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MICROSCOPIC STUDIES OF AL HAGGOUNIA 001 METEORITE

Elemental composition, mineral composition and microstructure of Al Haggounia 001 meteorite found in 2006 were studied by analytical electron microscopy. It was established that orthopyroxene dominated by enstatite (En89-82Fs16-10Wo1-2), sodic plagioclase (Ab81-84An10-12Or4-5), graphite, and oxidized kamacite identified in the sample represent extraterrestrial minerals typical of enstatite meteorites. Chemical and mineral composition, and texture confirm that Al Haggounia is EL chondrite rather than aubrite, and terrestrial weathering significantly changed primary meteorite minerals.

Keywords: Meteorite, Al Haggounia 001, extraterrestrial minerals.

1. INTRODUCTION

Al Haggounia 001 meteorite was found in southern Morocco in 2006. The meteorite was classified as enstatite achondrite (aubrite) in 2007 [1]. Preliminary data show that enstatite (En98Fs1Wo1) and plagioclase (Ab78An16Or5) are dominant minerals, and troilite, graphite, daubreelite, oldhamite, kamacite (rich in Si), and schreibersite are also present [1]. It was established that the meteorite exhibits extensive weathering and is similar to and can be paired with certain Northwest Africa meteorites such as NWA 2828 and NWA 2965 [1-3]. The rock is porous, with a large number of voids. The rusty brown colour of the outer surface is due to severe alteration. The interior of the meteorite changes from bluish gray to rusty brown near the fractures, and yellow patches of altered sulphur are widespread [1-3]. According to the recent data Al Haggounia 001 should be reclassified as unusual enstatite chondrite of low petrologic type (EL3, W4) [2, 3].

The aim of the paper was to determine elemental and mineral composition of Al Haggounia 001 meteorite, and to characterize its microstructure.

2. EXPERIMENTAL

The meteorite sample (1.8 g, 24 mm x 17 mm × 2 mm, bulk density 3.05 g/cm^3) was prepared as a polished plate (Fig. 1). A Tescan VEGA 5135 scanning electron microscope (SEM) was used to identify minerals and analyze the microstructure and texture of the meteorite.

Fig. 1. Macroscopic view of the Al Haggounia 001 meteorite sample

Elemental composition and elemental maps of the meteorite were determined by energy dispersive X-ray (EDX) method using EDX Link 3000 ISIS X-ray microanalyser (Oxford Instruments) with Si(Li) detector. Back scattered electron (BSE) images of various parts of the meteorite were collected and analyzed. BSE electrons coming from the collimated beam of electrons scattered by the minerals of the sample were collected by YAG scintillator detector. Because the number of counts is directly proportional to the atomic number of the object, the white spots on the image mark the heavy elements, gray spots represent medium elements, and black spots reveal the light elements in the sample [4, 5].

3. RESULTS AND DISCUSSION
3.1. Elemental composition of the meteorite

Figure 2 shows energy dispersive (ED) X-ray spectrum of the Al Haggounia 001 meteorite and Tables 1 and 2 present mean elemental composition and atomic ratios of selected elements of the meteorite. A relatively wide region of the meteorite with area of about 25 mm^2 was irradiated with electrons to generate X-ray quanta. Data of Hutchison [6], Sears [7], Wasson and Kalleyman [9] and Koblitz [10] on the elemental composition of enstatite chondrites (EL class), and enastatite achondrites (aubrites) are also included in the Table 1.

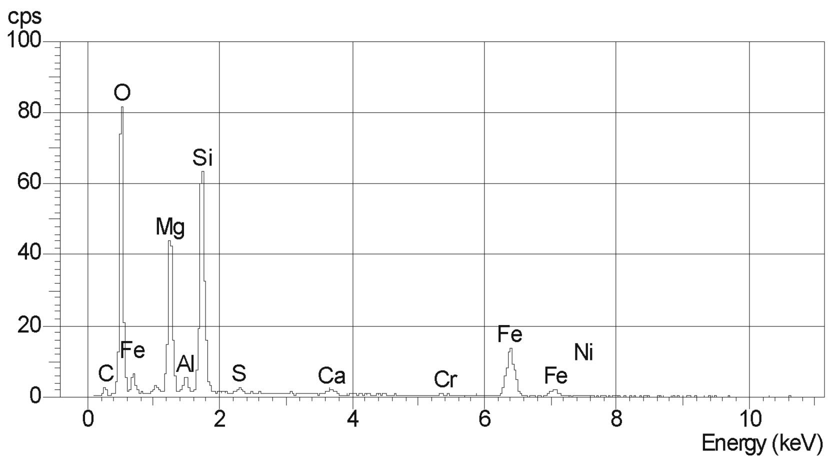

Fig. 2. ED spectrum of Al Haggounia 001 meteorite revealing elements contributed to the mean composition of the sample

