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Faculty of Mechanical Engineering

MASTER`S THESIS

Material analysis of meteorites

Materiálový rozbor meteoritů

Emil Leonczak
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Thesis consultant:	dr. Ing. Anna Karczemska – Technical University of Lodz

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ANNOTATION

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Abstract:

The aim of master`s thesis was to carry out the material analysis of meteorites. Thanks to their extraterrestrial origin meteorites are very interesting objects of scientific research. Carbon contained in meteorites can be found in various forms, i.e. graphite, diamond, lonsdaleite – extraterrestrial hexagonal diamond. This carbon and other phases and compounds can be source of information about the solar system formation, the conditions under which the minerals crystallized and transformed to the present state. Meteorites in this work were analysed paying special attention to the presence of carbon and allotropic forms in which carbon can be found. Theoretical part of thesis presents the division of meteorites, allotropic forms of carbon and methods of carbon detection in this extraterrestrial objects. Experimental part contains results of own research carried out with using optical microscopy, Scanning Electron Microscopy with X-Ray microanalysis, Raman spectroscopy and nanohardness measurement method. Results are presented in tables, graphs and pictures.

Anotace:

Cílem práce bylo vykonat materiálový rozbor meteoritů. Díky mimozemskému původu jsou meteority velmi zajímavým předmětem vědeckých zkoušek. Vyskytují se v nich různé varianty alotropových uhlíků, mezi jinými grafit, diamant (lonsdaleit – hexagonální mimozemský diamant) a také jiné fáze a sloučeniny nám mohou dát informace o formování naší sluneční soustavy, podmínkách krystalizace minerálů a transformace v přítomné formě. Meteority byly zkoumány především z hlediska výskytu uhlíku a jeho alotropových variant. V teoretické části byla představena klasifikace meteoritů, druhy a varianty alotropových uhlíku, v kterých se vyskytuje, a také metody vyhledávání uhlíku v těchto mimozemských objektech. Experimentalni část obsahuje výsledky vlastních zkoušek vykonaných s použitím těchto metod: optické mikroskopie, rastrovací elektronové mikroskopie s rentgenovou mikroanalýzou (EDS), spektroskopie Ramana a také měření nanotvrdosti. Výsledky byli prezentovány ve formě tabulek, diagramů a snímků.

Abstrakt:

Celem pracy było przeprowadzenie analizy materiałowej meteorytów. Dzięki pozaziemskiemu pochodzeniu są one bardzo ciekawym obiektem badań naukowych. Występujący w nich w różnych postaciach węgiel m.in. grafit, diament, lonsdaleit – heksagonalny pozaziemski diament oraz inne fazy i związki, mogą dostarczyć nam informacji na temat formowania się naszego Układu Słonecznego, warunków krystalizacji minerałów i przekształcania się ich w obecną postać. Meteoryty zostały przebadane głównie pod kątem obecności węgla i jego odmian alotropowych. W części teoretycznej przedstawiony został podział meteorytów, rodzaj i odmiany alotropowe węgla w jakich on występuje oraz metody badań służące do wykrywania węgla w tych pozaziemskich obiektach. Część doświadczalna zawiera wyniki badań własnych przeprowadzonych z wykorzystaniem metod: mikroskopii optycznej, skaningowej mikroskopii elektronowej z mikroanalizatorem rentgenowskim EDS, spektroskopii Ramana oraz pomiaru nanotwardości. Wyniki zaprezentowane zostały w postaci tabel, wykresów i zdjęć.

"What can be more beautiful than the sky that embraces all that is beautiful"

Nicolaus Copernicus

Gratitude:

I thank my mentor supervisor, prof. dr hab. Stanislaw Mitura, dr h. c. for help and giving me valuable hints in the course of writting this thesis. I express my gratitude to Mrs. E. Slowikowska and Mr. R. Zdancewicz for giving samples to research. I give my thanks to Technical University of Lodz and Technical University of Liberec for helping me with carrying out the research. I thank my beloved fiancée, my family and all my friends for words of encouragement and faith. I would like to thank Mr. Z. Rozek for help and care during stay in Liberec.

Specification of abbreviation and designation.

CVD	- Chemical Vapor Deposition
EDS	- Energy Dispersive X-Ray Spectroscopy
K	- Kelvin – a unit increment of temperature and is one of the seven SI base units, K = °C + 273.15
T	- Tesla – is the SI derived unit of magnetic flux density (or magnetic induction) and defines the intensity (density) of a magnetic field
m	- metre – is a measure of length
nm	- nanometre – is a unit of length in the metric system, 1×10^{-9} m
s	- second – unit of time, and is the International System of Units (SI) base unit of time
kg	- kilogram – is the SI base unit of mass
B.C.	- Before Christ
NASA	- National Aeronautics and Space Administration
wt %	- weight %
vol %	- volume %
HED	- Howardite – Eucrite – Diogenite
UV	- ultraviolet
ppm	- parts per million
HTHP	- High Temperature High Pressure
SEM	- Scanning Electron Microscope
AFM	- Atomic Force Microscope.
HRTEM	- High-Resolution Transmission Electron Microscopy
SIMS	- Secondary Ion Mass Spectrometry
WD	- Working Distance [mm]
cm^{-1}	- wave number
GPa	- gigapascal, 10^9Pa

CONTENT:

I. Introduction.

The aim of this work is to analyse the material composition of meteorites. This analysis will be carried out according to the amount and kind of carbon. The most important issue of my research will be the meteorite called Canyon Diablo found in Arizona in the U.S.A., however some of meteorite breccias found in Poland will be investigated.

Meteorites, as extraterrestrial objects, are extremely interesting because of the processes they are exposed to in outer space as well as during their way into the Earth. Many similar processes to these mentioned above, e.g. CVD (*Chemical Vapor Deposition*) method, are used in techniques while producing the artificial diamond.

As it is widely known, carbon is one of the basic chemical elements of which our world is built. One can find it in biotic or abiotic world as well as in some meteorites.

Nowadays the development of technology gives us enormous possibilities in doing research. Using methods such as: optical microscopy, Raman spectroscopy, Scanning Electron Microscopy with X-Ray microanalysis EDS, I would like to show that meteorites contain various allotropic forms of carbon.

All the investigations were carried out thanks to prof. dr hab. Stanislaw Mitura, dr h.c. in Institute of Materials Science and Engineering in Lodz and in Faculty of Mechanical Engineering of Technical University of Liberec.

II. Theoretical part.

1. The Universe.

1.1. The history of the Universe.

Everything that exists and surrounds us is the Universe. Stars, planets, matter, space, energy and time and other space objects are the elements of the universe [1]. There ale many theories which describe the history of origin of the Universe. One of them called the Big Bang says that the Universe began 14 billion years ago as the result of the immense explosion. The Earth and other planets, numerous stars and galaxies came into being and they were the consequence of that explosion. All of them were initially concentrated in one element which was not bigger than the sand grain, singularity. This explosion caused drastic changes in history [2], [3].

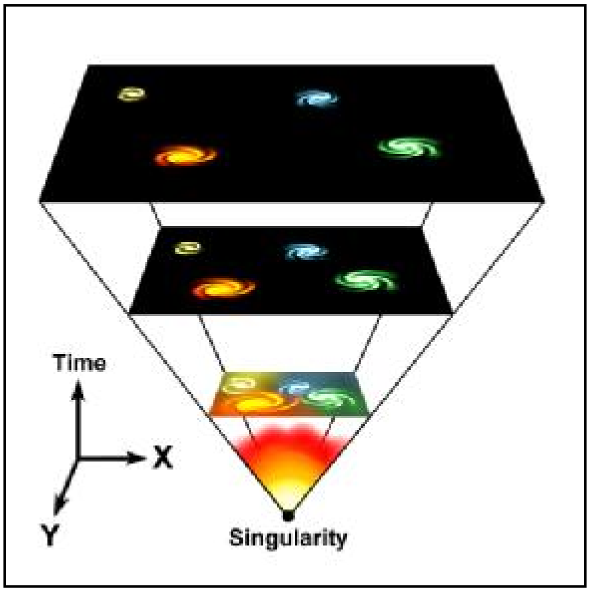


Fig. 1. The Universe expansion, according to [4].

George Lemaȋtre was the first to introduce this theory. It appeared in 1931 and was named "*The Hypothesis of Primeval Atom*". In early 60s of the XXth century British scientist Fred Hoyle introduced the term *big bang* which characterized the phenomenon. Nowadays the time when the Big Bang took place is regarded as the hypothetical beginning of the Universe [5].

What was before the Big Bang? The best answer may be found in words of one of the greatest scientists Leon Max Lederman [5]:

"*In the very beginning there was a void - a curious form of vacuum - a nothingness containing no space, no time, no matter, no light, no sound […].*" [6].

The temperature of the Universe at its beginning was about 10^{32}. At that time it was hyperspacial 10 – dimensional creature. Its unstability resulted in its disintegration into 4 and 6 – dimensional creature. That disintegration occurred after the time $t = 10^{-43}$ s called the Planck time. The 6 – dimensional creature became very small (10^{-32} cm), whereas the 4 – dimensional one started expanding rapidly. Our visible Universe is the effect of constant changes which were taking place throughout time (it expanded 10^{50} times). In the following second parts the temperature cooled to about 10^{14} K and protons and neutrons were formed. First constant atoms of oxygen and hydrogen appeared after about 700 000 years. Our Universe needed such a long time to lower the temperature to about 3000 K, which enabled the existence of atoms mentioned above [1], [2], [5].

1.2. Physical conditions.

The Universe is the space in which there are particular physical conditions. It is a wonderful place where one can find extreme physical conditions. There are various states of matter, the smallest and the largest density, extreme temperatures, the shortest and the longest distances [7].

Matter density in space is between $10^{-23} – 10^{18}$ kg/m^3, magnetic induction may reach the value of 10^{11} T (in stars "Magnetars"), temperatures are between 2.7 – 10^9 or even 10^{11} K, and gravitational fields are about 10^{12} m/s^2. To compare the conditions on the Earth, the highest vacuum is about 10^{-10} kg/m^3 and geomagnetic field is only 6 T (instantaneous 200 T) [7].

Various nature of objects in the Universe, different mechanisms of radiation and objects which appear depending on the value of electromagnetic wave are the best evidence that there exist the sources of high energy gamma radiation, X-Ray, active galaxies and stars radiating mainly in ultraviolet, infrared, microwave and radio objects and stars and galaxies which one can recognize thanks to the sense of sight in visible light [7].

1.3. Panspermia Theory.

It is one of the theories explaining the origin of life on Earth. According to this theory life did not start on Earth, but it had existed in eternal Universe and it was transferred from one solar system to another in the form of spores of microorganisms [8]. They might have been transferred, e.g. with the help of meteorites [9].

The resting spores of microorganisms may survive in tenuous atmosphere in the height of dozens of kilometres. According to this theory meteorites might have been used as protection from radiation in space. It was observed that the small number of meteorites protects the genetic material of microorganisms from the harmful influence of radiation in space. Thanks to meteorites the spores of microorganisms theoretically might have travelled from one planet to another and in beneficial conditions started life on them [9].

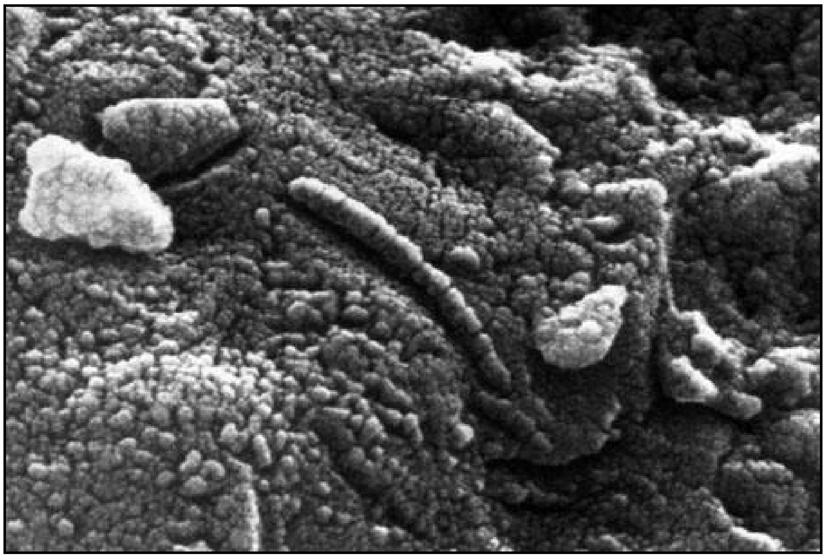


Fig. 2. Microstructure of meteorite ALH84001 showing biogenic origin, according to [10].

Panspermia term was introduced by Greek philosopher Anaksagoras in Vth century B.C. But the theory itself was created and revived by Herman von Helmholtz in 1879 and Svante Arrhenius in 1903 [10].

Many eminent scientists supported this theory. One of them was Francis Harry Compton Crick who rejected the idea of self – contained origin of life deriving from abiotic matter [9]:

"If a particular amino acid sequence was selected by chance, how rare of an event would that be?[…] Suppose the chain is about two hundred amino acids long; […] Since we have just twenty possibilities at each place, the number of possibilities is twenty multiplied by itself some two hundred times. This is conveniently written 20^{200}*, that is a one followed by 260 zeros!..."* [11].

The other great scientist supporting this theory was Sir Fred Hoyle. In 1981 he shocked men of science, as he rejected chemical evolution and supported Panspermia theory [9]:

"A junkyard contains all the bits and pieces of a Boeing-747, dismembered and in disarray. A whirlwind happens to blow through the yard. What is the chance that after its passage a fully assembled 747, ready to fly, will be found standing there?" [12] [used as argument against the origin of proteins from amino acids] [9].

Nowadays there are a lot of discussions about this theory. Scientists from NASA Ames Research Center while analysing spectrographic spectrum of different space objects, discovered polyatomic hetero molecules (molecules which contain atoms different than carbon and hydrogen). The compounds thanks to stellar winds are spread all over the galaxies and planetary systems. The newest investigations let us sate that there are atoms of nitrogen in these compounds. Nitrogen is one of the most important atoms in human organism, as well as is essential element of prebiotic chain [14].

It is possible that many investigations carried out at present, concerning this unpopular and controversial theory, let the scientists answer this extremely difficult question – “*how did life start on Earth*?”.

2. Meteorites.

2.1. Introduction.

Meteorites are extraterrestrial objects which managed to get through the Earth’s atmosphere and reached the ground. Meteorites are also the rocks which fell on Earth from interplanetary space and they are the remaining parts after the creation of the Solar System, and some of them are primitive matter [3], [15].

Most meteorites are parts of planetoids which create the belt between Mars and Jupiter or they are destroyed planetoids after the space collisions. They may be also pieces of planets. There are Mars and Moon meteorites among them. The time of the beginning of meteorites is similar to that of the beginning of Earth, i.e. about 4,6 billion years ago [3], [15].

Falls of meteorites is the phenomenon which does not occur so often. However they spectacular and make some people feel terrified. Large meteorites fall onto the ground making craters. The solid body of the meteorite falling down with the speed of several kilometres per second, compresses the ground suddenly. Kinetic energy changes into thermal energy and as the result the matter evaporates and the compressed gas generates. This gas explodes and scatters around tiny pieces of the meteorite and the ground (*Fig. 3*). As the result of the meteorite impacts there are created breccias around the craters. Breccias are the rocks which were formed out of pieces of the crushed original rocks. Breccias may be formed out of the rocks changed as a result of violent impact [15], [16].

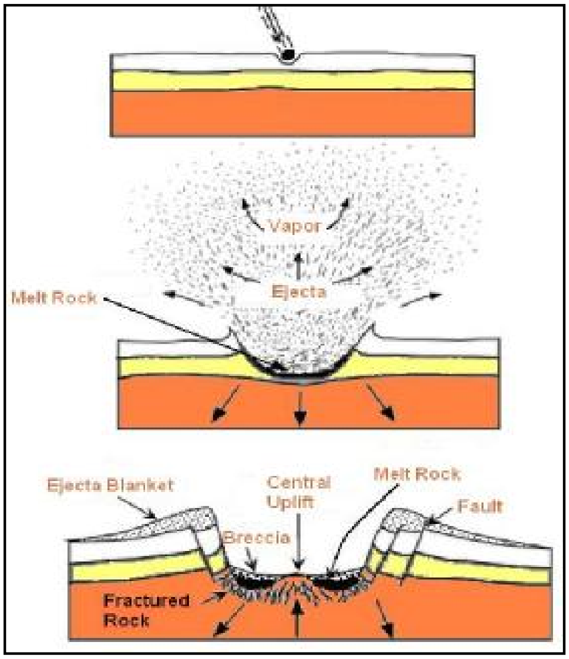


Fig. 3. Mechanics of impact cratering, according to [18].

Fig. 4. Stone meteorite – Baszkowka, according to [17].

The characteristic feature of meteorites is their fusion crust. They also may be identified on the basis of visible on them so called regmaglypts (“thumb – print” like deformations). They are formed during the meteoroids fall (parent body of meteorites) through the Earth atmosphere with high space speed (*Fig. 4*). Initial velocity while reaching the atmosphere is about 14 – 22 km/s, and terminal velocity at the very moment of impact is about 0,1 km/s [15].

2.2. Minerals in meteorites.

The bodies which are of crystal structure and they are formed by different chemical compounds but also by chemical elements are called minerals. They are basic components of meteorites. In nature one can find natural minerals, e.g. rocks, but there are synthetic minerals obtained in laboratories as well. On the other hand nature forms substances which are not of crystal structure. They are amorphous substances such as glaze which was formed as the result of rapid cooling of melted rock – magma. Crystal bodies are formed in the opposite way, because they undergo slow cooling processes. These processes of crystallization may proceed from gaseous or solid state, as well as from solutions [16].

Minerals which may be frequently found in meteorites are represented in *Table. 1*. The number of minerals which are in lithosphere is much bigger than that in meteorites. However, in meteorites there are minerals that cannot be found on Earth (*Tab. 2*). The big number of the minerals is unstable because of earth conditions – the influence of the atmosphere and water are destructive for them [16].

Type and proportion of minerals in meteorites help us specify the conditions in which they formed, e.g. temperature, pressure and chemical constitution of parent substance. Thanks to that one can learn about the history of meteorites [3], [16].

Table 1. Minerals occuring in meteorites (most often), according to [16].

Group of chemical compound	Mineral	Chemical formula of mineral
Silicates	olivines	$(Mg, Fe)_2 SiO_4$
	orthopyroxenes	$(Mg, Fe) SiO_3$
	clinopyroxenes	$(Mg, Fe, Ca) SiO_3$
Aluminosilicates	plagioclases	$Na Al Si_3O_8$ – $Ca Al_2 Si_2O_8$
	augite	$(Ca, Mg, Fe^{2+}, Al)_2 (Si, Al)_2O_6$
Free elements	kamacite	alloy 93 – 96% Fe, 4 – 7% Ni
	taenite	alloy>80% Fe, Ni>20%
	graphite	C
Sulfides	troilite	FeS
	pentlandite	$(Fe, Ni)_9S_8$
	daubreelite	$FeCr_2S_4$
	oldhamite	CaS
Oxides	quartz	SiO_2
	cristobalite	SiO_2
	tridymite	SiO_2
	magnetite	Fe_3O_4
	rutile	TiO_2
	chromite	$Fe Cr_2O_4$
	ilmenite	$Fe TiO_3$
Phosphates	whitlockite	$Ca_3(PO_4)_2$
	farringtonite	$Mg_3(PO_4)_2$
	chloric apatite	$Ca_5(PO_4)_3 Cl$
Other	schreibersite	$(Fe, Ni)_3 P$
	cohenite	Fe_3C

Table 2. Minerals occuring in meteorites but naturally nonoccuring, according to [16].

Group of chemical compound	Mineral	Chemical formula of mineral	Discovery year
Free elements	lonsdaleite – diamond – 2H	C	1967
	iron – nickel	$Fe – Ni$ (1:1)	1967
	ε - iron	$Fe – Ni$	1966
	taenite	$Fe – Ni$ (0.2 – 0.8)	186
Carbides	chalypite	Fe_2C	1867
	haxonite	$(Fe, Ni)_{23}C_6$	1972
Nitrides	carlsbergite	CrN	1971
	osbornite	TiN	1870
Oxides	sinoite	Si_2N_2O	1964
Phosphides	rhabdite	$(F, Ni, Co)_3 P$	1865
	schreibersite	$(F, Ni, Co)_3 P$	1846
	barringerite	$(F, Ni, Co) P$	1965
	perryite	$(Ni, Fe)_2(Si, P)$	1965
Sulfides	brezinaite	$(Cr, Fe, V, Ti, Mn)S_4$	1969
	daubrèelite	$Fe Cr_2 S_4$	1876
	gentnerite	$(Cu_8Fe_3Cr_{11})S_8$	1966
	heideite	$(Fe, Cr)_{x+1}(Ti, Fe)_2S_4$	1973
	niningerite	$(Mg, Fe, Mn)S$	1967
	oldhamite	$Ca S$	1862
Phosphates	brianite	$Na_2CaMg(PO_4)_2$	1966
	buchwaldite	$Na Ca PO_4$	1975
	farringtonite	$Mg_3(PO_4)_2$	1961
	merrillite	β- $Ca_3(PO_4)_2$	1976
	panethite	$Na_2(Mg, Fe)_2(PO_4)_2$	1966
	stanfieldite	$Ca_4Mg_3Fe_2(PO_4)_6$	1967
Silicates	krinovite	$NaMg_2CrSi_3O_{10}$	1968
	merrihueite	$(K, Na)_2 Fe_5 Si_{12} O_{30}$	1965
	ringwoodite	$(Mg, Fe)_2SiO_4$	1969
	roedderite	$(K, Na)_2Mg_5Si_{12}O_{30}$	1965
	ureilite		1965
	= kosmochlor	$Na Cr(SiO_3)_2$	1897
Aluminosilicates	yagiite	$(Na, K)_3 Mg_4(Mg, Fe, Ti, Al)_8 (Si, Al)_{24}O_{60}$	1969

In addition, it should be said something about two minerals that are not shown in above – mentioned tables. These minerals are: chaoite and cliftonite. The first one is carbin. It was first time discovered in 1968 in meteor crater in Nördlingen valley (Germany). The other one, cliftonite, is polycrystalline aggregate of graphite with regular structure discovered in several meteorites. At first, it was considered to be a pseudomorph form of graphite after diamond. However, series of experiments showed that it is probably product of cohoenite (Fe_3C) decomposition [29], [36], [58].

