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MICROSCOPIC INVESTIGATIONS OF GOLD BASIN AND EL HAMMAMI CHONDRITES

Elemental and mineral composition of Gold Basin and El Hammami meteorites discovered in 1995 and 1997 have been studied by analytical electron microscopy and optical microscopy. It was established that the main meteorite minerals: olivines, pyroxenes, kamacite and taenite as well as troilite identified in the samples represent extraterrestrial minerals typical of the ordinary chondrites. Feldspars represented by plagioclase, orthoclase, magnetite, calcite, chromite and silica have been also present in the studied samples. Chemical and mineral composition, iron content, petrologic types of chondrules, their abundance and sizes, the presence of troilite veins and abundance of nonoxidised iron phases confirm H class of El Hammami chondrite, i.e.. olvine-bronzite class, and L class of Gold Basin, i.e. olivine-hyperstene class.

Keywords: meteorites, chondrites, Gold Basin, El Hammami, chondrules.

1. INTRODUCTION

Meteorites are extraterrestrial rocks that survived the fiery transition through the Earth's atmosphere and have reached the ground. They are sources of extraterrestrial minerals formed mostly in the early solar system but some minerals are presolar matter. Meteorite samples like terrestrial rocks are multicomponent objects and their physical and chemical characteristics, texture and internal structure contribute to understanding processes in the young solar system, in stars, in interstellar and circumstellar regions [1-18]. Meteorites are unique objects important for modern science and technology.

Traditionally meteorites are divided into three main groups: stony meteorites, stony-iron meteorites and iron meteorites. In a modern classification meteorites are divided into two main groups: undifferentiated (chondrites, primitive achondrites), and differentiated (iron meteorites, stony-irons and most of achondrites).

The aim of the paper was to determine the elemental and mineral composition, as well as the texture of Gold Basin and El Hammami meteorites. Gold Basin meteorite has been found in the USA in 1995 and El Hammami in Mauritania in 1997. El Hammami belong to falls and Gold Basin to finds. Gold Basin has been classified as L4 ordinary chondrite, and El Hammami as H5 ordinary chondrite [18, 25].

2. EXPERIMENTAL

As meteorites are rare or unique objects only one slice of each of the chondrites was available for the studies. Our meteorite samples was prepared as polished plates (Fig. 1). A Tescan VEGA 5135 scanning electron microscope (SEM) and an Axiotech Zeiss optical microscope were used to analyse the surface microstructure, to image various minerals and phases, and texture of the meteorites.

Fig. 1. Macroscopic view of Gold Basin meteorite. Chondrules and the fine-grained polycrystalline matrix, iron-nickel phases, and brecciated texture common in ordinary chondrites can be seen from the figure. Field of view: 42 mm x 25 mm

Elemental composition and elemental maps of the meteorites 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 meteorites and optical images were collected and analysed. 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 [19, 20]. 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 meteorites

3.1.1. Elemental composition

Figure 2 shows ED spectrum of Gold Basin meteorite and Table 1 presents mean elemental composition of the extraterrestrial sample. The spectrum was obtained from the relatively wide region (area of about 25 mm^2).

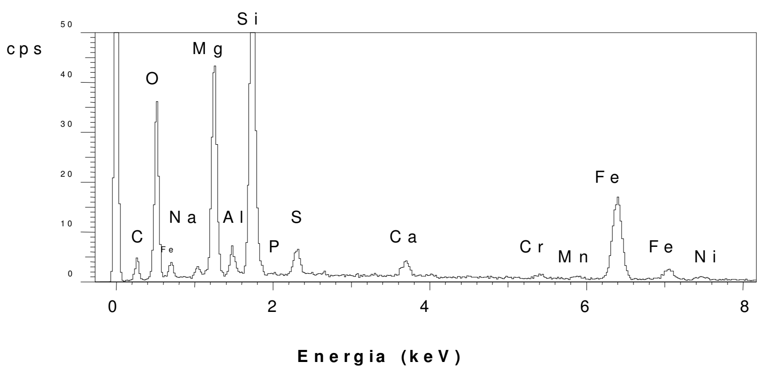


Fig. 2. ED spectrum of Gold Basin meteorite revealing elements contributed to the mean bulk composition of the meteorite

The main chemical components of the Gold Basin meteorite are: Si (19.56 wt%), O (41.84 wt%), Fe (16.6 wt%) and Mg (14.47 wt%) that constitute over 92 % of the whole mass of the minerals forming the meteorite. The remained eight percent of the weight contains elements: Ca (1.19 wt%), Al. (1.65 wt%), S (1.77 wt%), Ni (1.03 wt%), Na (0.73%), Cr (0.52 wt%), Mn (0.43 wt%), P (0.20 wt%) and trace amounts of carbon and the other elements which content has not been determined (Table 1). The content of main elements of the Gold Basin meteorite is comparable with the literature data for stony meteorites [8], and for chondrites of low iron content class, ie for L class, in particular [5, 6, 10]. According to the figures the agreement between our results and literature data for main elements and oxides present in the Gold Basin meteorite and in olivine-hyperstene chondrites is satisfactory.

