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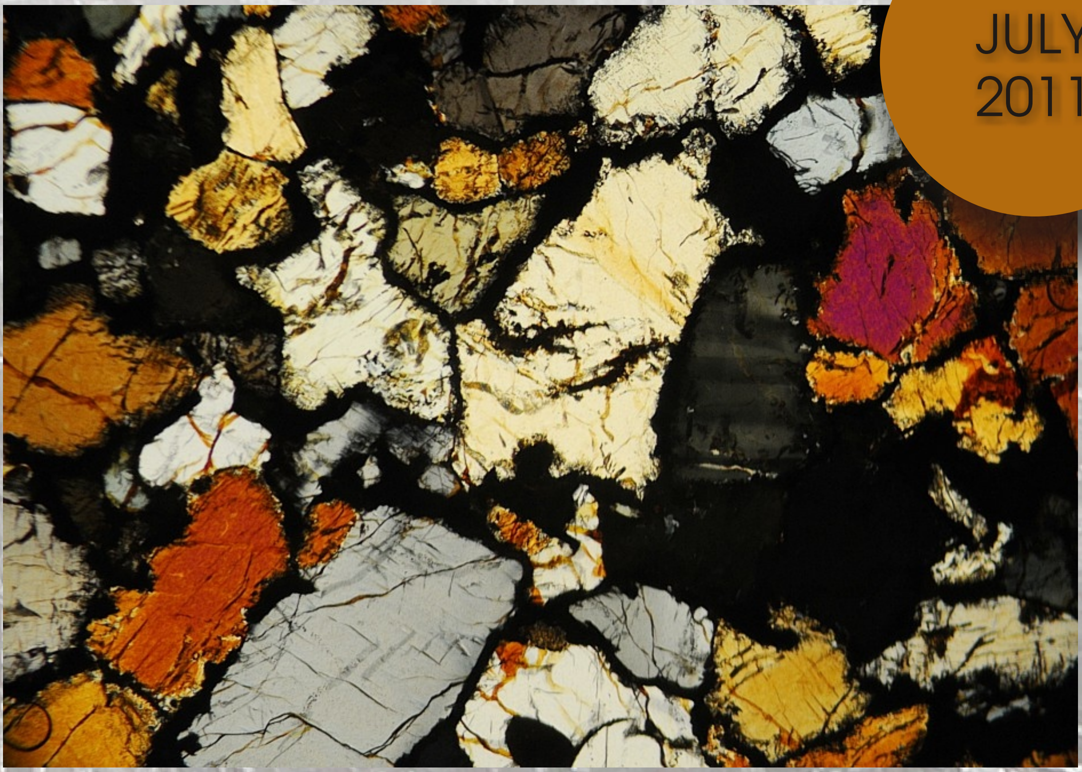

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Foto on cover: thin section of NWA 5928 ureilite

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JOURNAL INFORMATION

Meteorites provides a coherent international forum for the publication of research in the field of meteoritics and its related disciplines. The topics of interest range from, but are not limited to, meteorites and other kinds of extraterrestrial matter and their sources of origin through the examination of the mineral resources of the Solar System, to tektites, impactites, and impact structures.

Meteorites invites the submission of articles covering the broadly defined field of meteorites. In addition to publication of research results, however, authors are encouraged to share and present astronomical, petrological, mineralogical, geochemical, and isotopic data on all groups and types of meteorites. Meteorites is intended to serve as a basic reference source for in-depth analyses and compilations on particular meteorite groups and their parent bodies, as well as the genesis and evolution of the Solar System, as well as other planetary systems.

Considering the progress of human space exploration and conceivable colonization of other planets, this data will likely play an important role in the recognition and exploitation of extraterrestrial mineral resources. Therefore, in light of the potential benefits, Meteorites editors have no intention of rejecting paper submissions pertaining to the research of meteorites with provisional names and pending classifications, esp. prior to their approval by the Committee on Meteorite Nomenclature of the Meteoritical Society.

Meteorites invites the publication of important papers intended as reference sources for other researchers, as well as compilations and interpretations of other works on meteorites of lesser scientific importance and their parent bodies. Not only does Meteorites welcome submissions of research descriptions and results regarding ‘rare’ meteorites, and topics such as newly-discovered extraterrestrial mineral species, but it also gladly accepts articles covering more common groups of meteorites. Due to their relatively low scientific value in terms of current research trends, many interesting research results are quietly filed away into archives instead of being published in leading scientific journals.

Our intention is not to compete with existing journals, but to add to the currently limited publication space for researches on meteorites. Meteorites editors will gladly accept any reliable research results, including submissions that are virtually impossible to publish in today’s existing journals due to the apparent mediocrity of the specimens studied. At Meteorites, we believe that even profoundly studied meteorites can have a significant and relevant bearing on our knowledge and understanding of the Solar System. Meteorites will, in time, develop into a repository of data and knowledge available for everyone with an interest in extraterrestrial matter.

Our purpose is to develop a new interdisciplinary journal covering the multitude of subject matters involved in meteorite research. Due to an insufficient amount of publication space, the increasing number of specimens available for research, and a growing list of research centers, only a small percentage of valuable submissions is ever brought to publication.

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DIAMONDS IN UREILITES

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Abstract: The presence of diamonds in meteorites was confirmed for the first time in the Novo-Urei ureilite in 1888. Ureilites are a rare class of achondrites, often referred to as primitive achondrites. They are composed of olivine and pyroxene (pygeonite), as well as graphite inclusions often coexisting with diamonds.

The following three main hypotheses of diamond origin in ureilites have been proposed: the HPHT process, graphite-to-diamond conversion under shock compression due to impact on the parent body (the most popular theory, as of the time of publication), and the CVD process in the solar nebula.

The samples of all types of ureilites, from less shocked up to highly shocked, were examined using Raman Spectroscopy and Scanning Electron Microscopy.

The results show the presence of diamonds in all of our samples. Of particular significance is the comparison of Raman spectra of diamonds and graphite phases of different ureilites.

Keywords: Diamond properties and applications; diamond; meteorite; ureilite, Raman spectroscopy

INTRODUCTION

The presence of diamonds have been confirmed in different types of meteorites: carbonaceous chondrites, ureilites, and iron meteorites. Meteoritic diamonds are of particular interest for research as they exist in different polytypes (3C, 2H, 6H, 8H, 10H, 21R) (Phelps, 1999a), have different sizes (from nanometers up to millimeters), and are of different origin. As nanodiamonds contain isotopic anomalies, they are believed to have formed before our solar system and are thus called presolar. Phelps (1999b) underlines that the theories of meteoritic diamond genesis have been evolving in accordance with the development in diamond synthesis.

It is evident that further studies of both meteoritic and laboratory diamonds are very closely related. Before Lonsdaleite was synthesized under laboratory conditions, it had been identified from the Canyon Diablo meteorite. There is a lot to learn from nature.

Moreover, meteorites can give us clues about our solar system by direct studies conducted within our laboratories rather than distant snapshots or telescope viewing. Since the material of meteorites is believed to have been created with the formation of the solar system, further investigation will yield more knowledge of the origins of our sun and planets. Such studies of Earth are difficult as geological activity has recycled the original composition of material; however, in the vastness of space, the original materials found in meteorites and their parent bodies, asteroids, have largely been preserved.

One of the least understood groups of meteorites is the class of primitive achondrites called ureilites. The first of their kind were found in Central Russia in 1886 in the village of Novo-Urei and more have been found mainly within deserts such as the Sahara and Antarctica. They are the most unique of this meteorite group. Ureilites contain olivine and pyroxene (pigeonites) along with material rich in carbon and noble gases. Behind the origin of diamond in ureilites

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is a shock process and some authors claim that a low pressure process similar to CVD.

The aim of this work is to compare the similarities and differences of diamonds among five different samples of ureilites through Raman spectroscopy and scanning electron microscope-energy dispersive spectroscopy (SEM-EDS). Studies of the results along with comparison of the amount of shock of each meteorite may give further insight into the origin of these diamonds and ureilites. Presently, there has been little literature on the subject of the relationship between ureilites, diamonds, and how their connection may give more clues to origin of this enigmatic group. It is part of previous research concerning diamonds in meteorites (Szurgot et al., 2006; Karczemska et al., 2007; Gucsik et al., 2008).

EXPERIMENTAL

We examined five polished slices of ureilites from different locations: Sahara 98505 (Morocco), DAG 868 (Libya), Dhofar 836 (Oman), JAH 054 (Oman), NWA 2634 (Morocco). Selection of samples was based on their shock stages from less shocked (DAG 868) to highly shocked (Sahara 98505).

Mean and local elemental composition of the samples were determined by energy dispersive X-ray (EDX) method using EDX Link 3000 ISIS X-ray microanalyser (Oxford Instruments) and X-ray microprobe analyser EDX THERMO NORAN. Scanning electron microscopes Vega 5135 (Tescan) and HITACHI S-3000 N were used to characterize the microstructure of the samples.

Raman spectra were recorded using the confocal Raman micro-spectrometer T-64000 (Jobin-Yvon) equipped with the microscope BX-40 (Olympus). The 514.5 nm Ar line was used for sample excitation. Other parameters of spectrum acquisition (time, laser power) were adjusted to obtain spectra of sufficient quality. The laser beam diameter was 1.5 µm, the light intensity across the beam was of Gaussian distribution.

RESULTS

Scanning Electron Microscopy (SEM) pictures show characteristic black vein-like carbon phases which fill the spaces between mm-sized olivine and pyroxene (Fig. 1). Carbon can be seen enclosed in olivine and pyroxene (Fig. 1c). Carbon phases are usually rounded by iron phase (white color on SEM photographs).

Using microRaman spectroscopy we found diamonds in all five samples. The results of Raman spectroscopy (diamond peaks positions and full width at half maximum values – FWHM) from five ureilites are presented in table 1. A number of samples have several results from different locations in carbon veins. Figure 2 shows chosen Raman spectra of all five samples which have been studied.

DISSCUSSION

Ureilites are the second largest achondrite group classified as primitive achondrites. They are enigmatic due to their close relationship with chondritic matter - primitive oxygen isotopic ratios and achondritic igneous texture (Clayton & Mayeda, 1988). Currently there are 240 officially classified ureilites, in great majority from hot and cold deserts. They are ultramafic coarse-grained rocks, composed mainly of olivine and pyroxene (pigeonite) (Hutchinson, 2004). Relatively high abundances of carbon (up to 6 vol. %) are characteristic for this group. Other accessory phases are iron and sulfide. Carbon polymorphs in ureilites are represented by amorphous carbon, graphite, carbide, diamond and lonsdaleite (Wright & Parnell, 2007). Carbon is usually present in vein-like, long-shaped fills between mm-sized olivine and pyroxene crystals, sometimes even inside these minerals, what is in good agreement with our SEM results (Fig. 1).

Diamonds are present as micrometer-sized crystals (1–10 µm) set in fine granular graphite. The origin of diamonds in this enigmatic group is well-discussed by various authors, from the popular theory of metamorphic transformation of graphite during impact, to the process of chemical vapour deposition (CVD) in the solar nebula (Miyamoto et al., 1988).

