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MICROSCOPIC INVESTIGATIONS OF SHISR 007 METEORITE

Elemental composition, mineral composition and microstructure of Shisr 007 meteorite found in 2001 have been studied by analytical electron microscopy. It was established that the main meteorite minerals: olivines, pyroxenes, troilite, and graphite identified in the sample represent extraterrestrial minerals typical of olivine-pyroxene achondrites. Chemical and mineral composition, and texture confirm previous classification of this achondrite as ureilite.

Keywords: Meteorite, ureilite, Shishr 007, EDX spectra, extraterrestrial minerals.

1. INTRODUCTION

Extraterrestrial rocks are important materials for modern science and technology [1-5]. The rocks are divided into two main groups: undifferentiated (chondrites, primitive achondrites), and differentiated (iron meteorites, stony-irons and most of achondrites). Ureilites belong to primitive achondrites and contain various carbon phases, especially extraterrestrial diamond.

The aim of the paper was to determine the elemental and mineral composition of the Shisr 007 meteorite, and to characterize its microstructure. The meteorite was found in Oman in 2001, and in 2002 has been classified by Franz Wlotzka and Rainer Bartoschewitz as ureilite [6]. According to our knowledge no detailed studies of microstructure of Shisr 007 meteorite have been conducted so far. According to the recent data Shisr 007 meteorite contains large carbonaceous materials composed of fine diamonds and graphite [7].

2. EXPERIMENTAL

Meteorites are rare and unique objects and only one slice was available for the studies. The meteorite sample was prepared as a polished plate **(**Fig. 1). A Tescan VEGA 5135 scanning electron microscope (SEM) was 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 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 [8, 9].

Fig. 1. Macroscopic view of the Shisr 007 meteorite sample

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

Figure 2 shows energy dispersive (ED) X-ray spectrum of the Shisr 007 meteorite and Table 1 presents mean elemental composition of the meteorite. A relatively wide region of the meteorite with area of about 25 mm^2 has been irradiated with electrons to generate X-ray quanta. Data of Krinov [11], Szurgot [10], and Vdovykin [2,12] on the elemental composition of stony meteorites, NWAXXX ureilite, and of Novo Urei ureilite are also included in the table.

Table 1

Mean elemental composition of Shisr 007 meteorite, stony meteorites and ureilites

Element	Shisr 007 meteorite wt %, (atomic %)	NWA XXX ureilite wt %, (atomic %) [10]	Novo Urei ureilite wt % [2,12]	Average ureilites wt % [12]	Stony meteorites wt % [11]
O	49.72 (61.86)	31.59 (44.29)	38.69	38-42	41.0
Si	12.93 (9.17)	23.15 (18.49)	18.57	19	21.0
Mg	13.74 (11.25)	28.49 (26.29)	22.23	22.5*	14.3
Fe	14.70 (5.24)	11.72 (4.71)	15.64	14.5	15.5
S	0.24 (0.15)		0.58	0.6	1.82
Al	0.47 (0.37)		0.26	0.23	1.56
Ca	1.08 (0.54)	0.83 (0.47)	0.57	0.62*	1.80
Ni	0.26 (0.09)	0.44 (0.17)	0.12	0.13	1.10
Na			0.13	0.04-0.06	0.80
Cr	0.34 (0.13)	0.46 (0.20)	0.47	0.4-0.5	0.40
Mn		0.55 (0.23)	0.31	0.20-0.32	0.16
P			0.04	0.03-0.09	0.10
C	6.98 (11.57)	2.76 (5.16)	2.23	1.5-2.5* 4.1**	0.16
K				0.01-0.03	0.07
Ti			0.08	0.07	0.12
Co			0.05	0.05-0.06	0.08
Total	100 (100)	100 (100)	100		100

*unoxidized
**oxidized during terrestrial weathering.

Table 1 shows that the main chemical components of the meteorite are: Si (12.9 wt %), O (49.7 wt %), Fe (14.7 wt%) and Mg (13.7 wt%) that constitute about 91% of the whole mass of the minerals forming the meteorite. The remaining nine percent of the weight contains elements: C (7.0 wt %), Ca (1.1 wt %), S (0.2 wt %), Ni (0.3 wt %), and Cr (0.3 wt %). Apart from the weight percents also atomic content of the elements in the meteorite are presented.

