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Studies on Uruq al Hadd meteorite

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Abstract

Uruq al Hadd (UaH02) meteorite is found in the southwest of Oman close to the border with Yemen. Mössbauer spectroscopy has been used to assess the mineralogy of iron-bearing phases in this meteorite, supported by X-ray diffraction and electron-probe microanalysis (EPMA). Mössbauer spectra measured at 295 and 78 K exhibit paramagnetic doublets superimposed on magnetic sextets. The doublets are assigned to the silicate minerals olivine and pyroxene and the magnetic sextets reveal the presence of at least four magnetic phases: troilite ($Fe_{49.2}S_{50.8}$), kamacite ($Fe_{92.2}Ni_{7.8}$), taenite (FeNi), iron oxides and oxy-hydroxides. Both iron oxides and oxy-hydroxides are terrestrial alteration products. Weathering is not pervasive suggesting a relatively young terrestrial age. The mole percentages of fayalite in olivine and ferrosilite in pyroxene determined by EPMA, classifies the meteorite as an H3 chondrite of W1 weathering stage.

Keywords: Uruq al Hadd; Chondrite; Meteorite; Mössbauer; Oman

1. Introduction

The presence of iron in minerals constituting the meteorites provided valuable information about their classification, characterization and their thermal history. The ordinary chondrites, the largest group in the chondrite meteorites that accounts for more than 80% of the all known fall meteorites is basically classified into three subgroups: H-, L-, and LL-group in a decreasing order of the total iron contents (Knudsen, 1989; Verma and Tripathi, 2004). As being detected by different techniques the iron in all ordinary chondrites is present as Fe^{2+} in the silicates and sulfides minerals and as Fe^0 in the Fe–Ni metals. Therefore, any significant Fe^{3+} may be attributed to the product of terrestrial weathering (Rubin, 1997).

In recent years, large numbers of meteorites have been found in the deserts of Oman. For example, several hundred specimens have been recovered in the last 5 years. The range of petrological types and locations represented has opened up a new and potentially important field of research. Among these specimens a meteorite weighing 2.75 kg was found in Uruq al Hadd area in the southwest of Oman, close to the border with Yemen. This specimen was brought to the Directorate General of Commerce and Industry for identification. In this paper, we report our detailed investigation on this meteorite and the type of weathering products formed using Mössbauer spectroscopy, supported by data obtained by optical microscopy, X-ray diffraction (XRD), and electron-probe microanalysis (EPMA).

2. Experimental

A small piece of the meteorite was taken from a layer below the exposed fusion crust. The sample was then ground and the resulting powder was used for XRD and

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Mössbauer spectroscopy. The powder XRD measurement was carried out using a Philips PW1820 diffractometer with the range of 2θ from 10° to 70° and a PDP11 micro-computer for analysis. The sample has been prepared for XRD by pressing the powder into the middle of the well of the aluminum sample holder using a glass slide several times to insure that the top of the sample is coplanar with the top of the aluminum holder. The phases were identified by performing multiple searches on a database using PW 1876 PC-identify and PW 1877 automatic powder diffraction (APD) software package.

Mössbauer spectra were obtained at 295 and 78 K on a powdered sample using a constant-acceleration Mössbauer spectrometer with 50 mCi ^{57}Co in Rh source. The low-temperature measurement was performed using liquid nitrogen flow cryostat. The spectrometer was calibrated with α-Fe foil spectrum at room temperature. The measured data were analyzed using a non-linear least squares fitting program assuming Lorentzian lines. The linewidth and the intensity of the two lines of each quadrupole doublet were constrained to be equal. When the magnetic interaction dominates the electric interaction, the quadrupole splitting (QS) is described by the formula $QS = ((v_6-v_5)-(v_2-v_1))/2$ (where v_1, v_2, … v_6), are the peak positions in the sextet with increasing velocities).