The theories of diamond formation in space are based on the development of diamond synthesis. The high temperature, high pressure theory (HPHT) has been well-known for years and widely described. Another popular theory of meteoritic diamonds' origin is a low-pressure process similar to the CVD process which, depending on several parameters, can produce diamonds varying in sizes from nanometers up to micrometers. Nanodiamonds can also be synthesized by detonation method. Nanodiamonds of detonation origin are often compared to the presolar nanodiamonds found in primitive meteorites such as carbonaceous chondrites. As stated before, artificial diamonds and the process of their synthesis are our main source of knowledge on diamond formation in space. And, sometimes, quite the contrary, a discovery of material formed in space is the first step towards its synthesis in the laboratory (lonsdaleite is a good example).

The presence of nitrogen signature in carbonaceous material of Novo-Urei-like meteorites (Fisenko et al., 2004) is an argument for the possible occurrence of nanodiamonds in ureilites.

Diamonds in ureilites were used as shock-level indicators from low to high shock levels (Goodrich, 1992). Some authors (Bischoff et al., 1999) describe occurrence of µm-sized diamonds and shock changes in olivine from ureilites as being related to their shock stages (from S1 to S6). They claim that diamonds cannot be found in weakly-shocked meteorites. Certain ureilites, however, like DAG 868, though classified as the least-shocked (studied in this paper), do contain diamonds. Takeda et al. (2001) describing DAG 868, suggests a non-CVD origin of diamonds in this ureilite due to low levels of pressure in catalytic transformation of graphite to diamond even in less-shocked rocks.

We obtained a few different Raman peaks of diamonds in our ureilite samples ranging from 1323 cm^{-1} in JAH 054, to 1334 cm^{-1} in Sahara 98505 (Tab. 1).

Table 1. Raman spectra peaks of diamonds from five ureilites

Ureilite Name	Diamond Peak Raman Spectra cm^{-1}	FWHM (full width at half maximum) cm^{-1}
DAG 868	a) 1332	9.7
Dhofar 836	b) 1328	11.2
	c) 1332	8.05
JAH 054	d) 1330	6.1
	e) 1321	8.3
	f) 1323	14.3
NWA 2634	g) 1332	4.3
	h) 1329	11.1
Sahara 98505	i) 1334	22.2
	j) 1333	15.2

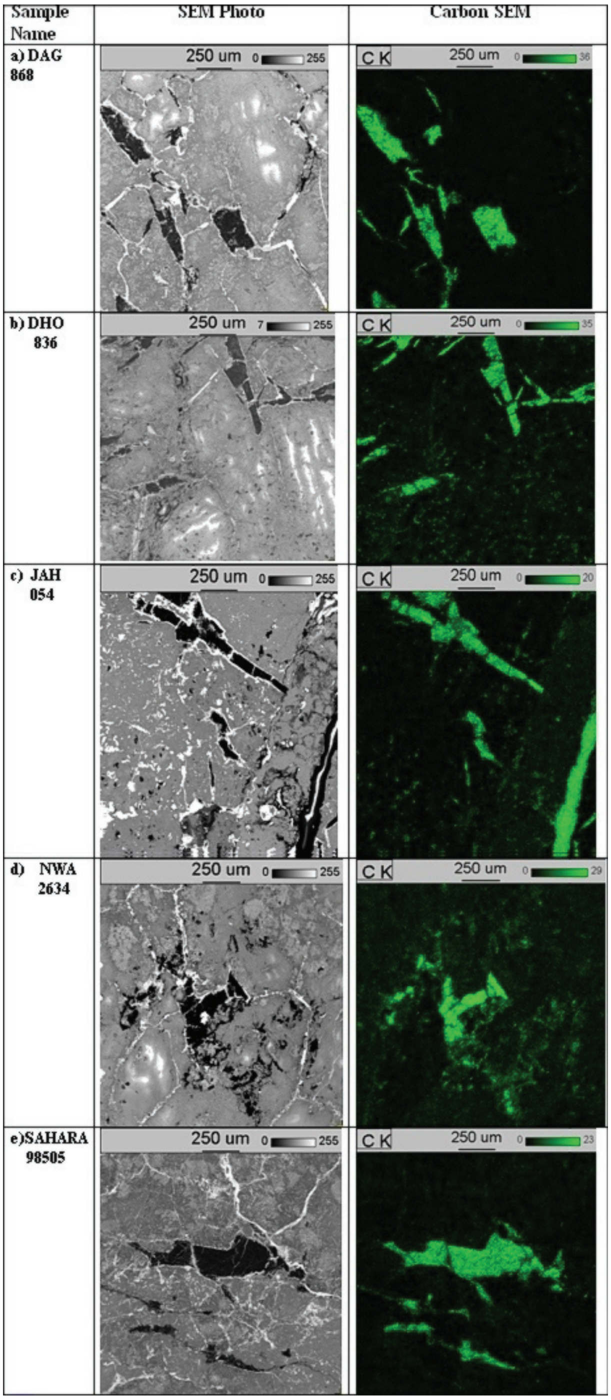

Fig. 1. Views from Scanning Electron Microscope (SEM), carbon SEM for five different ureilites, 1) DAG 869, 2) DHO 836, 3) JAH 054, 4) NWA 2634, 5) Sahara 98505

In JAH 054 we acquired a different Raman shifts from 1321 cm^{-1} to 1330 cm^{-1}. For the FWHM (full width at half maximum) parameter, we also have different results from narrow peaks like 4.3 cm^{-1} in NWA 2634, to broad peaks of 22.2 cm^{-1} in Sahara 98505 (Tab. 1 and Fig. 2). Figure 2 also shows the coexistence of diamond and graphite. In sample DHO 836 D band is 1332 cm^{-1} and G band is 1616 cm^{-1}, NWA 2634 diamond have 1329 cm^{-1} and graphite

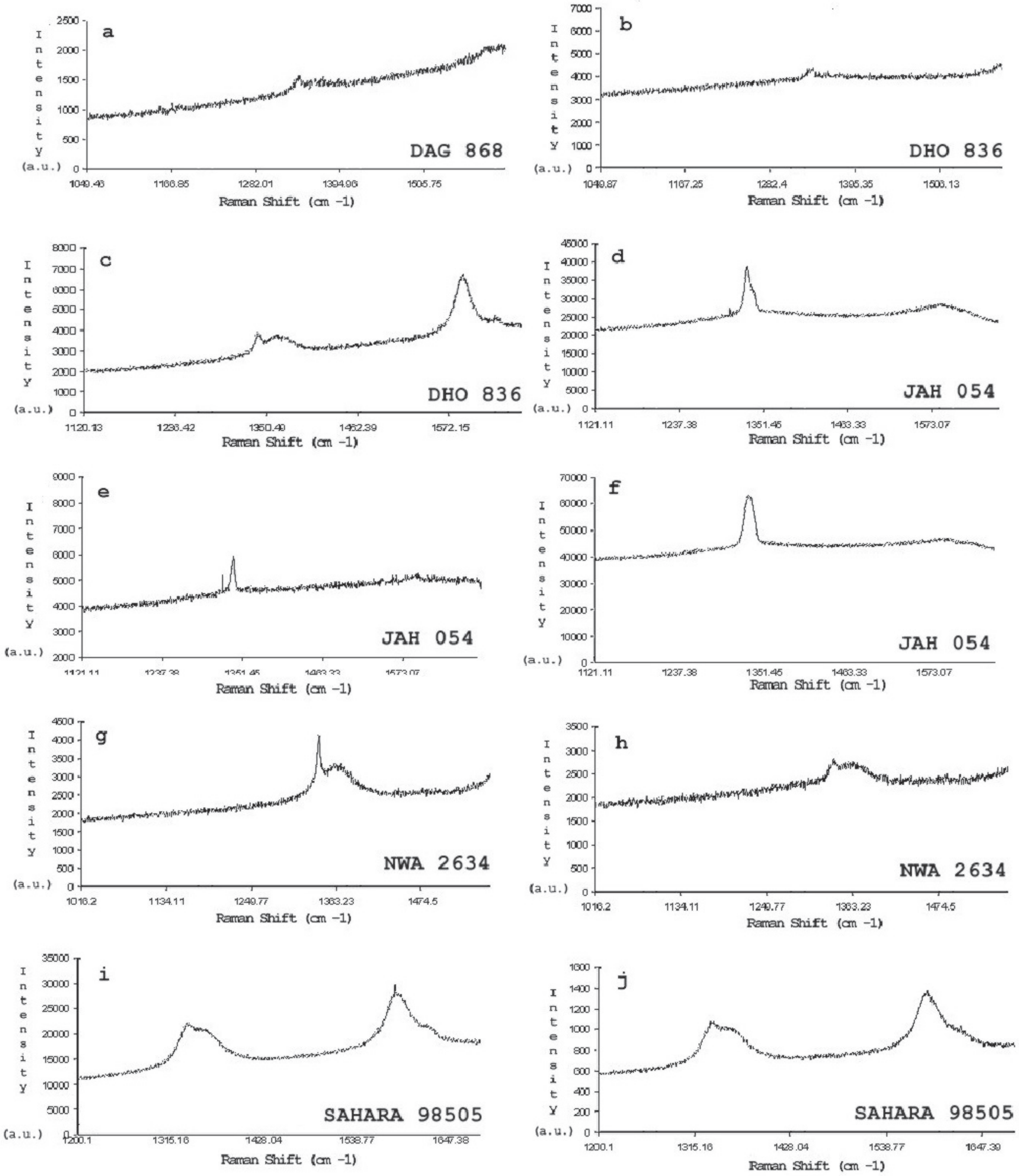

Fig. 2. Raman spectra of five examined ureilites

1354 cm^{-1}, in Sahara 98505 D band is 1333 cm^{-1} and G band is 1620 cm^{-1}. In perfect monocrystalline graphite there is only the G band in the first order region at 1580 cm^{-1}. The 1350 cm^{-1} band (D1) is commonly called “the defect band” and appears in poorly-organized CM or microcrystalline graphite (Beyssac et al., 2003).The other bands in the second-order region, which appear in the poorly organized CM are: 1150 cm^{-1} (strongly debated), 1500 cm^{-1}, 1620 cm^{-1} (D2) (Perraki et al., 2006).

In a perfect monocrystalline diamond, the band of 1332±0.5 cm^{-1} appears, with a full width at half maximum (FWHM) of 1.65±0.02 cm^{-1}. The increased width and shift of this Raman peak indicates an increase in structural disorder or the very small crystal sizes and the compressive/tensile stresses in the lattice, respectively (Perraki et al., 2006; Yushin et al., 2005).

The other authors (Nemanich et al., 1988; Prawer & Nemanich, 2004; Morell et al., 1998) write that both monocrystalline and polycrystalline diamond of the grain size above ~20 μm exhibit the first strong and narrow (FWHM of about 1–3 cm^{-1}) order peak at ~1332 cm^{-1}. If the size of crystals decreases below a micrometer, the FWHM of diamond peak increases to values of about 10 cm^{-1} or more. It is caused by a decrease in crystal perfection and an increase of the non-diamond content in the sample.

Yushin et al. (2005) writes: "The diamond peak at ~1320 cm^{-1} is down-shifted and broadened (FWHM of 30 cm^{-1}) with respect to the single crystal diamond peak (1332 cm^{-1}). This downshift is thought to occur due to the phonon confinement or changes in the phonon DOS accompanying the decrease of particles size into the nanometer range."

In this research, the differences in Raman shift and FWHM in diamonds can be caused by shock changes, a decrease in crystal perfection (defects), different polytypes of diamonds, or different sizes of crystals.

Various Raman peaks and FWHM can be interpreted as diamonds of different sizes (of sub-micrometer size range), structural defects caused by shock changes during impact, or different diamond polytypes.