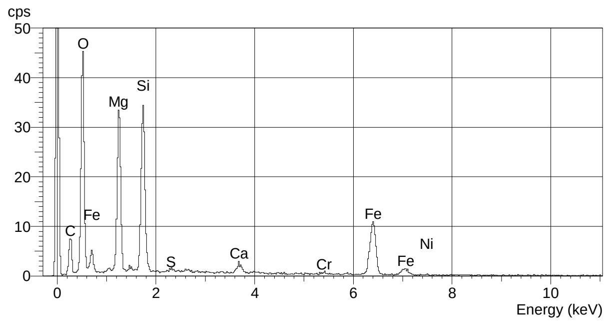

Fig. 2. ED spectrum of Shisr 007 meteorite revealing elements contributed to the mean compostion of the sample

The content of the main elements of our meteorite is comparable with the literature data for stony meteorites [11], and for achondrites classified as ureilites [1,2,12,13]. The same conclusion can be drawn from the analysis of oxides content in the Shisr 007 meteorite, and oxides content in ureilites [1,2,12,13].

The various oxides abundance in Shisr 007 is as follows: SiO_2 (27.67 wt%), MgO (22.78 wt%), FeO (18.9 wt %), CaO (1.51 wt%), NiO (0.34 wt%), Cr_2O_3 (0.5 wt%). Sulfur is present as troilite (FeS, about 0.7 wt %), most iron is present in silicates, but also in veins of free (3.7-6.2 wt%) or oxidized metal. Iron free metal content has been estimated assuming that proportion of Ni and Fe is the same as for kamacite (1:14.4), but is equal to 6.2 wt % if ratio 1:24 will be taken as the reference, since kamacite in ureilites contains less Ni (about 4% [12]) than in other meteorites.

According to the figures the agreement between our results and literature data for elements, oxides, and sulfide present in Shisr 007 meteorite and in ureilites seems to be relatively good, but differences can be also noticed. For example, Mg and Si content in our Shisr 007 sample is less than in other ureilites, but C and O content higher. Mg/Si weight ratio in Shisr 007 is 1.06, and in ureilites is in the range 1.03-1.21 [12], C/O ratio in Shisr amounts to 0.14, and in ureilites is 0.04-0.06 [12], Cr/Ni ratio in Shisr amounts to 1.31, and in ureilites 2.2-7 [12]. Troilite (FeS) content in Shisr 007 (0.7 wt %) is within the range established in ureilites (0.68-1.72 wt %) [12]. Fe in metal in Shisr 007 is between 3.7-6.2 wt %, whereas in ureilites is 0.34-5.86 [12]. Our data indicate that Shisr 007 meteorite may belong to oxidized weathered ureilites.

3.2. Mineral composition and texture

Since the elements Fe, Mg, Si and O make up about 90 percent: both in weight and in number of atoms, for all meteorites e.g. [1,2,11], as well as for our Shisr 007 meteorite (Table 1), it was concluded that common meteorite minerals are: olivine $(Mg,Fe)_2SiO_4$, pyroxene $(Mg,Fe)_2Si_2O_6$, calcium-poor pyroxene $(Mg,Fe,Ca)SiO_3$, and non-oxidized metallic nickel-iron (kamacite). SiO_2, MgO, FeO, and CaO content proves that olivines and pyroxenes constitute about 70 weight percent of the Shisr 007 meteorite. Since carbon content in Shisr 007 meteorite is, according to our data, relatively high (about 7 wt %), various carbon phases, mainly graphite and diamond, should be relatively abundant. The high carbon and high oxygen content is probable caused by weathering on the Earth and carbon compounds, mainly carbonates are possible.

Figures 1 and 3 show optical images of the Shisr 007 meteorite revealing main characteristics of the meteorite: the presence of olivine (OL) and pigeonite (Pig) crystals, and the matrix of the meteorite. Electron microscope image and X-ray map (Cameo image) of distribution of minerals in Shisr 007 meteorite is shown in figure 4.

BSE images of the meteorite are shown in Figures 5 and 6. The meteorite reveals texture typical of ureilites. BSE images reveal various minerals present in this multicomponent meteorite sample (Figs. 5, 6). White dots, patches and veins in Figs. 5 and 6 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 meteorites.

