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## MICROSTRUCTURE OF NWA 4435 METEORITE

*Elemental composition, mineral composition and microstructure of NWA 4435 meteorite found in 2006 has been studied by analytical electron microscopy and optical microscopy. It was established that the main meteorite minerals: olivines, pyroxenes, troilite, and graphite identified in the sample represent extraterrestrial minerals typical of carbonaceous chondrites. Chemical and mineral composition, petrologic type of chondrules, their abundance and sizes, the presence of troilite, and abundance of oxidized iron phases confirm CV3 class of this chondrite.*

**Keywords:** meteorites, carbonaceous chondrites, NWA 4435, chondrules.

### 1. INTRODUCTION

Meteorites are extraterrestrial rocks important for modern science and technology [1-18]. They are divided into two main groups: undifferentiated (chondrites, primitive achondrites), and differentiated (iron meteorites, stony-irons and most of achondrites). Carbonaceous chondrites are the special group of chondrites that apart from the chondrules and CAI's inclusions contain in the matrix some amounts of carbon phases and organic compounds including amino acids.

The aim of the paper was to determine the elemental and mineral composition of the NWA 4435 meteorite, and to characterize its microstructure. The meteorite was found in Algeria in 2006, and in 2008 has been classified as CV3 carbonaceous chondrite [19]. According to our knowledge no detailed studies of microstructure of NWA 4435 meteorite have been conducted so far.

## 2. EXPERIMENTAL

As meteorites are rare or unique objects only one slice was available for the studies. Our meteorite sample was prepared as a polished plate. A Tescan VEGA 5135 scanning electron microscope (SEM) and an Axiotech Zeiss optical microscope were used to analyze the surface microstructure, to image various minerals and phases, and texture of the meteorite.

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 and optical images 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 [20, 21]. The EDX microanalyser apart from the high energy lines detected also low energy characteristic X-ray lines,  $O_K$  line of oxygen (0.523 keV) and  $Fe_L$  line of iron (0.705 keV), in particular.

## 3. RESULTS AND DISCUSSION

### 3.1. Chemical composition of the meteorite

#### 3.1.1. Elemental composition

Table 1 presents mean elemental composition of the NWA 4435 meteorite determined by EDX technique. A relatively wide region of the meteorite with area of about 25 mm<sup>2</sup> has been irradiated with electrons to generate X-ray quanta. Table 1 shows that the main chemical components of the meteorite are: Si (11.3 wt %), O (38.6 wt %), Fe (30.5 wt%) and Mg (9.7 wt%) that constitute about 90 % of the whole mass of the minerals forming the meteorite. The remained ten percent of the weight contains elements: Ca (4.1 wt %), Al (1.4 wt %), S (1.6 wt %), Ni (0.6 wt%), Cr (1.5 wt%), K (0.8 wt%) and C (about 1 wt %). EDXRF technique applied to reveal also trace elements showed that Mn (0.2 wt %), Ti (0.1 wt %) and Co (0.46 wt %) also occur in the sample. Apart from the weight percents also atomic content of the elements in the meteorite are presented. The content of main elements of our meteorite is comparable with the literature data for stony meteorites [8], and for carbonaceous chondrites of CV3 class [5, 6, 10, 18]. The same conclusion can be drawn from the analysis of

oxides content in the NWA 4435 meteorite compiled in Table 1, and oxides content in carbonaceous chondrites C3 class [13]. We can see from the table that various oxides abundance is as follows: SiO<sub>2</sub> (24.17 wt%), MgO (16.15 wt%), FeO (23.71 wt%), Al<sub>2</sub>O<sub>3</sub> (2.56 wt%), CaO (5.70 wt%), NiO (0.78 wt%), Cr<sub>2</sub>O<sub>3</sub> (2.18 wt%), Na<sub>2</sub>O (1.58 wt%), MnO (0.26 wt%), K<sub>2</sub>O (0.91 wt%), and TiO<sub>2</sub> (0.17 wt%). Sulfur is present as FeS (4.28 wt %) called troilite, and iron is also present as free metal Fe<sub>m</sub> (8.78 wt %). Fe<sub>m</sub> content has been estimated assuming that proportion of Ni and Fe is the same as for kamacite (1:14.4). Data of Wood [13] on oxides, sulfide and Fe<sub>m</sub> content in carbonaceous chondrites are also included in the table. According to the figures the agreement between our results and literature data for elements, oxides, and sulfide present in NWA 4435 meteorite and in carbonaceous chondrites of CV3 and C3 types (groups) is satisfactory.