The examined thin sections using light microscopy and the mineral analysis using electron microprobe were carried out at the University of Bern, Switzerland where the analysis was concentrated on the silicate. The microprobe analysis was further carried out at the Central Science Laboratory, University of Tasmania, Australia concentrating on the opaque minerals using a Camera SX50 EPMA with a beam current of 25 nA and an accelerating voltage of 15 kV.

3. Results and discussion

Fig. 1 (a) and (b) shows images obtained from the thin sections of the meteorite under polarized transmitted and reflected light. The images show that the meteorite is a chondritic with granular texture. Fig. 1(a) shows a large well-defined circular chondrule at the center of the image. The ground mass consists of pyroxene, olivine, plagioclase, troilite, kamacite and chromite. Olivine is the most abundant groundmass phase. Fig. 1(b), which was obtained under reflected light shows a large chondrule at the upper left corner of the image. In addition some metal and troilite grains are indicated. The metal and troilite show a low weathering grade. The gray irregular-shaped materials are oxides resulting from the weathering of metal and troilite.

The powder XRD diffraction analysis indicated that the principal phases in UaH02 meteorite are olivine, pyroxene, troilite, and kamacite in decreasing order of abundance. The results are in full agreement with those reported in literature (Gismelseed et al., 1994; Abdu and Ericsson, 1997).

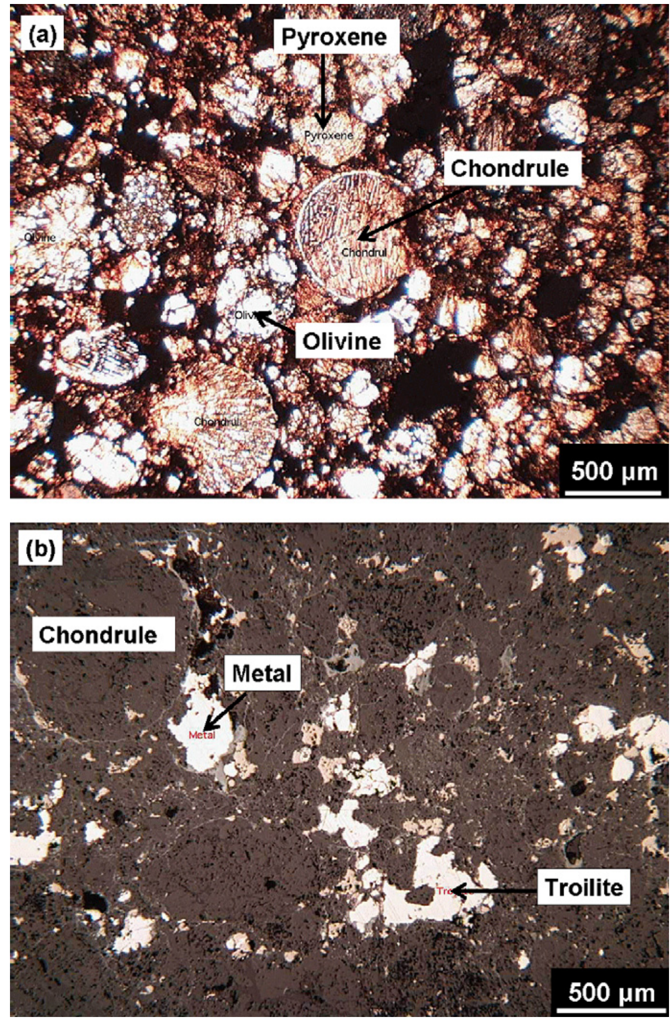

Fig. 1. (a) Photomicrograph of a thin section of UaH02 which was taken under polarized transmitted light shows circular chondrules at the center and lower center of the image. Some olivine and pyroxene grains are indicated. The dark areas are metal and troilite grains. (b) The texture shows a large chondrule in the upper left corner. Metal and troilite are indicated. The thin-section image was taken under reflected light.