2.3. Meteorites classification.

2.3.1. General classification.

Traditionally meteorites are divided into stony meteorites, stony-iron meteorites and iron meteorites. First detailed classifications appeared in XIXth century. They were created by: Gustaw Rose (1863) – classification known as Rose – Tschermak classification – Brzeziny, G.T. Priror (1920) – classification based on chemical – mineral properties. After some time those classifications were changed and substituted by B. Mason between 1962 and 1967. He suggested dividing meteorites into chondrites, achondrites, iron meteorites and stony-iron meteorites. Today this classification is called Prior-Mason classification [16].

At present, it is also popular to divide meteorites into parent meteorites (undifferentiated ones) which are stony meteorites (chondrites), and differentiated meteorites which are stony meteorites (achondrites), iron and stony – iron meteorites. The first group of meteorites consists of meteorites which did not undergo differentiation as the result of action of pressure and heat. The second group was affected by these factors [16].

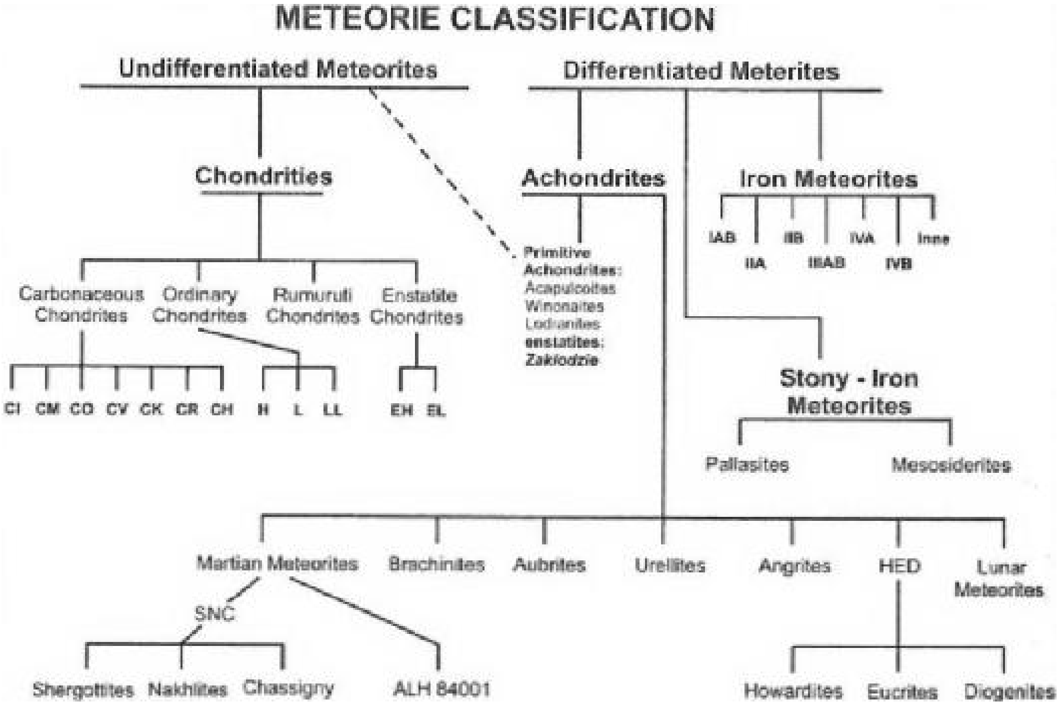


Fig. 5. Meteorite classification according to Bischoff [15].

2.3.2. Chondrites.

These are meteorites which occur most frequently. Their characteristic feature are tiny, round particles of silicates measuring from 0,01 to 3 mm (sometimes to 1 cm) called chondrules (*Fig. 6, 7*). They are rich in magnesium olivine and pyroxene and they compose the chondrite matrix. This matrix usually has the same composition as chondrules. Additionally, there are carbon phases and compounds, as well as some iron as free metal in them [3], [15], [16]. The content of minerals in chondrites is represented in *Table 3*.

Table 3. Main minerals contained in chondrites, according to [16].

Mineral	Chemical formula	wt % dependent on chemical group
Olivine	$(Fe,Mg)_2SiO_4$	0-60
Pyroxene	$(Fe,Mg)_2SiO_3$	14-60
Diopside*	$CaMgSi_2O_6$	0-(4-5)
Orthoclase	$NaAlSi_3O_8$**	(5-6)-10
Troilite	FeS	(5-6)-(5-10)
Kamacite	$FeNi$	1-5
Taenite	$FeNi$	traces – 4

* - also pyroxene ; ** - sometimes contains 10-15% $CaAl_2Si_2O_8$, 1-6% $KAlSi_2O_8$ is aluminosilicate.

Fig. 6. Pyroxene – olivine chondrule. There are also present smaller chondrules and crystals of pyroxenes, olivines and non clear minerals, next to bigger one, according to [17].

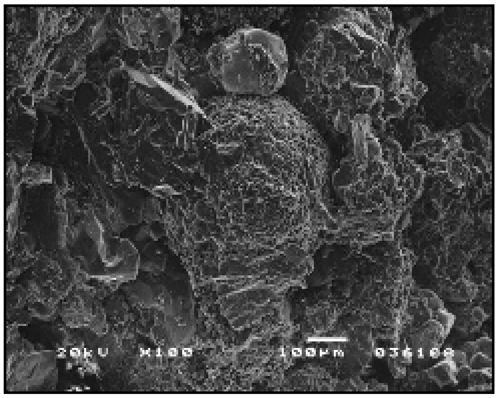


Fig. 7. Porous chondrule, image from SEM, according to [17].

In 1967 W.R. Van Schmusen and J.A. Wood introduced chemical – petrologic classification of meteorites. It has been widely known and used so far [16].

Due to chemical, classifications chondrites are divided according to the amount and the level of oxidation of iron contained in them (*Fig. 8*). Iron contained in chondrites may be zero – valent, bivalent and trivalent [16]:

- Fe^0 – iron-nickel alloy (taenite, kamacite);
- Fe^{+2} – component of silicate minerals, forms ferrous sulfide (troilite);
- Fe^{+3} – magnetite;

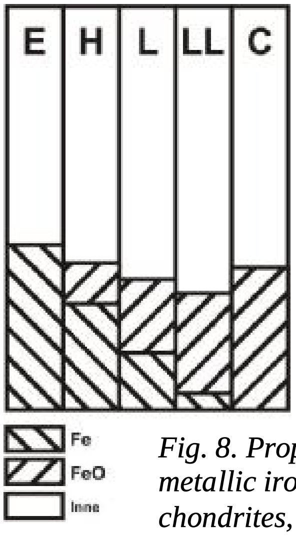


Fig. 8. Proportion between metallic iron and iron oxide in chondrites, according to [16].

In this classification letters are used according to the symbol of chemical group [3], [16]:

- E – enstatites;
- C – carbonaceous chondrites;
- H (*High iron*) – high carbon content;
- L (*Low iron*) – low iron content;
- LL (*Low iron – Low metal*) – low iron content and low metallic iron content;

We can also find the letter O which stands for Ordinary chondrite. In this group there are chondrites H, L, LL, which creates the whole [16]. The other factor which determines the classification according to Van Schmus and Wood is the inner structure of chondrites (petrologic). There are six types of chondrites and they are divided according to the following criteria [16]:

- chondrite mineralogy;
- texture of parent rock and chondrules;
- the presence of glaze;
- water content H_2O;
- carbon content C;
- nickel content in iron-nickel alloy;
- nickel content in sulfides;

Table 4. Some characteristics of petrologic types, according to Van Schmus and Wood [16].

Chondrules	Mother rock	Carbon C (%)	H_2O (%)
1 – deficiency	delicate, non-transparent	2,8	20
2 – very clearly	non-transparent	0,6-2,8	4-18
3 – very clearly	non-transparent	0,2-1,0	2
4 – clearly definite	transparent fine-crystalline	0,2	2
5 – clearly outline	recrystallization	0,2	2
6 – weakly definite	recrystallization	0,2	2

Table 5. Chemical – petrologic classification of chondrites, according to Van Schmus and Wood [16].

Chemical group	Petrologic type of chondrites					
	1	2	3	4	5	6
E			E3	E4	E5	E6
H			H3	H4	H5	H6
L			L3	L4	L5	L6
LL			LL3	LL4	LL5	LL6
C	C1	C2	C3	C4		

In literature we can find such symbols of chondrites as [16]:

- EH (EI) – enstatites with high iron content (*High iron*);
- EL (EII) – enstatites with low iron content (*Low iron*);
- R – usually meteorite breccia with 24% wt contain of iron oxidized to Fe^{+2}. This iron is frequently in a form of olivines and sulfides;

2.3.2.1. Carbonaceous chondrites.

It is very interesting group of chondrites because of its high carbon content. Carbonaceous chondrites (*Fig. 9*) are the most primitive of the meteorites (they were not differentiated under the influence of temperature and pressure). The distinguishing feature of this group of chondrites is their chemical compounds and mineral contain, which does not occur in the rest of chondrites (*Tab. 6*) [3], [16].

Fig. 9. Carbonaceous chondrite Allende CV3, according to [20].

Table 6. Extra minerals contained in carbonaceous chondrites, according to [16].

Mineral	**Chemical formula**
Serpentine	$Mg_3Si_2O_5(OH)_4$
Magnetite	Fe_3O_4
Spinel	$MgAl_2O_4$
Corundum	Al_2O_3
Melilite	$Ca_2MgSi_2O_7$

Serpentine, Magnetite – low-temperature minerals; Spinel, Corundum, Melilite – high-temperature minerals.

Carbonaceous chondrites, as all chondrites, contain iron (20 – 25%), which is oxidized to Fe^{+2} and Fe^{+3} and occur in a form of chemical compounds Fe_3O_4, olivines (about 40%), pyroxenes (30%). It is distinctive that carbonaceous chondrites contain only trace amount of ferrous sulfide – troilite FeS [3], [16].

Graphite, carbides and carbonate minerals (e.g. $CaCO_3$ – calcite, $MgCO_3$ – magnesite) are carbon types which may be found in carbonaceous chondrites. They also contain sulphur in a form of sulfates ($CaSO_4$ – calcium sulfate, $MgSO_4$ – magnesium sulfate and others), sulphur in organic compounds and in an unbounded form S^0. They are composed of water H_2O, which may occur in minerals structure ($CaSO_4\ 2H_2O$ – hydrated calcium sulfate) [16].

According to chemical-petrologic classification chondrites may be divided into seven groups (*Tab. 7*) [16].

Table 7. Chemical – petrologic classification of carbonaceous chondrites, according to [16].

Carbonaceous chondrites group	**Petrologic type**					
	1	**2**	**3**	**4**	**5**	**6**
CI	+	-	-	-	-	-
CM	-	+	-	-	-	-
CO	-	-	+	-	-	-
CV	-	-	+	-	-	-
CK	-	-	-	+	+	+
CR	-	+	-	-	-	-
CH	-	-	+	-	-	-

where: C – designation of carbonaceous chondrite; I, M, O, V, K, R – group of meteorites (I – Ivuna, M – Mighei, O – Ornans, V – Vigarno, K – Koroand, R – Renazzo); H – High content of iron.

One can distinguish a carbonaceous chondrite denoted by CB letters as it is named after Bencubbin meteorite found in Australia in 1930. Its characteristic feature is high iron and nickel content (exceeding 50%). This group is additionally divided into [19]:

- CB_a - contain big metallic globules and chondrules;
- CB_b – richer in metal and containing smaller chondrules and metallic globules;

2.3.3. Achondrites.

Achondrites (*Fig. 10*) are stony meteorites, which contain chondrules. They are igneous rock – liquid silicate mass which was formed as a result of melting parent meteorite bodies. Many of them are of crystalline structure. The crystals here are significantly bigger and that is the main factor which distinguish them from other stony meteorites. These meteorites have only iron Fe^{+2} in the form of silicates. Basically, they do not contain troilite – FeS (ferrous sulfide) or other sulfides [3], [16].

Fig. 10. Achondrite (diogenite), according to [21].

Initially achondrites were divided into two groups. Poor in calcium (1 – 5% CaO) and rich in calcium (2 – 25% CaO). This classification was suggested by G.T Priror. In 60s of XXth century this classification was modified by B. Mason (*Tab. 8*). This classification, however was not efficient and therefore they decided to introduce the additional one, based on structural and chemical features of meteorites. There were 3 types of achondrites according to this classification [16]:

- primitive achondrites – they are similar to their precursors chondrites, they are not a numerous group;
- planetary chondrites – e.g. achondrites resembling basalts, called HED group, they are the most numerous group;
- achondrites originate from planets like Earth – Martian and lunar;

Table 8. Classification of achondrites according to B. Mason [16].

Customary name	**Main minerals**	**Name of mineralogy**
Ca – poor achondrites		
Aubrites	enstatite	enstatite achondrites
Diogenites	hypersthene	hypersthene achondrites
Chassignites	olivine	oliwin achondrites
Ureilites	olivine and pigeonite	olivine – pigeonite achondrites
Ca – rich achondrites		
Angrites	augite	augite achondrites
Nakhlites	diopside and olivin	diopside – oliwin achondrites
Eucrites	pyroxene and plagioclases	pyroxene – plagioclase achondrites
Howardites	pyroxene and plagioclases	pyroxene – plagioclase achondrites

Table 9. Classification of achondrites according to their origin [16].

Type of meteorite	Name	Origin source
Primitive	acapulcoites	??
	winonaites	
	lodranites	
Planetary	howardites	Vesta – probably
	eucrites	
	diogenites	
	aubrites	Other planets
	angrites	
	ureilites	
	brachinites	
From bigger planetary bodies	lunars	Moon Mars
	shergottites	
	nakhlites	
	chassignites	
	ALH 84001	

2.3.4. Iron meteorites.

This group, similarly to achondrites, contains meteorites built up with igneous rock. They represent similar structure to the material from which the Earth's core is built. Iron meteorites are composed of iron – nickel alloy (Fe – Ni) with a small amount of cobalt (Co). This alloy is usually contains in average: Fe – 90,8%, Ni – 8,6%, Co – 0,6%. There are also iridium (Ir), germanium (Ge), gallium (Ga), chromium (Cr), sodium (Na), phosphorus (P), sulphur (S), and carbon (C) [3], [16].

Iron – nickel alloy (Fe – Ni) in meteorites is segregated into 2 phases [3], [15], [16]:

1. **α phase** – body – centered – cubic known as kamacite, (band iron), with 4 – 7% Ni content;
2. **γ phase** – face – centered – cubic known as taenite, (beam iron), with ≤ 30% Ni content;

There are also such minerals in iron meteorites as troilite (FeS), phosphides $(Fe, Ni)_3P$ – schreibersite and rhabdite, cohenite (Fe_3C) and free carbon (C) as graphite and cliftonite [16].

Characteristic feature of iron meteorites are so called Widmanstatten structures (*Fig. 11*). They are characteristic shapes (regular pattern of straight intersecting lines) which is revealed on the surface by etching in dilute acid (*NITAL*). Among iron meteorites there such on which these structures will not be visible, but there will be revealed the lines known as Neumann lines. They are characteristic parallel lines of thickness (1-10 µm) which cross at different angles [3], [16].

Fig. 11. Widmanstatten structure, according to [19.]

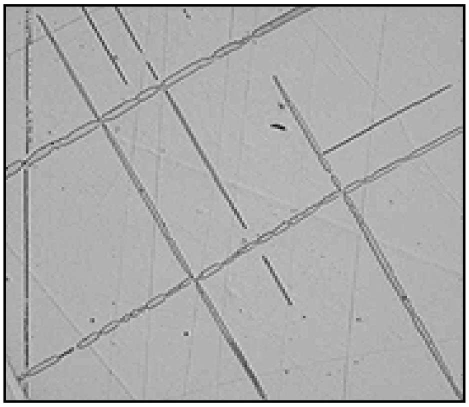


Fig. 12. Neumann lines, according to [22].

Iron meteorites are divided into three main groups (*Tab. 10*). This is structural classification based on nickel content (Ni) [15], [16]:

Table 10. Classification of iron meteorites according to Mason [16].

Typ of iron meteorite	**Symbol**	**Ni (%) content**	**Numbers of meteorites (%)**
Hexaedrite	H	5-6	11
Octahedrite	O	6-14	78
Ataxite	D	>12	7

- Hexaedrites – these are meteorites which consist of kamacite crystals, usually mono crystals (sometimes of grainy structure). The name hexaedrite comes from crystalizing kamacite in the form of cubes. On their surface Widmanstatten structures cannot be found but only Neumann lines are possible to observe [16];
- Octahedrites – contain kamacite and taenite. Their characteristic features are Widmanstatten structures in forms of lamellae (thickness 0,2 – 3,3 mm) of kamacite and taenite set interchangeably. The name comes from the arrangement of lamellae which are parallel to the planes of the lattice in an octahedral geometry [16];

- Ataxites – their structure depends on the nickel content (Ni). If there is less nickel than 20% in them, their main component is taenite. If there is more nickel than 20% ataxites are of irregular built and they create beams of kamacite and taenite – plessite [16];

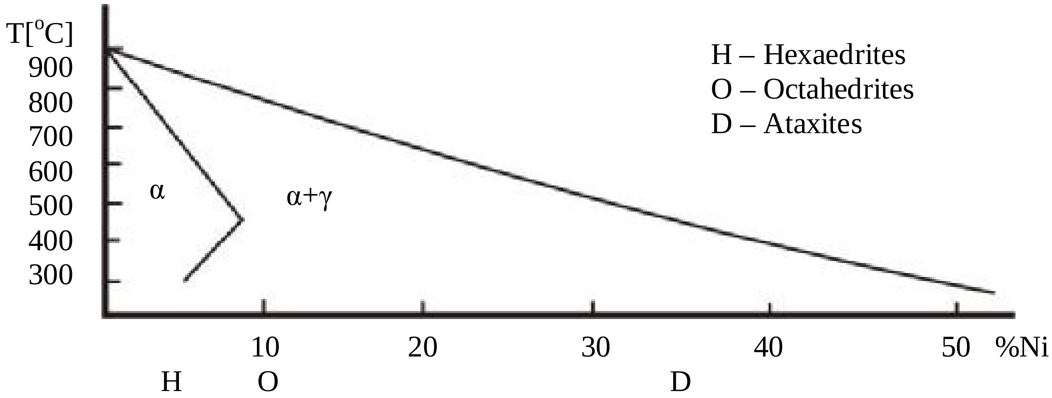


Fig. 13. Phase diagram in nickel – iron alloy, according to [16].

There is another significant classification of iron meteorites based on the width of kamacite beam. It was introduced by V.F. Buchwald in the 70s of XXth century. According to this classification hexaedrites are meteorites with quite wide kamacite beam exceeding 55 mm. On the other hand ataxites have very thin kamacite beam between 0,006 to 0,03 mm. Octahedrites were classified according to *Table 11* [16].

Table 11. Classification of octahedrites according to thickness of kamacite beam [16].

Octahedrites class	**Symbol**	**Thickness of kamacite beam (mm)**
Coarsest structure	Ogg	>3,3
Coarse structure	Og	1,3 – 3,3
Medium structure	Om	0,5 – 1,3
Fine structure	Of	0,2 – 0,5
Finest structure	Off	<0,2
Plessitic structure	Opl	<0,2

Apart from classifications mentioned above, there is chemical classification, too. It divides meteorites into 13 groups: IAB, IC, IIAB, IIC, etc. These groups were created on the basis of their chemical composition. Chemical elements which decides upon the classification are gallium (Ga) and germanium (Ge) – their trace amounts and the nickel (Ni) content. Hexaedrites were classified as IIAB group, ocahedrites as groups IAB, IC,

IIC, IID, IIE, IIF, IIAB, IIICD, IIIE, IIIF, IVA, and ataxites belong to IVB group. Meteorites from IAB, IICD and IIE are so called non – magmatic (abnormal), and the other are magmatic. The first have been formed as the result of CVD processes (*Chemical Vapor Deposition*), and the latter as the result of crystallization from a metal melt [3].

Fig. 14. Iron meteorite Sikhote Alin, according to [22].

2.3.4.1. Iron meteorite Canyon Diablo.

This is one of the most interesting meteorites and therefore is the main object of my study.

This meteorite fell down on the ground about 40,000 years ago in Arizona in the United States and it formed a huge crater, which is called "*Coon Butte*", "*Crater Mountain*" or "*Meteor Crater*". The impact was so strong that it made a crater 1045 meters wide and 185 meters deep. In 1963 the scientists estimated that the energy needed to make such a crater was 1,7 megatons. Such energy may be delivered by a mass of 63,000 tons travelling at 14 km per second. This meteorite is represented by thousand of fragments scattered around the crater [24], [25], [annex 2].

Meteor Crater was discovered in 1891 by eminent geologist G.K. Gilbert. Gilbert first suggested meteoric origin of lunar craters. His suggestion was that the crater Canyon Diablo was formed as a result of steam explosion. In 1903 a lawyer – mining engineer – geologist Daniel Barringer recognized the crater as a potential site for mining a huge iron mass. Unfortunately, His mining undertaking did not succeed. In 1908 George Merrill suggested that the meteorite probably vaporized on impact. In the following years scientists were finding its remains. The biggest one to be found weighed 454 kg, and a total weight of all the fragments exceeds 30 tons [24].