Table 1  
Mean elemental composition of NWA 4435 meteorite and carbonaceous chondrites

Element	Element NWA 4435 (wt%)	Element NWA4435 (atomic%)	Element carbonaceous chondrites [5,10] (Vigarano CV3 <sub>red</sub> [18]) (wt %)	Oxides NWA4435 (wt%)	Oxides carbonaceous chondrites (C3 class [13]) (wt%)
O	38.58	59.98	34.8 (35.81)		
Si	11.30	10.01	15.6 (15.37)	SiO <sub>2</sub> (24.17)	SiO <sub>2</sub> (33.75)#
Mg	9.74	9.97	14.5 (14.22)	MgO (16.15)	MgO (23.86)
Fe <sub>t</sub>	30.54	13.60	23.5 (24.71)	FeO (23.71)	FeO (24.32)
S	1.56	1.21	2.2 (2.32)	FeS (4.28)	FeS (6.08)
Al	1.36	1.25	1.75 (1.75)	Al <sub>2</sub> O <sub>3</sub> (2.56)	Al <sub>2</sub> O <sub>3</sub> (2.65)
Ca	4.07	2.53	1.9 (1.84)	CaO (5.70)	CaO (2.32)
Ni	0.61		1.34 (1.32)	NiO (0.78)	NiO (0.33)
Na	(1.17*)		0.33 (0.36)	Na <sub>2</sub> O (1.58)	Na <sub>2</sub> O (0.55)
Cr	1.49 (0.7*)	0.71	0.36 (0.35)	Cr <sub>2</sub> O <sub>3</sub> (2.18)	Cr <sub>2</sub> O <sub>3</sub> (0.51)
Mn	(0.2*)		0.145 (0.15)	MnO (0.26)	MnO (0.20)
P			0.099 (0.10)		P <sub>2</sub> O <sub>5</sub> (0.32)
C	1		0.56 (1.12)		C (0.46)
K	0.76 (0.02*)	0.48	0.031 (0.048)	K <sub>2</sub> O (0.91)	K <sub>2</sub> O (0.05)
Ti	(0.1*)		0.098 (0.135)	TiO <sub>2</sub> (0.17*)	TiO <sub>2</sub> (0.12)
H			2.5 (0.19**)	H <sub>2</sub> O (nd)	H <sub>2</sub> O (1)
Co	(0.46*)		(0.044)		Co (0.06)
Fe <sub>m</sub>	8.78			Fe <sub>m</sub> (8.78)	Fe <sub>m</sub> (2.34)

(\*) Content revealed by EDXRF technique. (\*\*) Data for Mokoia CV chondrite.  
(nd) not determined. Fe<sub>t</sub> means iron total, and Fe<sub>m</sub> means iron as free metal. (#) Data for silicates.

### 3.1.2. Mineral composition, texture and meteorite class

Since the elements Fe, Mg, Si and O make up 90 percent: both in weight and in number of atoms, for all meteorites [21], as well as for our NWA 4435 meteorite (Table 1), it was concluded that common meteorite minerals are: olivine  $(\text{Mg,Fe})_2\text{SiO}_4$ , pyroxene  $(\text{Mg,Fe})_2\text{Si}_2\text{O}_6$ , calcium-poor pyroxene  $(\text{Mg,Fe,Ca})\text{SiO}_3$ , and non-oxidized metallic nickel-iron (kamacite).  $\text{SiO}_2$ ,  $\text{MgO}$ ,  $\text{FeO}$ , and  $\text{CaO}$  content proves that olivines and pyroxenes constitute about 70 weight percent of the NWA 4435 meteorite. The identification of olivines, orthopyroxenes, clinopyroxenes, feldspars and graphite in the NWA 4435 meteorite has been done by Raman spectroscopy, and detailed report of these studies will be published in a separate paper. Weisberg et al. [19] established that fayalite (Fa,  $\text{Fe}_2\text{SiO}_4$ ) content in olivines of NWA 4435 meteorite is in the range 1.3-56 mol % ( $\text{Fa}_{1..3-56}$ ), and ferrosilite (Fs,  $\text{Fe}_2\text{Si}_2\text{O}_6$ ) content in Ca-poor orthopyroxene in the range of 2.4-31.5 mol % ( $\text{Fs}_{2.4-31.5}$ ).

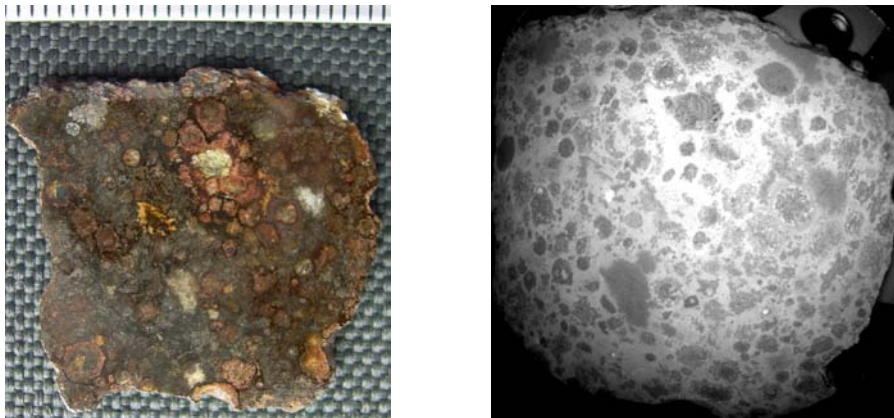


Fig. 1. (a) Optical image, and (b) BSE image of NWA 4435 meteorite. Chondrules, fine-grained polycrystalline matrix, and CAI's inclusions create texture common in carbonaceous chondrites. Field of view: 33 mm x 33 mm