Table 1 shows that the main chemical components of the meteorite are: Si (16.95 wt%), O (53.49 wt%), Fe (14.12 wt%) and Mg (12.61 wt%). They constitute about 97 % of the whole mass of the minerals forming the meteorite, and Al (1.15 wt%), Ca (0.70 wt%), S (0.38 wt%), Ni (0.41 wt%), and

Cr (0.20 wt%) include remained three percent of the weight. Apart from the weight percents also atomic content of the elements in the meteorite is presented.

Table 1
Mean elemental composition of Al Haggounia 001 meteorite, enstastite chondrites (EL class) and aubrites

Element	Al Haggounia 001 wt %, (atomic %)	EL chondrites wt%, [9,6]	EL chondrites wt%, [10]	Aubrite Norton County [7]
O	53.49 (69.64)	31.0	39.97*	46.36*
Si	16.95 (12.57)	18.6	18.15	25.40
Mg	12.61 (10.80)	14.1	13.13	24.55
Fe	14.12 (5.27)	22.0	19.89	1.60
S	0.38 (0.24)	3.3	2.92	0.70
Al	1.15 (0.89)	1.05	1.05	0.32
Ca	0.70 (0.36)	1.01	0.75	0.69
Ni	0.41 (0.15)	1.30	1.56	0.04
Na		0.58	0.54	0.09
Cr	0.20 (0.08)	0.305	0.30	0.05
Mn		0.163	0.19	0.12
P		0.117	0.12	0.01
C		0.36	0.4	
K		0.074	0.07	0.03
Ti		0.058	0.06	0.04
Co		0.067	0.9	
Total	100 (100)	100	100	100

*calculated using the sum of remained elements.

The content of the main elements of our meteorite is comparable with the literature data for enstatite meteorites [6-10]. The same conclusion can be drawn from the analysis of atomic ratios for selected elements traditionally used in analyses of meteorites. The Fe/Si, Mg/Si, Ca/Si, Al/Si, Fe/Mg, Ca/Al, mg# = 100 Mg/[Mg+Fe], fe# = 100 Fe/[Mg+Fe], and mg = 100 Mg/[Mg+Fe+Ca] ratios for Al Haggounia 001, EL chondrites and Norton County aubrite are compiled in Table 2.

According to the data Fe/Si, Mg/Si, Ca/Si, Al/Si, Fe/Mg, Ca/Al, mg#, mg, and fe# ratios are in the range of values established for EL chondrites or are close to the values exhibited by EL chondrites rather than values characteristic of enstatite achondrites. The significant differences between our sample of Al Haggonia and Norton County indicate that Al Haggonia is not an aubrite.

Iron in Al Haggounia is present in silicates, in veins of oxidized metal, and in suphides.. Al Haggounia shows low value of Fe/Si atomic ratio and much higher oxygen content in comparison with other EL chondrites (Tables 1, 2).

Table 2

Atomic ratios in Al Haggounia 001, EL chondrites and in Norton County aubrite

Ratio	Al Haggounia 001	EL chondrites [9,6]	EL chondrites [10]	EL chondrites [8]	Aubrite Norton County [7]
Fe/Si	0.42	0.593	0.55[1)]	0.62	0.032[1)]
Mg/Si	0.86	0.871	0.84[1)]	0.83	1.12[1)]
Ca/Si	0.029	0.038	0.029[1)]	0.038	0.019[1)]
Al/Si	0.071	0.058	0.055[1)]	0.113[2)]	0.012[1)]
Fe/Mg	0.49	0.68[1)]	0.66[1)]	0.75[1)]	0.029[1)]
Ca/Al	0.404	0.65	0.48[1)]	0.55[2)]	1.45[1)]
mg	66	59[3)]	59[3)]	56[3)]	96[3)]
mg#	67	60[3)]	60[3)]	57[3)]	97[3)]
fe#	33	40[3)]	40[3)]	43[3)]	3[3)]