Canyon Diablo is an iron meteorite. According to structural classification it is a coarse-grained octahedrite (Og). The width of Widmanstatten bands is from 0,5 to 2 mm, The chemical composition classifies it in IA group. There are following elements [24]:

- 7,1% Ni;
- 0,46% Co;
- 0,26% P;
- about 1% C;
- about 1% S;
- 80 ppm Ga;
- 320 ppm Ge;
- 1,9 ppm Ir;

It contains many minerals. They are [27]:

- Chromite – iron magnesium chromium oxide;
- Cohenite – iron carbide;
- Daubreelite – iron (II) chromium sulfide;
- Diamond and lonsdaleite (hexagonal diamond) – carbon;
- Graphite – carbon;
- Haxonite – iron nickel carbide;
- Kamacite – free element;
- Schreibersite – iron nickel phosphide;
- Taenite – free element;
- Troilite – iron sulfide;
- Moissanite – the second hardest natural mineral – silicon carbide – carborundum;

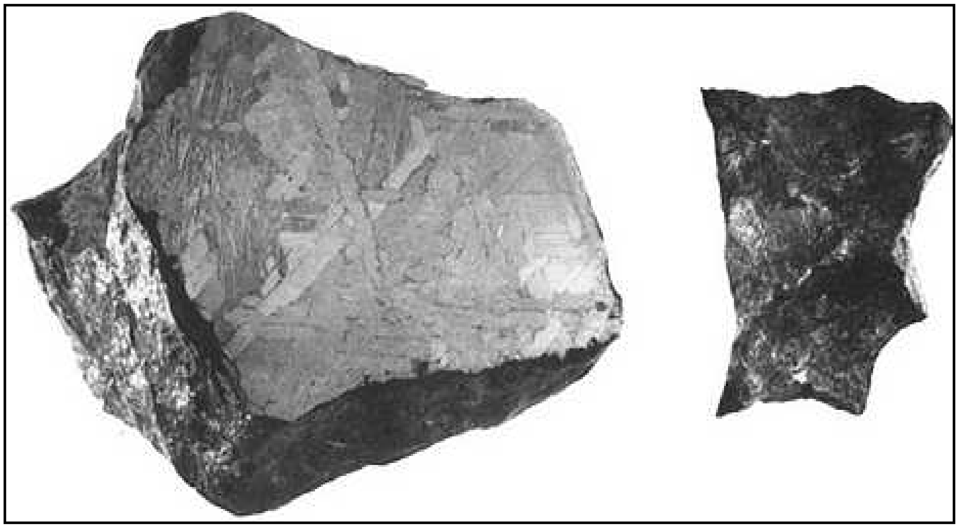


Fig. 15. Iron meteorite Canyon Diablo, according to [28].

2.3.5. Stony – Iron meteorites.

Main components of these meteorites are: iron-nickel alloys and silicate minerals. They are divided in two groups: pallasites and mesosiderites. Both of them are quite different. Pallasites (*Fig. 16*) generally originate from outer surface of asteroids. Iron – nickel alloy forms the matrix of pallasites, in which olivine crystals (35-85 vol %) are set. They are usually from 0,5 to 1 mm big. There are also small amounts of iron in the form of kamacite, taenite and plessite (fine – grained mixture of kamacite and taenite). Troilite (FeS), schribersite $(FeNi)_3P$ and phosphides are minerals which occur in pallasites [3], [15], [16].

The other group of stony – iron meteorites are mesosiderites (*Fig. 17*). This group contains fragments of impact breccias formed as a result of collisions of asteroids. They are built up with poor in calcium piroxenes, basalt, olivines and metals in the forms of bigger and smaller lumps, grains, pebbles or intergrowths. All the components of these meteorites come from the bodies, which took part in collisions [3] [15], [16].

Fig. 16. Stony – iron meteorite, pallasite, according to [24].

Fig. 17. Stony – iron meteorite, mesosiderite, according to [24].

3. Carbon in meteorites.

3. 1. Basic information about carbon.

Carbon is one of the elements which occurs in nature. In lithosphere there is about 480 ppm (0,048%) of carbon. It may be in [29]:

- Calcite $CaCO_3$;
- Dolomite $MgCO_3 \cdot CaCO_3$;
- Magnesite $MgCO_3$;
- Siderite $FeCO_3$;

It is a very interesting element because of its properties and that is why it is an object of many studies. It is used in numerous fields of science and industry, e.g. medicine, car industry. Carbon creates many allotropic forms. It may be a diamond, graphite (nanotubes, fullerenes) and carbines [29], [30].

Diamond is the hardest natural mineral. Its unit cell (*Fig. 18*) consists of 8 atoms (4 carbon bonds C – C). These atoms are bounded with strong covalent bonds σ (orbital of sp^3 type) which make angles 109,5° between them (*Fig. 19*).

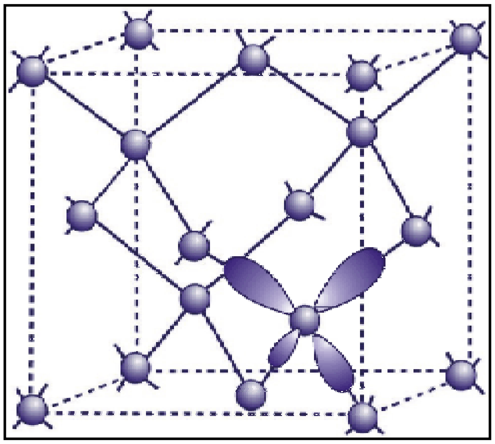


Fig. 18. Elementary cell of diamond, according to [29].

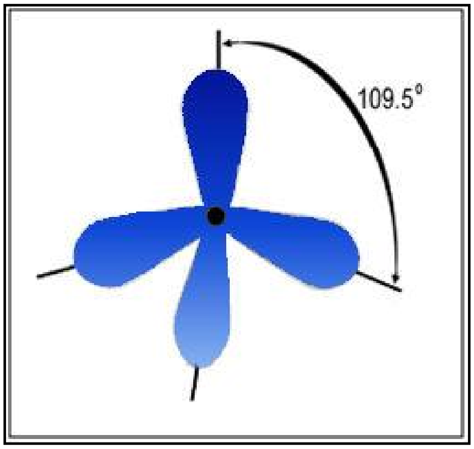


Fig. 19. Electron structure round one atom of carbon in diamond (four orbitals s sp ^{3} make an angle 109,5^0), according to [31].

The structure of diamond is a regular face – centered cubic lattice A_1. In crystallographic direction [100] the distance between carbon atoms is 0,154 nm. Diamond is very hard, however it has certain cleavage planes (111), [29], [30].

There is also different form of diamond found for the first time in Canyon Diablo meteorite. It is lonsdaleite – hexagonal diamond. It has bonds σ (orbital of sp^3 type). The distance in crystallographic direction [100] is the same as of these of diamond (0,154 nm), the planes (001) of lonsdaleite and diamond (111) are also identical. Lattice parameters of its cell are: a = 0,252 nm, c = 0,412 nm [29].

The other allotropic form of carbon is graphite. The structure of graphite consists of planes (001) set interchangeably in the distance of 0,335 nm (*Fig. 20*). In every plane carbon atoms are bonded into hexagonal structures and the distance between them is 0,142 nm. Every carbon atom forms three covalent bonds – σ (orbital of sp^3 type) in each plane and one bond π (orbital p) between the planes (001). Bonds of σ type are very strong (stronger than in diamond), whereas π bonds are weak. The differences in strength of bonds result in high anisotropy of graphite [29], [30].

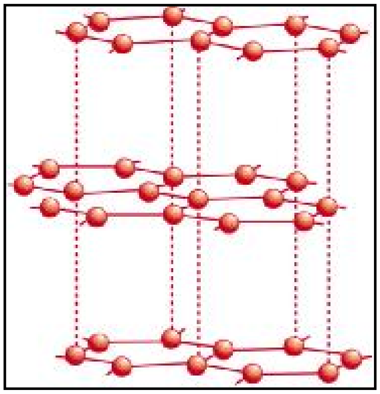


Fig. 20. Graphite structure, according to[32].

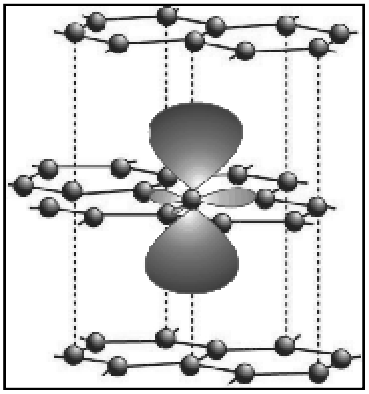


Fig. 21. Elementary cell of graphite, according to [29].

Fullerenes are molecules resembling regular and empty sphere, ellipsoid or tube. They are formed with dozens to hundred of carbon atoms. Fullerenes were gained for the first time in 1985 as a result of vaporization of graphite in carbon arc in helium gas stream. The name Fullerenes comes from the name of an American architect and philosopher Richard Buckminster-Fuller. One of the most famous fullerenes is molecule C_{60} which is in shape resembling a soccer ball (*Fig. 23*) and its radius is about 0,357 nm. It is formed with 20 regular hexagons and 12 pentagons. There are two types of carbon to carbon links C – C [29], [30], [33]:

- C = C length 0,139 nm (a common side of 2 touching hexagons);
- C – C length 0,144 nm (a common side of a pentagon and a hexagon);

In nature there are other fullerene molecules, e.g. C_{70} formed with 25 hexagons and resembling a rugby ball; C_{84}, C_{180}, $C_{240,}$ etc. [29].

Nanotube (*Fig. 22*) is a graphite plane closed in a cylindrical structure. Nanotubes have very good mechanical and electrical properties. Their most important feature is high tensile strength. It is because they have strong carbon links in their plate. In nature there are single – wall nanotubes (radius from 1,2 to 2,0 nm) and multi – wall nanotubes (cylindrical) with radius up to 25 nm [29], [30], [34].

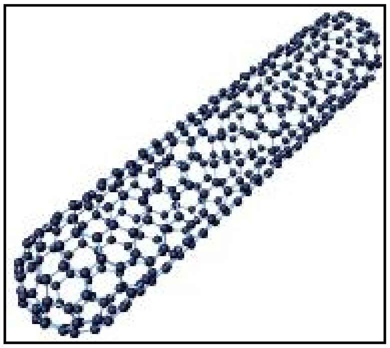


Fig. 22. Nanotube structure, according to [35].

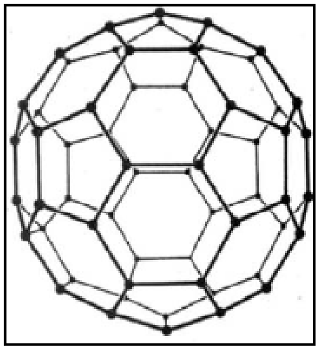


Fig. 23. Fullerene C_{60}*, according to [30].*

The least known allotropic forms of carbon are carbines. They resemble white crystals. Their history is strictly connected with the discovery of chaoite mineral in 60s. They come from a meteorite and are believed to be formed as a result of a change of graphite in high temperatures and pressures, which are in a meteorite before the collision with Earth. Carbine was classified as a new allotropic form of carbon with quite long atomic chains. At present there are two types of carbines [29], [36]:

- **α – carbine** – hexagonal type of cellular net with parameters: a = 0,892 nm, c = 1,536 nm. It has carbon triple bonds (– C = C –), it is also called polyacetylen.
- **β – carbine** – hexagonal type of cellular net with parameters: a = 0,824 nm, c = 0,768 nm. It has cumulen bonds (= C = C =), it may be called polycumulen.

Table 12.Physical and chemical properties of allotropic forms of carbon, according to [37].

Properites	**Diamond**	**Graphite**	**Fullerene C_{60}**	**Nanotube**
Density [g/cm^3]	3,515	1,9 – 2,3	1,69	1,33 – 1,4
Specific gravity	3,52	2,2	1,7 – 1,9	2
Hardness (Moh`s scale)	10	1 – 2	1 – 2	1 – 2
Melting point [^{o}C]	3550	3652 – 3697	>800 (sublimes)	Similar to graphite
Boiling point [^{o}C]	4827	4200	n/a	n/a
Electrical conductivity	Insulator	Conductor	Semiconductor	Conductor to semiconductor
Hybridization	sp^3 – tetrahedral	sp^2 – trigonal planar	sp^2 – trigonal planar	sp^2 – trigonal planar
Crystal shape and/or structure	Cubic	Tabular	Truncated icosahedron	Cylindical

3.2. Extraterrestrial carbon.

Carbon in meteorites may occur in various forms, e.g. graphite, diamond (also hexagonal diamond – lonsdaleite), carbines (chaoite), fullerenes, amorphic carbon and as a component of numerous organic and inorganic compounds. They are all in two groups: presolar and solar grains [3].

Generally all the meteorites have some amounts of carbon. Some of them have more and some of them less, but usually it is not a huge amount (maximum a couple of vol %) [3].

Carbonaceous chondrites have the highest amounts of carbon. Some of them exceed 5 wt % [Tagish Lake (CI2) – 5.81 wt %, Orgueil (CI1) – 4.5 wt %, Ivuna (CI1) – 4.03 wt %]. The rest of chondrites have much smaller amounts of carbon (*Tab. 12*) [3], [16].

Table 13. Mean bulk carbon content in the chondrite classes [3].

Chondrite class	C content (% wt)[1]	C content (% wt)[2]
CI **CM** **CR**	2,8 1,82 1,97	3,2 2,2 1,44
CH	-	0,8
CO **CV** **CK**	0,38 0,43 0,1	0,45 0,56 0,1
R	-	0,06
LL	0,22	0,12
L	0,12	0,09
H **EL**	0,11 0,32	0,11 0,36
EH	0,42	0,4

1 – according to D. W. Sears, „*The origin of chondrules and chondrites*”, Cambridge University, Cambridge 2004.

2 – according to R, Hutchison, „*Meteorites: a petrologic, chemical and isotope syntheses*”, Cambridge University, Cambridge 2004.

In achondrites carbon content is low. Carbon content in achondrites rich in calcium is 0,02 – 0,47 wt %. Ureilites – achondrites poor in calcium, are an exception, because carbon content in them is between 1,94 and 4,10% wt. An achondrite Novo Urei may be an example. It contains 2,23% wt of carbon. [3], [16].

Carbon is inhomogeneously distributed in iron meteorites and that is why there are examples of carbon content in some of them, represented in *Table 14* [3].

Table 14. Mean bulk carbon content in iron meteorites [3].

Type of iron meteorites	C content [% wt][1,2]	C content [% wt][3]
Heksaedrite	0,19	0,005 – 0.013
Octahedrite	0,01 – 0,6	0,002 – 0,2
Ataxite	0,1	0,003 – 0,051

1 – according to J. A. Wood, in: *The Moon, Meteorites and Comets,* B. M. Middlehurst, G. Kuiper (eds), Chicago 1963, p. 337.

2 – according to G. J. H. Mc Call, *Meteorites and their origins*, David and Charles, Devon 1973.

3 – according to B. Mason, *Meteorites, in: Data on Geochemistry,* Ch. B, US Government, Washington 1979.

The amount of carbon in stony meteorites is small, about 0,08 wt % [3].

Meteorites usually have carbon in the form of diamond or graphite. However, diamond is the form occurring most frequently, e.g. in achondrites ureility half of identified carbon is in the form of diamond [3].

Diamond in meteorites was discovered for the first time in 1888, in Novo Urei achondrite and then in 1891, in iron meteorite Canyon Diablo. It was also found in carbonaceous chondrites – Allende, Murchison, Tagish Lake, Orqueil, Renazzo and ordinary chondrites – Bishunpur, Krymka. The biggest diamonds found in meteorites were about 2 mm big, but in most cases they were about several nanometers big [3].

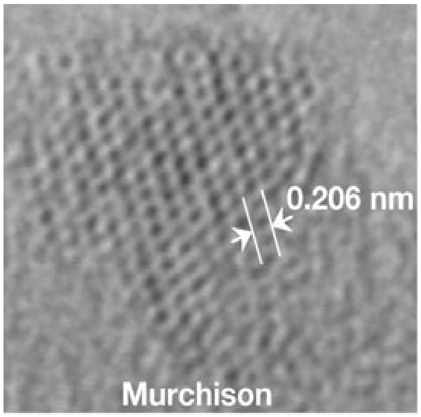


Fig. 24. Size of diamond grains in carbonaceous chondrite Murchison, according to [38].

Isotopic anomalies of xenon (Xe), neon (Ne), tellurium (Te) and anomalies of oxygen (O) and rock – forming elements such as: magnesium (Mg), calcium (Ca), titanium (Ti), silicon (Si), barium (Ba), chromium (Cr) let the scientist discover presolar grains. The grains were found in primitive chondrites, which parent bodies were formed in the same way as our solar system (*Fig. 25*). The Solar System has been formed by gravitational collapse of interstellar molecular cloud (gas and dust from Red Giant, Novae and Supernovae) [3], [16], [26].

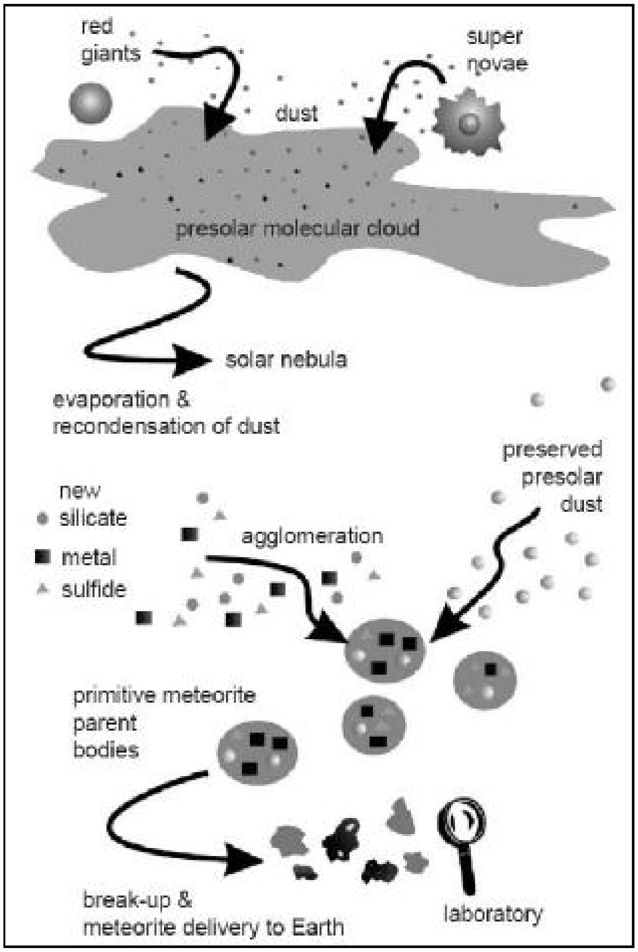


Fig. 25. Process of formation and presolar grains storage up today, according to [26].

There are different known presolar grains in meteorites. They occur in a form of carbon and its compounds (*Tab. 15*), oxides, nitrides and organic polymers. Carbon and its compounds are mainly (*Fig. 26*) [3], [16] :

- diamond;
- graphite;
- carbides (SiC, TiC, FeC, ZrC, MoC);

Table 15. Forms of presolar carbon, according to [26].

Mineral	Size	Stellar source	Discovery papers
Diamond	2nm	AGB?, SN?	Lewis i in. (1987)
Silicon carbide (SiC)	0,1 – 20 µm	AGB, SN, N	Bernatowicz i in. (1987) Tang i Anders (1988)
Graphite	1 – 20 µm	AGB, SN	Amari i in. (1990)
Carbides in graphite	10 – 200 nm	AGB, SN	Bernatowicz i in. (1991, 1996)

AGB – asymptotic giant branch stars; SN – supernovae; N – novae

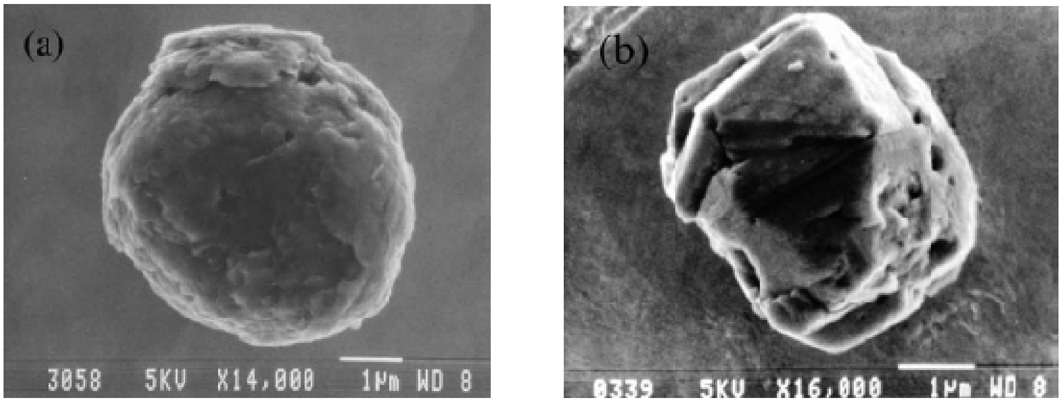


Fig. 26. Secondary electron images of presolar grains, according to *[26]:*
a) graphite grain;
b) SiC grain;

The most abundant of presolar grains form of carbon is diamond (***Tab.** 16, 17*). The individual presolar grains of diamond are very small (1 – 3 nm) and that is why many of them have not been discovered. Such a tiny crystal of diamond may have from 60 to 1000 carbon atoms. Diamond is strongly connected with isotopic anomalies of xenon (Xe) of a light type (^{124}Xe) as well as a heavy one (^{136}Xe). Thanks to these anomalies they managed to isolate presolar grains in meteorites [3], [16].

There are bigger presolar grains in graphite. Its grains are round and their diameters may be about 1 to 10 µm. However, graphite occurs in meteorites in smaller amounts than in diamond (*Tab. 16, 17*). In this case thanks to neon isotope (^{22}Ne) they managed to isolate grains of presolar graphite [16].

Xenon (Xe) and neon (Ne) isotopes are also responsible for isolating silicon carbide (SiC). The former, more precisely isotope ^{130}Xe, is connected with the presence of delicate carbides, the latter – isotope ^{22}Ne is connected with the presence of coarse – grained carbides. The diameters of silicon carbide grains are from 0,03 to 10 µm and there are more of them in meteorites than graphite grains. As far as the other carbides are concerned, it is only known that their grains are usually present in other presolar grains, e.g. in graphite grains and their diameters are very small (Å) [16].

Table 16. Abundances of carbon presolar grains in meteorites, according to [3].

Meteorite	Diamond [ppm]	Graphite [ppm]
Tagish Lake (CI)	3650 – 4330	ND
Orgueil (CI)	1436	10,3
Murchison (CM2)	1162 – 1400	7,4
Murray (CM2)	1039	9,6
Renazzo (CR2)	1500 – 2450	0,1
Acfer 214 (CH)	1170 – 1740	0,8 – 1,2
Kainsaz (CO)	1733	ND
Leoville (CVR)	1554 – 3166	ND
Allende (CV3)	885 – 1817	ND
Axtell (CV3)	820 – 1552	ND
Vigarano (CV3)	1806	
Krymka (LL 3.1)	1008 – 1543	<0,066
Bishunpur (LL 3.1)	901 – 1555	0,16
Semarkona (LL 3.0)	1134 – 1515	0,22
Adrar (L 3.2)	1088 – 1188	0,14
Allan Hills 81032 (L 3.4)	1100	ND

ND – not determined

Table 17. Abundance of presolar diamond and presolar graphite in different meteorites (ppm by mass), according to [3].