Figure 1a shows optical image of the NWA 4435 meteorite revealing main characteristics of the meteorite: the presence of chondrules, and the matrix. BSE image of the meteorite is shown in Figure 1 b. The meteorite reveals brecciated texture, and calcium aluminum inclusions (CAIs). BSE images of the matrix reveal various minerals present in this multicomponent meteorite sample (Figs. 2, 3). White patches in Figs. 1b, 2 and 3 are troilite, and kamacite (brighter), grey and dark areas in BSE images are mostly olivines and pyroxenes, and black areas are graphite, the common minerals of all chondrites.

The typical feature of all chondrites is the presence of chondrules, small rounded spherules composed usually of olivines and pyroxenes. In our NWA 4435 meteorite abundance of various types of chondrules is of the order about 35 vol %, CAIs about 15 vol %, the rest (about 50 vol %) is the matrix that is composed of fine granulated material of various minerals. Chondrules and surrounding matrix are shown in Figures 1 and 2, both as optical and BSE images. An analysis of the distribution of chondrule sizes expressed by their diameters has shown that the smallest chondrules have 0.2mm diameter, and the largest chondrules have 4 mm diameter. The maximum of the distribution histogram lies between 0.8 mm and 1.5 mm, and the mean chondrule diameter is about 1.2 mm. About 80% of all chondrules have their size in the range of 0.2-2 mm. The larger chondrules are less abundant. The mean chondrule diameter (1.2 mm) in NWA 4435 meteorite is nearly the same as the mean chondrule diameter (1 mm) established in CV carbonaceous chondrites [5, 7, 14].

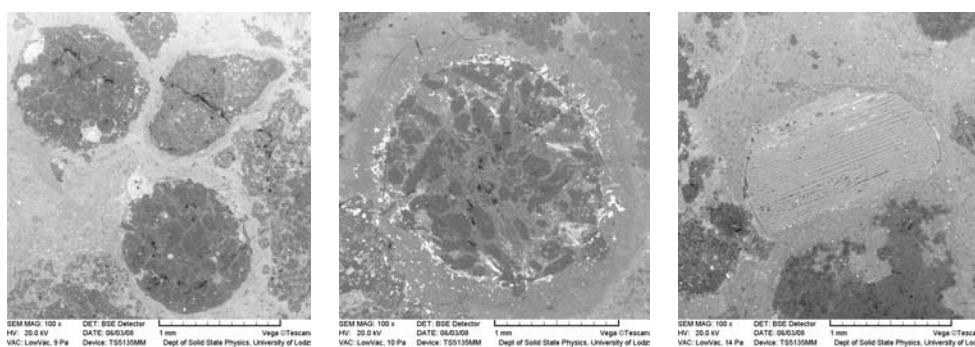


Fig. 2. BSE images of chondrules and matrix showing various minerals present in this multicomponent meteorite piece. White areas are FeS, and FeNi phases, grey and dark areas are mostly olivines and pyroxenes, the major minerals of chondrites. In figures (a) and (b) it may be noticed that chondrules contain globules of sulfide (FeS) and metal (bright), and the matrix is fairly uniform in the brightness (mid-grey) since it is composed dominantly of  $\mu\text{m}$  sized olivines which have a fairly uniform composition close to  $\text{Fa}_{50}$  like that established in Vigarano CV3 chondrite [5]. Matrix is generally brighter than Fe-poor chondrules and brighter than mineral clasts.

Chondrules of different textural types have been observed in NWA 4435 meteorite under the optical and electron microscopes: porphyritic olivine (PO) chondrules, barred olivine (BO) chondrules, radial pyroxene (RP) chondrules, granular chondrules, rimmed chondrules and others (Figs. 1, and 2). Of all chondrule types FeO-poor porphyritic chondrules are most abundant in NWA

4435 chondrite, which is typical of CV chondrites [14]. PO chondrules are shown in Figs. 2a and 2b, and BO chondrule in Fig. 2c.

