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Investigations of Al-Dalang and Al-Hawashat meteorites

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Abstract Mössbauer spectroscopy, X-ray diffraction (XRD) measurements, and electron microprobe analysis (EMPA) have been performed on two meteorites named Al-Dalang and Al-Hawashat after identifying their falling sites in the Western region of Sudan. These two meteorites are ordinary chondrites with similar mineralogy. XRD and EMPA show that the two specimens consist of primary olivine, ortho-pyroxene and later crystallising clino-pyroxene as reaction rims against plagioclase. Fe-metal phases are dominated by kamacite (≈6 wt.% Ni) and minor amounts of tetrataenite (≈52 wt.% Ni). Troilite (FeS) and alabandite (MnS) are optically observed as sulphide phases. The Mössbauer measurements at 295 and 78 K are in agreement with the above characterizations, showing at least two paramagnetic doublets which are assigned to olivine and pyroxene and magnetic sextets assigned to kamacite (hyperfine field ≈33.5 T) and troilite FeS (hyperfine field ≈31 T).

Keywords Mössbauer spectroscopy · Ordinary chondrites · Meteorite · Petrography · Kordofan

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1 Introduction

Meteorites are rocks that are made up of a variety of minerals. Most meteorite minerals are similar to those occurring in earth rocks, but a few of the rare minerals are found only in meteorites. Meteorites are classified by their mineralogy and composition. A variety of characteristics are used to classify meteorites among them; mineralogy petrology and some spectroscopic techniques but the grouping based on these data are not always consistent with each other because of the diverse possibilities. However, some meteorites of different types appear to be related to each other and possibly come from the same solar system body.

The present study deals with the investigation of two newly fallen meteorites named Al-Dalang and Al-Hawashat meteorites. Al-Dalang meteorite (sample A1), which recovered as a one piece of 0.85 kg; found in September 2001 near Al-Dalang town in the Southern Kordofan Sudan (coordinates: 12°4.19′N and 30°2.0′E). Al-Hawashat meteorite (sample A2), of about 0.30 kg is the second meteorite fell on 3rd of October 2006 (9:00 pm) in Al-Hawashat village 30 km to the west of Al Obeid the capital of the Northern Kordofan; (coordinates: 13°11.53′N and 30°2.0′E). (Classifications data of the two meteorites have been submitted to Meteoritical Bulletin Database for registration).

2 Experimental

The electron micro probe analyses (EMPA) were done at Uppsala University using a Cameca SX50 wavelength dispersive spectrometer having a takeoff angle of 40°. Back scatter electron pictures were taken at six different spots on each of the two thin sections using an acceleration voltage of 20 kV.

The powdered materials used for XRD and Mössbauer absorbers were made by grinding a small piece from the interior of each meteorite. Powder X-ray diffraction (XRD) was performed using a Philips PW 1820 diffractometer in the range of 2θ from 10° to 70° and a PDP11 microcomputer for analysis. The phases were identified by performing multiple searches on a database using PW 1876 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 (25 μm thick) foil spectrum at RT and the isomer shifts are given relative to the center of this spectrum. The experimental data were analysed using a least-square fitting program capable of handling the static full Hamiltonian case ("Recoil"). 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: $\Delta E_Q = \frac{eQV_{ZZ}}{2}\sqrt{1+\frac{\eta}{3}^2}$, where the parameters have their usual meanings. However, in the magnetic case, the quadrupole interaction is described by: $\varepsilon = \frac{(v6-v5)-(v2-v1)}{2}$, where $v_1, v_2, \ldots v_6$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

Table 1 Average atomic composition of the silicate phases in the two meteorites A1 and A2 as identified using EMPA