Table 1

Mean elemental composition of Gold Basin and El Hammami meteorites and chondrites

Element	**Element Gold Basin** (L4 chondrite) **wt%**	**Element El Hammami** (H5 chondrite) **wt%**	**Stone meteorites wt% Krinov [8]**	**Chondrites H class wt% Hutchison [5] (Wasson [10])**	**Chondrites L class wt% Hutchison [5] (Sears [6] for Leedey chondrite)**
O	41.84	38.91	41.0	35.7	37.7 (41.05)
Si	19.56	18.49	21.0	16.9 (16.60)	18.5 (18.46)
Mg	14.47	13.66	14.3	14.0 (13.85)	14.9 (15.03)
Fe	16.60 1-10 Mason 1962	20.99 16-21 Mason	15.5	27.5 (27.01)	21.5 (18.01)
S	1.77	1.44	1.82	2.0 (1.96)	2.2 (2.34)
Al	1.65	1.79	1.56	1.13 (1.11)	1.22 (1.16)
Ca	1.19	1.69	1.80	1.25 (1.23)	1.31 (1.30)
Ni	1.03	1.08	1.10	1.60 (1.57)	1.20 (1.21)
Na	0.73	1.22	0.80	0.64 (0.63)	0.70 (0.08)
Cr	0.52	0.34	0.40	0.37	0.39 (0.36)
Mn	0.43		0.16	0.23 (0.23)	0.26 (0.26)
P	0.20	0.39	0.10	0.11	0.095 (0.08)
C	trace	trace	0.16	0.11	0.09 (0.08)
K	trace	trace	0.07	0.08	0.083 (0.09)
Ti			0.12	0.06 (0.06)	0.063 (0.07)
Co			0.08	0.08	0.059 (0.06)
Cr	0.52		0.40	(0.36)	0.39 (0.36)
Total	100	100	100		100

Figure 3 shows ED spectrum of El Hammami meteorite and Table 1 presents the mean elemental composition of the extraterrestrial sample. As in previous meteorite the spectrum was obtained from the relatively wide region (the same area of about 25 mm^2) The main chemical components of the El Hammami meteorite are: Si (18.49 wt%), O (38.91 wt%), Fe (20.99 wt%) and Mg (13.66 wt%) that constitute about 92% of the whole mass of the minerals forming the meteorite. The remained eight percent of the weight contains elements: Ca (1.69 wt%), Al. (1.79 wt%), S (1.44 wt%), Ni (1.08 wt%), Na (1.22%), Cr (0.34 wt%), P (0.39 wt%) and trace amounts of carbon and the other elements which content has not been determined (Table 1). The content of main elements of the El Hammami meteorite is comparable with the literature data for stony meteorites [8], and for chondrites of high iron content class, ie for H class, called olivine-bronzite chondrites in particular [5, 6, 10].

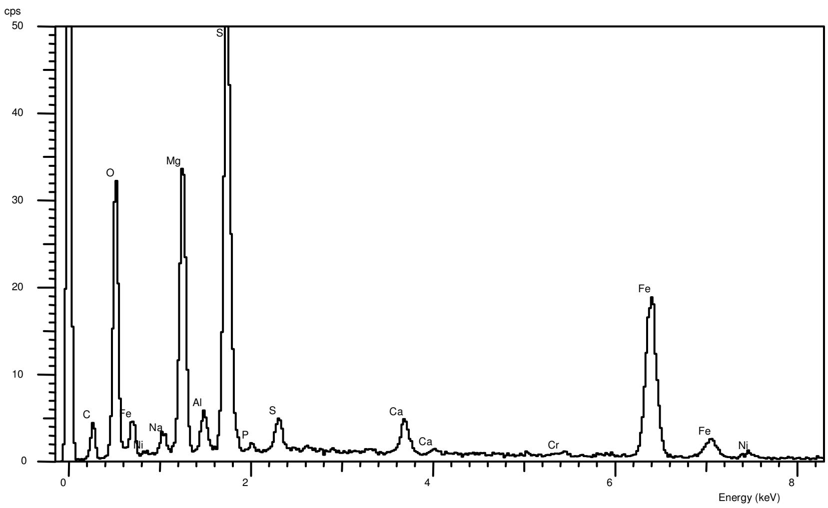


Fig. 3. ED spectrum of El Hammami meteorites revealing elements contributed to the mean bulk composition of the meteorite