Chondrites group	Diamond [ppm]	Graphite [ppm]
CI	940 – 4330	10
CM	750 – 1500	5 – 6
CR	400 – 2450	
CH	87 – 1740	0,13
CO	300 – 1733	<0,15?
CV	240 – 3166	0,20 for CV oxidized, below detection limit for CV reduced
LL 3.0/3.1	100 – 130	
L 3.4/3.7	54 – 64	
H 3.4	36 – 1100	
EH 3-4	50 – 67	

Extraterrestrial carbon is different than the terrestrial one. The example may be diamond. Its specific gravity, structure or IR (*Infrared Radiation*) absorption are different tan of normal diamond [3]. The comparison of properties is represented in *Table 18*.

Table 18. Properties comparison between natural and extraterrestrial diamond, according to [3], [39], [40].

Natural diamond	**Extraterrestrial diamond**	
	Solar diamond e.g. lonsdaleite	**Presolar diamond (*presolar grains*)**
1. Density: 3,51 g/cm^3 **2**.Structure: regular, having parameters: a = 3.5668, Z = 8; V = 45.38 **3**. Molecular weight: 12.01 gm **4**. Hardness (Moh`s scale): 10 **5**. Colour: white, grey, black, blue **6**. Refractive index: 2,41 – 2,44	**1**. Density: 3,2 – 3,3 g/cm^3 **2**.Structure: hexagonal, having parameters: a = 2.52, c = 4.12, Z = 4; V = 22.663. 3.Molecular weight: 12.01 gm **4**. Hardness (moh`s scale): 7 – 8 **5**. Colour: brownish-black, light brownish-yellow **6**. Refractive index: 2,40 – 2,41	**1**. Density: 2,22 – 2,33 g/cm^3

In comparison with terrestrial diamond, which is of regular cubic structure, extraterrestrial diamond may have numerous structures, e.g. cubic structure, (3C), hexagonal (e.g. 2H) and rhomboedrical (e.g. 21R). These structures may exist separately or coexist, e.g Canyon Diablo may have structures 3C, 2H, 21R, whereas Novo Urei has 3C and 2H [3].

As far as the way of forming of extraterrestrial carbon is concerned, there are different theories on that subject. Most frequently enumerated are [3]:

- CVD method (*Chemical Vapor Deposition*);
- shock wave after a meteorite impact;
- ultraviolet radiation (UV) affecting carbon grains;
- radiation mechanism;

Thanks to CVD method an artificial nanodiamond may be created. It proceeds in vacuum and it is assisted with electrons. There are identical conditions in outer space, and therefore thanks to this method very tiny presolar grains of diamond are formed. Bigger diamond grains are probably formed as of changing graphite in high temperature and pressure (*HTHP – High Temperature High Pressure*). Such conditions may be a result of a shock wave created in a very moment when a meteorite hits the ground. Probably, in this way some diamond in Canyon Diablo have been formed [3].

4. Methods of meteorite investigation.

As the technology continues its development these days, there are enormous possibilities to detect carbon in meteorites. There are various techniques, which may be used to investigate extraterrestrial objects. The most important are: Raman spectroscopy, Scanning Electron Microscopy (SEM) with X-Ray analysis, Atomic Force Microscopy (AMF), High Resolution Transmission Electron Microscopy (HRTEM), Secondary Ion Mass Spectrometry (SIMS), (nanoSIMS), optical microscopy [3], [41], [42], [43], [44].

Raman spectroscopy is a technique which enables to carry out chemical and physical investigation of carbon in meteorites. Thanks to this technique one can estimate not only the presence of carbon in a sample, but also to specify its allotropic form (*Fig. 27, 29*). Raman spectroscopy is based on investigation of electromagnetic inelastically scattered radiation to molecules of particular substance. Wavelength of electromagnetic is usually a value of visible light, but it may be ultraviolet or infrared light, too. As the source of radiation, monochromatic laser of intense beam is used. Moreover, the detective system must be highly sensitive, because scattered radiation is from 4 to 8 orders of magnitude smaller than the intensity of incident radiation. The results of Raman spectroscopy are in forms of spectra which are the function of the scattered radiation intensity to the frequency of this radiation (*Fig. 28*) [3], [45], [46], [47].

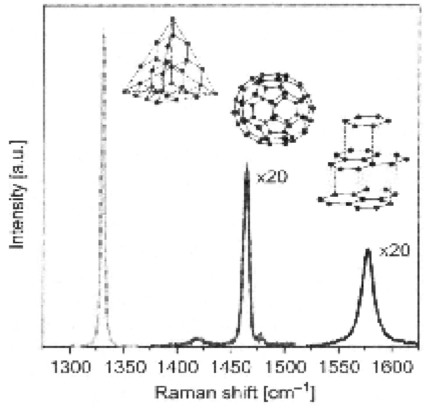


Fig. 27. Raman spectra of diamond, graphite and fullerenes. Insert present fragments of corresponding carbon structures, according to [3].

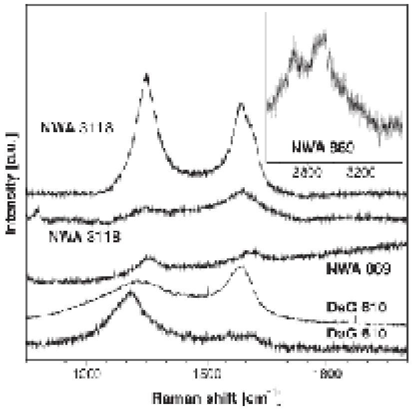


Fig. 28. First-order Raman spectra of some carbon phases in meteorites: NWA 869, NWA 3118, Morasko, DaG610 and Sikhote-Alin. The insert present the second-order Raman region, according to[48].

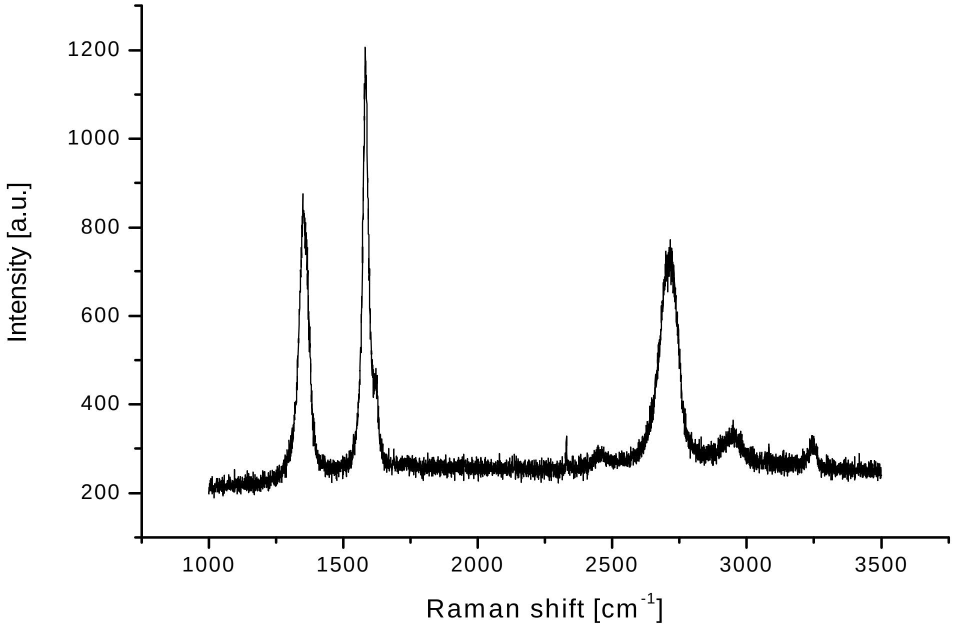


Fig. 29. Raman spectra of graphite nodule in the Canyon Diablo.
Diagram thanks to courtesy of dr. Marian Szurgot.

Scanning Electron Microscopy let us observe grains of carbon on meteorites surface under a high magnification (*Fig. 26*). SEM thanks to its X-Ray analyser may estimate the percentage of carbon amount on the surface of meteorite sample. The image we get is gained thanks to electron beam, which is directed straight to a sample in vacuum. The beam “sweeps” the researched area line by line. Next the signal, in a form of reflected or secondary electrons emitted by the sample, reaches the register system, where it is transformed and then visualized on monitor [41], [49].

Another type of scanning microscopy is Atomic Force Microscopy. This method enables to investigate carbon in meteorites but it only determines the structure of surface (size of single carbon atoms), adhesion or friction. This method is different from the latter one in a way that the measurement consists in the detection of movements of a sharp tip (probe), which moves around the sample surface. Deflection of the probe attached to a special cantilever enables to estimate the force between the atoms of the probe and the investigated surface. The results are transformed and visualized by a computer (*Figs. 29, 30*) [42], [50].

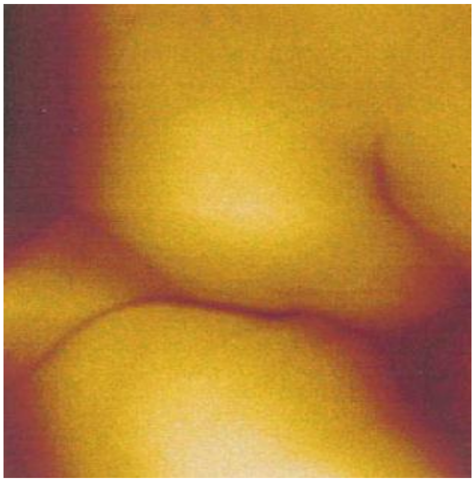


Fig. 30. AFM images showing 400 nm areas of the surface of a carbonate globule from Martian meteorite ALH 84001, according to [42].

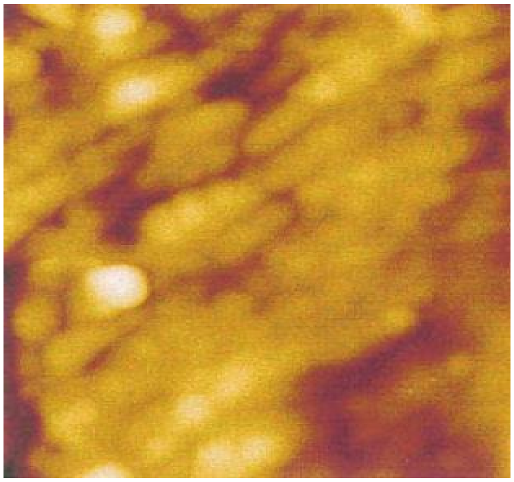


Fig. 31. 2-D AFM image of an area on the carbonate globule (scan size 4 µm x 4 µm) from Martian meteorite ALH 84001, according to[42].

High Resolution Transmission Electron Microscopy is a sort of an electron microscopy. It may be used to study the morphology and defects of carbon nanostructures in meteorites. In this method the sources of signal are electrons, which go through a very thin sample (<0.1 µm) located in vacuum. However, this method seems to be restricted, because of the difficulties while preparing the sample [43], [51].

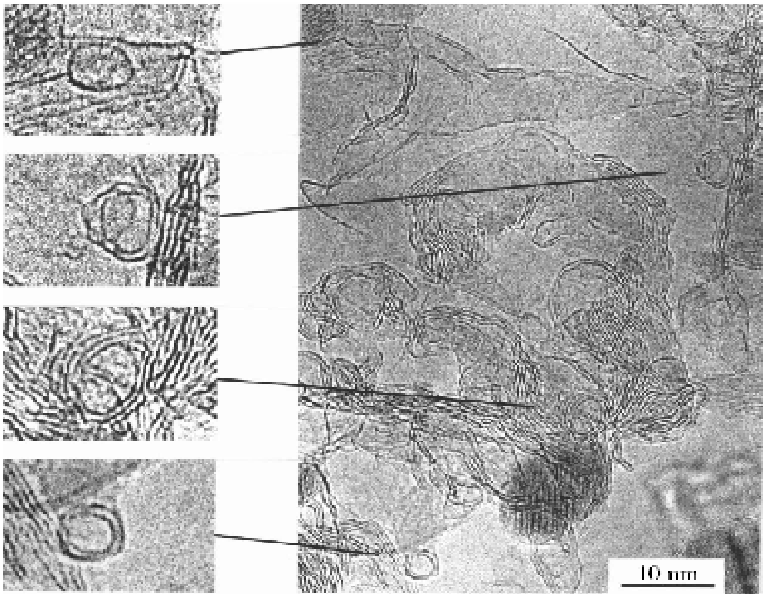


Fig. 32. Image from HRTEM showing high-magnification micrograph of carbon with enlarged areas showing individual closed carbon nanostructures, according to [43].

Secondary Ion Mass Spectrometry (SIMS), (nanoSIMS) is a destructive method. In this method the surface of the sample is sprayed in vacuum as a result of the interaction of the beam of primary ions with atoms of the sample. Spectrometry SIMS (nanoSIMS) is a surface analysis technique of solid bodies. This method enables to estimate quantity and quality of composition of the sample surface. Some spectrometers may register isotopes of elements and they are able to visualize the sample with sensitive surface analysis (to 40 nm) [44], [52].

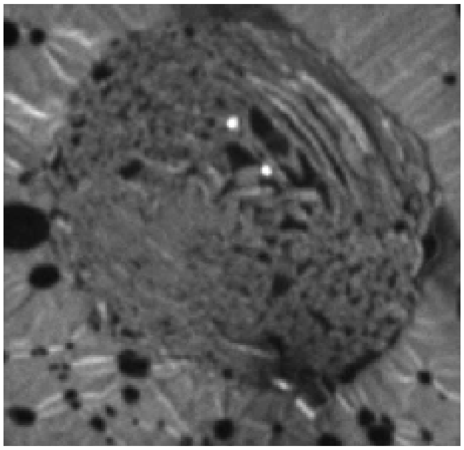


Fig. 33. NanoSIMS $^{16}O^{-}$ image (12 x 12 µm^{2}). Graphite grain containing two subgrains of TiC, according to[44].

Optical microscopy is also a method which allows us to study meteorites. It is the easiest one of all the techniques mentioned before and it does not enable to identify carbon in 100%. However is helpful and usually used as preliminary investigation to reveal the areas, where the carbon may occur. This technique facilitates more complicated investigations. Optical microscopy demands to prepare the sample properly. The surface must be ground and polished and in many cases it should be well – etched in order to show the proper structure of the sample.

III. Experimental part.

The aim of this study was to analyse the content of meteorites. It concerns mainly carbon content. Four samples of Canyon Diablo meteorite (samples N° 1, 2, 3, 4) and one sample of meteorite breccia (sample N° 5) were used in this study. There were some microscopic examinations and tests done:

- **Optical microscopy;**
- **Scanning Electron Microscopy with X-Ray microanalysis EDS;**
- **Raman spectroscopy;**
- **Nanohardness;**

5. Optical microscopy.

This test aims to identify areas, where carbon may be found. To show areas of interest some earlier preparations of samples had to be done. These preparations were:

a. **sample cut (meteorite breccia);**
b. **immersion of samples in resin;**
c. **grinding;**
d. **polishing;**
e. **etching;**
f. **surface analysis in optical microscope;**

a. Meteorite breccia (*Fig. 34*) because of its size was the only one which needed cutting. I used a milling machine “BUEHLER”, type – Delta® AbrasiMet® Abrasive Chop Cutter (*Fig. 35*).

Fig. 34.Meteorie breccia.

The place from cut off a small fragment which was destined to scientific research.

Fig. 35. Abrasive cutters "BUEHLER" model – Delta®AbrasiMet® Abrasive ChopCutter, according to [53].

b. All the samples were immersed were immersed in methacryl resin. I used a press "BUEHELER" - SimpliMet® 2 Hydraulic Specimen Mounting Press (*Fig. 37*).

Fig. 36. The sample which was put in resin.

Fig. 37. Mounting Press "BUEHLER" model – SimpliMet® 2 Hydraulic Specimen Mounting Press, according to [53].

c. The next step was to grind meteorite samples previously immersed in resin to show areas of researched surface. They were ground on abrasive papers: 600; 800; 1200; 2000 and on bench – grinder to metallographic specimen Metasinex (*Fig. 38*).

Fig. 38. Grinding machine "Metasinex" [54].

d. After grinding, the samples were polished on polishing machine Struers – model DP – U2 (*Fig. 39*). As the polishing agent, a special solution was used, which was made of:

- 150 ml colloidal silicon;
- 30 ml hydrogen dioxide solution H_2O_2;
- 150 ml water;
- 1ml nitric acid HNO_3;

This solution was used on purpose because widely used diamond paste, which contains carbon, might have disturbed the results of the experiment.

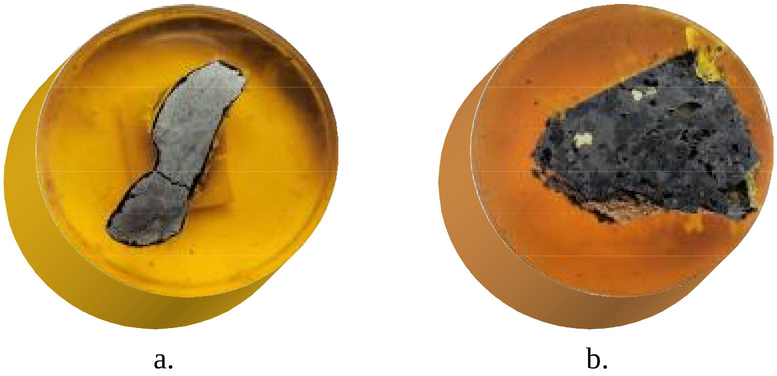
Fig. 39. Polishing machine "Struers – model DP – U2".

e. In order to show the carbon phases in microscope, the samples of meteorites were previously etched. It was used 5% NITAL (20 ml of ethanol C_2H_5OH and 1 ml of nitric acid HNO_3) – this is an agent used for etching of metallographic specimen and steel samples.

f. After preparation of all the samples I started to analyse the surface. I used an optical microscope “OLYMPUS” GX71 (*Fig. 40*) with digital camera DC – 90 built-in.

Fig. 40. Optical microscope “OLYMPUS” – model GX 71 with digital camera DC – 90.

The surface analysis was made on samples N° 1, 5 (*Fig. 41*). There were used magnifications: x50, x100, x500.



a. b.

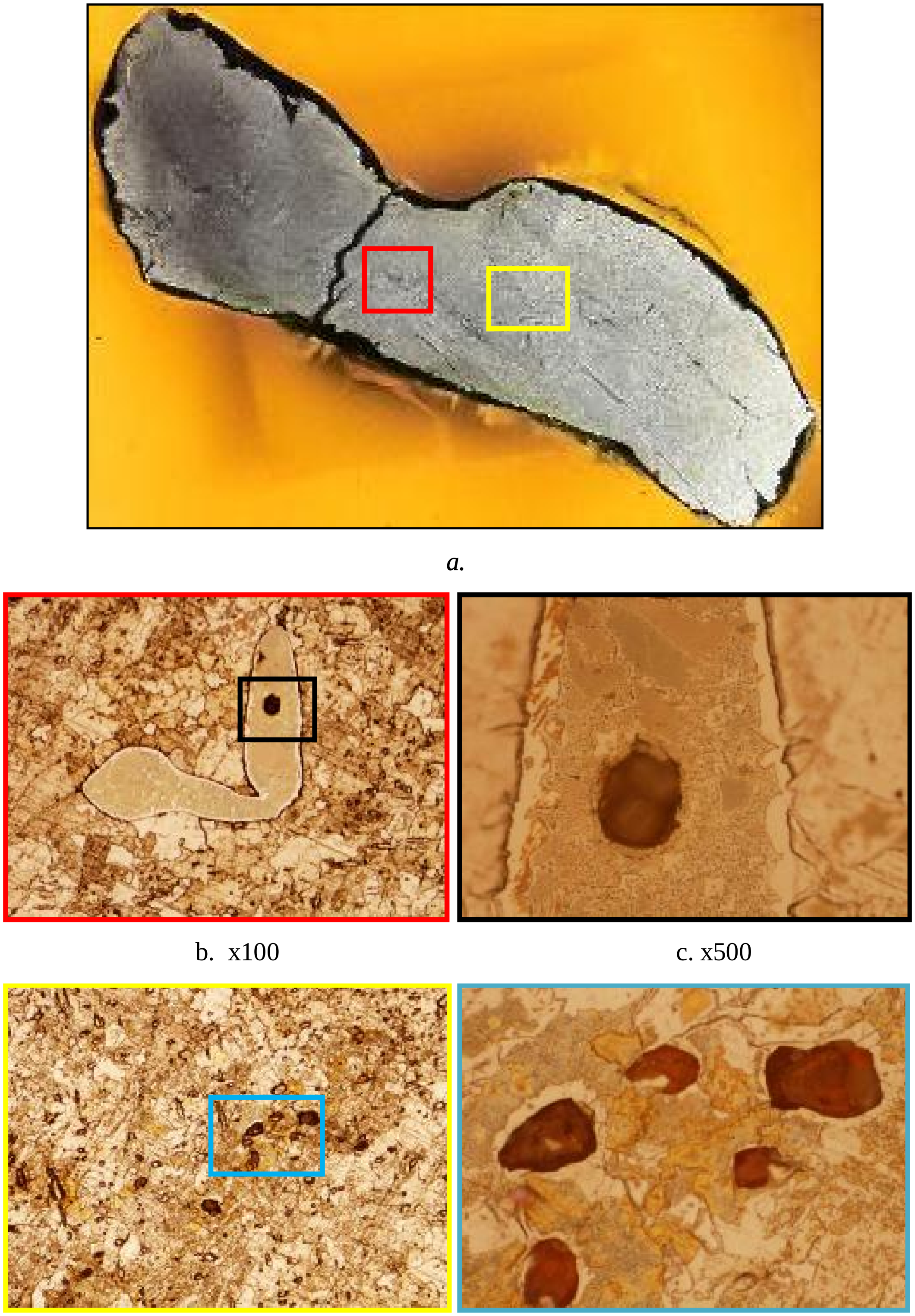
Fig. 41. Samples research by optical microscope .

a) Sample N° 1 – Canyon Diablo;

b) Sample N° 5 – meteorite breccia;

The results of optical microscopic analysis:

The results of microscopic analysis on samples N°1 and 5 show the areas, where carbon phases may be found (*Fig. 42, 43)*.



a.