The energy dispersive (ED) spectra shown in figures 7 and 8 represent local composition of the meteorite. They show that olivines, most frequenty Fo84Fa16 (fig.4), but also Fo46Fa54 (Fig. 4), Fo80Fa20 and Fo33Fa67, and pyroxenes (clinopyroxenes En66Fs16Wo18 (Fig. 4), En67Fs30Wo3, and En59Fs29Wo12 are dominant minerals in Shisr 007 meteorite. ED spectra revealed also the presence of accessory minerals such as: carbon phases (mainly graphite), troilite, chromite, oxidized Fe metal, kamacite. All of them are minerals characteristic of ureilites. Some olivines in our Shisr 007 sample contain about 0.52 wt% of Cr_2O_3, which is also typical of ureilites.

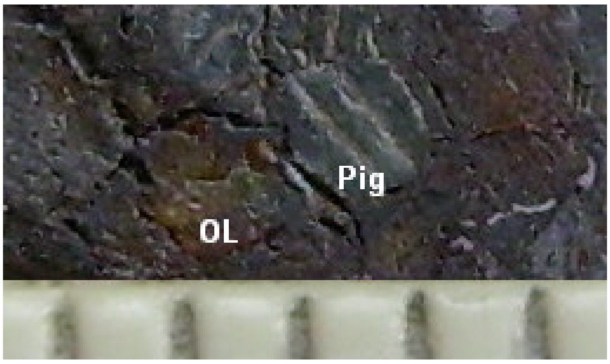

Fig. 3. Optical image of Shisr 007 showing olivine (OL) and pigeonite (Pig)

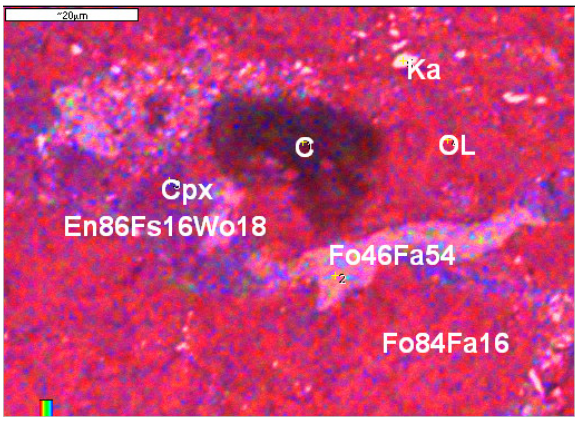

Fig 4. SEM X-ray cameo image showing the distribution of minerals in Shisr 007 meteorite: OL – olivine (red, rose), Cpx – clinopyroxene (blue), C – carbon phase, Ka-Fe oxidized metal (oxidized kamacite)

Russel and coworkers [6] established that fayalite (Fa, Fe_2SiO_4) content in olivines of Shisr 007 meteorite is in the range 11-19.4 mol % (olivine cores $Fa_{19.4}$, and olivine rims Fa_{11}), and ferrosilite (Fs, $Fe_2Si_2O_6$) content in Ca-poor clinopyroxene called pigeonite is $Fs_{17.4}$. The composition of pigeonite is $Fs_{17.4}$ Wo_9, Cr_2O_3 1.2%). According to Ando and coworkers [7] the core composition of olivine (Fo79) and pyroxene (En73) are close to the average composition of silicates in ureilites (e.g. [3]). According to our data olivines in Shisr 007 have similar Fa content (Fa16), but in some regions higher Fa content, and pyroxenes similar Fs content (Fs16), but in some regions higher or lower Wo content than previously established [6,7].

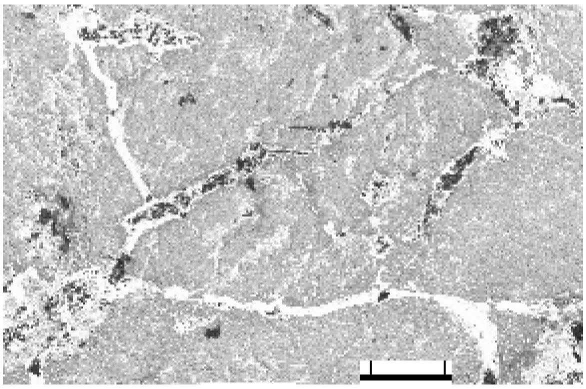

Fig. 5. BSE image of Shisr 007 showing Fe rich veins (white) and carbon phases (black) dispersed in olivine (grey) and pyroxene (also grey) crystals. Scale bar 0.2 mm