From our research (in the laboratory as well as in available literature), we believe that TPHT diamonds (micrometer-sized) and CVD diamonds (mostly nanometer-, but also micrometer-sized) can coexist together. The main difficulties in finding nanodiamonds (presolar diamonds) are the nano-sizes of grains and the fact that not every nanodiamond is of presolar origin.

Further research will be necessary to draw more precise conclusions.

CONCLUSION

Our research of five ureilites, based on micro-Raman spectroscopy, proved the occurrence of diamonds in Novo-Urei-like meteorites. Diamonds were found not only in highly-shocked ureilites, but also in the least-shocked specimens.

Various Raman shifts and FWHM do not lead to clear conclusions regarding examined diamonds formation.

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REFERENCES

Beyssac O., Goffe B., Petiet J.P., Froigneux E., Moreau M., Rouzaud J.N., 2003 – On the characterization of disordered and heterogeneous carbonaceous materials by Raman spectroscopy. *Spectrochimica Acta*, Part A, 59, 2267.

Bischoff A., Goodrich C.A., Grund T., 1999 – Shock-induced origin of diamonds in ureilites. *Lunar and Planetary Science XXX*, Abstract #1100.

Clayton R.N., Mayeda T.K., 1988 – Formation of Ureilites by Nebular Processes. *Geochim. Cosmochim. Acta* 52, 1313–1318.

Fisenko A.V., Verchovsky A.B., Seymanova L.F., Pillinger C.T., 2004 – Carbon, Nitrogen and Noble Gasses in diamond separates from the Novo-Urei ureilite. *67th Annual Meteoritical Society Meeting*. Abstract #5159.

Goodrich C.A., 1992 – Ureilites A critical review. *Meteoritics* 27, 327.

Gucsik A., Verchovsky A.B., Ott U., Marosits E., Karczemska A., Kozanecki M., Szurgot M., 2008 – Meteoritic nanodiamond: A Micro-Raman Spectroscopical Overview. *39th Lunar and Planetary Science Conference*, Abstract #1201.

Hutchison R., 2004 – Meteorites. A petrologic, chemical and isotopic synthesis. Cambridge University Press, New York.

Karczemska A., Kozanecki M., Szurgot M., Sokołowska A., Mitura S., 2007 – Raman spectroscopy studies of meteoritic diamonds. *Diamond Relat. Mater.* 16, 781, 1179–1185.

Karczemska A., Szurgot M., Kozanecki M., Szynkowska M.I., Ralchenko V., Danilenko V.V., Louda P., Mitura S., 2008 – Extraterrestrial, terrestrial and laboratory diamonds – Differences and Similarities. *Diamond Relat. Mater.* 17 (7–10), 1179–1185.

Miyamoto M., Matsuda J., Keisuke I., 1988 – On the vapour growth diamonds formation in the Solar Nebula. *Geophysical Research Letters* 15 (12), 1445.

Morell G., Quinones O., Diaz Y., Vargas I.M., Weiner B.R., Katiyar R.S., 1998 – Measurement and Analysis of Diamond Raman Bandwidths. *Diamond Relat. Mater.* 7, 1029.

Nemanich R.J., Glass J.T., Lucovsky, G. Shroder R.E., 1988 – Raman scattering characterization of carbon bonding in diamond and diamondlike thin films. *J. Vac. Sci. Technol., A, Vac. Surf. Films* 6 (3), 1783.

Perraki M., Proyer A., Mposkos E., Kaindl R., Hoinkes G., 2006 – Raman microspectroscopy on diamond, graphite and other carbon polymorphs from the ultrahigh-pressure metamorphic Kimi Complex of the Rhodope Metamorphic Province, NE Greece. *Earth and Planetary Science Letters* 241, 672.

Phelps A.W., 1999a – Interstellar diamond. II. Growth and identification. *Lunar and Planetary Science XXX*, Abstract #1753.

Phelps A.W., 1999b – Interstellar diamond. I Condensation and nucleation. *Lunar and Planetary Science XXX*, Abstract #1749.

Prawer S., Nemanich R.J., 2004 – Rama spectroskopy of diamond and doped diamond, *Philos. Trans. R. Soc. Lond. A* 362, 2477.

Szurgot M., Karczemska A., Kozanecki M., 2006 – Extraterrestrial diamond, [in:] Mitura S., Niedzielski P., Walkowiak B. (eds.), *Nanodiam*, PWN, Warsaw, 259–287.

Takeda H., Ishii T., Otsuki M., Nakamuta Y., Nakamura T., 2001 – Mineralogy of a New Weakly Shocked Ureilite, Dar Al Gani 868 with Diamonds. *64th Annual Meteoritical Society Meeting*, Abstract #5039.

Wright A., Parnell J., 2007 – Interpreting the Raman Signature of ureilite carbon. *Lunar and Planetary Science XXXVIII* Abstract #1228.

Yushin G.N., Osswald S., Padalko V.I., Bogatyreva G.P., Gogotsi Y., 2005 – Effect of Sintering on Structure of Nanodiamond. *Diamond Relat. Mater.* 14, 1721.

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PRIMITIVE ENSTATITE ACHONDRITES

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Abstract: Conclusions drawn from the breadth of analytical data on primitive achondrites and enstatite chondrites paired with results of research performed by the authors have led the authors to propose the establishing of a new group of meteorites: primitive enstatite achondrites. The group is defined as the residual remaining after the partial melting of their protolith, which, in the case of primitive enstatite achondrites, is the parent body of enstatite chondrites. In this article are characterized textural features and characteristics of their mineral, chemical, and isotopic composition. The most important of these defining features are the presence of relic chondrules and/or triple junctions of crystal faces, as well as characteristic atomic and molar ratios of main elements: Si, Al, Fe, Mg, Mn and Ca, and particularly the molar ratios Fe/Mn and Fe/Mg. Another important characteristic is the isotopic composition of entrained noble gases, especially ratios of the heaviest of the isotopes and oxygen isotopes, whose values should be close to that typical for enstatite chondrites.

It seems likely that the first meteorite to be classified as primitive enstatite achondrite will be the Zakłodzie enstatite achondrite.

Key words: Acapulcoite, lodranite, winonaite, brachinite, ureilite, metachondrite, primitive achondrite, enstatite chondrite, primitive enstatite achondrite.

The first criterion for dividing meteorites into “chondrites” and “achondrites” was the presence or lack of chondrules within a given meteorite. In accordance with that idea, amphoterites, in which chondrules are hardly visible, were formerly counted among achondrites. They are now deemed LL6 chondrites. Later, attention was paid to the fact that the texture of chondrites resembles terrestrial sedimentary rocks and the texture of achondrites is similar to that of terrestrial igneous rocks. However, when chemical compositions were taken into account, it was noticed that some achondrites had chemical compositions that were similar to those of chondrites, and some even exhibited relic chondrules. Assuming that achondrites originated as the product of melted chondritic material and the crystallization of the resulting magma, it was concluded that the achondrites of chondritic chemical composition were apparently so poorly melted that differentiation, which would change the chemical composition of the magma, could not occur. So the achondrites were called primitive to emphasize that they are poorly developed (Prinz et al., 1983).

When at the end of 19th century Aristides Brezina of the Naturhistorisches Museum in Vienna introduced the term “achondrites” for stony meteorites without chondrules, there were known only three achondrites and one stony-iron meteorite, which today are counted among primitive achondrites. Moreover these three achondrites were ureilites, as to which some doubts exist if there are reasons good enough to count them among primitive achondrites (Hutchison, 2006). From other side the undisputable today primitive achondrite Lodran, which fell in 1868 on territory of present Pakistan, was, until quite recently, counted among a special subgroup of stony-iron meteorites – the lodranites. The question of primitive achondrites could appear only after 1976, when near the town of Acapulco, Mexico, a 1.9 kg stone was seen to fall (Palme et al., 1981).

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Acapulcoites and lodranites

It was recently discovered that, despite minor primarily structural differences, acapulcoites and lodranites are of the same origin and should belong to one group. They differ mainly in that acapulcoites are texturally fine grained, equigranular rocks (grain size 150–230 µm) (Fig. 1), with chondritic olivine, pyroxene, plagioclase, metal and troilite contents. Lodranites are coarser rocks (grain size 540–700 µm) (Fig. 2) composed of olivine and pyroxene, with lower than chondritic contents of troilite and plagioclase. Acapulcoites and lodranites have similar oxygen isotopic compositions and they form one cluster on a diagram of relevant oxygen isotopes (Fig. 3) (Hutchison, 2006). Relic chondrules were subsequently found in a number of other acapulcoites, further confirming their close connection with a chondritic precursor (McCoy et al., 1996). Often, veins are visible, filled with metal and sulfide. Metal occurs as interstitial grains, too: as does plagioclase, when present. According to Hutchison (2006), acapulcoites resemble H chondrites in their plagioclase contents, metal, troilite and phosphate. However, Rubin (2007) suggests that carbonaceous chondrites of Renazzo type (CR) are a more probable progenitor of acapulcoites and lodranites.

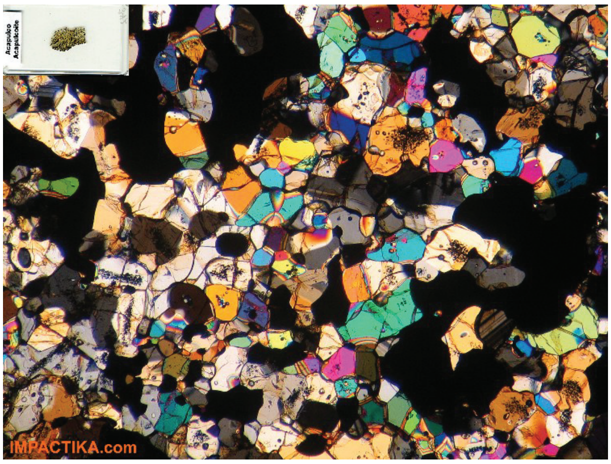

Fig. 1. A thin section of the type acapulcoite Acapulco with irregular, colorful grains of olivine, often with irregular fractures, but without visible traces of cleavage. Among translucent minerals (silicates) polysyntetically twinned plagioclase crystals can be found having gray interference colors. Black irregular grains are most probably FeNi metal and sulfides, mainly FeS (troilite). The rock shows finegrained, equigranular texture. Cross-polarized light. Field of view is about 3 mm wide. Photo courtesy of John Kashuba

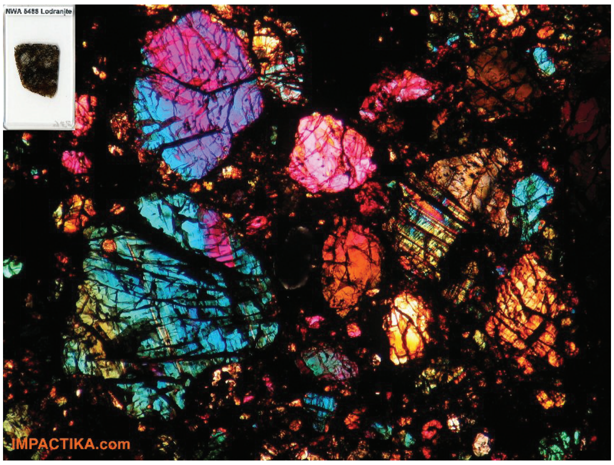

Fig. 2. A thin section of the NWA 5488 lodranite. Colorful olivine grains can be seen with many fractures, apparently larger than these in acapulcoites. Opaque minerals are surely FeNi metal, sulfides and limonite (the meteorite is rather heavy weathered). Cross-polarized light. Field of view is about 3 mm wide. Photo courtesy of John Kashuba

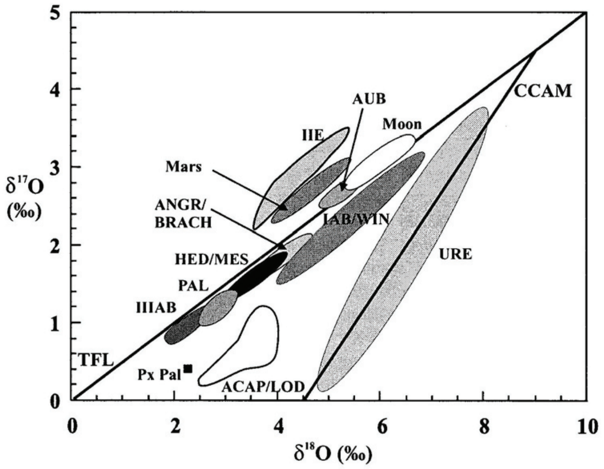

Fig. 3. Oxygen isotopic ratios of achondrites (after Clayton and Mayeda (1996); Hutchison, 2006)

Acapulcoites probably formed during the partial melting and recrystallization of a chondritic precursor above 950°C, but below the silicate solidus. Their texture formed possibly during slow cooling at high temperature, then rapid cooling through 500°C and finally slow cooling at low temperature. Lodranites were more strongly heated, sometimes even above the silicate solidus (about 1150°C), which caused the fractionation of basaltic melt. Their cooling went similarly as in the case of acapulcoites (Weissberg et al., 2006).