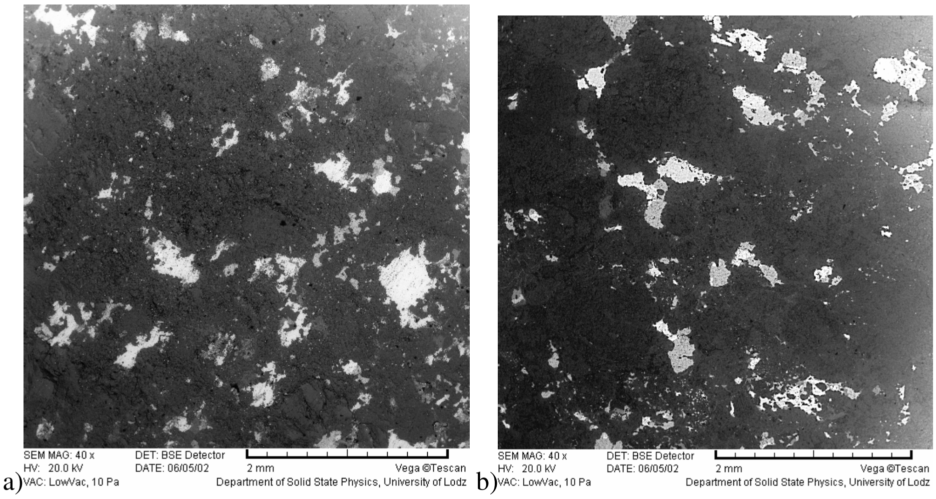


Fig. 4. BSE images of El Hammami and Gold Basin meteorites. FeNi phases kamacite and taenite are seen as white spots, troilite as grey, and silicate minerals are represented by dark colours. Chondrules, chondrule rims and the matrix can be seen in these images. (a) El Hammami, (b) Gold Basin

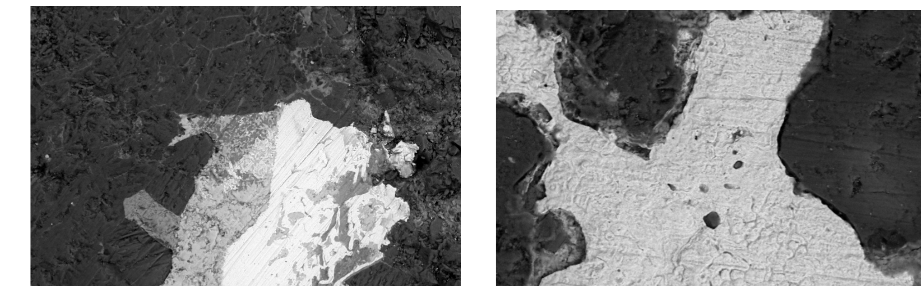
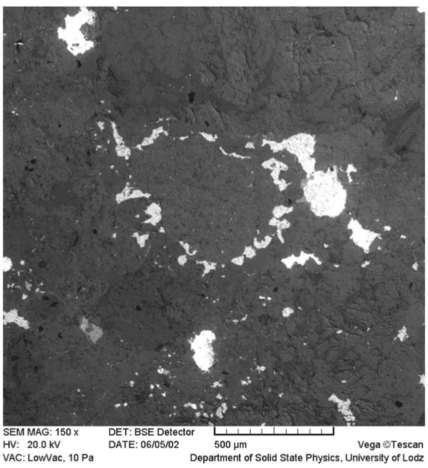


Fig. 5a,b. BSE images of matrix of El Hammami meteorite showing various minerals present in this multicomponent meteorite piece. White areas are Fe-Ni phases, grey are troilite, and dark areas are mostly olivines and pyroxenes, the major minerals of chondrites

3.1.2. Mineral composition and texture of meteorites

Since the elements Fe, Mg, Si and O make up over 90 percent: both in weight and in number of atoms, for all meteorites [21], as well as for our Gold Basin and El Hammami meteorites (Figs. 3, 4, Table 1), it was concluded that common meteorite minerals are: olivine, pyroxene, metallic nickel-iron as kamacite and taenite, and calcium poor pyroxene [21].

BSE images of the studied regions of the meteorites are shown in Figures 4-9, and optical images of thin sections of El Hammami and Gold Basin meteorites are shown in Figures 10-12. They reveal main characteristics of the meteorites: the presence of chondrules, matrix, and metal phases. BSE images of the matrix reveal various minerals present in this multicomponent meteorite sample (Figs. 4-9). White patches in these figures are FeNi phases, grey are troilite, and dark areas in BSE images are mostly olivines and pyroxenes, the main silicate minerals of all chondrites. Figure 9 shows the distribution of various elements: O, Mg, Si, Cr, S, Fe and Ni in El Hammami meteorite. From these chemical maps the presence and localization of various minerals: olivines, pyroxenes, kamacite, taenite, troilite and chromite can be indicated. It can be also noted from the figure that silicon, magnesium, iron and oxygen are the major elements in the meteorite.

a)


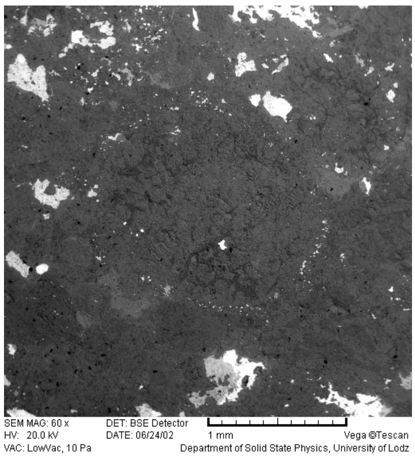
b)