[1)] Calculated on the basis of the weight content of elements. [2)] Calculated using weight content of elements in Pillister EL chondrite [7]. [3)] Calculated using Mg/Si, Fe/Si and Cs/Si atomic ratios and formulae: mg# = 100 (Mg/Si)/(Mg/Si+Fe/Si), mg = 100 (Mg/Si)/(Mg/Si+Fe/S+Ca/Si), fe# = 100 (Fe/Si)/(Mg/Si+Fe/Si).

The free metal is not observed in our sample. This means that kamacite has been oxidized during long terrestrial weathering and lost of some amount of iron and nickel, previously present as kamacite. Loss of some amount of sulphur previously forming troilite (FeS) and oldhamite (CaS), and some amount of Cr is also noticeable (Table 1).

3.2. Mineral composition and texture

Since the elements Fe, Mg, Si, O, Ca, Al make up 99 percent: both in weight and in number of atoms, of Al Haggounia meteorite (Table 1), it is evident that common meteorite minerals are calcium-poor pyroxene $(Mg,Fe,Ca)_2Si_2O_6$, and plagioclase feldspar (solid solution of albite $NaAlSi_3O_8$ and anorhite $CaAl_2Si_2O_8$). The presence of sulphides is indicated by sulphur, the presence of kamacite by nickel, and the presence of chromium compounds, possibly chromite by chromium. The data inducate that pyroxene and plagioclase are dominant minerals in Al Haggounia.

Figures 1 and 3 show optical images of the Al Haggounia sample revealing that the meteorite is seriously weathered. Pores, fractures (F) and veins (V) of oxidized metal are common, and meteorite is rusty-brown. Remnants of radial pyroxene (RP) chondrules can be seen. Small, dark-green (G) pyroxene crystals, 0.3 mm in diameter, can be noticed in some parts of the meteorite.

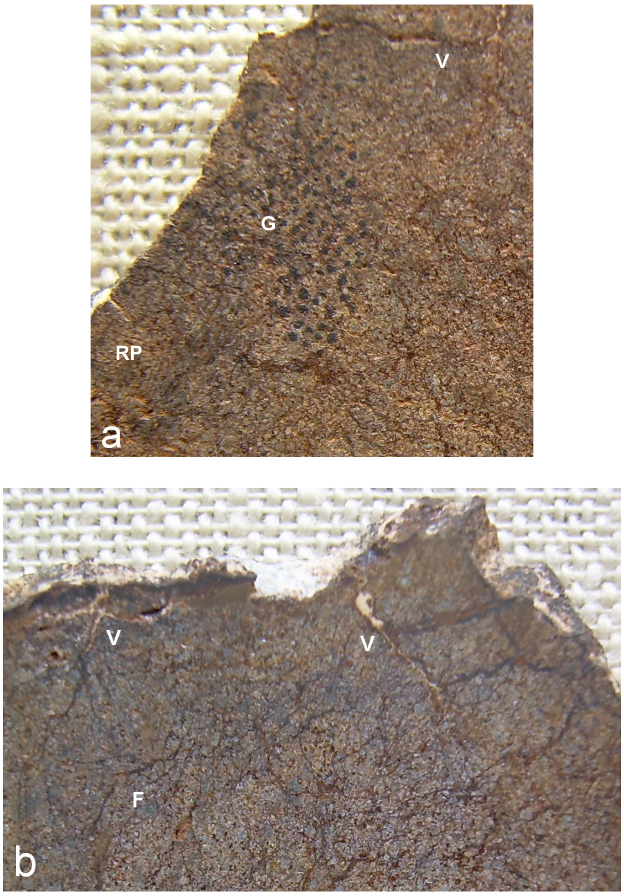

Fig. 3. Optical images of the meteorite revealing: veins (V) of oxidized metal, fractures (F), fragments of radial pyroxene (RP) chondrule, and a group of dark-green (G) pyroxene crystals. Field of view: (a) 11 mm x 12 mm, (b) 17 mm x 11 mm

Electron microscope images and X-ray maps (Cameo images) of distribution of minerals in Al Haggounia 001 meteorite are shown in figures 4, 5 and 6. White dots, patches and veins in BSE images (Figs. 4a, 5a, 6) are oxidized kamacite, grey and dark-grey areas are mostly pyroxenes, and/or plagioclase feldspar (sodic plagioclase), and the black areas are graphite, the common minerals of chondrites and achondrites.