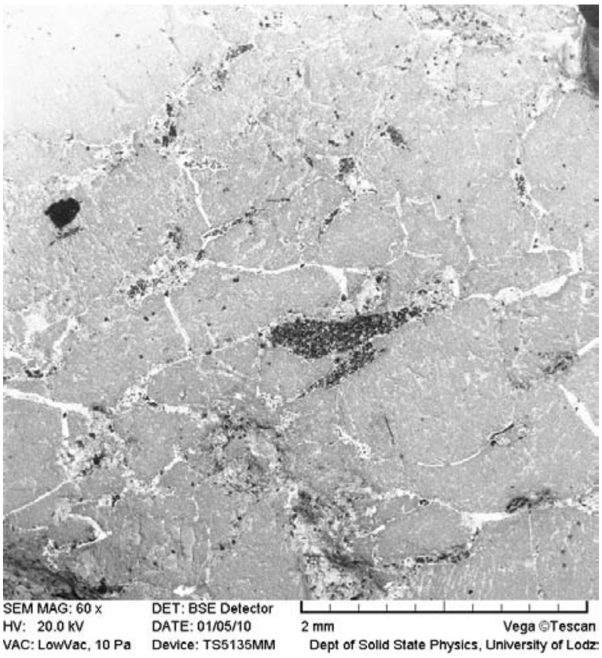

Fig. 6. BSE image of the Shisr 007 meteorite revealing typical of ureilites texture

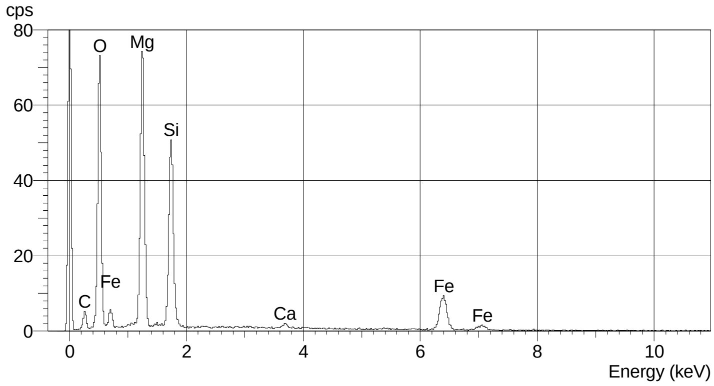

Fig. 7. ED spectrum of olivine ($Fo_{84}Fa_{16}$). Olivine is an orthorhombic mineral being solid solution between forsterite (Fo) Mg_2SiO_4 and fayalite (Fa) Fe_2SiO_4 end members

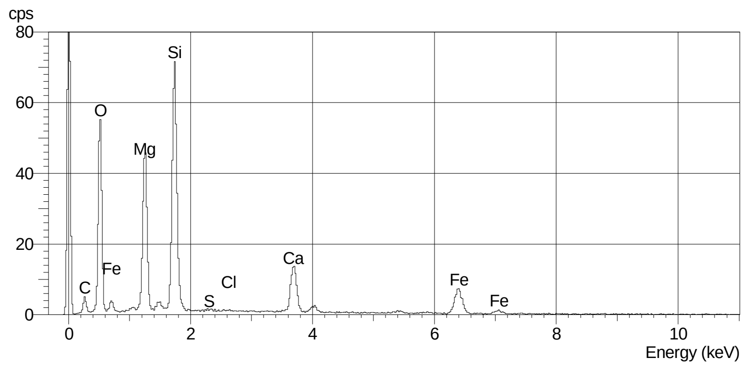

Fig. 8. ED spectrum of clinopyroxene with the composition: $En_{66}Fs_{16}Wo_{18}$, where En is enstatite $Mg_2Si_2O_6$, Fs is ferrosilite $Fe_2Si_2O_6$, and Wo is wollastonite $CaSiO_3$

The identification of olivines, clinopyroxenes, and graphite in the Shisr 007 meteorite has been done by us using Raman spectroscopy, and detailed report on the results studies will be published in a separate paper.

Figures 5 and 6 present BSE images of distribution of minerals at low magnification, and figures 9 and 10 at high magnification. The domination of olivine and pyroxene crystals, expected for the ureilite, is seen in these images. The free iron forms characteristic veins on borders of olivines and pyroxene crystals that include carbon phases.