Selected EPMA data for olivine, pyroxene and chromites are presented in Table 1, while Fig. 2 shows a triangular plot of the pyroxene compositions. Olivine compositions were normalized to four oxygens ($Mg^{2+} = 1.61$ and $Fe^{2+} = 0.373$) and are very uniform with the mole fraction of fayalite Fa19, the end member of olivine. Pyroxenes were normalized to six oxygens and site occupancies were calculated according to the IMA guidelines (Morimoto, 1988). It is an orthopyroxene of hypersthene type with a mole fraction of ferrosilite Fs16 ($Mg^{2+} = 1.65$ and $Fe^{2+} = 0.32$). Chromites were normalized to four oxygens and show variation in their composition; some grains are rich in Al^{3+} and Mg^{2+}, while the others are rich in Fe^{2+}. The analysis also shows the presence of kamacite with an average composition $Fe_{92.2}Ni_{7.8}$ and troilite of composition $Fe_{49.2}S_{50.8}$ as major phases in addition to minor Fe metal and pentlandite.

Table 1
Selected analysis of the main silicate phases and chromites from Uruq al Hadd meteorite

Oxide wt%	Olivine			Orthopyroxene			Chromites				
SiO_2	39.0	39.7	39.7	56.8	56.1	56.6	0.02	0.01	0.03	0.05	0.01
TiO_2	0.15	0.01	0.02	0.00	0.22	0.66	0.29	0.25	0.20	1.90	1.97
Al_2O_3	0.18	0.00	0.02	0.17	0.22	0.14	16.1	16.2	16.3	6.80	7.00
Fe_2O_3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2.40	2.10	2.30	0.80	0.70
Cr_2O_3	0.10	0.06	0.02	0.11	0.12	0.17	54.3	54.5	54.4	57.5	57.3
FeO	17.7	17.6	17.1	10.7	10.7	10.7	12.0	11.9	12.2	26.7	26.4
MnO	0.42	0.43	0.52	0.50	0.55	0.43	0.23	0.21	0.22	0.90	0.70
MgO	41.8	42.6	42.9	31.4	30.4	31.4	14.5	14.8	14.7	4.70	4.70
CaO	0.11	0.02	0.00	0.30	0.72	0.28	0.00	0.02	0.00	0.00	0.00
Na_2O	0.01	0.00	0.01	0.00	0.02	0.01	n.d.	n.d	n.d.	n.d.	n.d
K_2O	0.01	0.00	0.01	0.01	0.01	0.03	n.d.	n.d	n.d.	n.d.	n.d
V_2O_3	n.d.	n.d	n.d.	n.d.	n.d	n.d.	0.11	0.10	0.13	0.60	0.70
Total	99.8	100.3	99.9	98.1	98.2	99.4	99.6	100.2	99.7	99.9	98.2

n.d.: not detected.

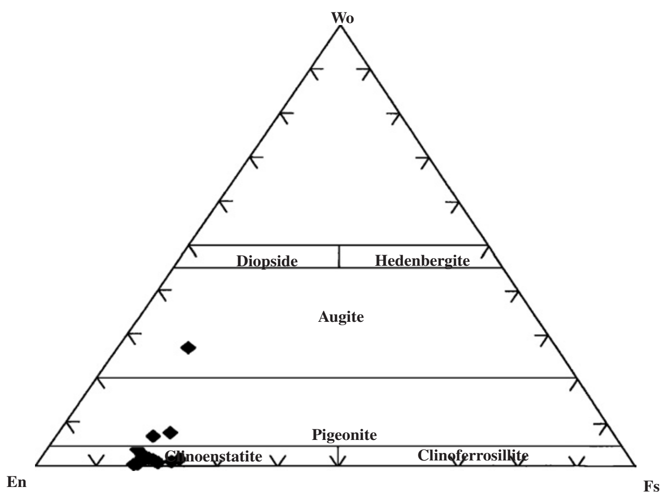

Fig. 2. Triangular plot showing the composition of pyroxene in UaH02 meteorite, Wo: wollastonite $CaSiO_3$, En: enstatite $MgSiO_3$ and Fs: ferrosilite $FeSiO_3$.