Now (April 2011), 47 acapulcoites are known, with nearly half of them found in Antarctica and nearly half on Sahara and Omani deserts. The great majority of them have been found in the past ten years. We now know of 29 lodranites and, similarly, most have been found in Antarctica and the Sahara Desert. At present, no lodranites have been found in Oman. The tight relationships between acapulcoites and lodranites has been additionally confirmed with finds of nine more stones in Antarctica and the Sahara, which are texturally and mineralogically intermediate between acapulcoites and lodranites (Meteoritical Bulletin Database, April 2011).

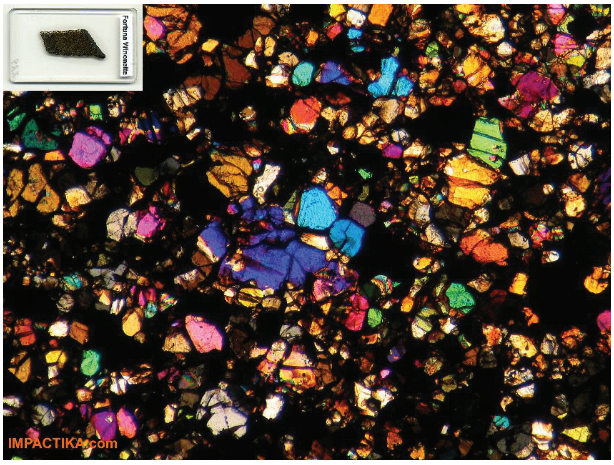

Fig. 4. A thin section of the Fortuna winonaite. Colorful grains of olivine can be seen together with gray pyroxene and possibly tiny grains of plagioclase. Opaque minerals are FeNi metal and troilite. Cross-polarized light. Field of view is about 3 mm wide. Photo courtesy of John Kashuba

Winonaites and IAB iron meteorites clan

Like acapulcoites and lodranites, winonaites generally have chondritic mineral and chemical composition as well as recrystallized, achondritic texture. These are fine-to-medium-grained rocks, mostly equigranular, and in some of them (Pontlyfni and Mount Morris) features resembling relic chondrules can be found. Their mineral composition is intermediate between the compositions of E chondrites and H chondrites. Veins of metallic nickel-iron and troilite are common. They may represent first partial melts from a chondritic precursor. Texturally, winonaites are similar to acapulcoites, but contain coarser grains and abundant cross-cutting metal-sulfide veins (Fig. 4) (Benedix et al., 1998). Today, 20 winonaites are known, most of which were found in the Sahara or Antarctica. The only witnessed fall of a winonaite (Pontlyfni) was recorded in Wales, in 1931 (Grady, 2000).

Silicate inclusions occur in about half of known irons of IAB clan, and are composed of variable amount of Ca-poor and Ca-rich pyroxene, olivine, plagioclase, troilite, graphite, phosphate and metallic FeNi as well as minor amounts of daubreelite and chromite. Their mineral composition resembles that of winonaites, and oxygen isotopic composition in silicates of IAB clan of iron meteorites is similar to that of winonaites too. These similarities have brought researchers to conclude that silicate inclusions in IAB iron meteorites and winonaites originated from the same or from very similar parent bodies (Benedix et al., 2000).

Brachinites

Brachinites are olivine-rich, medium-to-coarse-grained (0.1–2.7 mm), equigranular achondrites composed mainly of olivine (74–98%) grains of which meet in triple junctions, with minor amounts of augite (4–15%), plagioclase and Ca-poor pyroxene (0–10%), chromite (0.5–2%), iron sulphides (3–7%), phosphates, and Fe-Ni metal (Fig. 5). Lithophile element content in the Brachina meteorite is similar to the ranges seen in chondrites, suggesting that these elements were not fractionated, so brachinites are considered primitive achondrites (Nehru et al., 1996). However, in other brachinites, some depletion of Al, Ca, Rb, K, and Na is observed (Mittlefehldt & Lindstrom, 1998). The content of siderophile elements varies among brachinites. Textural and chemical differences among brachinites suggest that they could not all originate via the same processes or from the same parent body (Mittlefehldt et al., 2003). There are now18 brachinites known, half of which were found on Sahara, five (including the very first, Brachina) in Australia and four in Antarctica. There is no witnessed fall among them (Meteoritical Bulletin Database, April 2011).

The origin of brachinites is still a subject of controversy. They may represent recrystallized chondritic material, residues from partial melting, or magmatic cumulates (Warren & Kallemeyn, 1989; Nehru et al., 1996). Mittlefehldt presented evidence that brachinites are magmatic cumulates from a differentiated asteroid and should be considered achondrites rather than primitive achondrites (Mittlefehldt et al., 2003).

Ureilites

Ureilites are the largest group of primitive achondrites with 273 known as of April 2011, including six witnessed falls, the last being the spectacular fall of Almahata Sitta (Fig. 6) (Jenniskens et al., 2009). As

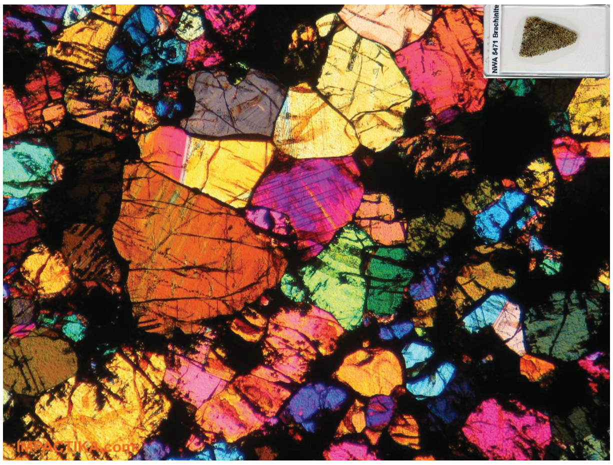

Fig. 5. A thin slice of possible brachinite NWA 5471 (not classified yet officially). Fractured, colorful olivine crystals can be seen. Cross-polarized light. Field of view is about 3 mm wide. Photo courtesy of John Kashuba

Fig. 6. A 0.29 g slice of the Almahata Sitta ureilite. Photo courtesy of Andrzej S. Pilski

would be expected, Antarctic and Saharan finds comprise the majority of known ureilites. Most of them are monomictic breccias (Meteoritical Bulletin Database, April 2011). Their textures, mineralogy and lithophile element chemistries suggest that they are highly fractionated rocks from an achondrite parent body. However, their oxygen isotopic compositions do not follow a mass-dependent fractionation trend characteristic of planetary differentiation; rather, they plot along the carbonaceous chondrite line, suggesting a possible relationship to the CV chondrites. Despite that, the assertion that ureilites are *primitive* achondrites is still very much debated (Goodrich, 1992).

Ureilites are olivine-pyroxene rocks with interstitial carbon in the form of graphite and diamonds, with additional Fe-Ni metal, sulfides and minor silicates. There are three major types of ureilites: (1) olivine-pigeonite, (2) olivine-orthopyroxene, (3) polymict (Weisberg et al., 2006). With the exception of polymict ureilites and a few other rare exceptions, ureilites are devoid of feldspar. The ureilites that have not been heavily modified by shock display elongated olivine and pyroxene grains about 1 mm in size that form triple junctions at 120° and have curved intergranular boundaries (Fig. 7). The mineral fabric of some ureilites suggests the settling and compaction of crystals.

The presence of interstitial carbon raises difficulties in understanding ureilite petrogenesis. The carbon contains trapped noble gases in abundances similar to those of primitive chondrites. If ureilites formed during high temperature igneous processes, one would expect these gases to have been driven off. A better explanation for the retention of these noble gases in carbon would be late-stage injection (Weisberg et al., 2006). Another question pertains to ureilites' diamonds, and whether they are shock formed or they formed from chemical vapor deposition in early solar nebula. A well-known characteristic of ureilites is that the olivine in contact with graphite has been reduced with regards to iron. It is visible in olivine grains with reduced rims that are composed of Fe-poor olivine with tiny blebs of Ni-poor metal (Weisberg et al., 2006).

The polymict ureilites are polymict breccias containing monomict ureilite fragments, feldspar-bearing lithic clasts, isolated mineral fragments, fragments of chondrules and chondrites, and dark chondritic inclusions (Fig. 8) (Ikeda & Prinz, 2000; Ikeda et al., 2000).