Fig. 6. Electron microscope (BSE) images of olivine chondrules and matrix in Gold Basin meteorite. Notice various minerals present in this chondrite. White areas are Fe-Ni phases, grey represent troilite, and dark areas are mostly olivines and pyroxenes

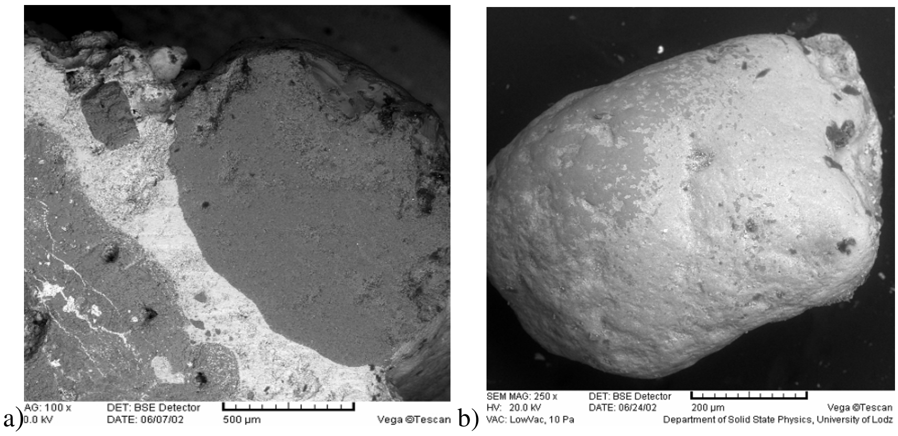


Fig. 7. BSE images of chondrules and the matrix of El Hammami meteorite. (a) orthoclase chondrula with the magnetite rim. The rim is surrounded by kamacite, (b) Silica chondrula

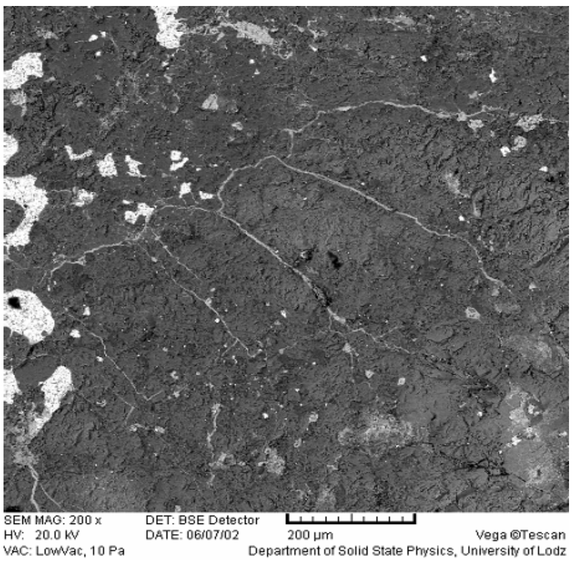


Fig. 8. Electron microscope (BSE) image of the matrix of El Hammami meteorite showing troilite (FeS) veins