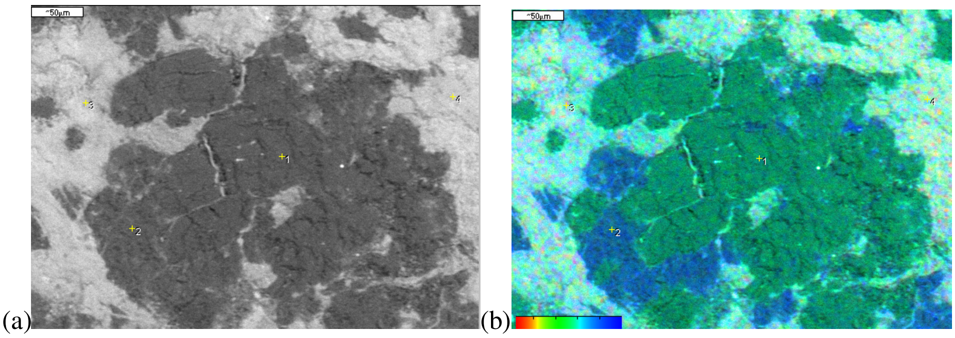

Fig. 4. (a) BSE image, and (b) X-ray Cameo image showing the distribution of minerals and texture of Al Haggounia meteorite. 1 – enstatite (En89Fs10Wo1), 2 – plagioclase feldspar (Ab81An16Or4), 3, 4 – oxidized kamacite. The range of photon energy in (b): 0.2 keV (red) – 5 keV (blue). Scale bar: 50 µm

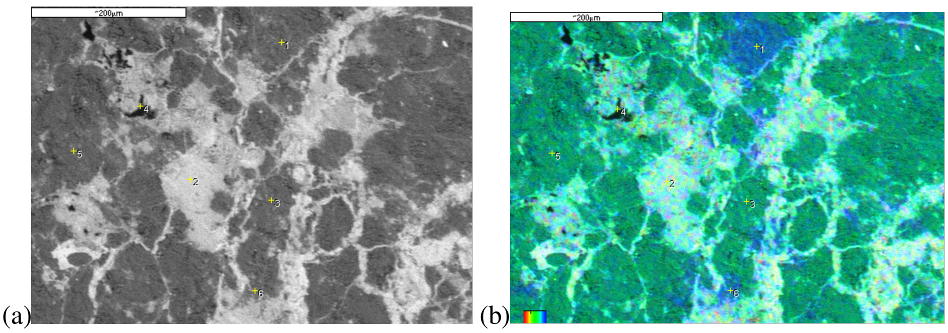

Fig. 5. (a) BSE image, and (b) X-ray Cameo image showing the distribution of minerals and texture of Al Haggounia meteorite. 1 – plagioclase feldspar (Ab83An12Or5), 2 – oxidized kamacite, 3 – pyroxene (En76Fs22Wo2), 4 – carbon phase (graphite), 5 – siderite, 6 – feldspar (Ab84An11Or5). (b) The range of photon energy: 0.7 keV (red) – 1.74 keV (blue). Scale bar: 200 µm

The energy dispersive (ED) spectra revealed apart from the average also local composition of meteorite. It was established that orthopyroxene enstatite with the composition: En89Fs10Wo1 (Fig. 7), En82Fs16Wo2, En76Fs22Wo2, and plagioclase feldspars: Ab81An15Or4, Ab83An12Or5 (Fig. 8), Ab84An10Or5 (in veins also Ab85An15, Ab97An3) are dominant minerals of Al Haggounia meteorite. En is enstatite $Mg_2Si_2O_6$, Fs is ferrosilite $Fe_2Si_2O_6$, Wo is wollastonite $CaSiO_3$, Ab is albite $NaAlSi_3O_8$, An is anorhite $CaAl_2Si_2O_8$, and Or is orthoclase $KAlSi_3O_8$.

