturbing noises in the Earth's subsurface, as observed by residents of the affected localities. It is worthy to note that the meteorite impact that occurred in Oyo State didn't occur in a built-up area, gas station etc. which could have resulted in catastrophic events claiming lives and properties.The location and the effect of the meteorite on the locals has been gazetted by the Oyo State Government [4]. A burnt tree and scorched soil were found at the location (Fig. 1). The hot meteorite, moving at high velocity, ca 20.9 km/s is estimated to weigh 160 kg, releasing a calculated energy of 0.23 kt has been officially named Aba Panu meteorite, (after a town 18.3 km N30^0 E of Ipapo) and classified as ordinary chondrite L3 [5].

A recent report [6] on the degassing and volatile content experiments on Aba Panu meteorite did not give the exact location of the source of dispersed fragments from which the samples they studied were obtained.

However, in this paper, a fragment of the Aba Panu newly fallen meteorite collected at Ipapo was for the first time, experimentally studied, using combined X-ray diffraction (XRD), Fields Emission Scanning Electron Microscope (FE-SEM) with EDS and Mössbauer Spectroscopy (MS) techniques. The data obtained is interpreted in this paper in terms of crystal chemistry, mineralogy and oxidation state of the iron-bearing phases in the meteorite. The findings are discussed on the basis of the meteorite classification.

2 Experimental methods

For ultra-high resolution imaging, a Field Emission Scanning Electron Microscope (FE-SEM) Jeol JSM-7600 FE-SEM was used, coupled with Energy dispersive x-ray spectroscopy (EDS) to determine the chemical composition of the meteorite constituents. The sample was mounted onto a standard aluminum SEM Stub, using carbon tape and coated with a hid platinum film. Semi-quantitative EDS X-ray microanalysis was performed using EDS spot analysis with acquisition time 60 s and maximum process time, to achieve best resolution of peaks in the spectra. Mineral phases were assessed from atomic proportions of the constituent elements, obtained by semi-quantitative EDS X-ray microanalysis.

The powdered materials used for XRD and Mössbauer absorbers were made by grinding a small piece from the interior of the meteorite, to avoid the burned crust on its surface. Powder X-ray diffraction (XRD) was performed using a Philips PW 1820 diffractometer in the range

Fig. 1 Showing (**a**) the half-buried meteorite and scorched soil (**b**) a burned tree (**c**) fragments of meteorite and a broken branch of a tree (**d**) a fresh surface of meteorite fragment . **Source:** Official photographs obtained from the Mineral Development Agency, Oyo State Government Nigeria [4]. They were taken soon after the meteorite impact at Ipapo

of 2θ from 10° to 70° and a PDP11 microcomputer for analysis. The phases were identified by performing multiple searches on a database using PW1876 PC-identify and PW 1877 APD (automatic powder diffraction) software programs.

Mössbauer measurements were done in transmission geometry using a constant acceleration spectrometer (Wissel GmbH manufacturer) with a 50 mCi ^{57}Co in Rh source. The low temperature measurement was performed using a liquid nitrogen flow cryostat (Cryo Industries Inc.). The spectra were recorded in an MCA of 1024 channels and then later contracted to 512 channels before folding. The spectrometer was calibrated with an α-Fe foil (25 μm thick) foil spectrum at RT and the isomer shifts are given relative to the center of this spectrum. The experimental data were analyzed using a least-square fitting program (Recoil) capable of handling the static full Hamiltonian case. The linewidth and the intensity of the two lines of each quadrupole doublet were constrained to be equal. The magnitude of the quadrupole splitting (ΔE_Q) is given by the peak separation in the paramagnetic doublet which is related to nuclear and solid state parameters through:

$$\Delta E_Q = \frac{eQV_{ZZ}}{2}\sqrt{1+\frac{\eta^2}{3}}$$

where the parameters have their usual meanings. However, in the magnetic case, the quadrupole interaction is described as:

$$\varepsilon = \frac{(v_6 - v_5) - (v_2 - v_1)}{2}$$

where v_1, v_2, ….v_6 are the peak positions in the sextet with increasing velocities. This formula is only valid when the magnetic interaction is much stronger than the electric interaction (dominating interaction). This condition is fulfilled for the sextets emanating from kamacite and taenite, which have hyperfine fields of 33.6 and 30.3 Tesla, respectively. As will be discussed below, in most cases the troilite pattern could only be well fitted using the full Hamiltonian which is applicable for combined interaction.