Chondrules, CAI's and matrix are retained nebular objects of great importance. As the chondrules in NWA 4435 are very sharply defined the petrologic type of this meteorite is 3. Iron in NWA 4435 is present mainly as oxidized metal. All these features prove that NWA 4435 meteorite belongs to CV3 class of carbonaceous chondrites.

This classification has been additionally confirmed by the analysis of bulk density of the NWA 4435 meteorite, and bulk density of carbonaceous chondrites. The bulk density of NWA 4435 meteorite sample determined by the Archimedean method is equal to  $3.5 \cdot 10^3 \text{ kg/m}^3$ , and bulk density of carbonaceous chondrites C3 type varies between  $3.4$  and  $3.6 \cdot 10^3 \text{ kg/m}^3$  [24].

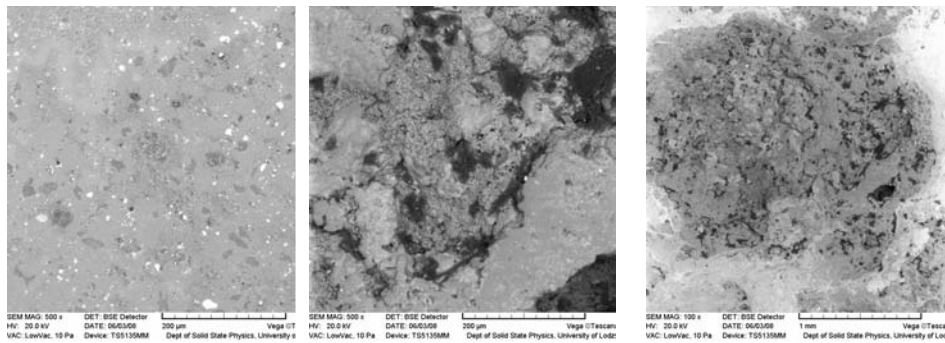


Fig. 3. Back-scattered electron (BSE) images of: (a) matrix, and (b), (c) CAI inclusion. White patches are troilite (FeS), and kamacite ( $\alpha$ -Fe,Ni), black patches reveal graphite (C), and mid-grey is olivine.

The comparison of atomic ratios of metals to silicon, i.e. Mg/Si, Fe/Si, and Ca/Si, and Al/Si, also support this meteorite class. In NWA 4435 meteorite the atom ratios are as follows: Mg/Si = 1.0, Fe/Si = 1.36, Ca/Si = 0.25, Al/Si = 0.12. In CV chondrites we have: Mg/Si = 1.07, Fe/Si = 0.76, Ca/Si = 0.084, Al/Si = 1.37 [5, 6, 7]. The NWA 4435 meteorite contains more iron and more calcium, and less silicon, and magnesium than other CV chondrites. The atomic ratio  $Fe_m/Fe_t = 0.29$  for the NWA 4435 meteorite is in the range of ratios encountered in CV type carbonaceous chondrites (0-0.3) [7]. Our results indicate that physical and compositional properties of NWA 4435 meteorite are consistent with CV type carbonaceous chondrites.

BES images of NWA 4047 meteorite show that chondrules contain magnesium-rich olivine with composition of close to forsterite (Fo,  $\text{Mg}_2\text{SiO}_4$ ), which is manifested by dark-grey color of euhedral olivine crystals seen in Figs. 2a, and b. Matrix of NWA 4047 meteorite consists mainly of iron-rich olivine. In BSE images the color of matrix is generally brighter (mid-gray) than Fe-poor chondrules and brighter than mineral clasts (Figs. 1b, 2, and 3a). Matrix of NWA 4435 is fairly uniform in the brightness since it is composed dominantly of  $\mu\text{m}$  sized olivines which have a fairly uniform composition (approximately  $\text{Fo}_{50}\text{Fa}_{50}$ ). It proves that NWA 4435 meteorite is similar to Vigarano CV3 chondrite [5, 18].

Since compositional and mineralogical features of CV3 chondrites are noted in NWA 4435 meteorite therefore, it should be classified as type CV3 carbonaceous chondrite. The same classification was done in the latest issue of Meteoritical Bulletin [19].

### 3. CONCLUSIONS

1. The presence of chondrules and minerals typical of meteoritic matter such as olivines, pyroxenes, CAI's, and troilite are a proof that our sample represents extraterrestrial matter.
2. The NWA 4435 meteorite belongs to carbonaceous chondrites of CV3 class.

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## **MIKROSTRUKTURA METEORYTU NWA 4435**

### **Streszczenie**

Badano skład chemiczny i mineralny oraz mikrostrukturę meteorytu NWA 4435. Zanalizowano chondry i ciasto skalne meteorytu. Obecność chondr, troilitu, inkluzji wysokotemperaturowych oraz tekstura próbki świadczą o pozaziemskim pochodzeniu badanej skały i przynależności tego meteorytu do chondrytów węglistych klasy CV3.