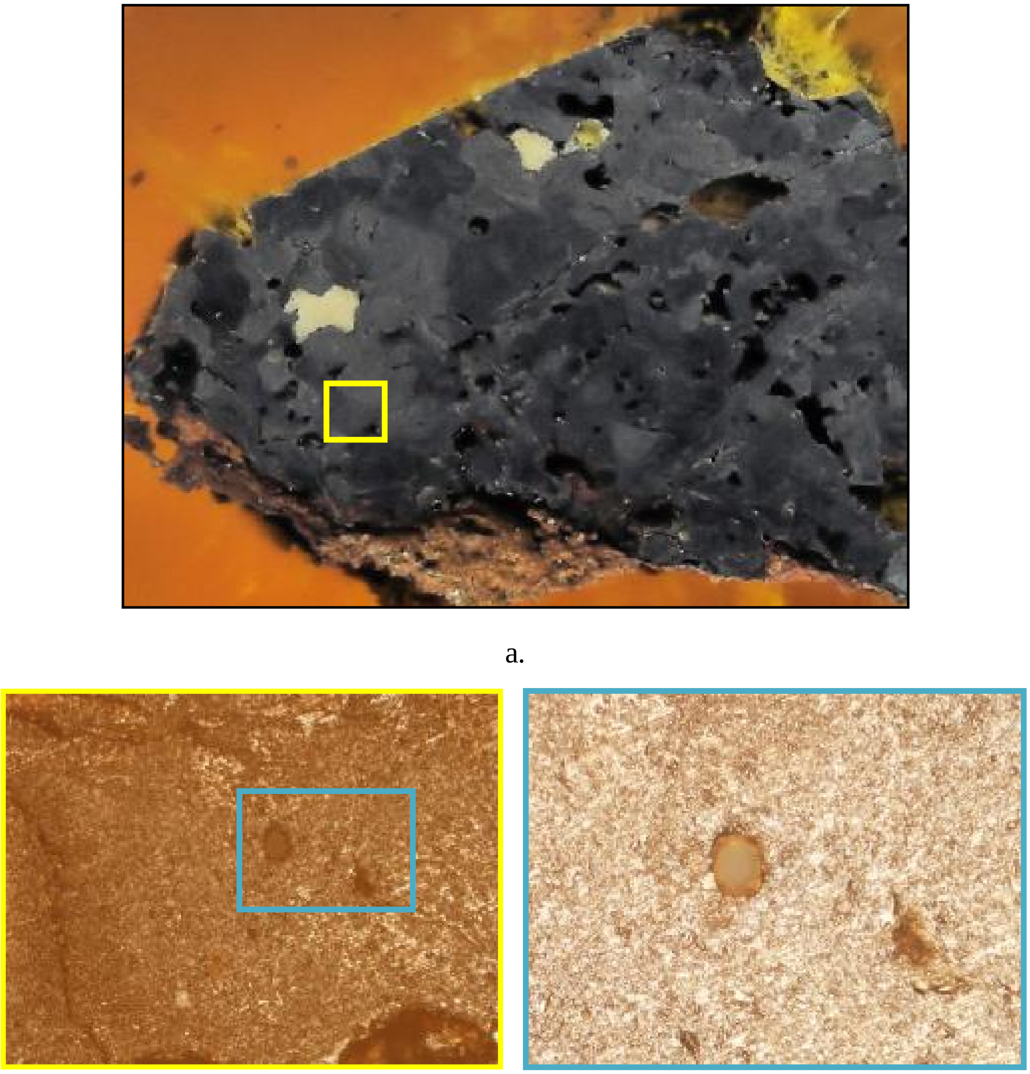
b. x100

c. x500

d. x100

e. x500

Fig. 42. Sample N° 1 – Canyon Diablo – area where probably is carbon phase: a) General view; b) magnification x100; c) magnification x500; d) magnification x100; e) magnification x500.



a.

b. x50

c. x100

Fig. 43. Sample N° 5 – meteorite breccia – where probably is carbon phase: a) General view; b) magnification x50; c) magnification x100.

6. Scanning Electron Microscopy with X-Ray microanalysis EDS.

This examination was carried out in order to analyse the chemical content of Canyon Diablo meteorite. This microanalysis was made on two samples (N° 2 and 3) (*Fig. 44*). For this examination Scanning Electron Microscope “HITACHI” S-3000N was used (with a X-Ray microanalysis – EDS unit THERMO NORAN) (*Fig. 45*).

a. b.

Fig. 44. Samples used to X – Ray microanalysis.
a) Sample N° 2 – Canyon Diablo; b) Sample N° 3 – Canyon Diablo.

Fig. 45. Scanning Electron Microscope „HITACHI” – model S-3000N (with Energy Dispersive Spectrometer – EDS “THERMO NORAN”) [55].

The results of X-Ray microanalysis:

Sample N° 2 was examined 4 times in different areas. Moreover, a distribution map of elements was made on it. The sample N° 3 was examined twice in different areas. The results are shown below:

Sample N° 2: *Measurement 1*

Measurement conditions:

- magnification – x40; vacuum – 15kV; working distance WD – 14.8 mm;

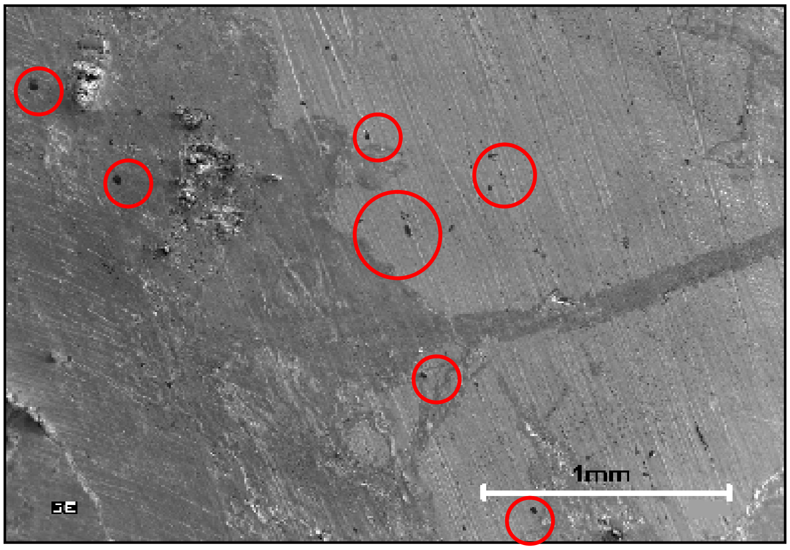


Fig. 46. Image from SEM. Surface fragment of sample N° 2 – measurement 1. Mark area – some places of carbon occurence.

Table 19. Result of chemical composition analysis of sample N° 2 – measurement 1.

Element	**Atom [%]**	**Element [wt %]**	**wt % - Err. [1 – sigma]**
C	19,10	6,14	+/- 0,29
O	24,71	10,58	+/- 0,30
Si	1,38	1,04	+/- 0,08
Fe	50,99	76,24	+/- 0,93
Ni	3,82	6	+/- 0,75

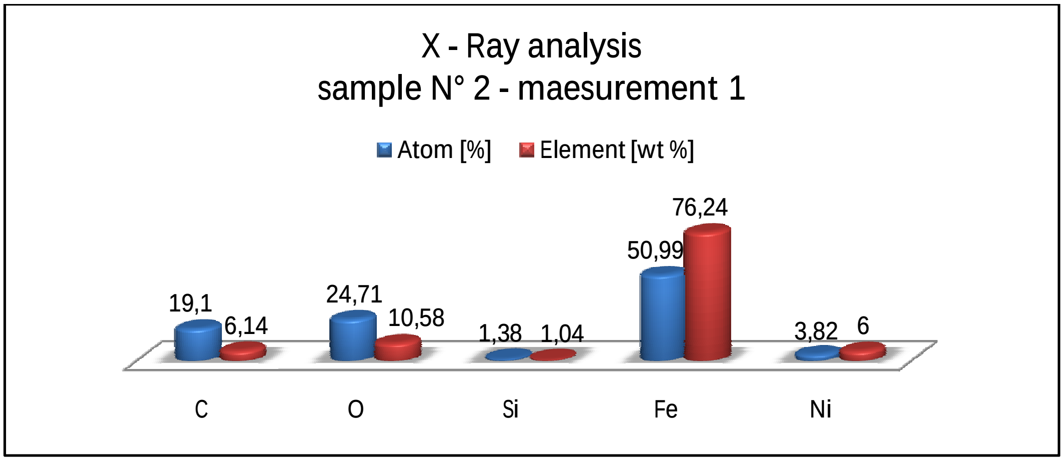


Fig. 47. Result of chemical composition analysis of sample N° 2 – measurement 1.

Measurement 2

Measurement conditions:

- magnification – x40; vacuum – 15kV; working distance WD – 14.8 mm;

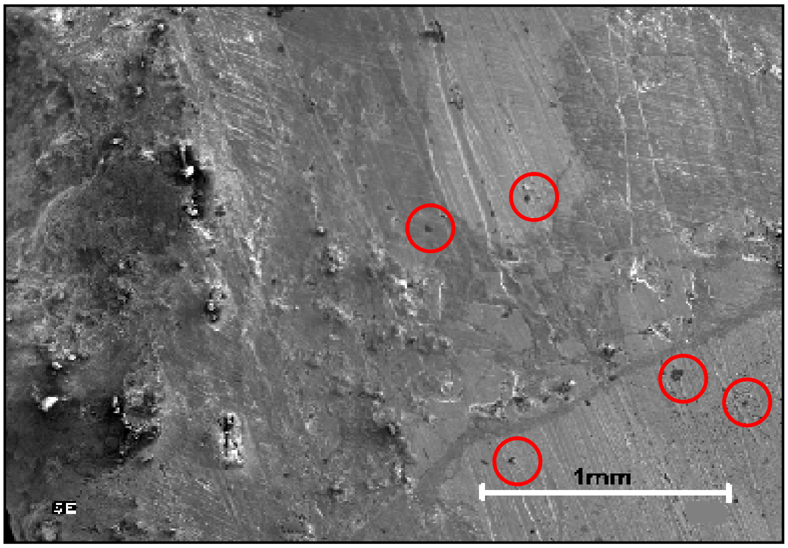


Fig. 48. Image from SEM. Surface fragment of sample N° 2 – measurement 2. Mark area – some places of carbon occurence.

Table 20. Result of chemical composition analysis of sample N° 2 – measurement 2.

Element	Atom [%]	Element [wt %]	wt % - Err. [1 – sigma]
C	34,38	14,73	+/- 0,28
O	30,26	17,27	+/- 0,38
Si	2,62	2,62	+/- 0,10
Fe	31,14	62,04	+/- 0,90
Ni	1,60	3,34	+/- 0,36

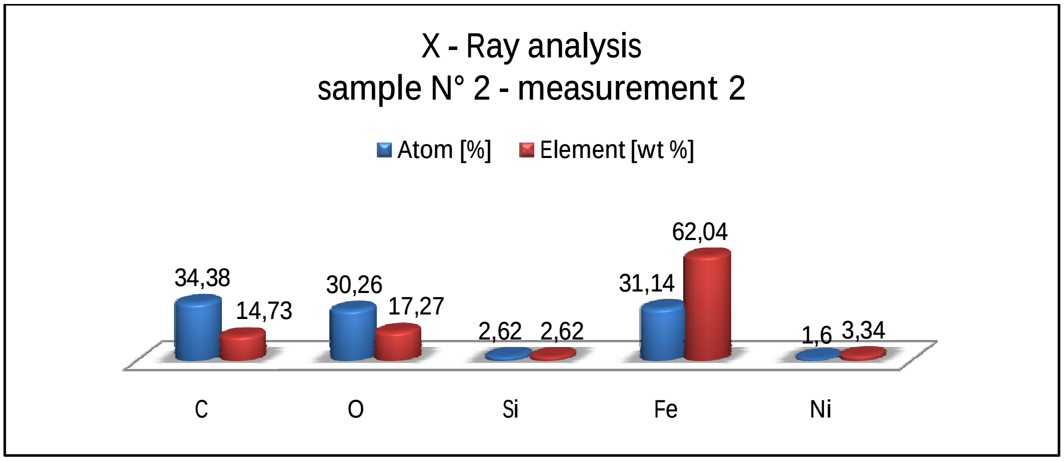


Fig. 49. Result of chemical composition analysis of sample N° 2 – measurement 2.

Measurement 3

Measurement conditions:

- magnification – x40; vacuum – 15kV; working distance WD – 15 mm;

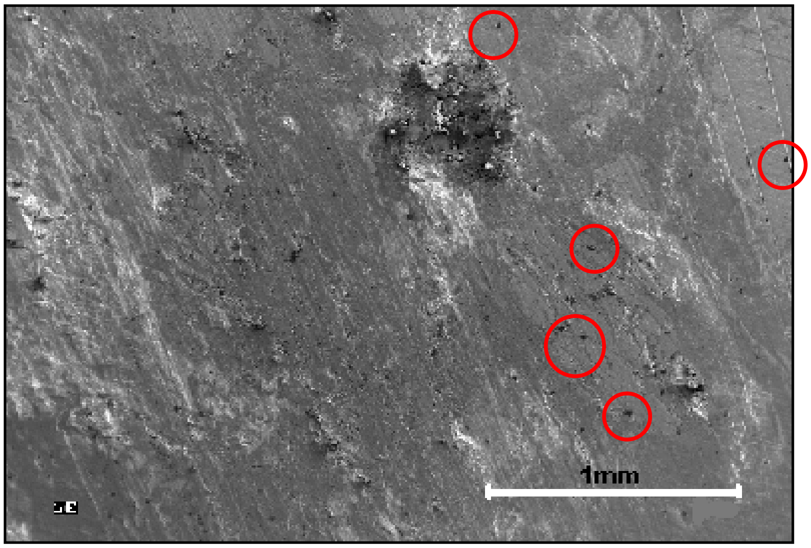


Fig. 50. Image from SEM. Surface fragment of sample N° 2 – measurement 3. Mark area – some places of carbon occurence.

Table 21. Result of chemical composition analysis of sample N° 2 – measurement 3.

Element	**Atom [%]**	**Element [wt %]**	**wt % - Err. [1 – sigma]**
C	18,94	7,00	+/- 0,24
O	36,62	18,03	+/- 0,34
Si	1,88	1,62	+/- 0,10
Fe	40,27	69,20	+/- 1,03
Ni	2,30	4,15	+/- 0,82

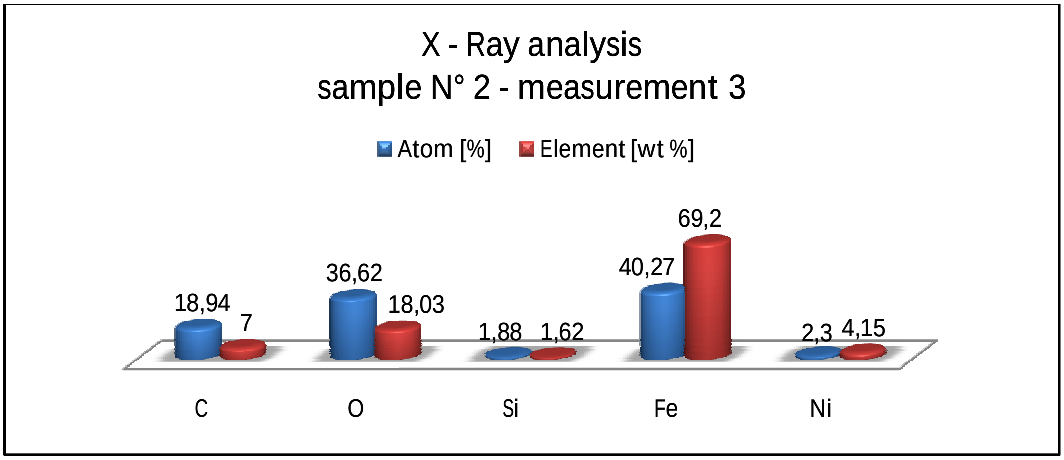


Fig. 51. Result of chemical composition analysis of sample N° 2 – measurement 3.

Measurement 4

Measurement conditions:

- magnification – x350; vacuum – 15kV; working distance WD – 14.7 mm;

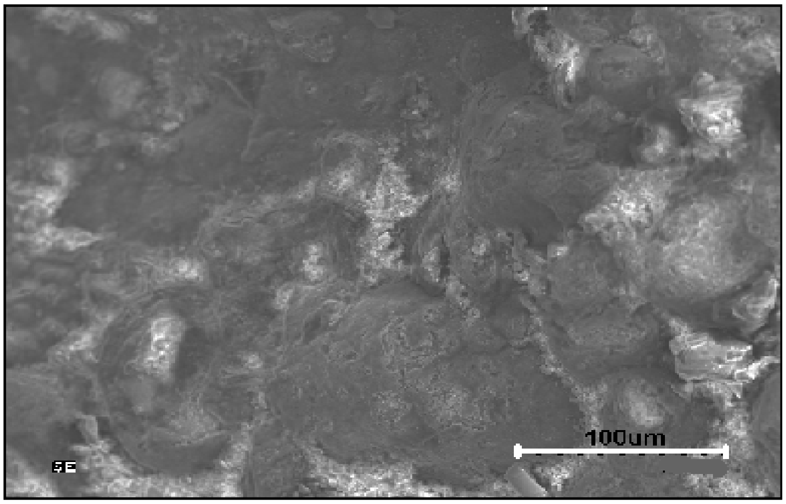


Fig. 52. Image from SEM. Surface fragment of sample N° 2 – measurement 4.

Table 22. Result of chemical composition analysis of sample N° 2 – measurement 4.

Element	**Atom [%]**	**Element [wt %]**	**wt % - Err. [1 – sigma]**
C	39,50	23,43	+/- 0,40
O	37,45	29,58	+/- 0,56
Si	8,45	11,72	+/- 0,17
Fe	10,43	28,75	+/- 0,53
Ni	0,16	0,47	+/- 0,25
Al	2,85	3,80	+/- 0,13
K	0,71	1,38	+/- 0,07
Ca	0,44	0,87	+/- 0,07

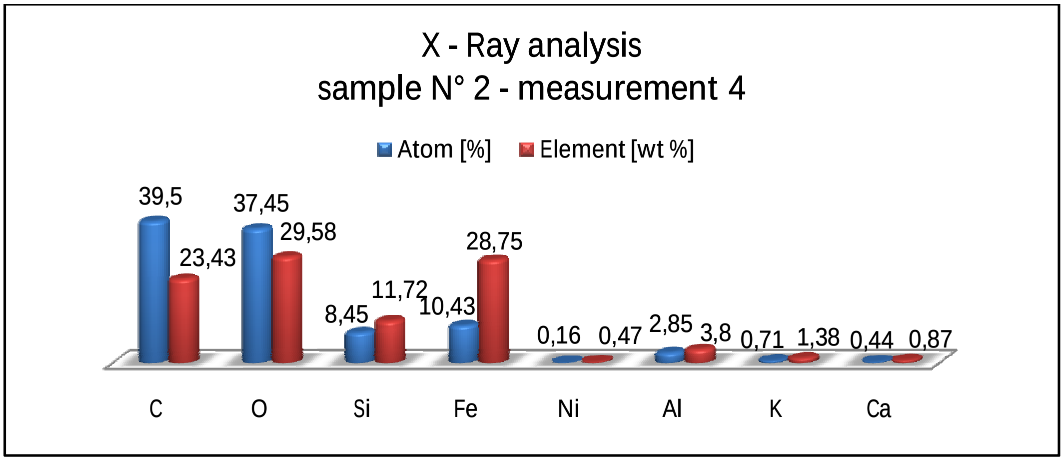


Fig. 53. Result of chemical composition analysis of sample N° 2 – measurement 4.

Sample N° 3: *Measurement 1*

Measurement conditions:

- magnification – x40; vacuum – 15kV; working distance WD – 14.4mm;

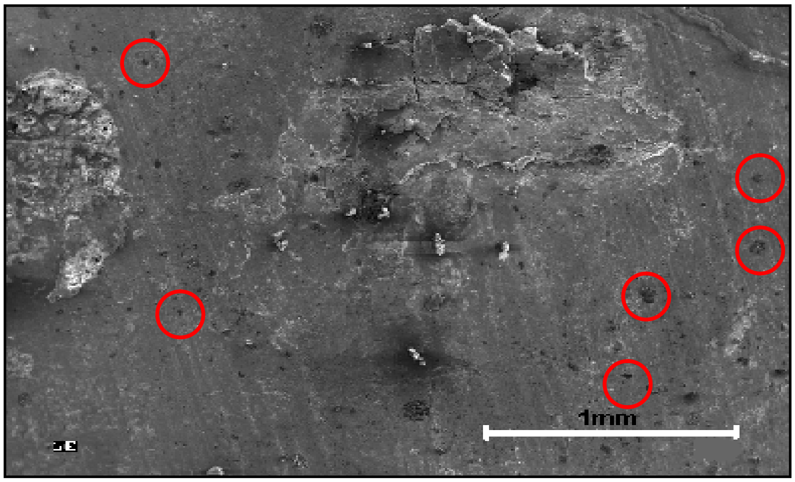


Fig. 54. Image from SEM. Surface fragment of sample N° 3 – measurement 1. Mark area – some places of carbon occurence.

Table 23. Result of chemical composition analysis of sample N° 3 – measurement 1.

Element	Atom [%]	Element [wt %]	wt % - Err. [1 – sigma]
C	18,58	7,01	+/- 0,31
O	38,80	19,51	+/- 0,36
Si	0,51	0,45	+/- 0,05
Fe	38,14	66,94	+/- 0,99
Ni	2,08	3,85	+/- 0,40
Al	0,33	0,28	+/- 0,06
K	0,07	0,09	+/- 0,06
Ca	1,49	1,87	+/- 0,08

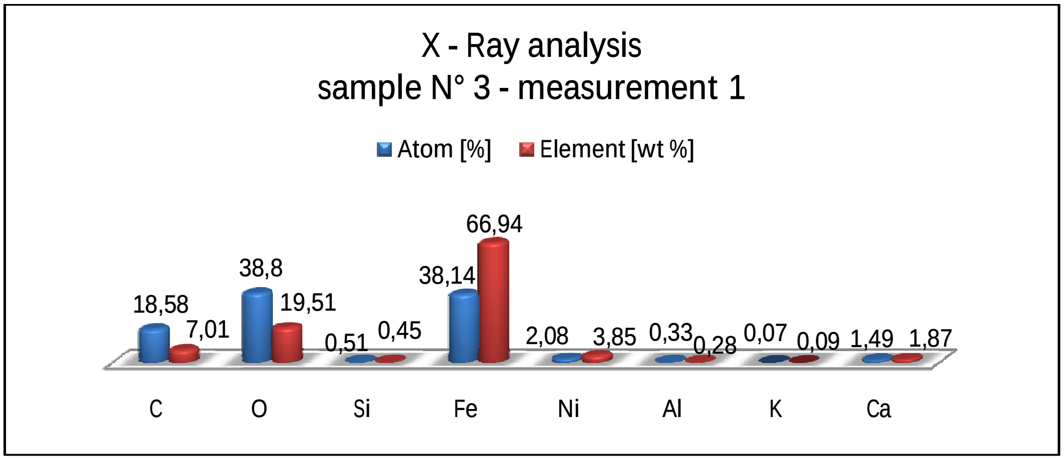


Fig. 55. Result of chemical composition analysis of sample N° 3 – measurement 1.