Because of their textural, mineralogical, and chemical similarity to terrestrial ultramafic rocks, ureilites are thought to be products of magmatic differentiation. The olivine-augite-orthopyroxene ureilites resemble magmatic cumulates (Goodrich et al. 1987, 2001). The olivine-pigeonite ureilites have been interpreted to be partial melt residues. The missing basaltic

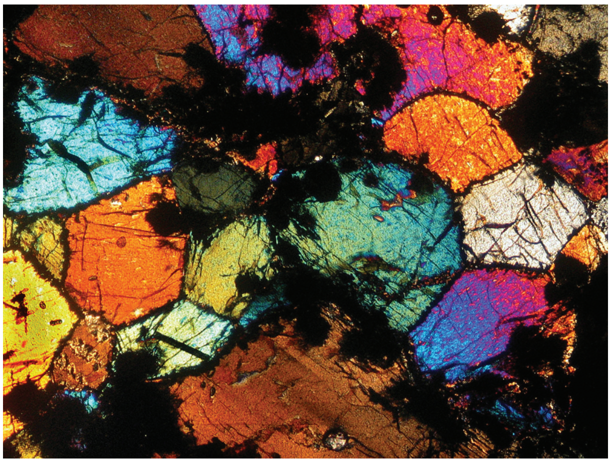

Fig. 7. Typical ureilite (NWA 3140) with anhedral crystals, triple junctions, and opaque material surrounding and within grains. Some minor poikilitic texture is evident. Crossed-polarized light. Field of wiew is 3.2 mm wide. Photo courtesy of John Kashuba

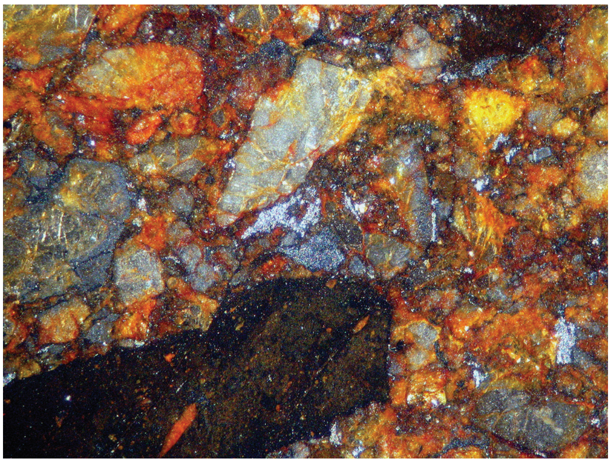

Fig. 8. Mixed mineral grains, dark clasts, and metal. DaG 319 polymict ureilite. Thin section in reflected light. Field of wiew is 3 mm wide. Photo courtesy of John Kashuba

component has been explained as being lost through explosive volcanism on ureilite parent bodies (Warren & Kallemeyn, 1992). Observed differences in oxygen isotopic compositions of ureilites may suggest that ureilites formed via the melting of chondritic material in a number of isolated magma chambers and not from a common magma source (Takeda, 1987). Recently, ureilites have been interpreted to be mantle rocks from a partially melted asteroid (Goodrich et al., 2004).

Metachondrites

During the meeting of the Meteoritical Society in 2005, A. J. Irving and T. E. Bunch with colleagues (Irving et al., 2005) suggested that metamorphic rocks, formed as the result of the recrystallization of chondrites so extensive that chondrules are no longer discernible, should be called metachondrites. They distinguished five metachondrite groups by correlating ratios of oxygen isotopes with definite chondrite groups. Some meteorites, counted among primitive achondrites, fitted well to those groups, and those authors stated clearly that they were of opinion, that the term “metachondrites” should replace term “primitive achondrites”. However, in the classification of meteorites on internet site of the Northern Arizona Meteorite Laboratory run by T. E. Bunch and J. H. Wittke, metachondrites and primitive achondrites form two independent groups.

DISCUSSION

Primitive achondrite criteria

It is generally accepted that primitive achondrites are residues left after the partial melting of chondrites. This melting occurred at temperatures too low for large-scale melting; differentiation of the magma was not possible. Temperatures were high enough only for the metamorphosing of chondritic rock to such an extent that only weak textural traces of the rocks’ original structure remained. But the chemical and isotopic composition of the rock was left generally unchanged. Primitive achondrites are residue resulting from melting processes in which some textural features and the chemical and isotopic composition of their chondritic protoliths were preserved.

One of the indicators of the primitive nature of achondrites is their so called “planetary distribution” of noble gas contents. The content of heavier noble gases in chondrites is very similar to their content in the terrestrial atmosphere. It is a peculiarity hard to explain, as it is widely accepted that chondrites formed in the solar nebula, where the distribution of noble gas contents should fit their distribution in the solar atmosphere. However, the solar distribution of noble gases is observed in regolith breccias only, which are thought to come from surfaces of asteroids that were exposed to solar wind (Hutchison, 2006). Maybe the planetary distribution could be an indicator that chondrites formed not directly from the solar nebula, but perhaps in some processes that occurred on young asteroids and planetismals. Regardless, the planetary distribution is characteristic of all chondrites and it is accepted that its appearance in some achondrites is an indication that they formed as the result of metamorphism rather than in igneous processes including differentiation, an observation that is in some cases supported by their chondritic chemical compositions (Busemann et al., 2000). The contents of noble gases typical for carbonaceous and ordinary chondrites is expressed in ratios $^{36}Ar/^{132}Xe = 74$ i $^{36}Ar/^{84}Kr = 89$, which is represented with the letter Q (Wieler et al., 1992).

Another indicator of the primitive nature of achondrites, including ureilites, is the ratio Mn/Mg $< 9.0 \cdot 10^{-3}$ atomic (Goodrich & Delaney, 2000). In chondrites the ratio is within the range $3.9–9.0 \cdot 10^{-3}$, whereas in differentiated achondrites the ratio exceeds $9.0 \cdot 10^{-3}$.

One final indication that some achondrites should be deemed primitive is that some have oxygen isotopic ratios similar to chondritic ones. This criterion would suggest too, that aubrites should be included into primitive achondrites as they have the same oxygen isotopic ratios as enstatite chondrites (Hutchison, 2006). However, the textures of aubrites show that they formed from the crystallization of magma rather than by recrystallization. On the other hand one can distinguish a number of enstatite achondrites texturally resembling lodranites – that may deserve to be called primitive enstatite achondrites.

A textural criterion of a primitive achondrite is the presence of triple junctions of crystals at 120°, denoting crystal growth as the result of recrystallization rather than by crystallization from magma. An additional criterion is the presence of relic chondrules.

A summary of characteristics of primitive achondrites is shown in the Tab. 1.

Primitive enstatite achondrites

Previously, scientists succeeded in matching some primitive achondrites like the acapulcoite-lodranite group and winonaites with parent chondritic rocks

Table 1. Properties of primitive achondrites (compiled using data from www4.nau.edu/meteorite/Meteorite/Book-PrimitiveAchond.html)

	acapulcoites and lodranites	winonaites and silicates of a IAB	ureilites	brachinites
Texture	ACA fine-grained LOD coarse-grained	fine- and medium-grained	coarse-grained	equigranular
Olivine/pyroxene	≤1	<1	>1	>>1
oliwine	Fa_{3-14}	Fa_{1-8}	Fa_{2-26}	Fa_{30-35}
FeO/MnO in olivine	24-30	18	17–22	50–60
Low Ca-pyroxene	Fs_{1-9}	Fs_{1-9}	Fs_{13-25}	<0.5 vol. %
FeO/MnO in pyroxene	13–17	15	–	40
Ca-pyroxene	$Fs_{46-50}Wo_{43-46}$	$Fs_{2-4}Wo_{44-45}$	$Fs_{13-32}Wo_{2-16}$	$Fs_{10-13}Wo_{38-47}$ (up to 5% TiO_2 and 12% Al_2O_3)
plagioclase	An_{12-31}	An_{11-22}	rarely or absent	An_{22-39}
silica	absent	absent	absent	absent
kamacite	<5 vol. %	<5 vol. %	<5 vol. %	absent
taenite	<5 vol. %	<5 vol. %	–	<0.5 vol. %
troilite	<5 vol. %	<5 vol. %	<0.5 vol. %	<5 vol. %
other minerals	phosphate, spinel, graphite	daubreelite, schreibersite, graphite	augite, graphite	oxides

which could be considered their likely protoliths. These precursors are the parent bodies of H chondrites or CR carbonaceous chondrites and an intermediate between H and E chondrites, respectively. One can clearly see lack of primitive achondrites which could result from the metamorphism of a protolith of E chondrite composition. There are a few enstatite meteorites that are difficlut to place in the existing classification scheme that certainly are not enstatite chondrites, and that are, according to some authors, impact melts (Burbine at al., 2000; Keil and Bischoff, 2008). The authors would like to suggest the determination of a new meteorite group: the primitive enstatite achondrites. They would include the enstatite meteorite Zakłodzie into that group, as well as the enstatite meteorites Happy Canyon, Ilafegh 009, QUE 94204 and Yamato 8404 (Pilski, 2004; Przylibski et al., 2005; Karwowski et al., 2007).

The proposal to define a new group of primitive enstatite achondrites, analogous with existing groups of primitive achondrites, is certainly not yet well substantiated. In order to justify it, ample discussion would be necessary. Characteristic textural features, proportions of minerals, chemical and isotopic compositions – all of these criteria would need to be determined. Some suggestions can be drawn from the discussion above, which should be supplemented by a short mineral-chemical-isotopic description of the protolith: the parent body of enstatite chondrites.

Like other primitive achondrites, the primitive enstatite achondrites should display characteristic textural features like the presence of relic chondrules and triple junctions, testifying to a metamorphic origin. The higher the grade of metamorphism, the fewer relic chondrules would be seen, and the more likely it would be for triple junctions to appear.

Among the definitive compositional criteria, the Mn/Mg ratio should be mentioned. From data for enstatite chondrites listed in Tab. 2 it can be calculated, that for enstatite chondrites the ratio should range from $5.0{\cdot}10^{-3}$ to $9.0{\cdot}10^{-3}$. Primitive enstatite achondrites should fall within the aforementioned range.

Isotopic ratios of noble gases may be diagnostic as well. Using the data listed in Tab. 3 it is possible to determine that ratios of noble gas isotopes in enstatite chondrites differ considerably from their values in ordinary and carbonaceous chondrites. Their mean values are $^{36}Ar/^{132}Xe = 196$ and $^{36}Ar/^{84}Kr = 182$, so it would appear that the same should be true for primitive enstatite achondrites. However, the above values are the means when taking into consideration all types of enstatite chondrites. When we analyze the changes in concentrations of heavy noble gases isotopes among petrologic types of enstatite chondrites, it becomes ap-

Table 2. Average element abundance for the enstatite chondrites (Lodders and Fegley, 1998, vide McSween & Huss, 2010; Hutchison (2006); Koblitz, 2010)