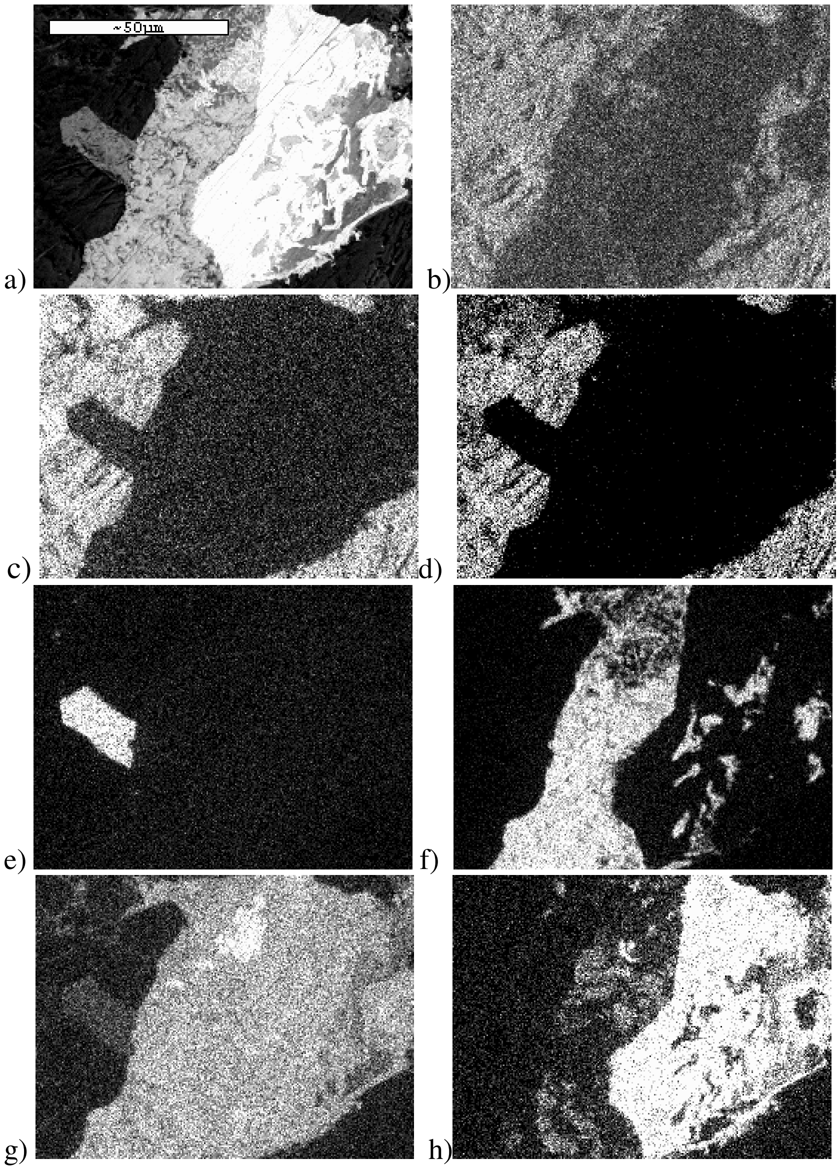


Fig. 9. Distribution (chemical map) of elements in El Hammami meteorite: a) BSE image, b) O, c) Mg, d) Si, e) Cr, f) S, g) Fe, h) Ni distribution. White color shows a high concentration of the element, dark absence of the element in a given region of meteorite. Field of view: 0.125 mm x 0.10 mm

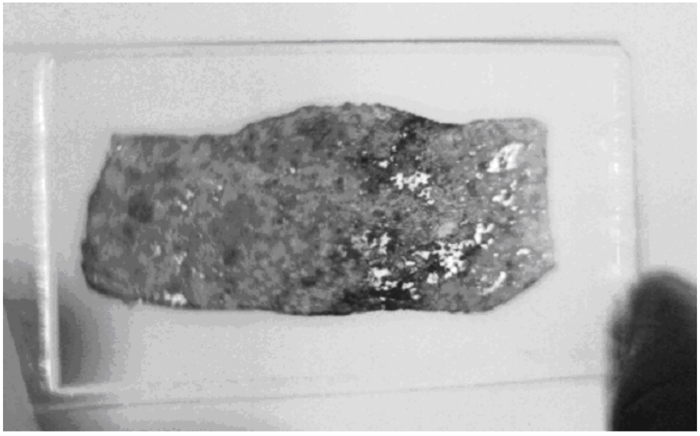
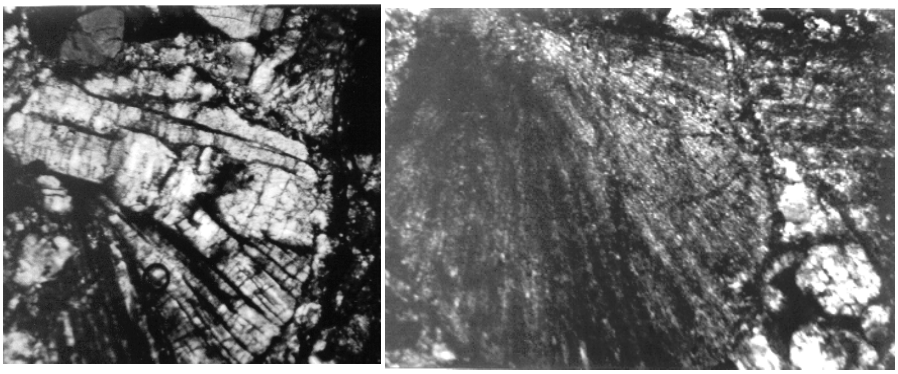


Fig. 10. Thin section of Gold Basin meteorite. White patches are Fe-Ni phases seen in reflected light



a) b)

Fig. 11. Optical images of pyroxene chondrules in Gold Basin meteorite: a) Porphyritic pyroxene (PP) chondrule, b) Rimmed radial pyroxene (RP) chondrule. In pyroxene crystals shown in figure (a) shock lamellae parallel running to each other can be seen which indicate shock grade S3 of this chondrite. Field of view: (a) 0.7 mm x 0.7 mm, (b) 1 mm x 0.7 mm

The typical feature of all chondrites is the presence of chondrules, small rounded spherules composed usually of olivines and pyroxenes. In our Gold Basin and El Hammami meteorites abundance of various types of chondrules is of the order 70-80%, matrix composed of fine granuled material of various minerals accounts for about 15-20%. Chondrules and matrix are shown in Figures 4-12 and 15, both as optical and BSE images.