3 Results and discussions

The X-ray diffraction patterns, shown in Fig. 2 indicate the presence of mineral phases which are commonly seen in ordinary chondrite meteorites, i.e. Olivine, pyroxene, troilite, and kamacite, in decreasing order of abundance.

SEM/EDS analyses of mineral phases showed that the Ipapo meteorite is characterized by Mg-rich olivine, low calcium pyroxene, plagioclase, chromite, kamacite FeNi alloy (5–7% Ni), Fe-sulphide (FeS); troilite. The findings of the major minerals are in full agreement with the XRD and Mössbauer results (see below). Results of semi-quantitative analyses confirms that most of the analyzed mineral phases conform well to stoichiometric minerals with minor deviations of oxygen from stoichiometric proportions [7]. Results of semi-quantitative X-ray analysis of the specimen are listed in Table 1.

As can be seen, olivine is the most abundant mineral in the ordinary chondrite, with a Mg-rich solid solution of both forsterite and fayalite, and is the prevalent mineral in the chondrules [7]. Pyroxene with low calcium content is usually an orthopyroxene [8]. The EDS X-ray spectrum of troilite shows mainly Fe and S elements and they indicate that the atomic ratio

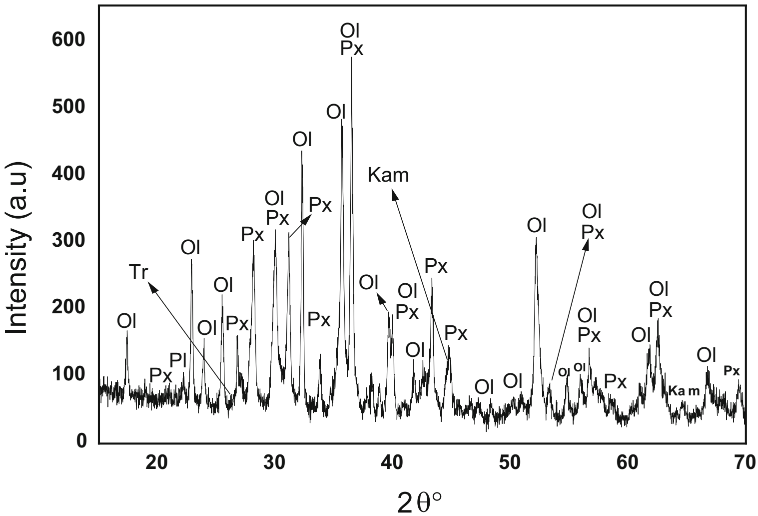


Fig. 2 X-Ray diffraction patterns for mineral phases in the Aba panu meteorite samples, olivine, pyroxene, troilite, and kamacite, phases, with the decreasing in order of abundance

Table 1 Average atomic composition of the silicate phases in the Aba panu meteorite calculated from the EDS data

Cations	Olivine (±0.0002)	Pyroxene (±0.0002)
Si^{4+}	0.9873	1.0000
Ti^{4+}	0.0000	0.0030
Fe^{3+}	0.0000	0.0000
Al^{3+}	0.0436	0.0353
Cr^{3+}	0.0095	0.0067
Mg^{2+}	1.4290	0.7813
Fe^{2+}	0.5036	0.2387
Mn^{2+}	0.0129	0.0079
Ca^{2+}	0.0000	0.0282
K^{1+}	0.0000	0.0000
Na^{1+}	0.0000	0.0000
Total	2.986	2.100

between Fe and S in FeS is less than 1.0. In addition, the EDS X-ray spectrum of kamacite represents basically a peak of Fe with relative peak of Ni (~6% of Ni see Table 2).