Element	Lodders & Fegley (1998)		Hutchison (2006)		Koblitz (2010)			
	EL	EH	EL	EH	EL	EH	EC	
	mean	mean	mean	mean	mean	mean	mean	range
Li (μg/g)	0.7	1.9	n.d.	n.d.	0.82	1.55	1.18	0.52–2.28
Be (ng/g)	n.d.	21	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
B (μg/g)	n.d.	1	n.d.	n.d.	0.49	0.95	0.72	0.43–1.19
C (mg/g)	4.3	3.9	3.6	4.0	4.3	3.6	3.9	1–8.4
N (μg/g)	240	420	n.d.	n.d.	523	300	412	300–530
O (mg/g)	310	280	310	280	n.d.	n.d.	n.d.	n.d.
F (μg/g)	140	155	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Na (mg/g)	5.77	6.88	5.80	6.80	5.38	5.95	5.67	0.04–10.79
Mg (mg/g)	138	107	141	106	136.6	117.7	127.2	99–187
Al (mg/g)	10.0	8.2	10.5	8.1	10.7	8.9	9.8	3.9–17.4
Si (mg/g)	188	166	186	167	189	167	178	144–222
P (μg/g)	1250	2130	1170	2000	1110	1370	1240	70–2620
S (mg/g)	31	56	33	58	23.2	49.6	36.4	0.2–66.1
Cl (μg/g)	230	570	n.d.	n.d.	163	431	297	7.5–994
K (μg/g)	700	840	740	800	673	750	711	4–1740
Ca (mg/g)	10.2	8.5	10.1	8.5	9.1	7.9	8.5	0.4–16.7
Sc (μg/g)	7.7	6.1	n.d.	n.d.	6.9	5.7	6.3	0.1–28.1
Ti (μg/g)	550	460	580	450	493	495	494	20–1080
V (μg/g)	64	56	n.d.	n.d.	47	50	48.7	0.2–100.0
Cr (μg/g)	3030	3300	3050	3150	2786	2740	2763	10–10790
Mn (μg/g)	1580	2120	1630	2200	1561	1906	1734	30–5080
Fe (mg/g)	248	305	220	290	290	332	311	75–921
Co (μg/g)	720	870	670	840	1197	953	1075	11.7–3920
Ni (mg/g)	14.7	18.4	13.0	17.5	24.3	20.4	22.4	0.9–82
Cu (μg/g)	120	215	n.d.	n.d.	189	238	213	73–921
Zn (μg/g)	18	290	n.d.	n.d.	78.3	272	176	2.9–820
Ga (μg/g)	11	16.7	n.d.	n.d.	35.3	21.6	28.47	7–73
Ge (μg/g)	30	38	n.d.	n.d.	107	84	94	13.7–202
As (μg/g)	2.2	3.5	n.d.	n.d.	5.4	4.8	5.1	0.3–16.7
Se (μg/g)	15	25	n.d.	n.d.	13.4	26.6	20.0	5.3–82
Br (μg/g)	0.8	2.7	n.d.	n.d.	1.3	2.2	1.7	0.1–6.3
Rb (μg/g)	2.3	3.1	n.d.	n.d.	2.1	2.6	2.3	0.7–7.5
Sr (μg/g)	9.4	7.0	n.d.	n.d.	57	6.9	31.9	6–107
Y (μg/g)	n.d.	1.2	n.d.	n.d.	n.d.	1.330	n.d.	n.d.
Zr (μg/g)	7.2	6.6	n.d.	n.d.	30.2	5.9	18.1	3.8–53
Mo (μg/g)	n.d.	n.d.	n.d.	n.d.	3.6	4.0	3.8	1.1–4.8
Ru (ng/g)	770	930	n.d.	n.d.	2642	1663	2152	457–7400
Rh (ng/g)	n.d.	n.d.	n.d.	n.d.	641	547	594	92–880
Pd (ng/g)	730	820	n.d.	n.d.	3613	2171	2892	389–5510
Ag (ng/g)	85	280	n.d.	n.d.	105	229	167	12–386
Cd (ng/g)	35	705	n.d.	n.d.	280	373	327	1–1150
In (ng/g)	4	85	n.d.	n.d.	5.6	68.3	36.9	0.2–131
Sn (ng/g)	1360	n.d.	n.d.	n.d.	0.5	2.1	1.3	0.5–3.3
Sb (ng/g)	90	190	n.d.	n.d.	312	279	295	58–1040
Te (ng/g)	930	2400	n.d.	n.d.	564	2082	1323	90–3460
I (ng/g)	80	210	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cs (ng/g)	125	210	n.d.	n.d.	171	178	175	35–338
Ba (μg/g)	2.8	2.4	n.d.	n.d.	18.0	2.7	10.4	1.3–32
La (ng/g)	196	240	n.d.	n.d.	260	259	260	73–3700
Ce (ng/g)	580	650	n.d.	n.d.	5262	762	3012	139–10000
Pr (ng/g)	70	100	n.d.	n.d.	62	140	101	47–680
Nd (ng/g)	370	440	n.d.	n.d.	3270	559	1914	224–6000
Sm (ng/g)	149	140	n.d.	n.d.	182	152	167	57–2260
Eu (ng/g)	54	52	n.d.	n.d.	92	55	74	25–638
Gd (ng/g)	196	210	n.d.	n.d.	236	248	242	106–1310
Tb (ng/g)	32	34	n.d.	n.d.	288	45	166	18–544
Dy (ng/g)	245	230	n.d.	n.d.	291	284	287	29–1300
Ho (ng/g)	51	50	n.d.	n.d.	51	68	59	26–259
Er (ng/g)	160	160	n.d.	n.d.	196	178	187	97–324
Tm (ng/g)	23	24	n.d.	n.d.	23	33	28	12–148
Yb (ng/g)	157	154	n.d.	n.d.	225	181	203	73–1990
Lu (ng/g)	25	25	n.d.	n.d.	116	26	71	11–300
Hf (ng/g)	210	140	n.d.	n.d.	658	140	399	96–1670
W (ng/g)	140	140	n.d.	n.d.	694	544	619	320–793
Re (ng/g)	57	55	n.d.	n.d.	197	79	138	24–392
Os (ng/g)	670	660	n.d.	n.d.	1478	788	1133	277–3590
Ir (ng/g)	560	570	525	565	928	679	803	1–3190
Pt (μg/g)	1.25	1.29	n.d.	n.d.	4.84	2.75	3.80	0.59–9.60
Au (ng/g)	240	330	225	330	432	421	427	9–2570
Hg (ng/g)	n.d.	60	n.d.	n.d.	930	465	698	260–1600
Tl (ng/g)	7	100	n.d.	n.d.	38	68	53	1–240
Pb (ng/g)	240	1500	n.d.	n.d.	225	1853	1039	85–2319
Bi (ng/g)	13	90	n.d.	n.d.	29	74	51	1–280
Th (ng/g)	38	30	n.d.	n.d.	238	34	136	23–450
U (ng/g)	7.0	9.2	n.d.	n.d.	60	9	34	4–110

n.d. – no data

Table 3. Noble gas concentrations and ^{129}Xe/^{132}Xe ratios in the enstatite chondrites calculated by authors on the data published by Patzer & Schulz (2001)

isotope	EL		EH		EC	
	mean	range	mean	range	mean	range
^{3}He*	31.1	0.79–90.9	28.4	0.06–153	29.8	0.06–153
^{4}He*	3932	167–77950	16462	185–274000	10196	167–274000
^{20}Ne*	109	1–1560	75	0.58–1220	92	0.58–1560
^{21}Ne*	6.3	0.31–17.2	5.1	0.02–16.5	5.6	0.02–17.2
^{22}Ne*	15.1	0.41–124	11.1	0.08–108	13.1	0.08–124
^{36}Ar*	62	2.45–387	36	0.81–143	49	0.81–387
^{38}Ar*	12.3	0.83–74.3	7.4	0.32–27.2	9.8	0.32–74.3
^{40}Ar*	4243	1183–7900	4711	1340–11215	4477	1183–11215
^{84}Kr$^{\$}$	2414	178–10940	2970	92.3–25700	2692	92.3–25700
^{132}Xe$^{\$}$	1498	147–6730	3505	75–34600	2502	75–34600
^{129}Xe/^{132}Xe	2.9	1.11–6.61	2.1	1.02–5.19	2.5	1.02–6.61
number of meteorites	25		29		54	

* in 10^{-8} ccSTP/g
$^{\$}$ in 10^{-12} ccSTP/g

parent that these concentrations differ between petrologic types (Patzer and Schultz, 2002; Patzer et al., 2002). As the most probable for primitive enstatite achondrites we should assume the values characteristic for enstatite chondrites type 3 as the most primitive. According to this statement we should adopt the Q ratio. So primitive enstatite achondrites should have ^{36}Ar/^{132}Xe and ^{36}Ar/^{84}Kr ratios close to the Q value; this is visible in the diagram in Fig. 9. Also, oxygen isotope ratios should be similar to those typical for enstatite chondrites: δ^{18}O 4–6‰, δ^{17}O 2–3‰, shown in Fig. 10. It should be noted, too, that the oxygen isotope ratios in enstatite chondrites follow the terrestrial fractionation line (TFL) (Hutchison, 2006).

To complement extrapolated characteristics of the mineral, chemical and isotopic compositions of the primitive enstatite achondrites' protolith (the parent body of enstatite chondrites), data on enstatite chondrites collected from the MetBase database (Koblitz, 2010) was thoroughly analyzed in addition to data from recent general reviews (Hutchison, 2006; McSween & Huss, 2010) whose authors offer a synthetic approach. Result of these analyses can be seen in tables 2 to 7 and figures 10 to 13.

The most important characteristic of mineral composition in enstatite chondrites is the presence of sulfides of primarily lithophile metals: namely Mn, Mg, Ca and K (Hutchison, 2006). The presence of

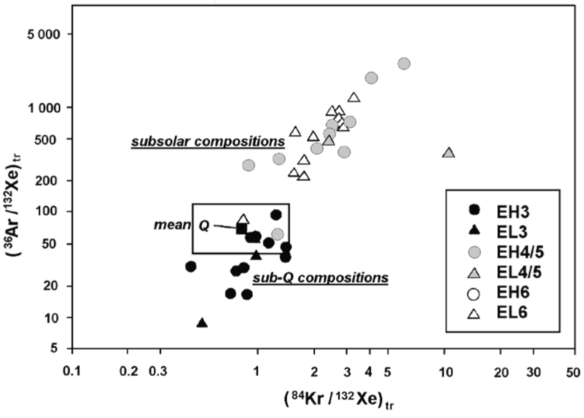

Fig. 9. Relative content of heavy noble gases in the enstatite chondrites and suggested primitive enstatite achondrites. The frame in the middle contains values for ordinary and carbonaceous chondrites (after Patzer et al., 2002)

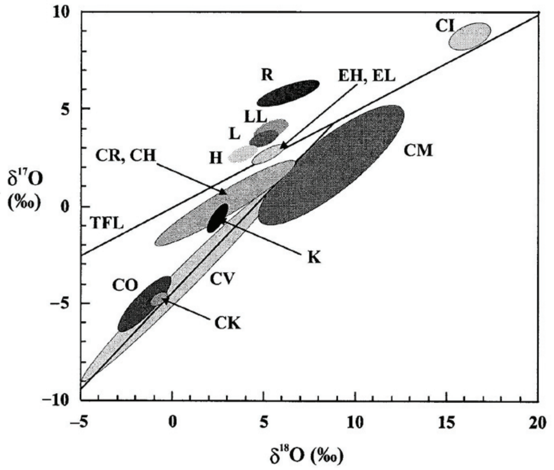

Fig. 10. Oxygen three-isotope plot, 13 chondrite groups and Kakangari triplet (Hutchison, 2006)

Table 4. Light noble gas isotopes concentrations and selected ratios of these isotopes in enstatite chondrites (Koblitz, 2010)

isotope	EL	EH	EC	range
$^{3}\text{He}^{*}$	33.5	24.7	29.1	0.61–153
$^{4}\text{He}^{*}$	3568	12999	8284	134–328900
$^{20}\text{Ne}^{*}$	75.9	77.5	76.7	0.71–2243
$^{21}\text{Ne}^{*}$	6.9	4.5	5.7	0.12–15.5
$^{22}\text{Ne}^{*}$	13.2	14.3	13.8	0.31–492
$^{36}\text{Ar}^{*}$	60.0	95.9	78.0	0.75–1903
$^{38}\text{Ar}^{*}$	11.9	15.6	13.8	0.38–363
$^{40}\text{Ar}^{*}$	4412	5349	4880	9–38000
$^{4}\text{He}/^{3}\text{He}$	107	526	316	4.19–4454
$^{3}\text{He}/^{21}\text{Ne}$	4.9	5.5	5.2	0.33–26.45
$^{4}\text{He}/^{21}\text{Ne}$	520	2875	1698	21.3–29577
$^{3}\text{He}/^{38}\text{Ar}$	2.8	1.6	2.2	0.04–75.3
$^{20}\text{Ne}/^{22}\text{Ne}$	5.8	5.4	5.6	0.71–12.6
$^{22}\text{Ne}/^{21}\text{Ne}$	1.9	3.2	2.6	0.14–44.2
$^{36}\text{Ar}/^{38}\text{Ar}$	5.0	6.2	5.6	0.7–5.6
number of meteorites	42	100	142	