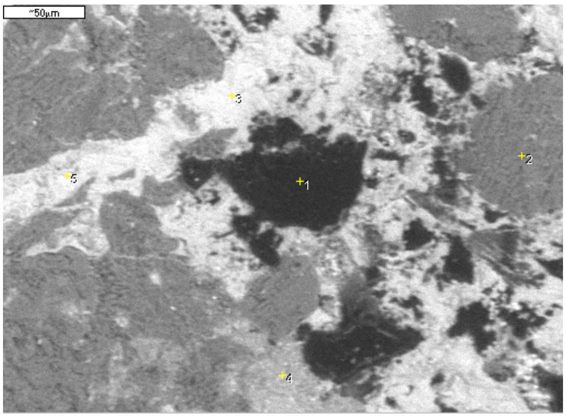

Fig. 6. BSE image of another part of Al Haggounia meteorite. 1 – carbon phase, 2 – pyroxene (En82Fs16Wo2), 3 – oxidized vein of kamacite (Fe, Ni) with orthopyroxene, 4 – plagioclase (Ab68An32) with oxidized kamacite and oldhamite, 5 – oxidized vein of kamacie with plagioclase (Ab96An4). Scale bar: 50 µm

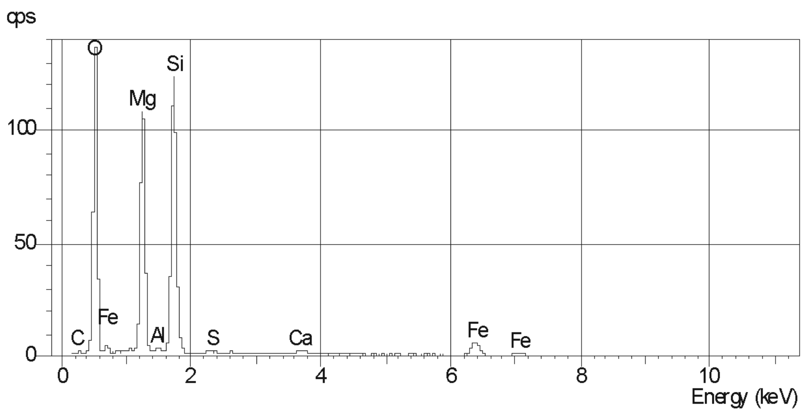

Fig. 7. ED spectrum of Al Haggounia 001 revealing orthopyroxene enstatite En 89Fs10Wo1

ED spectra revealed also the presence of accessory minerals such as: carbon phases, mainly graphite, troilite, chromite, oxidized Fe, Ni metal, (kamacite), chromite, ilmenite, and oldhamite. All of them are minerals characteristic of chondrites, enstatite chondrites, in particular. Orthopyroxene is enstatite but in our sample more ferroslilite is present in comparison with the literature data (En98Fs1Wo1[1]; En98.4Wo1.4 (for paired NWA 2828/2995) [2,3]).

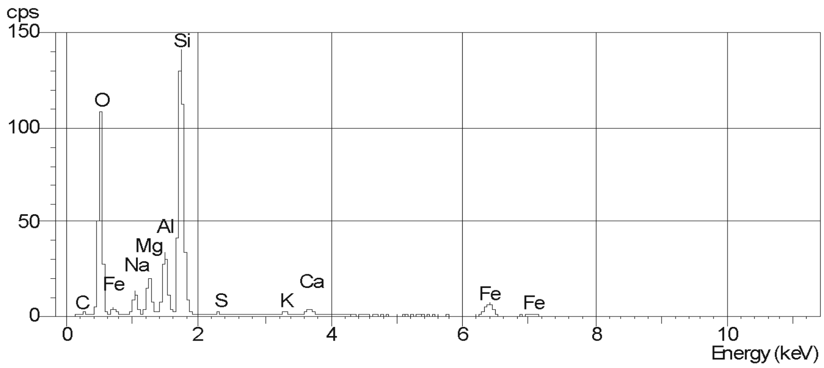

Fig. 8. ED spectrum of Al Haggounia 001 revealing plagioclase Ab83An12Or5.