Measurement 2

Measurement conditions:

- magnification – x40; vacuum – 15kV; working distance WD – 14.6 mm;

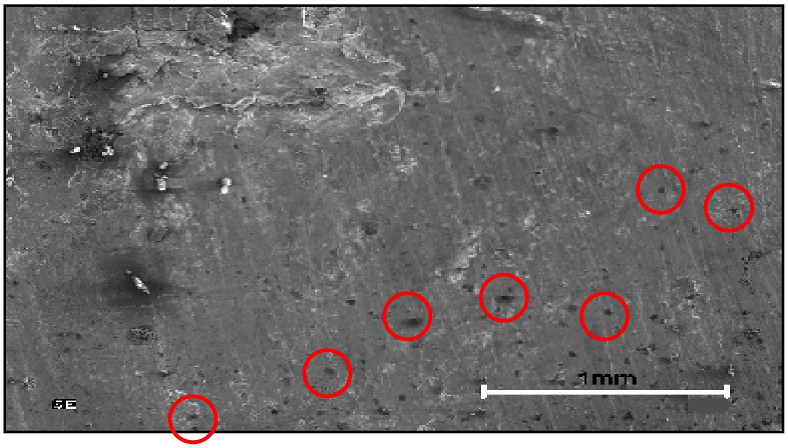


Fig. 56. Image from SEM. Surface fragment of sample N° 3 – measurement 2. Mark area – some places of carbon occurence.

Table 24. Result of chemical composition analysis of sample N° 3 – measurement 2.

Element	**Atom [%]**	**Element [wt %]**	**wt % - Err. [1 – sigma]**
C	17,32	6,41	+/- 0,21
O	38,62	19,04	+/- 0,32
Si	0,32	0,27	+/- 0,05
Fe	39,56	68,08	+/- 0,90
Ni	2,40	4,34	+/- 0,37
Al	0,64	0,53	+/- 0,05
K	0,20	0,24	+/- 0,05
Ca	0,29	0,36	+/- 0,06
Cl	0,66	0,72	+/- 0,06

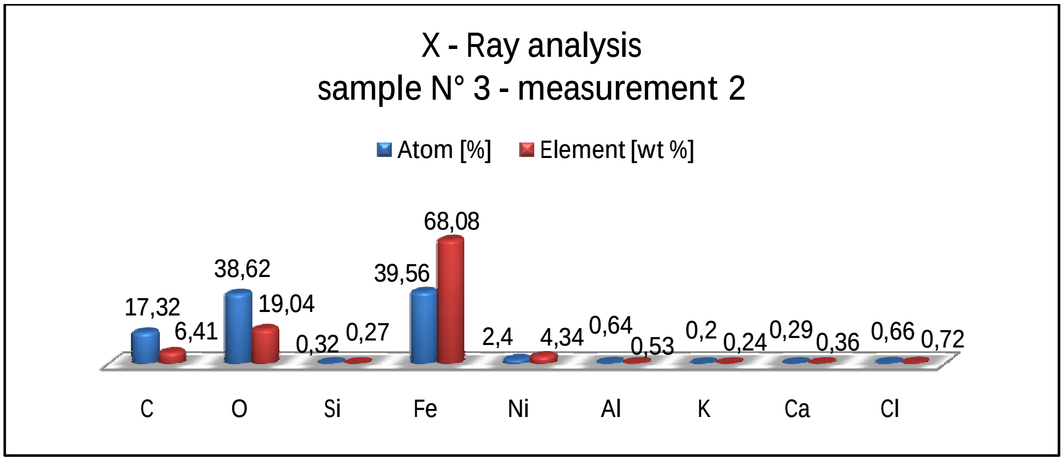
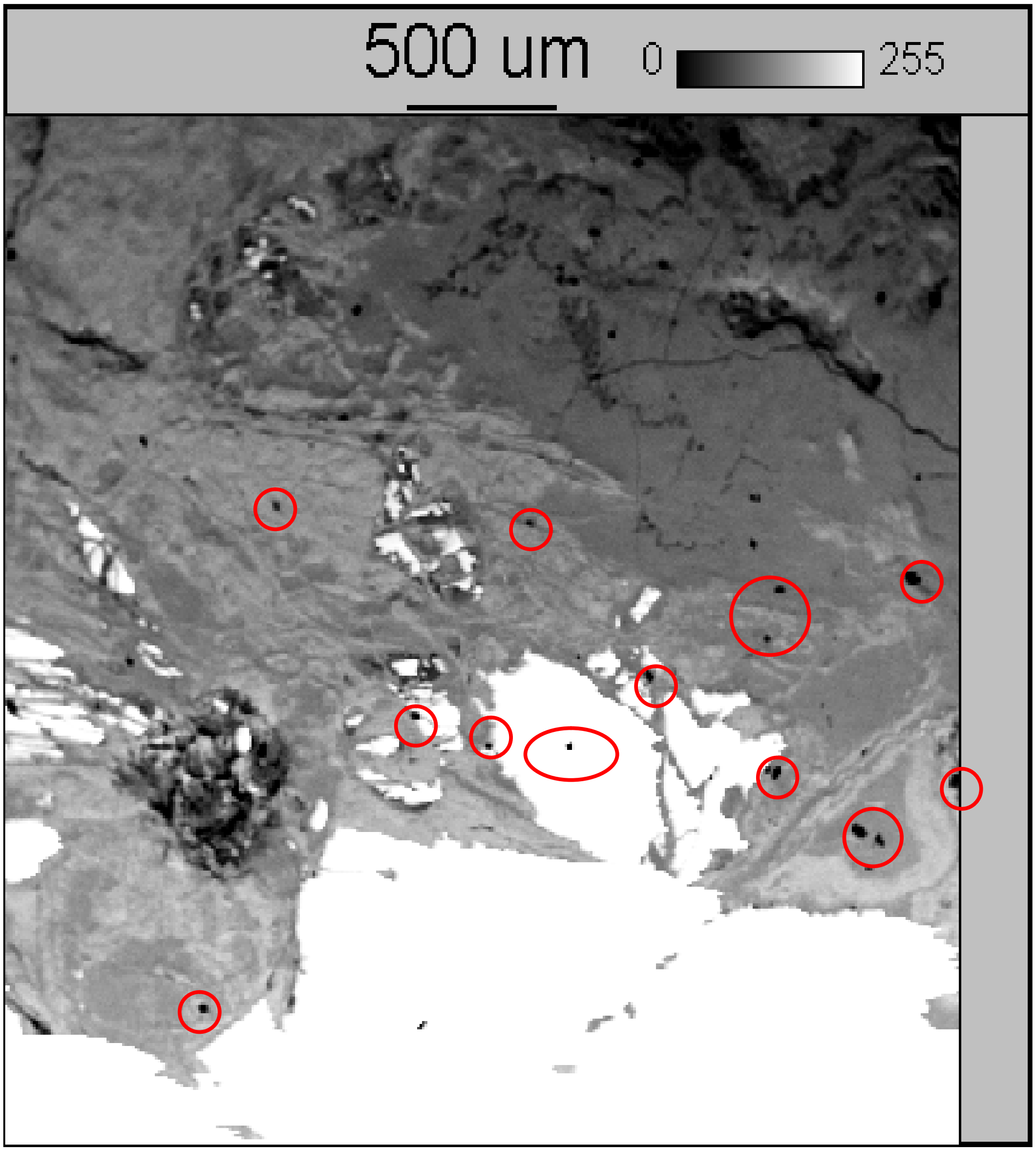


Fig. 57. Result of chemical composition analysis of sample N° 3 – measurement 2.

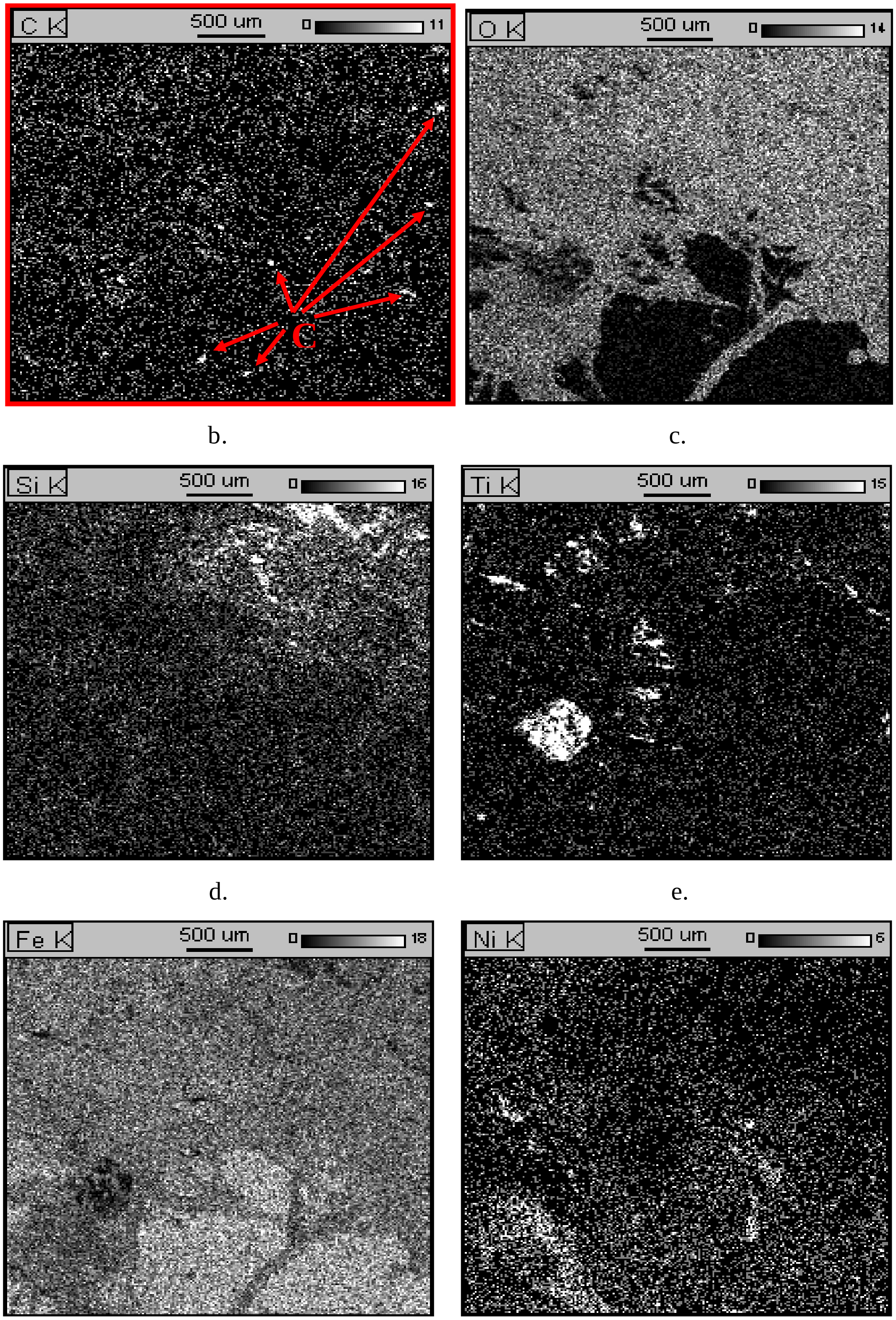
Distribution map of elements on the sample N° 2 surface:

image 1:



a.

○- *some places of carbon occurence.*



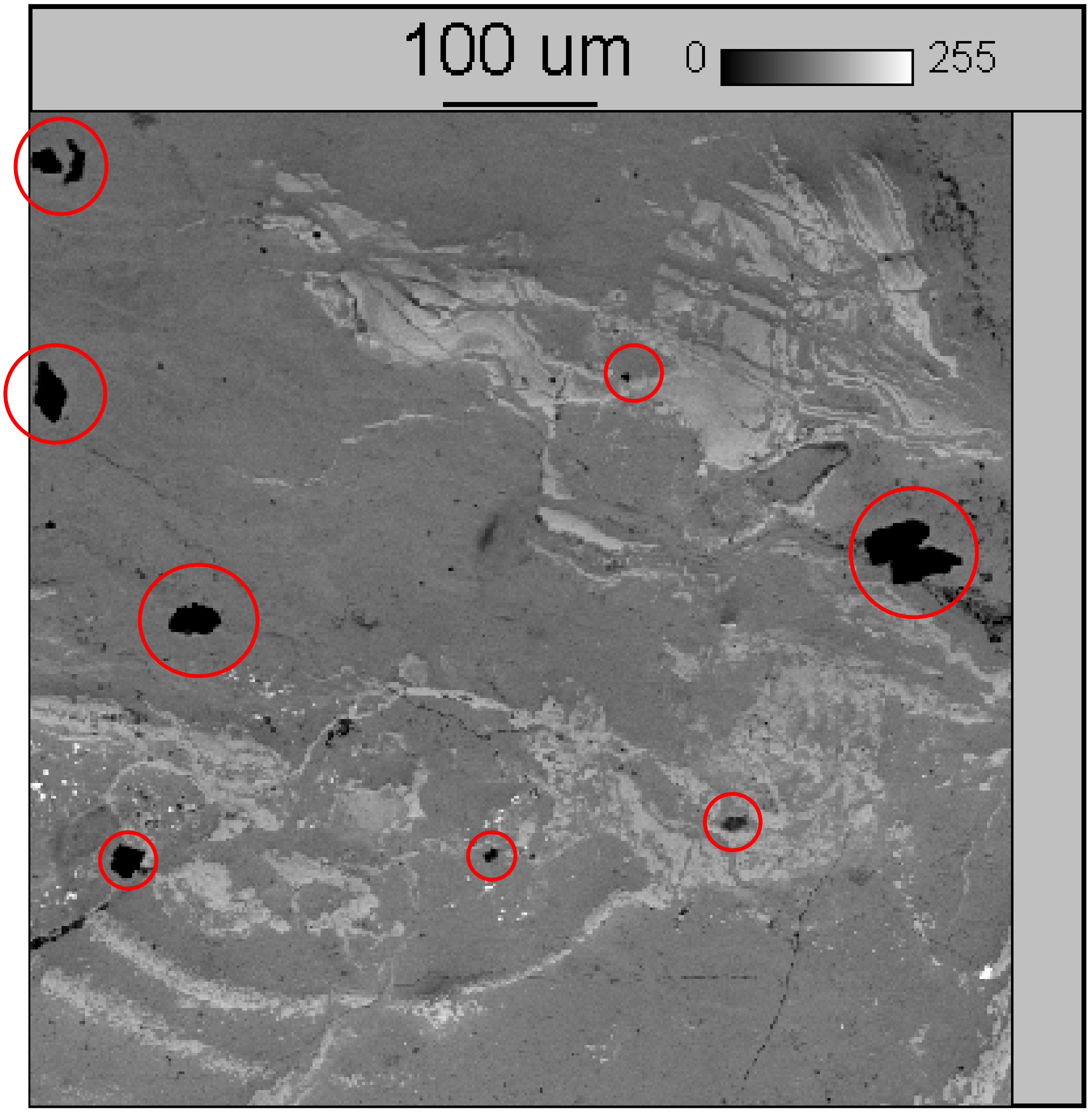
b. c.

d. e.

f. g.

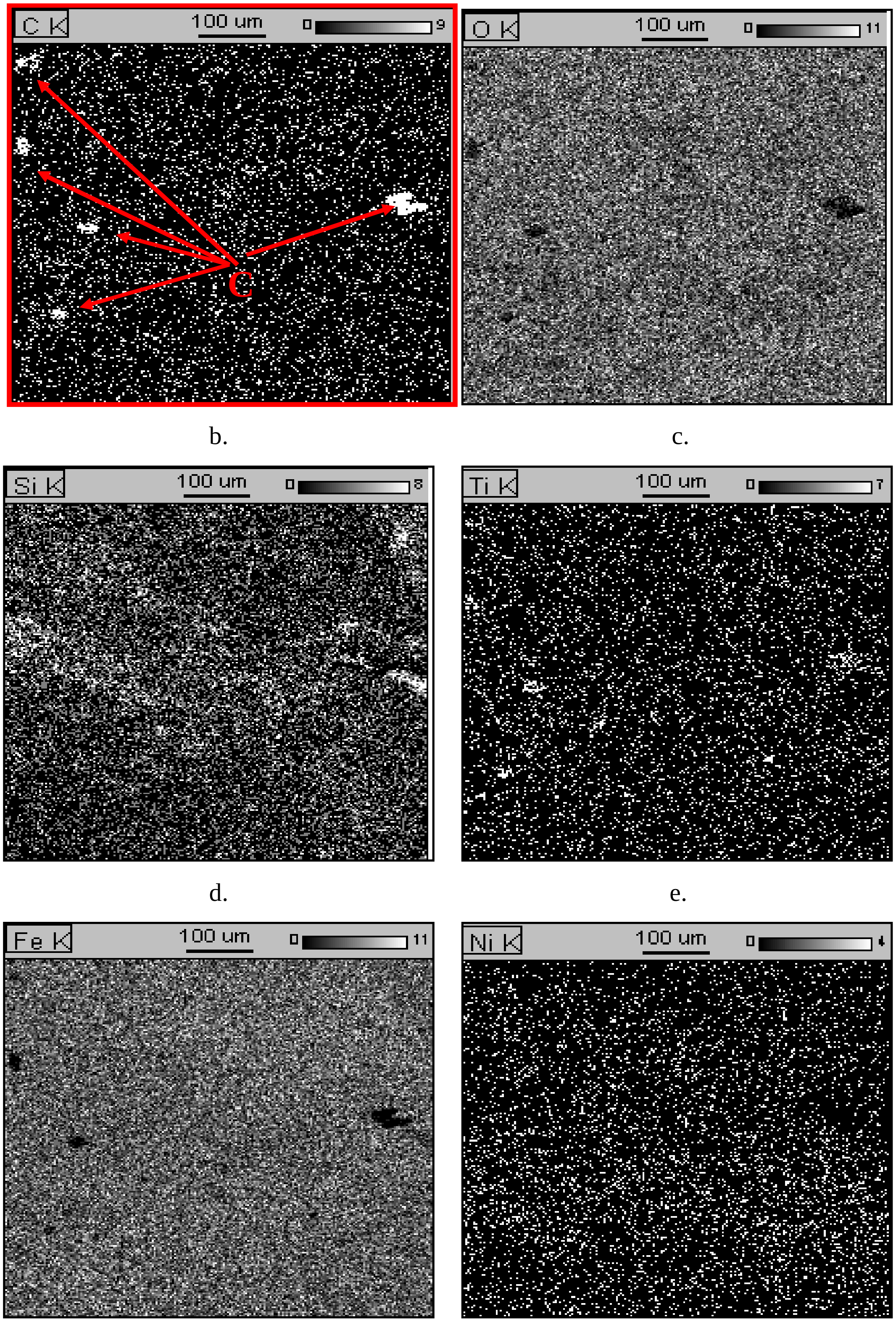
Fig. 58. Distribution map of elements on the sample N° 2 surface – image 1: a) General view; b) carbon map C; c) oxygen map O; d) silicon map Si; e) titanium map Ti; f) iron map Fe; g) nickel map Ni.

image 2:



a.

○- *some places of carbon occurence.*



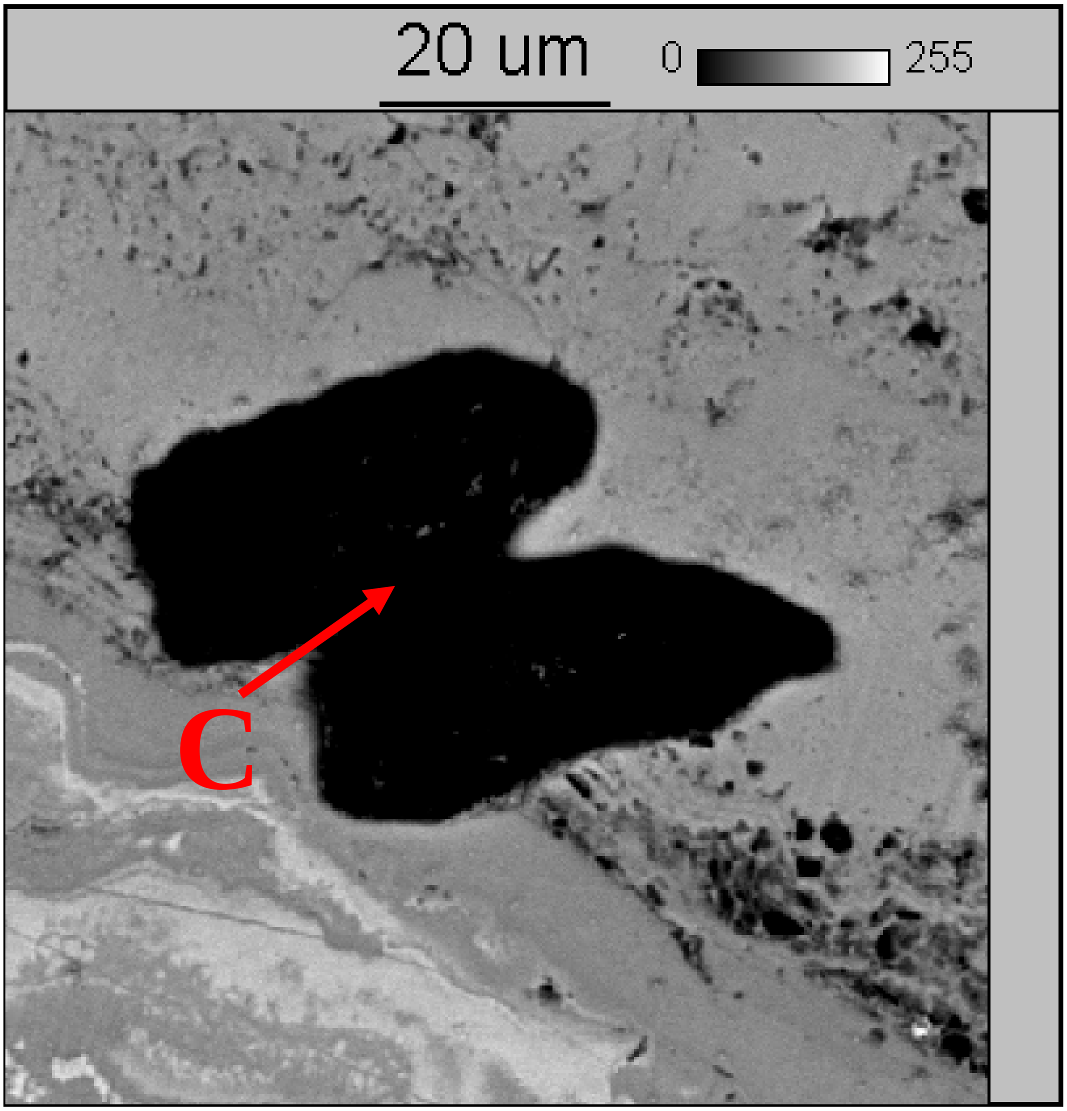
b. c.

d. e.