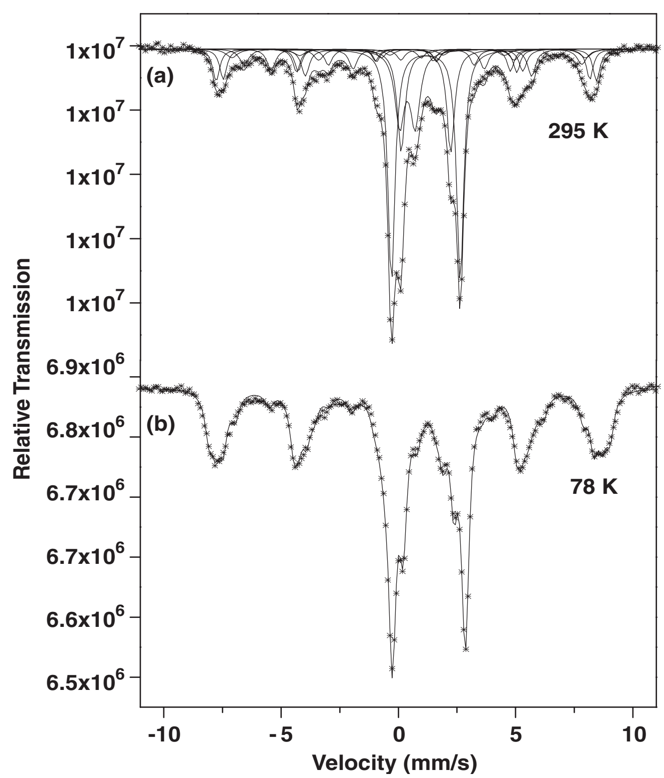

Fig. 3. Mössbauer spectra of UaH02 meteorite measured at (a) 295 K and (b) 78 K.

Troilite (FeS) as well as pentlandite, the most common FeNi sulfides in chondrites, are believed to have resulted from sulfidation of metal (FeNi) grains in an H_2S-containing environment, where asteroids are known to have experienced aqueous alteration (Zolensky and Loan, 2003). Although chromites, pentlandite and the assumed metallic Fe have been recognized from the EPMA data, XRD and Mössbauer analysis have failed to detect them. These suggest that either they are present at a rather low level of abundance in this meteorite or their absorption peaks are overlapping inside the peaks of the major components.

Fig. 3(a) and (b) presents the Mössbauer spectra of the meteorite measured at 295 and 78 K. The spectra are more complex in comparison to spectra of typical ordinary chondrites (Verma et al., 2003). The spectra consist of paramagnetic doublets superimposed on magnetic components. A good fitting was achieved when the linewidth of the components was constrained to 0.35 mm/s. The hyperfine interaction parameters obtained from the fitting of the 295 K 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 sulfide (troilite) and iron nickel (kamacite) phases. Results of the fitting parameters are collected in Table 2. On comparing the Mössbauer parameters of the identified four components with previous studies (Gismelseed et al., 1994; Abdu and Ericsson, 1997; Verma et al., 2003), the outer doublet is assigned to olivine and the inner doublet to pyroxene with

Table 2
Hyperfine Mössbauer parameters for Uruq al Hadd meteorite at 295 and 78 K