	A1 Dalang meteorite			A2 Al Hawashat meteorite		
	Ol	Opx	Plg	Ol	Opx	Plag
Si^{4+}	0.991	0.9906	2.849	0.9907	0.9817	2.9478
Ti^{4+}	0.0001	0.0019	0.001	0	0.0024	0.0008
Fe^{3+}	0	0	0.071	0	0	0.0100
Al^{3+}	0.0039	0.0031	1.045	0	0.0027	1.0344
Mg^{2+}	1.6207	0.8278	0.158	1.6412	0.8437	0
Fe^{2+}	0.3659	0.1649	0.000	0.3683	0.1658	0
Mn^{2+}	0.0088	0.0070	0.002	0.0081	0.0067	0
Ca^{2+}	0.0222	0.0104	0.111	0.0010	0.0114	0.0885
K^{1+}	0.0003	0.0001	0.051	0	0.0003	0.0615
Na^{1+}	0	0	0.766	0	0	0.8116
	3.0120	2.000	5.054	3.0093	2.0147	4.9546

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 dicussions

3.1 Petrography and optical analysis

Polished thin sections (20 × 17 mm) of sample A1 and A2 were studied in transmitted and reflected light in a polarising petrographic microscopy. Olivines were observed as chondrules, embedded in a mosaic of cryptocrystalline material, weakly coloured under crossed polarisers. Larger crystals of pyroxenes, yellow interference colours are observed with parallel extinction. Several orthopyroxenes were found with rims of clinopyroxenes or altered to clinopyroxenes. Radial orthopyroxenes with string plagioclases have clinopyroxene as a rim to the plagioclase. Plagioclase are sparely distributed over the thin section but dominate fracture fillings in both olivine and pyroxenes. Under reflected light at least three different opaque phases are identified, troilite, metals and unknown dark phase as small exsolution spheres in metal phases.

Using back scatter electron geometry, the EMPA detected the following minerals:

olivine, clino- and orthopyroxene (OPX), plagioclase (PLAG), troilite (FeS), and FeNi-alloy (FeNi) with varying composition. The results from the elemental analyses are given in Table 1 for the silicate phases and in Table 2 for the metal phases. The findings are in good agreement with the optical analysis.

The olivine compositions of Al-Dalang meteorite (sample A1) were normalized to four oxygens and are very uniform fayalite (Fa) with Fa(18.4 ± 0.1). The pyroxenes are homogenous with regard to the Fe-Mg ferrosilite (Fs) with Fs(16.6 ± 0.1). CaO content in the orthopyroxenes is low ($= 0.50 - 0.70$ wt.%). Plagioclases which are associated with high-Ca pyroxene, were normalized to 32 oxygen and are albitites $Ab_{84.7}Or_{4.5}An_{10.8}$. Some narrow “plagioclase” strings in olivine and pyroxene contain large amount of MgO and FeO (≈4–8 wt.%) and isotropic under polarizing microscope. On the other hand, as seen in

Table 2 Average atomic composition (in at.%) of the metal phases and troilite in the two meteorites A1 and A2 as identified using EMPA

	A1 Dalang meteorite				A2 Al Hawashat meteorite			
	Fe	Ni	Co	S	Fe	Ni	Co	S
Kamacite	93.52	5.98	0.50	–	94.56	5.13	0.31	–
Taenite	–	–	–	–	75.57	24.28	0.15	–
T.Taenite[a]	47.52	52.46	0.02	–	49.07	50.88	0.089	–
Troilite	50.10	–	–	49.90	49.79	–	–	50.21

[a] T.Taenite: tetrataenite

Tables 1&2, the Al-Hawashat meteorite (sample A2) is characterized by a typical structure having almost similar compositions of Al-Dalang meteorite (sample A1).

For the two samples the opaque minerals: troilite is found to have an average composition of $Fe_{0.5}S_{0.5}$, while kamacite has an average composition of $Fe_{0.937}Ni_{0.063}$. The analyses also show the presence of tetrataenite phase in the two meteorites while the taenite phase presents in Al-Hawashat meteorite only. Based on the schematic representation produced by Keil and Fredriksson [1, 2]; the olivine Fa content and the low-Ca pyroxene Fs content of the two meteorites match the H-type chondrite having petrographic type-6 for Sample A1 and petrographic type-4 for sample A2.