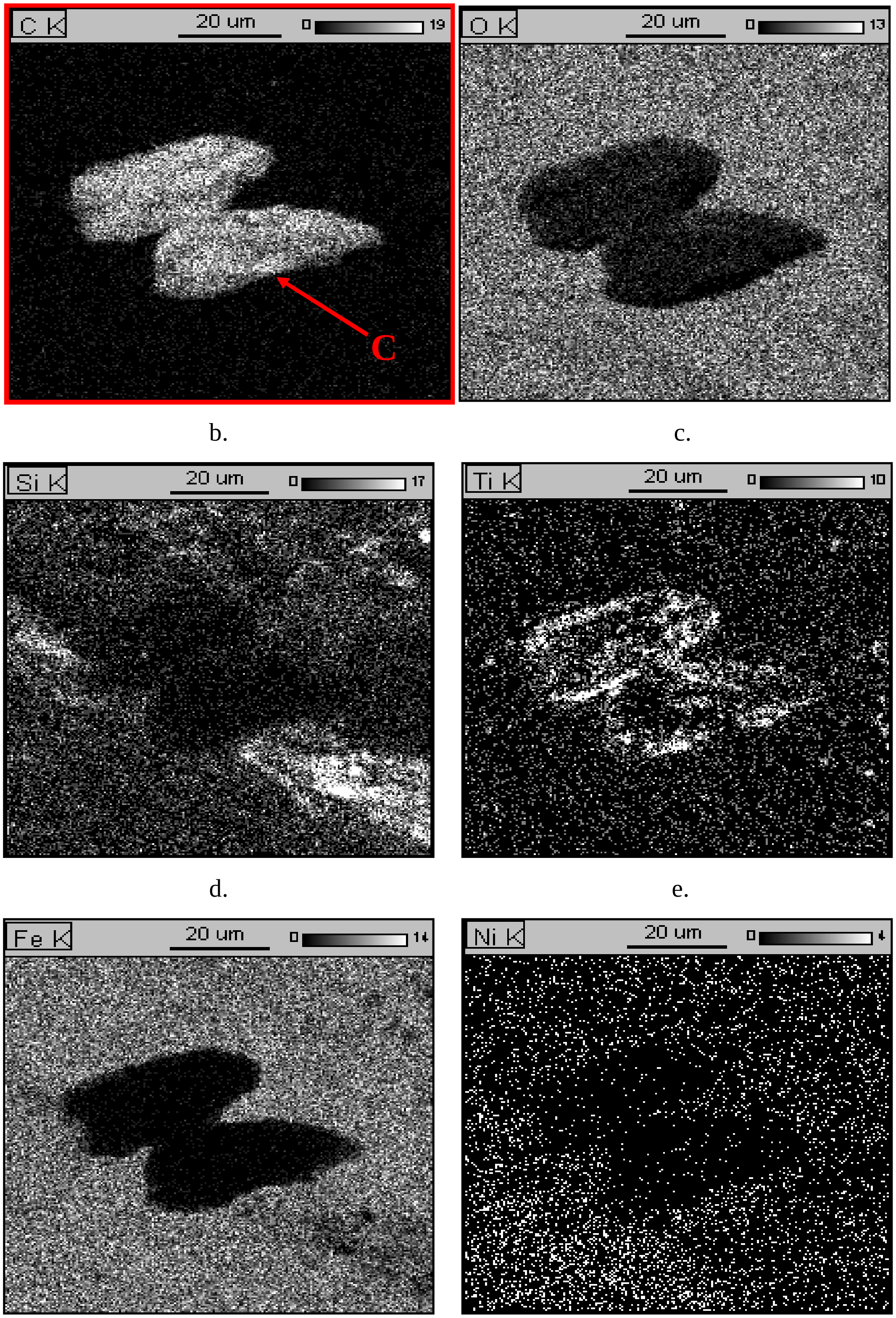
f. g.

Fig. 59. Distribution map of elements on the sample N° 2 surface – image 2: a) General view; b) carbon map C; c) oxygen map O; d) silicon map Si; e) titanium map Ti; f) iron map Fe; g) nickel map Ni.

image 3:



a.



b. c.

d. e.

f. g.

Fig. 60. Distribution map of elements on the sample N° 2 surface – image 3: a) General view – area 1; b) carbon map C; c) oxygen map O; d) silicon map Si; e) titanium map Ti; f) iron map Fe; g) nickel map Ni.

7. Raman spectroscopy.

The aim was to determine if carbon is present in the sample and to specify its allotropic type. The analysis was made on samples N° 1 and 5. The measurements of spectra were made with the use of Raman micro-spectrometer T – 64000 Jobin – Yvon with confocal microscope BX – 40 Olympus. As excitation source argon laser was used (wavelength 514,5 nm) of power about 200 to 250 mW.

Fig. 61. Micro – spectrometer Ramana T-64000 "Jobin-Yvon" [56].

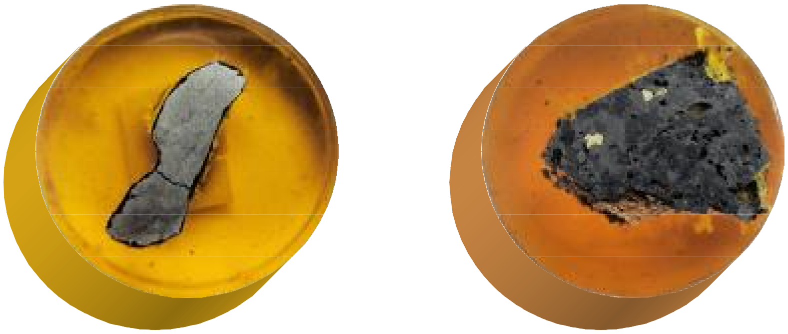


Fig. 62. Samples research by Raman Spectroscopy.

a) Sample N° 1 – Canyon Diablo;

b) Sample N° 5 – meteorite breccia;

Results of spectroanalysis:

Carbon phases:

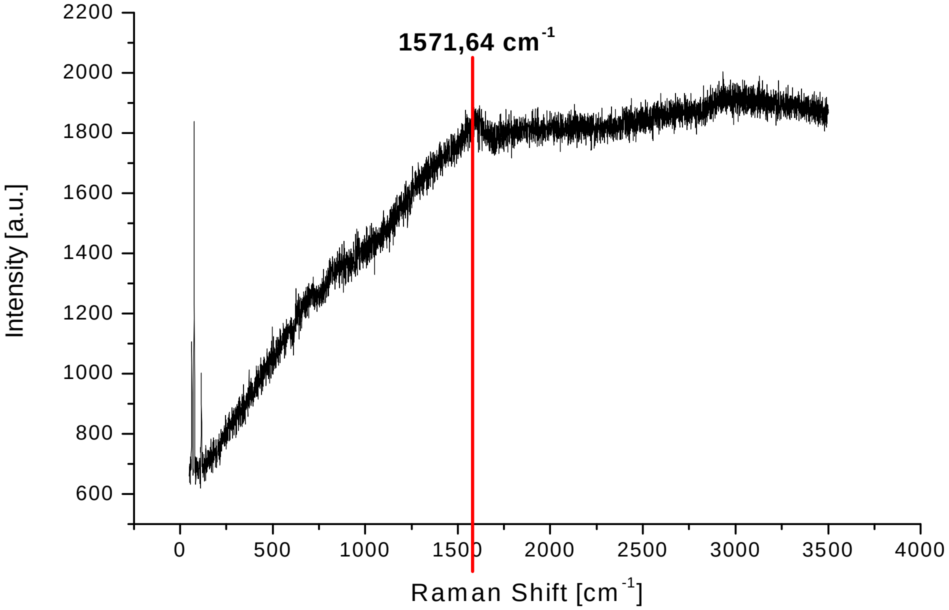


Fig. 63. Raman spectra of graphite obtained with first measurement of meteorite breccia.

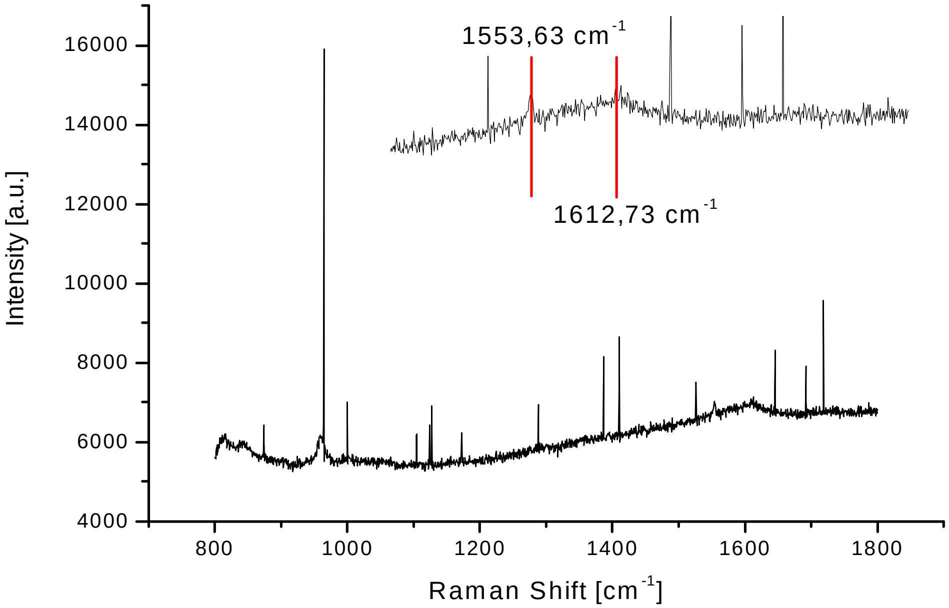
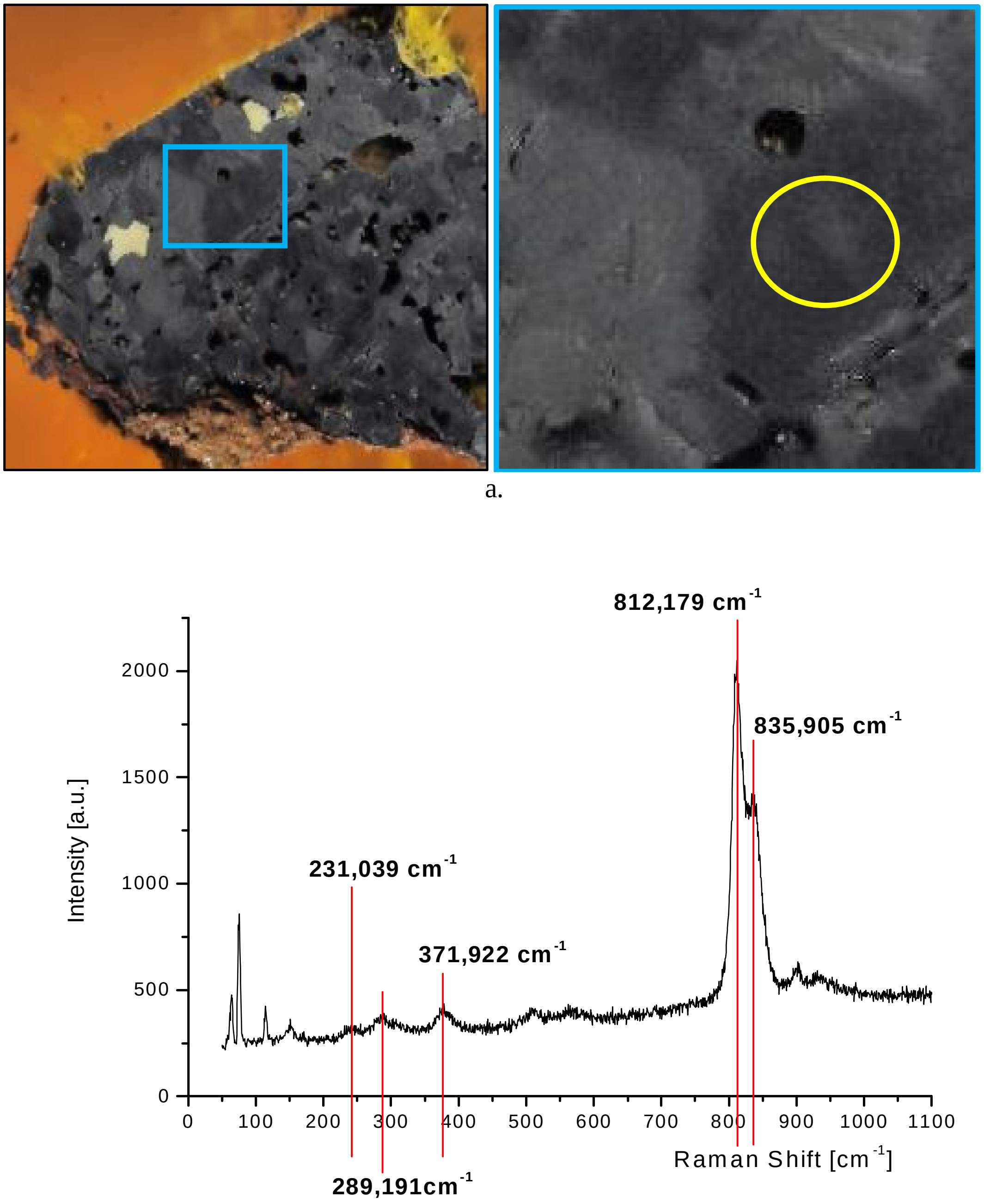


Fig. 64. Raman spectra obtained with secondary measurement of meteorite breccia. Magnification presents signal typical of graphite.

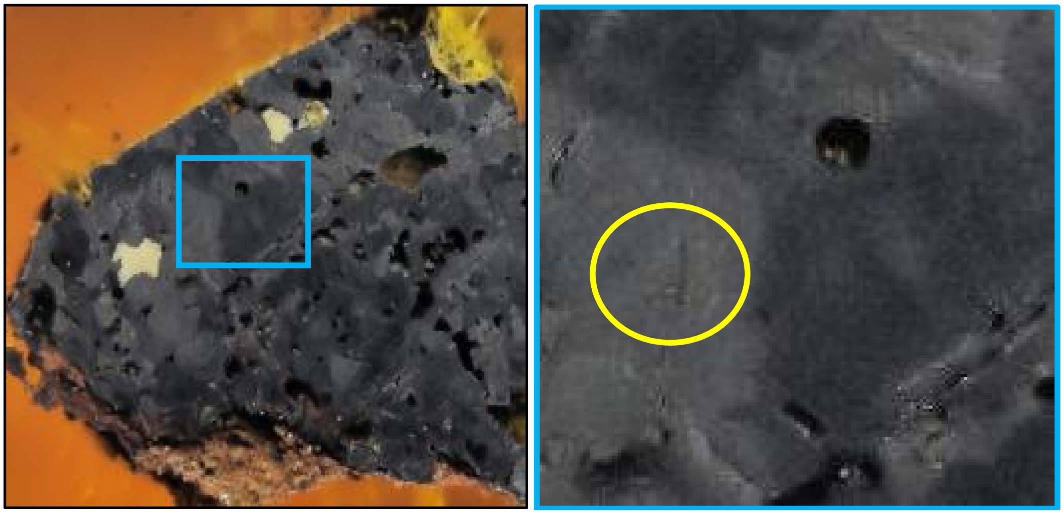
Minerals:



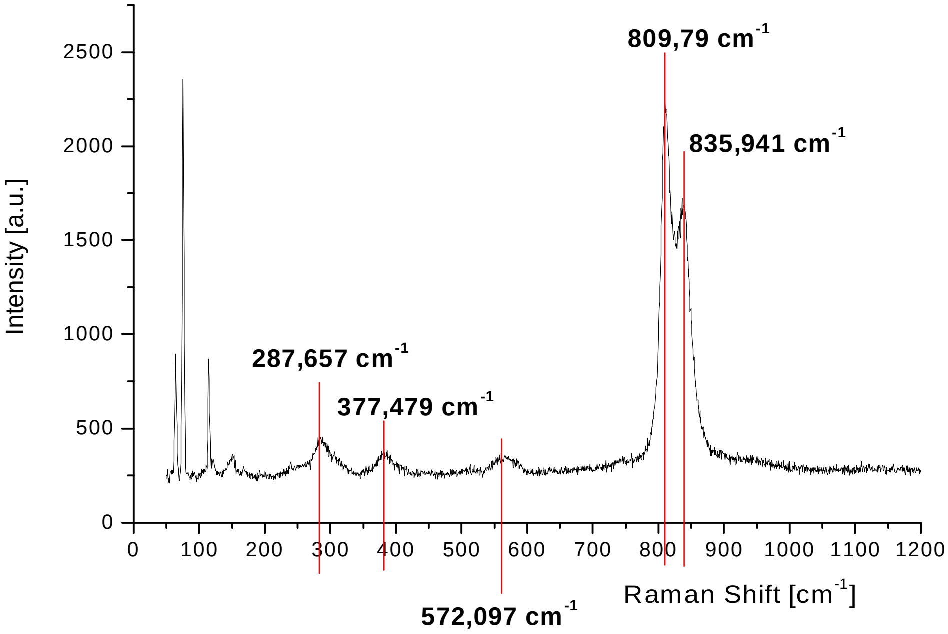
a.

b.

Fig. 65. Raman spectroscopy in meteorite breccia.
a) place of measurement;
b) Raman spectra – visible signal for olivine hematite;



a.

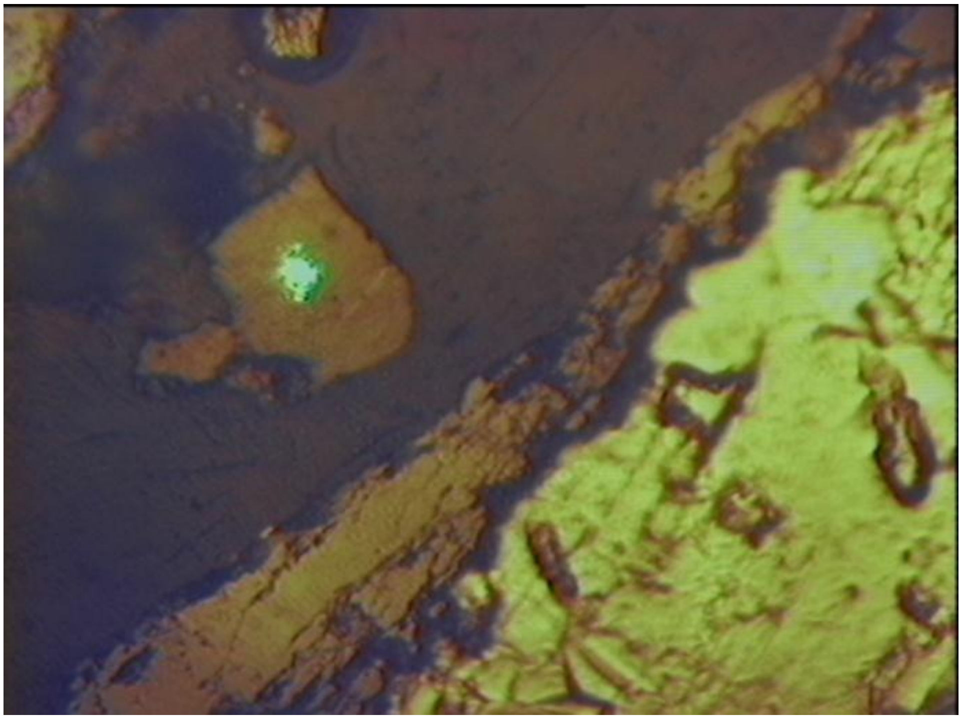


b.

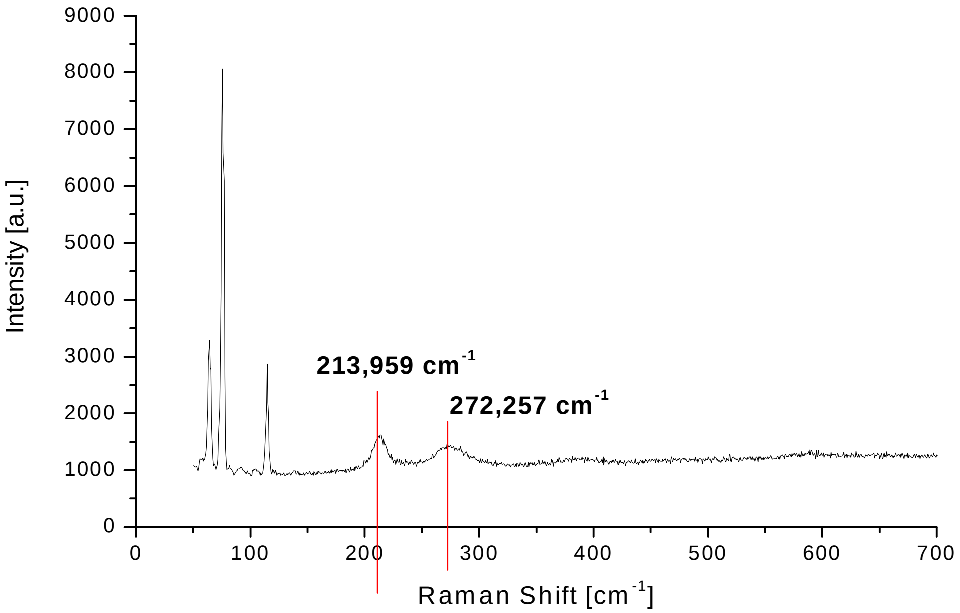
Fig. 66. Raman spectroscopy in meteorite breccia.

a) place of measurement;

b) Raman spectra – visible signal for olivine, hematite and probably magnetite;



a.



b.

Fig. 67. Raman spectroscopy in the Canyon Diablo meteorite. .
a) place of measurement;
b) Raman spectra – visible signal for hematite;

Table 25. Results of Raman spectroscopy.