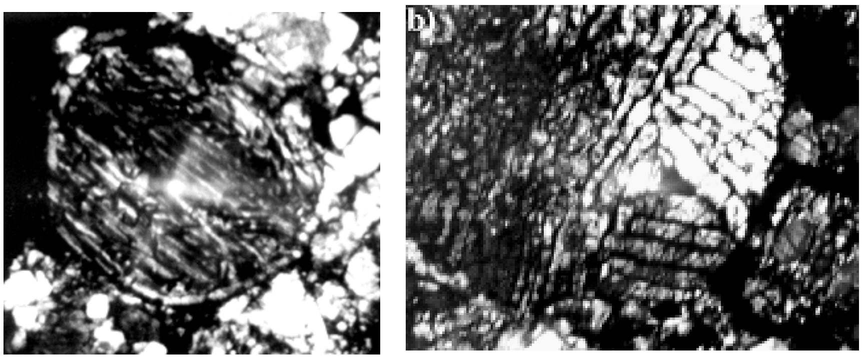


Fig. 12. Optical images of barred olivine (BO) chondrules: (a) El Hammami, (b) Gold Basin. Field of view: (a) 0.7 x 0.7 mm, 0.9 x 0.7 mm

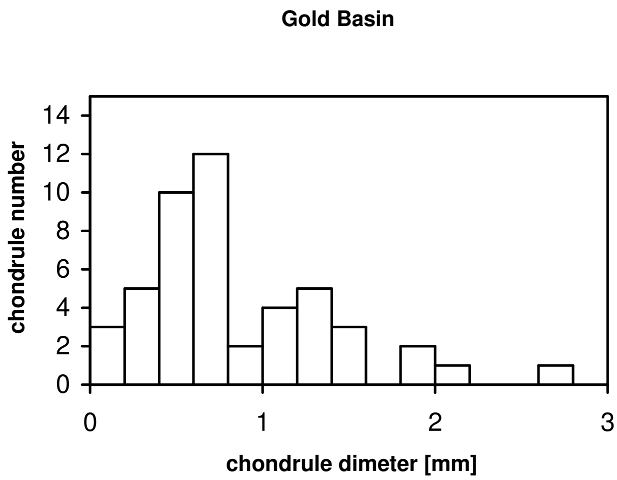


Fig. 13. The histogram of distribution of chondrule size in Gold Basin meteorite

In Figures 13 and 14 histograms of chondrule size, expressed by the diamenter are shown. The smallest chondrules have 0.05 mm diameter, the largest chondrules 2.8 mm. For Gold Basin the maximum of the histogram lies between 0.6 and 0.8 mm, which means that the mean chondrule diameter is about 0.7 mm. The probability of chondrule diameter of the range of 0.6-0.8 mm is 0.46. Moreover, about 91% of all chondrules have their size in the range of 0.1-1.6 mm. The larger chondrules are less abundant. According to Hutchison [5] for L class of ordinary chondrites to which Gold Basin belongs the mean chondrule size is 0.6-0.8 mm in accordance with our results.

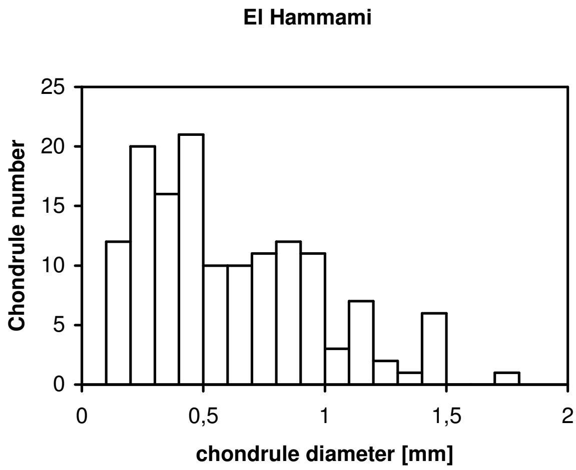


Fig. 14. The histogram of distribution of chondrule size in El Hammami meteorite

Figure 14 shows that the range of chondrule size and the mean chondrule diameter in El Hammami meteorite are smaller than in Gold Basin. The maximum of the histogram lies between 0.2-0.5 mm, and the mean chondrule diameter is about 0.3 mm, according to expectations for H class of ordinary chondrites [5]. The probability of chondrule diameter of the range of 0.2-0.5 mm is 0.40, and 99.3% chondrules have their size in the range of 0.1-1.5 mm.

Chondrules of different textural types have been observed in Gold Basin and El Hammami meteorites under the optical and electron microscopes: barred olivine (BO) chondrules, porphyritic olivine (PO) chondrules, porphyritic pyroxene (PP) chondrules, radial pyroxene (RP) chondrules, granular chondrules, rimmed chondrules and others (Figs. 6, 7, 11 and 12).

Meteorites are divided into different categories based on composition. The basic distinction is made on the basis of the presence of chondules. Chondrules, CAI's and matrix are retained nebular objects of great importance. Since our extraterrestrial samples contain chondrules they belong to chondrites. As the chondrules in Gold Basin and El Hammami are well defined the meteorites class is 4 or 5. High iron content present as free and oxidized metal in El Hammami

(Table 1) is the proof that it is H class of ordinary chondrites, i.e. olivine-bronzite class. In the case of Gold Basin iron content is smaller (Table 1), according to expectations for L class of chondrites, ie for olivine-hyperstene chondrites.