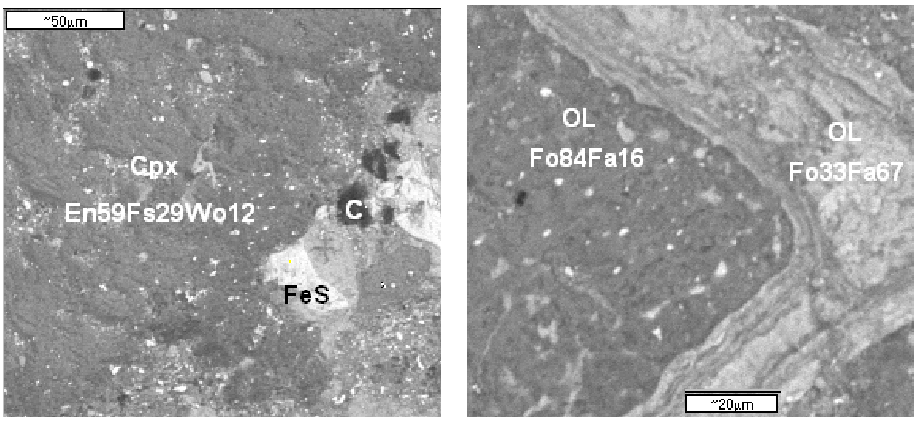

Fig 9. BSE images showing various minerals in Shisr 007 meteorite. Note: small patches of Fe metal are present inside of olivine (OL) and pyroxene (Cpx)

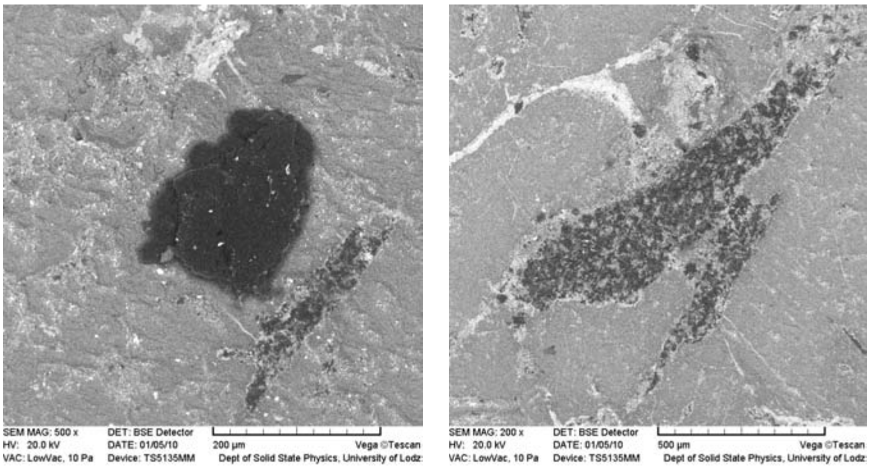

Fig. 10. BSE images showing the presence of carbon phases seen here in black

These BSE images reveal another feature typical of ureilites texture. Small, white dots and patches of free iron are dispersed inside olivines and pyroxenes. This means that the free iron is formed locally inside olivines and pyroxenes, not only on their borders. The black, small patches occasionally present inside olivines and pyroxenes indicate location of carbon phases which are also present inside of silicates.

The typical feature of all ureilites is the presence and domination of large olivine and pyroxene grains between which carbonaceous matter is included. An analysis of the mean size of olivine and pyroxene coarse grains (silicate aggregates resembling chondrules) in Shisr 007 meteorite has shown that it is of order of 1-2 mm, which is a typical value for ureilites. Carbon phases have been also detected and localized in the meteorite sample. Our results indicate that compositional, mineralogical and textural properties of Shisr 007 meteorite are consistent with olivine-pyroxene achondrites known as ureilites.

4. CONCLUSIONS

1. Elemental composition, mineral composition and microstructure of the Shisr 007 meteorite are typical of ureilites.
2. Mg and Si content in our Shisr 007 sample is less than in other ureilites, but C and O content is higher.
3. Olivines in Shisr 007 meteorite in some regions exhibit higher fayalite content, and pyroxenes higher or lower wollastonite content than previously established.
4. Shisr 007 ureilite has been oxidized during terrestrial weathering.

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BADANIA MIKROSKOPOWE METEORYTU SHISR 007

Streszczenie

Badano skład pierwiastkowy, skład mineralny i mikrostrukturę meteorytu pustynnego Shisr 007 wykrytego w Omanie w 2001 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 ureilitów. Stwierdzono, że zawartość fajalitu w pewnych oliwinach jest wyższa, a zawartość wollastonitu w pewnych piroksenach jest wyższa lub niższa niż poprzednio ustalono. Ureilit Shisr 007 uległ prawdopodobnie utlenieniu podczas wietrzenia na Ziemi.