* in 10^{-8} ccSTP/g

Table 5. Mean bulk composition of the enstatite chondrites (Wasson and Kallemeyn, 1988, vide Hutchison, 2006; Koblitz, 2010)

Element	Wasson & Kallemeyn (1988), vide Hutchison (2006)		Koblitz (2010)	
	EL	EH	EL	EH
	wt%			
Si	18.6	16.7	18.15	16.68
Ti	0.058	0.045	0.06	0.04
Al	1.05	0.81	1.05	1.01
Cr	0.305	0.315	0.30	0.24
Fe	22.0	29.0	19.89	21.71
Mn	0.163	0.220	0.19	0.17
Mg	14.1	10.6	13.13	11.17
Ca	1.01	0.85	0.75	0.59
Na	0.580	0.680	0.54	0.63
K	0.074	0.080	0.07	0.07
P	0.117	0.200	0.12	0.13
Ni	1.30	1.75	1.56	1.69
Co	0.067	0.084	0.9	0.8
S	3.3	5.8	2.92*	4.89*
H_20^{+}	–	–	1.16	1.82
H_20^{-}	–	–	0.15	0.68
C	0.36	0.40	0.4	0.36
O	31.0	28.0	n.d.	n.d.
Fe^{0}/Fe^{tot}	0.74	0.65	0.37	0.65
	ppb			
Ir	525	565	n.d.	n.d.
Au	225	330	n.d.	n.d.
number of analysed meteorites	n.d.	n.d.	21	23

* S calculated only from the composition of troilite
n.d. – no data

Table 6. Volatile-free mean compositions and selected atomic ratios of the enstatite chondrites (Wasson and Kallemeyn, 1988, vide Hutchison, 2006)

Element	EL	EH
	wt%	
Si	31.3	27.2
Ti	0.09	0.08
Al	1.76	1.32
Cr	0.52	0.51
Fe	37.0	47.3
Mn	0.27	0.36
Mg	23.7	17.3
Ca	1.70	1.39
Na	0.97	1.10
K	0.13	0.13
P	0.20	0.33
Ni	2.18	2.86
Co	0.12	0.14
	atomic ratio	
Mg/Si	0.871	0.731
Al/Si(x10^4)	585	505
Ca/Si(x10^4)	380	358
Fe/Si(x10^4)	5934	8730
Ca/Al	0.65	0.71

ferroan alabandite [δ-(Fe,Mn)S] is distinctive EL chondrites and niningerite [(Mg,Fe^{2+},Mn)S] is representative of EH chondrites. Other rare minerals characteristic of the strongly reducing conditions of the environment in which they formed in, may also be found. These are: keilite [(Fe,Mg)S], djerfisherite [K$_6$(Fe,Cu,Ni)$_{25}$S$_{26}$Cl], oldhamite [CaS], daubréelite [Fe^{2+}Cr$_2$S$_4$], and schreibersite [(Fe,Ni)$_3$P], as well as sinoite [Si$_2$N$_2$O], osbornite [TiN], and nierite [Si$_3$N$_4$]. Presolar grains of diamond and SiC may also be found in enstatite chondrites (Hutchison, 2006; McSween & Huss, 2010; Zhang et al., 1995). Chemical compositions of enstatite chondrites are characterized by a depletion of lithophile elements relative to other chondrite groups that supports the idea that they formed in strongly reducing conditions. In EL chondrites the content of Si in kamacite is <2 wt% and in EH chondrites is about 3 wt% (Hutchison, 2006).

In tables 2, 5, 6, and 7, data concerning of chemical composition of the enstatite chondrites are compiled. The data represent bulk compositions of both EH and EL chondrites, as well as compositional data for all known enstatite chondrites. They contain information about major and trace elements including rare earth elements. Based on that data, one can determine whether or not the chemical composition of an examined non-chondritic enstatite meteorite resembles the composition of an enstatite chondrite so that it might be regarded a primitive enstatite achondrite. The most useful information for determining the relationship between enstatite chondrites and achondrites would be the concentrations of elements characterized by narrow range of their contents in enstatite chondrites: namely Mg, Al, Si, Ca and Fe as major elements, W, Pt, Sn, Cs, Ga, Ge, Rb, Zr, Mo and Rh among trace elements, and Ho, Er and Tm among rare earth elements. The characteristic ranges of the concentrations of these elements in enstatite chondrites are shown in table 6 and in figures 11 and 12. The molar ratios Fe/

Table 7. Average abundance of Y, Sc and rare earth elements for the enstatite chondrites (McSween & Huss, 2010; Koblitz, 2010)

Group of metal	Element	McSween & Huss (2010)		Koblitz (2010)			
		EL	EH	EL	EH	EC	
		mean	mean	mean	mean	mean	range
LREE	La (ng/g)	196	240	260	259	260	73–3700
	Ce (ng/g)	580	650	2103	762	1433	139–10000
	Pr (ng/g)	70	100	62	140	101	47–680
	Nd (ng/g)	370	440	1632	559	559	224–6000
	Sm (ng/g)	149	140	182	152	167	57–2260
HREE	Eu (ng/g)	54	52	92	55	74	25–638
	Gd (ng/g)	196	210	236	248	242	106–1310
	Tb (ng/g)	32	34	288	45	166	18–544
	Dy (ng/g)	245	230	291	284	287	29–1300
	Ho (ng/g)	51	50	51	68	59	26–259
	Er (ng/g)	160	160	196	178	187	97–324
	Tm (ng/g)	23	24	23	33	28	12–148
	Yb (ng/g)	157	154	225	181	203	73–1990
	Lu (ng/g)	25	25	116	26	71	11–300
	Y (µg/g)	n.d.	1.2	n.d.	1.330	n.d.	n.d.
	Sc (µg/g)	7.7	6.1	6.844	5.690	6.267	0.13–28.10

n.d. – no data

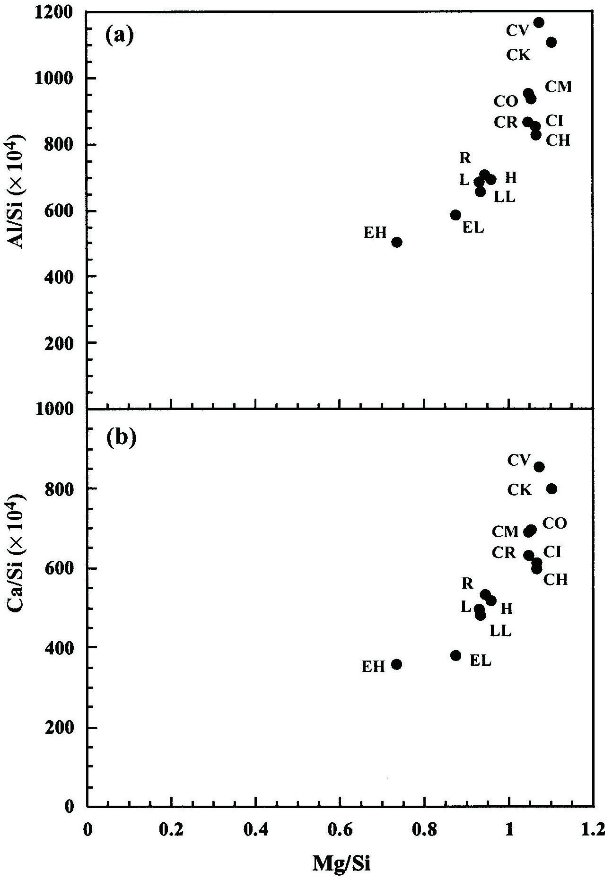

Fig. 11. Al/Si and Ca/Si versus Mg/Si in 13 chondrite groups (Hutchison, 2006). The ratios are atomic

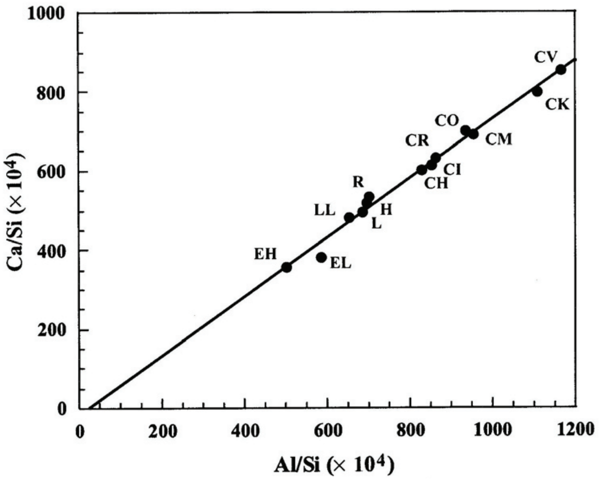

Fig. 12. Al/Si versus Ca/Si in 13 chondrite groups (Hutchison, 2006). The ratios are atomic

Mn and Fe/Mg, shown in figure 13, reveal the chemical evolution of a rock from a chondritic protolith to a melt that during its fractional crystallization produces cumulates and melts depleted with Mg (and enriched with SiO_2); if not, it will form a metamorphosed residue. In the latter case (metamorphosed restite with crystallized residual melt) or in the case when its composition differs only slightly from that of the protolith (the parent body of enstatite chondrites) the enstatite meteorite should be called a primitive enstatite achondrite.

Tables 3 and 4 contain information concerning the isotopic compositions of noble gases in enstatite chondrites. The tables list the mean values of specific isotopes as well as the ranges and ratios of concentrations of selected isotopes. Isotopic compositions of noble gases in primitive enstatite achondrites should not differ largely from the listed composition in enstatite chondrites. Similarly, the oxygen isotopic compositions expressed in the form of ratios $\delta^{18}O$ and $\delta^{17}O$ should be typical for enstatite chondrites and for the terrestrial fractionation line (TFL) (Fig. 10).

CONCLUSIONS

At present it is possible to single out a new group of meteorites – primitive enstatite achondrites. Though no meteorite has been classified officially to this group until now, examinations of other primitive achondrites and enstatite chondrites make it possible to propose standardized criteria that can be met by primitive enstatite achondrites.

Primitive enstatite achondrites represent the residual material following partial melting of a protolith, the parent body of enstatite chondrites. However, the temperature reached during that process was too low to facilitate the complete melting of the rock. For the same reason, differentiation of the magma was not possible. Thus, primitive enstatite achondrites are weakly metamorphosed residues (restites with crystallized residual melt) with traces of chondritic textures in the form of relic chondrules. In the slightly more metamorphosed primitive enstatite achondrites, distinctive triple junctions of adjoining mineral grains 120° angles can be observed. The melting process that created these primitive achondrites was relatively quick, so the parent enstatite chondrite material is only slightly metamorphosed compared to higher petrologic types of E chondrites, which were subjected to regional metamorphism for very long periods of time on their parent body.

The most important characteristic of the mineral composition of primitive enstatite achondrites is presence of sulfides of lithophile metals. In these meteorites one can find ferroan alabandite, niningerite, keilite, oldhamite, daubréelite, sinoite, schreibersite, osbornite, and other sulfides as well. These minerals are characteristic of strongly reducing conditions.