These classes have been additionally confirmed by the analysis of Ca/Si, Al/Si, Fe/Si, Mg/Si, Ni/Si and MgO/FeO ratios and amounts of matrix and chondrule abundance. The physical and compositional properties of El Hammami meteorite are consistent with H class chondrites, and of Gold Basin are consistent with L class chondrites.

Apart from the olivines $Mg,Fe)_2SiO_4$ and Ca-poor pyroxenes ($(Mg,Fe)_2Si_2O_6$ and $(Mg,Fe,Ca)SiO_3$) which are the major components of chondrules and matrix, the other typical of ordinary chondrites minerals have been identified in Gold Basin and in El Hammami meteorites: kamacite and taenite, both iron-nickel phases and troilite (FeS). Bronzite is a Ca-poor pyroxene the presence of which in El Hammami meteorite has been checked by Raman spectroscopy [26]. Porphyritic structure of some parts of Gold Basin meteorite has been also noted in the matrix of this meteorite (Fig. 15).

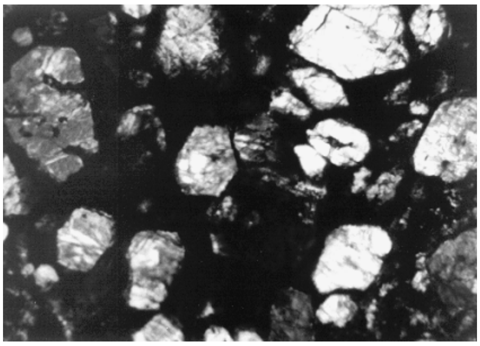


Fig. 15. Euhedral olivine and pyroxene crystals in the matrix of Gold Basin meteorite revealing the porphyritic structure of this region of the meteorite. Field of view 1 mm x 0.7 mm

Olivine is a mineral being the solid solution between forsterite (Fo) Mg_2SiO_4 and fayalite (Fa) Fe_2SiO_4 end members. Olivine in chondrules and in the matrix of Gold Basin and in El Hammami meteorites forms a substantial part of the chondrites. The average composition of olivine in Gold Basin according to literature data is $Fa_{24\pm1}$ (23-25 mol % of fayalite) [18, 25]. Our results for Gold Basin show that olivines in our sample of Gold Basin contain

Fa_{23-28} (23-28 mol % of fayalite). The expected Fa content in olivines of olivine-hyperstene chondrites varies from Fa_{22} to Fa_{32} [9, 11].

The average composition of olivine in El Hammami according to literature data is $Fa_{18.8}$ (18.8 mol % of fayalite) [18, 25]. Our results for El Hammami show that olivines in our sample of El Hammami contain Fa_{20-25} (20-25 mol % of fayalite). The expected Fa content in olivines of olivine-bronzite chondrites varies from Fa_{15} to Fa_{22} [9, 11].

Pyroxenes in Gold Basin meteorites have the composition $Fs_{20}Wo_{1}$, and in El Hammami meteorites $Fs_{16.7}Wo_{1.4}$ [18, 25]. Fs means ferrosilite $Fe_2Si_2O_6$ which is iron- rich half of Ca-poor pyroxenes, and Wo means wollastonite $CaSiO_3$ which is another end-member in pyroxene group. Unfortunately, we have not studied the composition of pyroxenes in our samples, but their presence in our extraterrestrial samples has been confirmed in thin sections of meteorites (Figs. 11, 15).

The composition of low Ca pyroxenes typical of olivine-bronzite chondrites class ranges from Fs_{15} to Fs_{22} and represent the orthopyroxene (Opx) called bronzite. The composition of low Ca pyroxenes typical of olivine-hyperstene chondrites class ranges from Fs_{20} to Fs_{30} and represent the orthopyroxene (Opx) called hyperstene [9-11]. The pyroxene composition in El Hammami matches the Fa content of olivines for H class chondrites, and in Gold Basin matches the Fa content of olivines for L class chondrites. Apart from ferrosilite and wollastonite pyroxenes contain also enstatite (En) $Mg_2Si_2O_6$.

Troilite veins (FeS) present in the matrix of El Hammami meteorite (Figs. 7, 8) are the result of the collision heating of the meteorite and melting of low temperature minerals: troilite and/or kamacite.

The mineral composition of El Hammami and Gold Basin meteorites have been studied in recent years [27-29]. Our results are in satisfactory agreement with these papers.

3. CONCLUSIONS

1. The presence of chondrules and minerals typical of meteoritic matter such as olivines, pyroxenes, iron-nickel phases: kamacite and taenite, and troilite veins are a proof that our samples represent extraterrestrial matter.
2. The relatively large content of non-oxidized iron-nickel confirms that the El Hammami meteorite belongs to ordinary chondrites of high iron content, ie. to H class called olivine-bronzite class.
3. Smaller iron content in Gold Basin meteorite confirms that this ordinary chondrite is L class, i.e. it is olivine-hyperstene chondrite.