	δ ($\pm$0.05) mms^{-1}		QS ($\pm$0.01) mms^{-1}		B ($\pm$0.2) (T)		A ($\pm$1) (%)	
	295 K	78 K	295 K	78 K	295 K	78 K	295 K	78 K
Olivine	1.17	1.29	2.94	3.11	—	—	30	29
Pyroxene	1.17	1.29	2.11	2.14	—	—	16	15
Fe^{3+}	0.38	0.45	0.66	0.69			13	05
Troilite	0.86	0.95	0.01	0.02	29.9	31.8	09	09
Kamacite	0.03	0.18	−0.10	−0.13	33.3	34.9	07	08
Magnetite [B]	0.64	0.68	−0.14	−0.04	44.6	46.8	06	07
Magnetite (A)	0.29	0.34	−0.11	0.04	47.0	48.2	04	04
α-FeOOH	0.30	0.50	0.19	−0.04	48.7	50.6	08	16
γ-Fe_2O_3	0.35	0.52	−0.01	0.04	50.4	52.7	07	07

The parameters are δ: isomer shift, QS: quadrupole splitting, B: magnetic field splitting in Tesla and A: relative absorption area. The line width is constrained to 0.35 mm/s.

Fe^{2+} in its more distorted M2 site as will be justified below from 78 K spectrum. The parameters of the two magnetic sextets are typical to the parameters of troilite and kamacite. In addition to these major components, one paramagnetic component and four magnetic components ascribed to terrestrial weathering were added to obtain a good fit. The additional paramagnetic subspectrum is attributed to the presence of oxyhydroxide components; if not come from some sulfide minerals (in which Fe is present in ferric state) (Zhang et al., 1994), while the magnetic subspectra are attributed to magnetite Fe_3O_4 in its non equivalent A and B sites, magnetic goethite α-FeOOH and maghemite γ-Fe_2O_3 as supported by XRD data. Oxyhydrites and magnetite are known to occur in ordinary chondrite due to weathering during their terrestrial life. Bland and coworkers (2004) have extensively studied the sequences of weathering in many ordinary chondrites and found that in most of the studied specimens the major weathering products are α-FeOOH, β-FeOOH, Fe_3O_4 and γ-Fe_2O_3. In many weathering corrosion products α-FeOOH and β-FeOOH show paramagnetic Mössbauer components at room temperature due to their particles size, but are magnetically ordered at 78 K if their particles size is not less than 10 nm (Oh et al., 1999).

However, the spectrum measured at 78 K (Fig. 3(b)) shows a reduction in the intensity of the third doublet from 13% at 295 K to 5% at 78 K and an increase in the intensity of the magnetic absorption lines. This could be due to the superparamagnetic ordering of α-FeOOH, and/or β-FeOOH at 78 K and the persisting doublet is for the same phases of very fine particle size. The QS of pyroxene shows no variation with temperature, which confirms the assumption, that Fe^{2+} occupies the more distorted site in pyroxene (Bancroft, 1973).

The intensity of the absorption in Mössbauer spectrum is related to the proportion of the total Fe in the individual phases. Such advantage of Mössbauer spectroscopy supports the characterization of several meteorites. Verma et al. (2003) developed a one-dimensional plot of the olivine/pyroxene in addition to a two-dimensional plot of 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 2, the studied meteorite can be characterized as ordinary chondrite meteorite (Verma et al., 2002, 2003). Further, from the olivine/pyroxene ratio of 1.9 and the values of their mole fraction Fa19 and Fs16 obtained from EPMA data, UaH02 meteorite is expected to be of petrologic type H3 meteorite (Dodd, 1981).

4. Conclusion

The Mössbauer spectra measured at 295 and 78 K, together with XRD data indicate the presence of the characteristic compositions of an ordinary chondrite together with secondary iron oxides caused by terrestrial weathering. The olivine and pyroxene compositions show that UaH02 is a low-grade metamorphic ordinary (relatively unaltered) H3 chondrite. The magnetic minerals are identified as troilite and kamacite. The small paramagnetic component of Fe^{3+} detected at room temperature is partially magnetically ordered at 78 K. The hyperfine interaction parameters are identical to those of goethite α-FeOOH and β-FeOOH. The iron oxide components indicate that this meteorite is relatively unweathered.

The study shows that Mössbauer spectroscopy is a useful technique for quantifying the oxidation grade of a meteorite, and it can be used for meteorite classification.

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