Plagioclase composition is comparable with the literature data (Ab78An16Or5 [1]; An14-15Or3-4 (for paired NWA2828/2995) [2, 3]). Comparison of ED spectrum representing mean composition of meteorite (Fig. 2) with the enstatite and plagioclase spectra (Figs. 7, 8) show that the three main minerals Al Haggounia meteorite are: enstatite, sodic plagioclase and kamacite. Our results indicate that compositional, mineralogical and textural properties of Al Haggounia meteorite are consistent with enstatite chondrites [6-18].

3. CONCLUSIONS

1. Elemental composition, mineral composition and microstructure of the Al Haggounia 001 meteorite are within the range of enstatite chondrites rather than enstatite achondrites.
2. Fe, Ni, and S content in Al Haggounia enstatite chondrite is lower, and O content is higher than in other EL chondrites. It is due to weathering during long terrestrial age (23 ka, fall in the Pleistocene Epoch [19]).
3. Enstatite, plagioclase and kamacite are dominant minerals of Al Haggounia.

REFERENCES

[1] **Connolly, H.C. Jr., Smith C., Benedix G., Folco L., Righter K., Zipfel J., Yamaguchi A., Chennaoui-Aoudjehane H.**, Meteoritical Bull. **92,** (2007) 1647; Meteoritics Planetary Sci. **42**, (2007) 1647.

[2] **Irving A.J., Bunch T.E., Rubin A.E., Wasson J.T**., 73rd Ann. Met. Soc. Mtg., (2010) #5378.
[3] **Bunch T, Wittke J., Irving A.J**., http://www4.nau.edu/meteorite/Meteorite/Al_Haggounia.html
[4] **Reed S.J.B.**, Electron Microprobe Analysis and Scanning Electron Microscopy in Geology, (Cambridge Univ., Cambridge, 2000).
[5] **Polański K.**, Analytical Electron Microscopy in Crystals Investigations, [in:], Crystals in Nature and Technology, L. Wojtczak, J. Ziomek (Eds) (University of Lodz, Łódź, 2008). p. 173. (In Polish).
[6] **Hutchison R**., Meteorites: a Petrologic, Chemical and Isotope Syntheses, (Cambridge Univ., Cambridge, 2004).
[7] **Sears D.V.**, The Nature and Origin of Meteorites, (Hilger, Bristol, 1978).
[8] **Sears D.V.**, The Origin of Chondrules and Chondrites, (Cambridge Univ., Cambridge, 2004).
[9] **Wasson J.T., Kallemeyn G.W**., Phil. Trans. R. Soc.Lond. **A325**,(1988) 535.
[10] **Koblitz J**., MetBase® 7.3 Meteorite Data Retrieval Software, (Ritterhude, 2010).
[11] **Papike J.J.** (Ed.), Planetary Materials, (Mineralogical Soc. America, Washington, 1998).
[12] **McSween H.Y. Jr**., Meteorites and Their Parent Planets, (Cambridge Univ., New York, 1999).
[13] **Norton O.R.**, The Cambridge Encyclopedia of Meteorites, (Cambridge Univ., Cambridge, 2002).
[14] **Kallemeyn G.W**., **Wasson J.T**., Geochim. Cosmochim. Acta **50**, (1986) 2153.
[15] **Keil K**., J. Geophys. Res. **73**, (1968) 6965.
[16] **Keil K**., Meteoritics **24**, (1989) 195.
[17] **Kimura M., Lin Y**., Ant. Met. Res. **12**, (1999) 1.
[18] **Zhang Y., Benoit P.H., Sears D.W.G**., J. Geophys. Res. **100**, (1995) 9417.
[19] **Chennaoui-Aoudjehane H., Jambon A., Rjimati E., Jull A.J.T., Leclerc-Giscard M.D**., 72nd Ann. Met. Soc. Mtg., (2009) #5037.

BADANIA MIKROSKOPOWE METEORYTU AL HAGGOUNIA 001

Streszczenie

Badano skład pierwiastkowy, skład mineralny i mikrostrukturę meteorytu pustynnego Al Haggounia 001 znalezionego w Maroku w 2006 roku. Do badań wykorzystywano analityczną mikroskopię elektronową. Ustalono, że zarówno skład pierwiastkowy, jak i skład mineralny, a także mikrostruktura tego nowego materiału pozaziemskiego potwierdzają jego przynależność do chondrytów enstatytowych klasy EL. Al Haggounia 001 uległ silnemu utlenieniu podczas długiego wietrzenia na Ziemi.