3.2 The XRD and Mössbauer investigation

X-ray diffraction matching results confirm the presence of the four kinds of iron-bearing minerals namely olivine, pyroxene, Fe-Ni alloys (kamacite/taenite) and troilite.

Each of the four Mössbauer spectra could be well fitted with two paramagnetic doublets and two magnetic sextets, as shown in Fig. 1. The obtained Mössbauer parameters are collected in Table 3. The assignments of the outer and inner paramagnetic doublets to olivine and pyroxene respectively is straightforward. The obtained Mössbauer parameters agree quite well to data obtained for other meteorites [3, 4]. The magnetically split subspectra of the two studied meteorites were attributed to metal phases minerals and troilite mineral. Depending on the average Ni content the metal phases in the meteorites are basically consist of i) kamacite (α-phase) which is the dominant metal phase in meteorites and characterized by a relatively low Ni content ($<$7 wt.%) ii) taenite (γ-phase) containing up to 55 wt.% of Ni and iii) an equiatomic FeNi phase; tetrataenite generally formed from the distortion of the fcc taenite when the meteorite parents slowly cooled below 320 °C [5].

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 exist) contents. The other two phases 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. However the Mössbauer spectrum of tetrataenite can easily be distinguished due to the presence of small quadrupole shift (0.4 mm/s) [6, 7]. Accordingly in the present meteorites, the first magnetic subspectra are assigned to kamacite (CS $\approx$ 0 mm/s, B $=$ 33.6 T at room temperature) which are in good agreement with published results [3, 4]. Although EPMA analysis has detected minute inclusions of taenite (in Al-Hawashat) and tetrataenite in both meteorites, here we assume the dominant metal phase in these subspectra is mainly due to the kamacite phase. From the Mössbauer data of Table 3 the relative absorption area

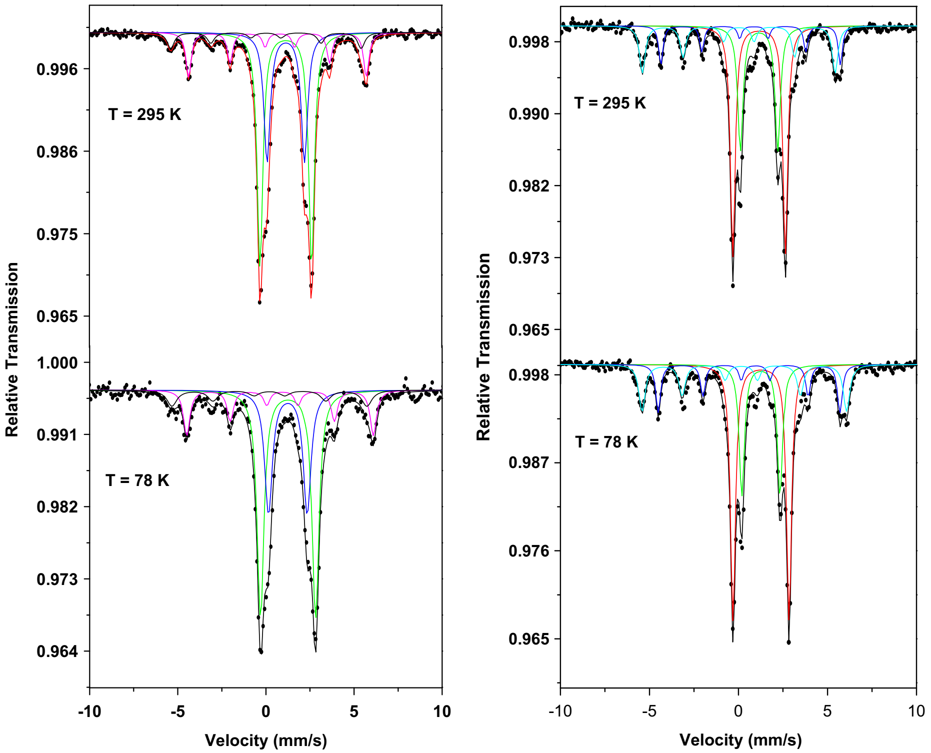

Fig. 1 Mössbauer spectra of the studied meteorites with indicated temperatures. *Left*: Sample A1 and *right*: sample A2. For details see Table 3