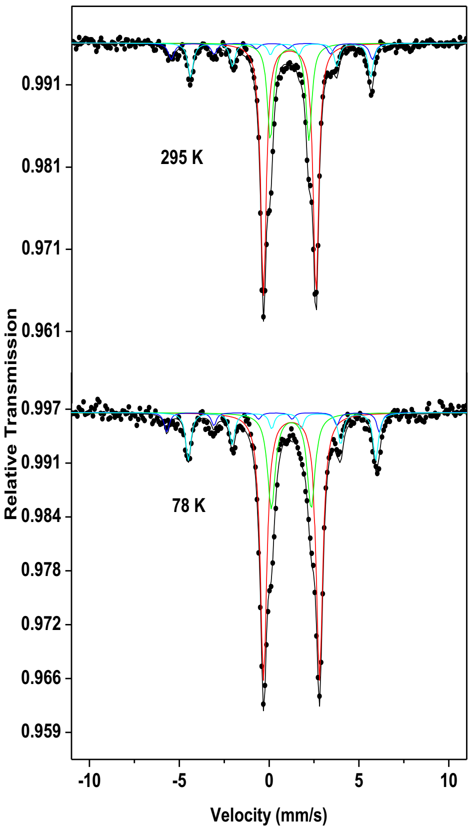
Mössbauer spectra of the meteorite measured at 295 and 78 K are shown in Fig. 3 (left). In comparison, the spectra are of typical ordinary chondrites [9], consisting of well resolved paramagnetic doublets superimposed on magnetic components. A good fitting was achieved when the spectra linewidths of the components were constrained to 0.35 mm/s. The hyperfine interaction parameters obtained from the fitted spectrum together with XRD results, attributed the major paramagnetic doublets to the presence of the silicate minerals; olivine and pyroxene, while the magnetic components were due to the iron nickel (kamacite) and iron sulfide (troilite) phases. Results of the fitting parameters are shown in Table 3. On comparing the Mössbauer parameters of the four identified components with previous studies [9–11], the outer doublet is assigned to olivine and the inner doublet to pyroxene with Fe^{2+} in its more distorted M2 sites [12]. This is justified from temperature independent of its quadrupole splitting, as seen in Table 2. The parameters of the two magnetic sextets are typical of the parameters of kamacite and troilite.

The Mössbauer spectrum of kamacite shows symmetrical 6-lines with a magnetic hyperfine field greater than 33.0 Tesla and depending on the Ni (and Co if it exists) contents. The other FeNi alloys, Taenite and tetrataenite are magnetic in their behavior but their Mössbauer subspectra are usually within the 6-lines of kamacite if they are not significant in their contents. Accordingly in the present meteorite, the first magnetic subspectra are assigned to kamacite (CS ≈ 0 mm/s, B = 33.6 T at room temperature) which are in good agreement with published results [13, 14].

Troilite (FeS), a magnetically ordered mineral mostly exists in ordinary chondrites and shows a spectrum with 31.6 Tesla magnetic field in addition to a rather strong quadrupole shift ($\varepsilon = (e^2qQ/2)\cdot(1+\eta^2/3)^{0.5} = \pm\ 0.85$ mm/s at room temperature, (see [15, 16] for details). Thus, due to such a large quadrupole shift, we have concluded that the ordinary sextet-model, assuming a dominant magnetic interaction, is not fully valid and therefore instead we have used the full static Hamiltonian model in fitting the Mössbauer data. We have assumed a

Table 2 Average atomic composition (in at.%) of the metal phases in the Aba panu meteorite as identified using EDS data

	Fe	Ni	S
Kamacite	93.0	7.0	–
Troilite	52.0	–	48.0



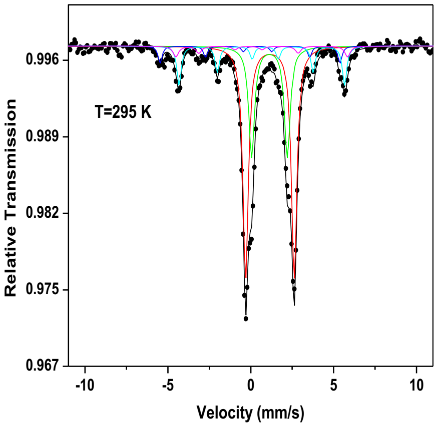


Fig. 3 (left) Mossbauer spectra of the Aba panu meteorite with indicated temperatures, (right) The 295 K Mossbauer spectrum of New Halfa meteorite for comparison [11]