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REFERENCES

[1] **Szurgot M.:** Crystals in Meteorites, [in:], Crystals in Nature and Technolog, L. Wojtczak, J. Ziomek (Eds.) (University of Lodz, Łódź, 2005. pp. 151-16 (In Polish).
[2] **Szurgot M., Karczemska A., Kozanecki M.:** Extraterrestrial Diamonds, [in:] Nanodiam, S. Mitura, P. Niedzielski, B. Walkowiak Eds), (PWN, Warsaw, 2006). Ch. 20, pp. 259-287.
[3] **Manecki A.:** Encyclopedia of Minerals in Polish with English Mineral Names. Minerals of Earth and Cosmic Matter, (AGH, Kraków, 2004). (In Polish).
[4] **Hurnik B., Hurnik H.:** Cosmic Matter on Earth, Its Origin and Evolution, (UAM, Poznań, 2005). (In Polish).
[5] **Hutchison R.:** Meteorites: a Petrologic, Chemical and Isotope Syntheses, (Cambridge Univ., Cambridge, 2004).
[6] **Sears D.V.:** The Nature and Origin of Meteorites, (Hilger, Bristol, 1978).
[7] **Sears D.V.:** The Origin of Chondrules and Chondrites, (Cambridge Univ., Cambridge, 2004).
[8] **Krinov E.L.:** Principles of Meteoritics, (Pergamon, New York, 1960).
[9] **Mason B.:** Meteorites, (Wiley, New York, 1962).
[10] **Wasson J.T., Kalleymen G.W.:** Philos. Trans. R. Soc. London **A325**, (1988) 535.
[11] **McCall G.J.H.:** Meteorites and Their Origins (David and Charles, Devon, 1973).
[12] **Wood J.A.:** Meteorites and the Origin of Planets, (McGraw Hill, New York, 1968).
[13] **Wood J.A. [in:]:** The Moon, Meteorites and Comets, B.M. Middlehurst, G. Kuiper (eds.) (Univ. Chicago, Chicago, 1963).
[14] **Kerridge J.K., Mattews M.S. (eds.):** Meteorites and the Early Solar System, (Univ. Arizona, Tucson, 1988).
[15] **Papike J.J. (ed):** Planetary Materials, (Mineralogical Soc. America, Washington, 1998).
[16] **McSween H.Y.Jr.:** Meteorites and Their Parent Planets, (Cambridge Univ., New York, 1999).
[17] **Norton O.R.:** The Cambridge Encyclopedia of Meteorites, (Cambridge Univ., Cambridge, 2002).
[18] **Grady M.:** Catalogue of Meteorites, (Cambridge Univ., Cambridge, 2000).
[19] **Polański K.:** Analytical Electron Microscopy In Crystals Investigations, [in:], Crystals in Nature and Technology, L. Wojtczak, J. Ziomek (Eds) (University of Lodz, Łódź, 2005. pp. 117-132 (In Polish).
[20] **Reed S.J.B.:** Electron Microprobe Analysis and Scanning Electron Microscopy in Geology, (Cambridge Univ., Cambridge, 2000).

[21] **Mason B.:** Amer. Mineral. **52**, (1967) 307.
[22] **Buchwald V.H.:** Handbook of Iron Meteorites, (Univ. California, Berkeley, 1975).
[23] **Brearley A.J., Jones R.H.** [in:]**:** Planetary Materials, Papike J.J. (ed), Rev. in Mineralogy, (Miner. Soc. America, 1998). Ch. 3, pp. 3.1-3.398.
[24] **Wilkinson S.L., Robinson M.S.:** Meteoritics Planetary Sci. **35**, (2000) 1203.
[25] **Grossman J.N.:** Meteoritical Bull. **82**, (1998) July, Meteoritics Planetary Sci. **33**, (1998) A223.
[26] **Szurgot M.:** unpublished data.
[27] **Kring D.A., Jull A.J.T., McHargue L.R., Hill D.H., Cloudt S., Klandrut S.:** Lunar and Planetary Science **XXIX**, (1999) # 1526.
[28] **Zarek W., Popiel E.S., Tuszyński M., Teper E.:** Nukleonika **49**, (Suplement 3) (2004) s. 59.
[29] **Ludwig A., Zarek W., Popiel E.:** Acta Physica Polonica A **100**, (2001) 761.

BADANIA MIKROSKOPOWE CHONDRYTÓW GOLD BASIN I EL HAMMAMI

Streszczenie

Badano skład chemiczny i mineralny meteorytów Gold Basin i El Hammami. Zanalizowano chondry i ciasto skalne. Obecność chondr oliwinowych, chondr piroksenowych, żył troilitowych oraz faz żelazo-niklowych: kamacytu i troilitu świadczą o pozaziemskim pochodzeniu badanych skał. Oprócz minerałów najbardziej rozpowszechnionych w meteorytach takich jak: oliwin, piroksen, kamacyt, taenit i troilit wykryto także plagiklazy, magnetyt, kalcyt, chromit, ortoklaz i krzemionkę. Zgodnie z uprzednią klasyfikacją Gold Basin jest chondrytem klasy L o niskiej zawartości żelaza, a El Hammami chondrytem typu H zawierającym dużo żelaza.