percentage of kamacite (metal phases) in Al-Dalang meteorite is less than the range (15–20 %) detected in the majority of ordinary chondrites [7] and references there in. Llorca J. et al. have attributed the behavior due to the oxidation suffered by the meteorites parents during their metamorphism stage, which most likely reduces the Fe content in metal phases and converted it to Fe^{2+} which got incorporated in the silicate olivine phase [8].

Troilite (FeS) is a magnetically ordered mineral mostly exist in ordinary chondrites and shows 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 [9, 10] for details). Thus due to such 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 fittings the Mössbauer data. We have assumed a randomly oriented V_{zz}-axis in space, as we have used powder 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 ($\eta << 1.0$) [10]. However, these are not uniquely determined parameter values as van Dongen Torman et al. 1975 [11] showed that an ensemble of related (η, Θ, φ)-values, with φ being the azimutal angle, are giving identical Mössbauer spectra. As seen in Table 3 the parameters obtained for troilite of both meteorites agreed well with the values quoted in [9, 10].

The ratio of olivine to pyroxene relative absorption area obtained from the Mössbauer measurements has been used extensively in many ordinary chondrites studies as a

Table 3 Obtained Mössbauer parameters of the two meteorites, measured at 295 and 78 K

Sample & Temp	$\delta(\pm0.02)$ mm/s	QS$^a(\pm0.01)$ mm/s	$\Gamma(\pm0.01)$ mm/s	$B(\pm0.2)$ Tesla	area (±1) (%)	assignment
A1; 295 K	1.15	2.93	0.39		46	olivine
	1.15	2.12	0.44		29	pyroxene
	0.02	0.01	0.48	33.5	08	kamacite
	0.74	-0.85^b	0.36	30.8	17	troilite
A1; 78 K	1.26	3.12	0.47		46	olivine
	1.25	2.18	0.52		28	pyroxene
	0.20	0.01	0.68	34.3	09	kamacite
	0.87	-0.96^b	0.42	32.3	17	troilite
A2; 295 K	1.15	2.96	0.32		42	olivine
	1.15	2.09	0.33		24	pyroxene
	0.01	0.01	0.40	33.6	20	kamacite
	0.76	-0.85^b	0.28	31.0	14	troilite
A2; 78 K	1.26	3.15	0.40		42	olivine
	1.26	2.17	0.40		23	pyroxene
	0.10	0.01	0.51	34.7	20	kamacite
	0.87	-0.96^b	0.35	32.3	15	troilite

[a] QS = ΔE_Q quadrupole splitting in paramagnetic component or QS = ε quadrupole shift in magnetic component

[b] 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

classification indicator to differentiate the meteorites into their H-, L-, and LL-groups [12, 13]. From our Mössbauer measurements, the deduced relative area of olivine/pyroxene of (1.6 ± 0.1) for Al-Dalang meteorite (sample A1) and (1.8 ± 0.1) for Al-Hawashat meteorite (sample A2) will fit them in the H–type classification The findings are in good agreement with the findings of the EMPA results.

4 Conclusion

Mössbauer spectroscopy, X-ray diffraction (XRD) measurements, and electron microprobe analysis (EMPA) have been performed on Al-Dalang and Al-Hawashat meteorites. The detected phases are olivine, pyroxene, troilite and Fe-Ni phases. The low olivine to pyroxene Mössbauer absorption area ratio of the two meteorites characterized them as H-type ordinary chondrites. For both, the mole fractions of fayalite and ferrosilite obtained from the microprobe analysis supported the Mössbauer findings.

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