randomly oriented V_{zz}-axis in space, as we have used powdered Mössbauer absorbers, but a fixed polar angle Θ between V_{zz} and B of 48° at room temperature and 49° at liquid nitrogen temperature, assuming the asymmetry parameter η close to zero ($\eta << 1.0$) [17]. However, these are not uniquely determined parameter values, as a previous report, [18] showed that an

Table 3 Obtained Mössbauer parameters of the Aba panu meteorite, measured at 295 K and 78 K

Temp	δ (±0.02) mm/s	QS*(±0.01) mm/s	B(±0.2) Tesla	area (±1) (%)	assignment
295 K	1.14	2.93		55	olivine
	1.14	2.15		23	pyroxene
	0.02	0.01	34.8	08	kamacite
	0.75	−0.85**	31.1	14	troilite
78 K	1.25	3.12		54	olivine
	1.24	2.22		24	pyroxene
	0.28	0.07	35.6	06	kamacite
	0.84	−0.96**	32.3	16	troilite

*QS = ΔE_Q quadrupole splitting in paramagnetic component or QS = ε quadrupole shift in magnetic component

**constrained value for troilite combined with the polar angle Θ between the hyperfine field H and the principal V_{zz} being 48° at 295 K and 49° at 78 K ensemble of related (η, Θ, φ)-values, with φ being the azimutal angle, are giving identical Mössbauer spectra. As seen in Table 2, the parameters obtained for the troilite in the present study agreed well with the values quoted in [15, 16].

The resonance area of the absorption lines in Mössbauer spectra is related to the proportion of the total Fe in the individual phases. This advantage of Mössbauer spectroscopy has supported the characterization of many meteorites. In a previous report, [9] a one-dimensional plot of the olivine/pyroxene was developed in addition to a two-dimensional plot of the area of metallic phases versus area of silicate phases. The former chart gives a better zone separation for the three groups, H, L and LL of the ordinary chondrites. Based on our fitting results, which are collected in Table 3, the meteorite studied can be characterized as an ordinary chondrite meteorite [9]. Further, from the olivine/pyroxene ratio of 2.3 calculated from their Mössbauer sub-spectra area, and the values of the olivine mole fraction Fa = (26.0 ± 0.3) % and pyroxene mole fraction Fs = (23.0 ± 0.3) % calculated from Table 1 data, the meteorite sample from Aba Panu has been shown to be of petrologic type L4 meteorite and is consistent with the findings in other reports on newly-found meteorites. [18–22]. The inconsistency of the petrographic type L3 in reference [5] compared with our findings can be attributed to the large errors in the values of Fa = (24.3 ± 5.7) and Fs = (17.0 ± 11.6) shown in that report.

Figure 3 (right) is the Mössbauer spectrum measured at 295 K for the New Halfa ordinary L4-type chondrite meteorite, which was recovered in 1994 in the eastern region of Sudan [11]. The Mössbauer parameters of that meteorite, shown in Table 3 [11], are identical to those in Table 3, obtained for the Aba Panu meteorite fragments collected at Ipapo. Furthermore, its mole fractions of fayalite Fa and ferosilite Fs in olivine and pyroxene are 23.5% and 23.2%, respectively, which are mostly in good agreement with the parameters obtained for the meteorite in this study.

4 Conclusion

The Aba Panu meteorite fragment in this study is characterized as an ordinary chondrite consisting of olivine with the mole fraction of fayalite Fa = (26.0 ± 0.3) and pyroxene of ferrosililite Fs = (23.0 ± 0.3). Kamacite and troilite are detected as opaque minerals. The ratio of olivine to pyroxene obtained from the area of the Mössbauer sub-spectra (Oli/Pyr = 2.32)~~,~~ is consistent with the meteorites that are classified as L-chondrites, while the value of Fa versus Fs identifies it as an L-4 petrographic type.

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