Investigation object		**Carbon phases**	**Sygnał [cm^{-1}]**
Meteorite breccia	**measurement 1**	graphite	1571,64
	measurement 2	graphite	1553,63; 1612,73
Investigation object		**Mineral**	**Sygnał [cm^{-1}]**
Canyon Diablo		hematite	213,959; 272,257
Meteorite breccia	**measurement 1**	olivine	812,179; 835,905
		hematite	231,039; 371,922
	measurement 2	olivine	809,79; 835,941
		hematite	287,657; 377,479
		probably magnetite	572,097

8. Nanohardness.

The test was made in Research Institute of New Technologies in West – Czech Republic University of Pilsno on "MTS" – Nano Indenter XP *(Fig. 68*). Sample N° 4 was examined *(Fig. 69*).

Fig. 68. Nano Intender „MTS" – Nano Indenter XP, according to [57].

Fig. 69. Sample 4 – Canyon Diablo.

Nanohardness results:

The trial was carried out 16 times. The results were averaged and represented in a form of a table and diagrams (hardness and Young's modulus vs displacement into surface). Additionally, the results were compared with nanohardness of tool-steel and constructional steel (samples after grinding, polishing and annealing). Conditions of measurement:

- max. depth of measurement 2000 nm;
- frequency loading 45 Hz;
- loading amplitude 2 mm;
- deformation rate 0,05^{-1};

Table 26. Result of nanohardness of the Canyon Diablo meteorite.

Material	E Average Over Defined Range [GPa]	H Average Over Defined Range [GPa]	E From Unload [GPa]	H From Unload [GPa]
Meteorie Canyon Diablo	207,91	3,782	183,448	2,211

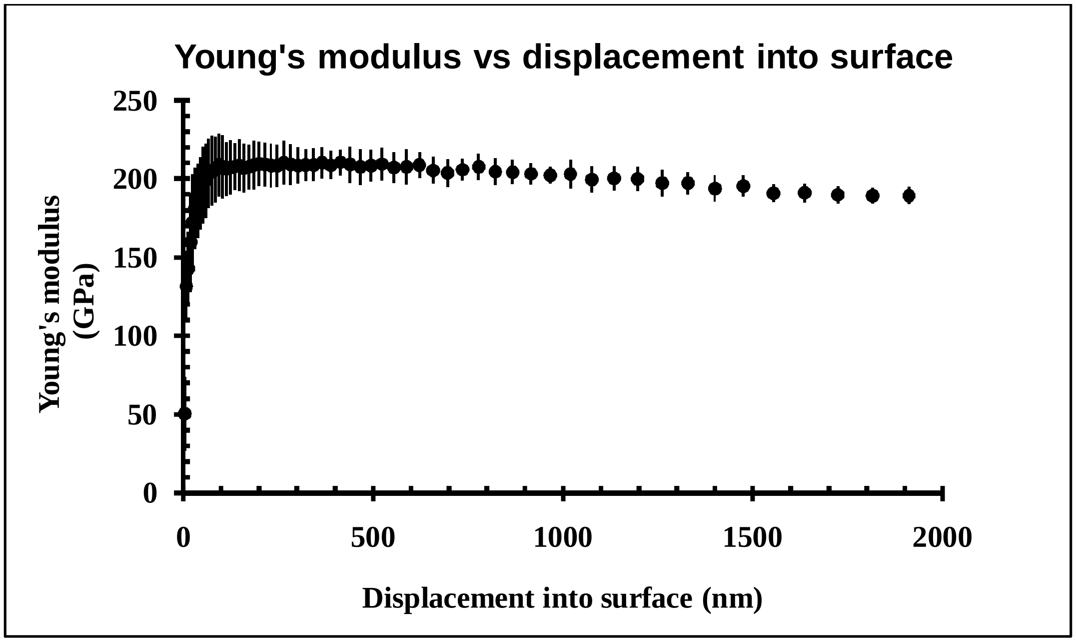


Fig. 70. Diagram of Young`s modulus vs Displacement into surface.

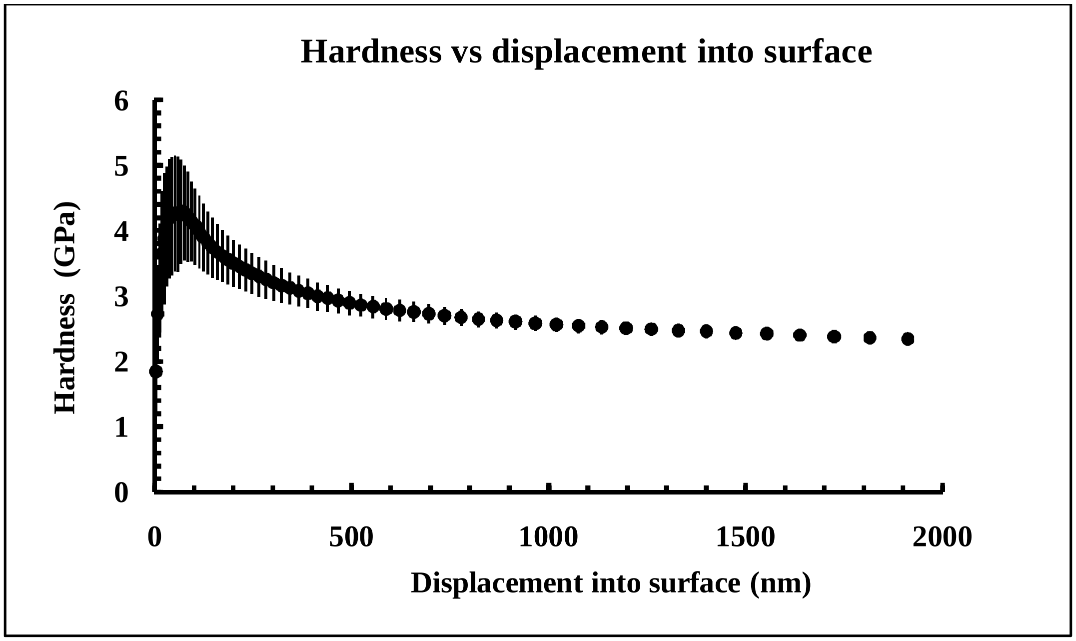


Fig. 71. Diagram of hardness vs Displacement into surface.

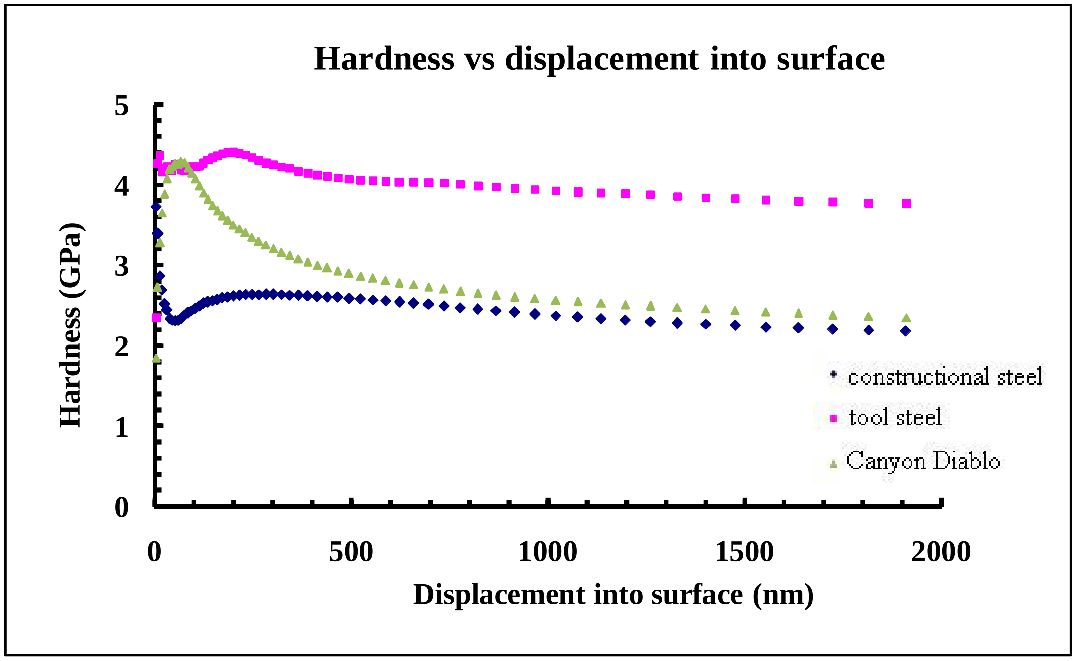


Fig. 72. Comparison of Hardness vs Displacement into surface among construction steel, tool steel and the Canyon Diablo.

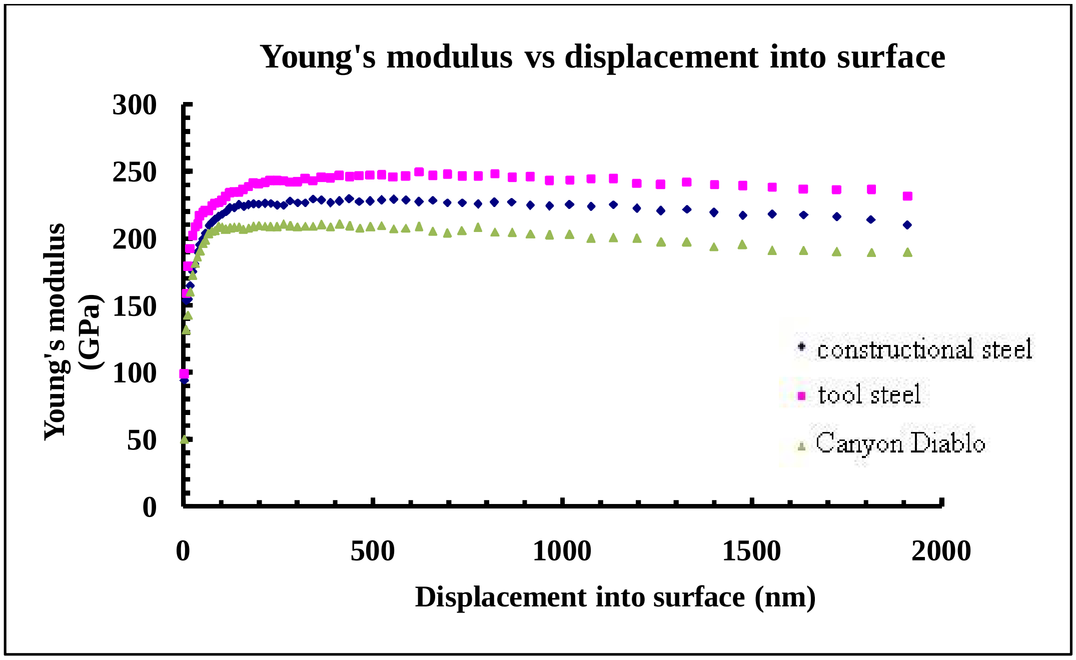


Fig. 73. Comparison of Young`s modulus vs Displacement into surface among construction steel, tool steel and the Canyon Diablo.

IV. Discussion on results and conclusions.

Thanks to their extraterrestrial origin meteorites are amazing objects of investigation. Using the latest investigation technologies one may find out more about their structure and chemical composition.

While doing this experiment I have concentrated mainly on carbon content and its forms.

First experiment was done with the use of optical microscopy. It was a preliminary experiment which aimed to constraint the area of searching of carbon phases in meteorite samples. After some preparations, the analysis was made and the areas of probable occurrence of carbon were found (*Fig. 42 and 43*). The areas were found on Canyon Diablo sample (N° 1) and meteorite breccia (sample N° 5).

Scanning Electron Microscopy with X-Ray microanalysis EDS was a very important examination used for analysis. There were analysed two samples of Canyon Diablo (N° 2 and 3). Each sample was examined in several areas. That is why it may be stated with no doubt that the samples contained carbon, which is visible in images got from SEM (*Fig. 46, 48, 50, 52, 54, 56*). Considering its amount in terms of its mass, it appears that there are from several to more than ten wt % of carbon, whereas analysing the amount of carbon atoms there are from a dozen to tens % of its atoms (*Tab. 19 – 24*). All examined samples contain such elements as: C, O, Fe, Ni, Al, K, Ca, Cl. A dominant element is iron, which occurs in amount about 60 – 70 wt %. There is also a significant amount of nickel (about several wt %). The occurrence of these elements confirms that the samples belong to iron meteorite, which structure is based on iron – nickel alloy.

The next argument for carbon occurrence in the meteorite is a distribution map of elements (*Fig. 58 – 60*). In the case of sample N° 2 it points the exact areas on the surface, where there are carbon grains. The map was made in 3 different elements to show more clearly the shape of carbon grains. There are also visible elements mentioned earlier as well as titanium can be observed in the sample.

Raman spectroscopy confirms carbon occurrence in meteorite breccia, unfortunately the examination did not reveal the occurrence of carbon in Canyon Diablo sample (sample N° 1). This method allows to specify clearly the form of carbon. The spectra gained show that the carbon occurs in a form of graphite. The measurement was done in 2 areas of samples. In both cases the occurrence of graphite was noticed which may be confirmed by signals: 1571.64 cm^{-1} – measurement 1 (*Fig. 63*) and 1553.63 cm^{-1}

and 1612.73 cm^{-1} – measurement 2 (*Fig. 64*). In these measurements the signals are not quite clear, which may be the result of a small amount of carbon or its high disintegration. Thanks to Raman spectroscopy there were identified the following minerals:

1. olivine – identified in meteorite breccia:
    a. measurement 1 (*Fig. 65*) – signals: 812,179 cm^{-1}; 835,905 cm^{-1};
    b. measurement 2 (*Fig. 66*) – signals: 809,79 cm^{-1}; 835,941 cm^{-1};
2. magnetite – probably identified in meteorite breccia:
    c. measurement (*Fig. 66*) – signal: 572,097 cm^{-1};
3. hematite – identified in Canyon Diablo and meteorite breccia:
    d. measurement 1 (*Fig. 65*), meteorite breccia – signals: 231,039 cm^{-1}; 371,922 cm^{-1};
    e. measurement 2 (*Fig. 66*), meteorite breccia – signals: 287,657 cm^{-1}; 377,479 cm^{-1};
    f. measurement 3 (*Fig. 67*), Canyon Diablo – signals: 213,959 cm^{-1}; 272,257 cm^{-1};

The last examination was nanohardness measurement. The results were represented in a form of two diagrams: hardness vs displacement into surface function (*Fig. 71*) and Young’s modulus vs displacement into surface function (*Fig. 70*). Additionally, the results gained were compared with these characteristic for constructional and tool steel (*Fig. 72 and 73*). It appears that meteorite nanohardness, which average value is 2.211 GPa (*Tab. 26*), is higher than the value of nanohardness of constructional steel and lower than the value of the same parameter of tool steel. The average value of Young module of meteorite is 183.448 GPa (*Tab. 26*) and is lower in comparison with both types of steel.

The aim of this study was material analysis of meteorites with a special attention to carbon occurrence and its allotropic forms. In my study I used four pieces of Canyon Diablo meteorite (they have their certificates – annex 1) and pieces of meteorite breccia. The samples were divided into groups, in which individual methods of analysis were used. Samples N° 1 and 5 were examined by means of optical microscopy and Raman spectroscopy and samples N° 2 and 3 with the use of Scanning Electron Microscope with X-Ray microanalysis EDS. Examined meteorite samples 2 and 3 (Canyon Diablo fragments) show carbon occurrence. But unfortunately its form was not determined. Examined samples N° 1 and 5 showed that only meteorite breccia (sample N° 5) contains carbon in a form of graphite. As a result it may be stated that carbon is non – uniformly placed in meteorites. In one place there may be a lot of carbon, whereas in the other there may be none. It is probably the situation, which occurred in my experiment. Samples N° 2 and 3 contain considerable amounts of carbon in comparison with sample N° 5 or 1 which probably do not contain carbon at all. Results are mainly determined by the area, from which the fragment comes from, in other words, from which the fragment was broken away from its parent meteorite. In many cases meteorites hit the ground and break and their fragments may be scattered around even a few kilometers away. Such situation occurred in the case of my samples (Canyon Diablo pieces), because they were found in different places, but they are parts of the same meteorite (annex 2). As it is widely known, meteorite while falling onto the ground enters atmosphere, which may be first element causing carbon decomposition in meteorite. Fragments coming from meteorite areas exposed to atmosphere may not contain carbon, because high temperature of atmosphere may have burnt (oxidated) carbon. In the case of fragments, which were not exposed to strong attack of atmosphere, carbon might have survived. Similar situation occurs when meteorite impacts the surface of the ground. Pieces coming from the exact place of impact may not contain carbon. As a result of influence of high temperature and pressure carbon might have vaporized, melted or burnt down.

The only identified form of carbon in my experiment was graphite. The source of diamond in meteorites may be diamond dust occurring in interplanetary space or transforming graphite affecting by high temperature and pressure (*HTHP – High Temperature High Pressure*), while a meteorite falls down. According to information mentioned above it may be stated that in examined samples, diamond was not found, because the area the samples come from was not exposed to factors strong enough to transform graphite into diamond or which is more probable, diamond does not occur in them.

In samples there were identified chemical elements: C, O, Fe, Ni, Al, K, Ca, Cl, Ti. Iron and nickel are basic elements occurring in iron meteorites. The analysis of chemical composition of Canyon Diablo is similar to data found in literature, however there is a difference between carbon contents. It results from different concentration of carbon in meteorites. Canyon Diablo fragments tested by means of X-Ray analysis (samples 2 and 3) showed considerable carbon concentration, which means that they might have come from the areas influenced by unfavorable conditions (e,g. of atmosphere and high temperature).

V. Summary.

Investigations connected with material analysis of meteorites, especially carbon, are becoming more and more popular. They join different scientists and fields of science, e.g. materials science, physics, geology and chemistry. This study will be a part of a complex science project called “*Comparison of nanomolecules and micromolecules of carbon coming from meteorites and synthetically obtained on Earth with the use of the latest investigation methods*”.

The aim of the experiment was to analyse the material composition of meteorites. Meteorites were tested in terms of carbon content and its allotropic forms.

The thesis consists of theoretical and experimental part. In theoretical part there were presented meteorites, their types and allotropic forms and methods used to detect carbon in extraterrestrial objects. The experimental part contains the results of my own experiment.

First, microscope analysis was made in order to find probable areas of occurrence of carbon phases in meteorite.

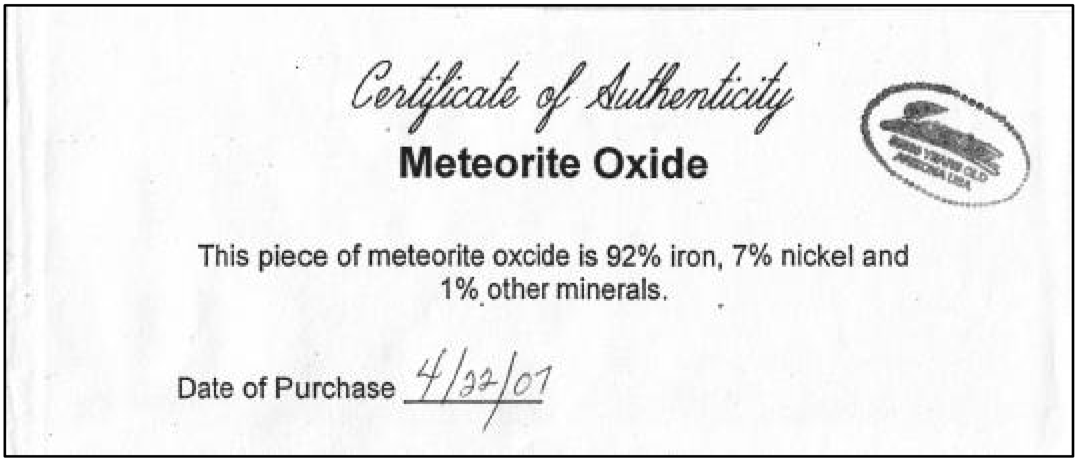
The other examination was Scanning Electron Microscopy with X-Ray microanalysis EDS. Its aim was to determine chemical composition of Canyon Diablo fragments and to find areas of carbon phases.

Raman spectroscopy was the next step of my experiment. It allows to determine forms of carbon and types of minerals in Canyon Diablo meteorite and meteorite breccia.

The last test was nanohardness measurement. It was used to measure nanohardness and Young module and to compare their parameters with the nanohardness parameters of chosen types of steel.

The results were represented in forms of tables, diagrams and photographs. On the basis of experiments there were formed conclusions concerning occurrence of different allotropic forms in meteorites.

VI. Annexes.



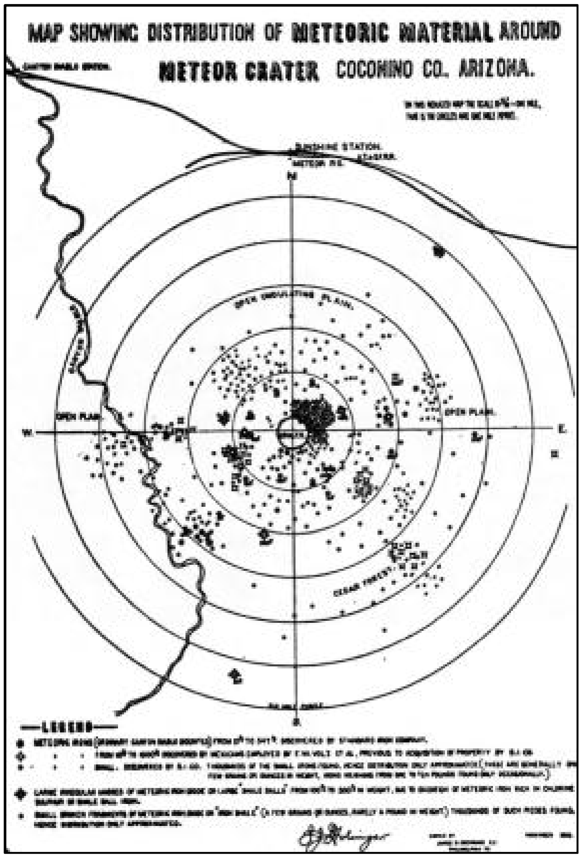
Certificate of Authenticity

Meteorite Oxide

This piece of meteorite oxide is 92% iron, 7% nickel and 1% other minerals.

Date of Purchase 4/22/01

Annex 1. Certificate of Canyon Diablo fragments authenticity.



Annex 2. Meteor Crater and Surrounding area, showing distribution of meteorite material. D.M. Barringer, Report to Academy of Sciences, 1909, according to [55]

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