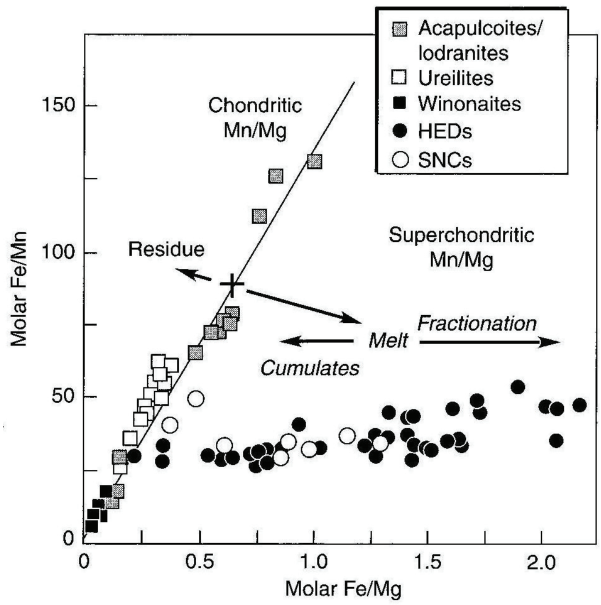

Fig. 13. Diagram used to distinguish achondrites that crystallized from melts and primitive achondrites that represent the solid residue once melt has been extracted (McSween & Huss, 2010)

The chemical and isotopic compositions of primitive enstatite achondrites should be similar to those of enstatite chondrites. Of special importance would be similarity in oxygen isotopic compositions and of isotopic compositions of heavy noble gases. The chemical composition of primitive enstatite achondrites should reflect visible characteristics of enstatite chondrites in atomic and molar ratios of main elements: Si, Al, Fe, Mg, Mn, and Ca. Especially the molar ratios of Fe/Mn and Fe/Mg allow the incorporation of an enstatite achondrite into the group of primitive enstatite achondrites – if their values are located within the field of chondrites or what might be determined to be unfractionated melt residue (see: Fig. 13).

The first enstatite meteorite to be included into the group of primitive enstatite achondrite, should be the Zakłodzie enstatite achondrite (Przylibski T. A. et al., 2005). Detailed examinations of this meteorite and of other similar enstatite meteorites that are possible candidates for the primitive enstatite achondrites group, both classified and waiting for classification, are currently being conducted by the authors.

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REFERENCES

Benedix G.K., McCoy T.J., Keil K., Bogard D.D., Garrison D.H., 1998 – A petrologic and isotopic study of winonaites: Evidence for early partial melting, brecciation, and metamorphism. *Geochim. Cosmochim. Acta,* 62, 2535–2553.

Benedix G.K., McCoy T.J., Keil K., Love S.G., 2000 – A petrologic study of the IAB iron meteorites: Constraints on the formation of the IAB-winonaite parent body. *Meteoritics & Planet. Sci., 35,* 1127–1141.

Burbine T.H., McCoy T.J., Dickison T.L., 2000 – Origin of plagioclase-"enriched", igneous enstatite meteorites (abstract). *Meteoritics & Planetary Science*, *35*, A36.

Busemann H., Baur H., Wieler R., 2000 – Primordial noble gases in "Phase Q" in carbonaceous and ordinary chondrites studied by closed-system stepped etching. *Meteoritics & Planetary Science,* 35, 949–973.

Clayton R.N., Mayeda Y.K., 1996 – Oxygen isotope studies of achondrites. *Geochim. Cosmochim. Acta, 60,* 1999–2018.

Goodrich C. A., 1992 – Ureilites: A critical review. *Meteoritics, 27,* 327–352.

Goodrich C.A., Jones J.H., Berkley J.L. 1987 - Origin and evolution of the ureilite parent magmas: Multi-stage igneous activity on a large parent body. *Geochim. Cosmochim. Acta, 51,* 2255–2273.

Goodrich C.A., Delaney J.S., 2000 – Fe/Mg-Fe/Mn relations of meteorites and primary heterogeneity of primitive achondrite parent bodies. *Geochim. Cosmochim. Acta, 64,* 149–160.

Goodrich C.A., Fioretti A.M., Tribaudino M., Molin G., 2001 – Primary trapped melt inclusions in olivine in the olivine-augite-orthopyroxene ureilite Hughes 009. *Geochim. Cosmochim. Acta, 65,* 621–652.

Goodrich C. A., Scott E. R. D, Fioretti A. M., 2004 – Ureilitic breccias: Clues to the petrologic structure and impact disruption of the ureilite parent body. *Chem. Erde, 64,* 283–327.

Grady M. M., 2000 – Catalogue of Meteorites, Fifth edition. NHM London.

Hutchison R., 2006 – Meteorites: A petrologic, chemical and isotopic synthesis. Cambridge University Press, Cambridge, UK.

Ikeda Y., Prinz M., 2000 – Magmatic inclusions and felsic clasts in the Dar al Gani 319 polymict ureilite. *Meteoritics & Planet. Sci., 36,* 481–500.

Ikeda Y., Prinz M., Nehru C. E., 2000 – Lithic and mineral clasts in the Dar al Gani (DAG) 319 polymict ureilite. *Antarct. Meteorit. Res., 13,* 177–221.

Irving A. J., Bunch T. E., Rumble D.III, Larson T. E., 2005 – Metachondrites: Recrystallized and/or residual mantle rocks from multiple, large chondritic parent bodies: 68th Met. Soc. Meeting, #5218.

Jenniskens P., Shaddad M.H., Numan D., Elsir S., Kudoda A.M., Zolensky M.E., Le L., Robinson G.A., Friedrich J.M., Rumble D., Steele A., Chesley S.R., Fitzsimmons A., Duddy S., Hsieh H.H., Ramsay G., Brown P.G., Edwards W.N., Tagliaferri E., Boslough M. B., Spalding R.E., Dantowitz R., Kozubal M., Pravec P., Borovicka J., Charvat Z., Vaubaillon J., Kuiper J., Albers J., Bishop J.L., Mancinelli R.L., Sandford S.A., Milam S.N., Nuevo M., Worden S.P., 2009 – The impact and recovery of asteroid 2008 TC3. *Nature, 458*, 26 March, 485–488.

Karwowski Ł., Kryza R., Przylibski T.A., 2007 – New chemical and physical data on keilite from the Zakłodzie enstatite achondrite. *American Mineralogist*, *92*, 204–209.

Keil K., Bischoff A., 2008 – Northwest Africa 2526: A partial melt residue of enstatite chondrite parentage. *Meteoritics & Planetary Science*, *43*, 1233-1240.

Koblitz J., 2010 – MetBase® 7.3 Meteorite Data Retrieval Software. Ritterhude, Germany.

McCoy T.J., Keil K., Clayton R.N., Mayeda T.K., Bogard D.D., Garrison D.H., Huss G.R., Hutcheon I.D., Wieler R., 1996 – A petrologic, chemical and isotopic study of Monument Draw and comparison with other acapulcoites: Evidence for formation by incipient partial melting. *Geochim. Cosmochim. Acta, 60,* 2681–2708.

McSween H.Y., Jr., Huss G. R., 2010 – Cosmochemistry. Cambridge University Press, Cambridge, UK.

Mittlefehldt D.W., Lindstrom M.M., 1998 – Petrology and geochemistry of lodranite GRA 95209 (abstract). *Meteoritics & Planet. Sci., 33,* A111.

Mittlefehldt D.W., Bogard D.D., Berkley J.L., Garrison D.H., 2003 – Brachinites: Igneous rocks from a differentiated asteroid. *Meteoritics & Planet. Sci., 38,* 1601–1625.

Nehru C.E., Prinz M., Weisberg M.K., Ebihara M.E., Clayton R.E., Mayeda T.K., 1996 – Brachinites: A new primitive achondrite group (abstract). *Meteoritics, 27,* 267.

Palme H., Schultz L., Spettel B., Weber H.W., Wänke H., Christophe Michel–Levy M., Lorin J.C., 1981 – The Acapulco meteorite: Chemistry, mineralogy and irradiation effects. *Geochim. Cosmochim. Acta, 45,* 727–752.

Patzer A., Schultz L., 2001 – Noble gases in enstatite chondrites I: exposure ages, pairing, and weathering effects. *Meteoritics & Planetary Science*, *36*, 947–961.

Patzer A., Schultz L., 2002 – Noble gases in enstatite chondrites II: The trapped component. *Meteoritics & Planetary Science*, *37*, 601-612.

Patzer A., Hill D.H., Boynton W.V., Franke L., Schultz L., Jull A.J.T., McHargue L.R., Franchi I.A., 2002 – Itqiy: A study of noble gases and oxygen isotopes including its terrestrial age and a comparison with Zakłodzie. *Meteoritics & Planetary Science*, *37*, 823–833.

Pilski A., 2004 – Primitive enstatite achondrites. *3rd Meteorite Conference in Poznań*, 41–46. (in Polish).

Prinz M., Nehru C.E., Delaney J.S., Weisberg M., 1983 – Silicates in IAB and IIICD irons, winonaites, lodranites and Brachina: A primitive and modified primitive group (abstract). *Lunar and Planetary Science XIV,* 616–617. Lunar and Planetary Institute, Houston.

Przylibski T.A., Zagożdżon P.P., Kryza R., Pilski A.S., 2005 – The Zakłodzie enstatite meteorite: Mineralogy, petrology, origin and classification. *Meteoritics & Planetary Science*, *40, Supplement*, A185–A200.

Rubin A.E., 2007 – Petrogenesis of acapulcoites and lodranites: A shock-melting model. *Geochimica et Cosmochimica Acta, 71*, 2383–2401.

Takeda H., 1987 – Mineralogy of Antarctic ureilites and a working hypothesis for their origin and evolution. *Earth Planet. Sci. Lett., 81,* 358–370.

Warren P.H., Kallemeyn G.W., 1989 – Allan Hills 84025: The second brachinite, far more differentiated than Brachina, and an ultramafic achondritic clast from L chondrite Yamato 75097. *Proc. Lunar Planet. Sci. Conf. 19th,* 475–486.

Warren P.H., Kallemeyn G.W., 1992 – Explosive volcanism and the graphite-oxygen fugacity buffer on the parent asteroid(s) of the ureilite meteorites. *Icarus, 100,* 110–126.

Weisberg M.K., McCoy T.J., Krot A.N., 2006 – Systematics and Evaluation of Meteorite Classification. *Meteorites and the Early Solar System II.* 19 – 52.

Wieler R., Anders E., Baur H., Lewis R.S., Signer P., 1992 – Characterisation of Q-gases and Rother noble gas components in the Murchison meteorite. *Geochim. Cosmochim. Acta, 56,* 2907–2921.

Zhang Y., Benoit P.H., Sears D.W.G., 1995 – The classification and complex thermal history of the enstatite chondrites. *Journal of Geophysical Research, 100*, 9417–9438.

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$$v > \sqrt{\frac{2MG}{r}} \tag{1}$$

where:
v – escape velocity, $\mathrm{m \cdot s^{-1}}$,
M – mass of body from which object is projected, kg,
G – universal gravitational constant, $\mathrm{N \cdot m^{2} \cdot kg^{-2}}$,
r – radius of body from which object is projected, m.

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Hutchison R., 2004 – Meteorites: A petrologic, chemical and isotopic synthesis. Cambridge University Press, New York.

Consolmagno G.J., Britt D.T., 2004 – Meteoritical evidence and constraints on asteroid impacts and disruption. *Planetary and Space Science*, 52 (12), 1119–1128.

Przylibski T.A., Zagożdżon P.P., Kryza R., Pilski A.S., 2005 – The Zakłodzie enstatite meteorite: Mineralogy, petrology, origin, and classification. *Meteoritics* & *Planetary Science*, 40 (9), Supplement, A185–A200.

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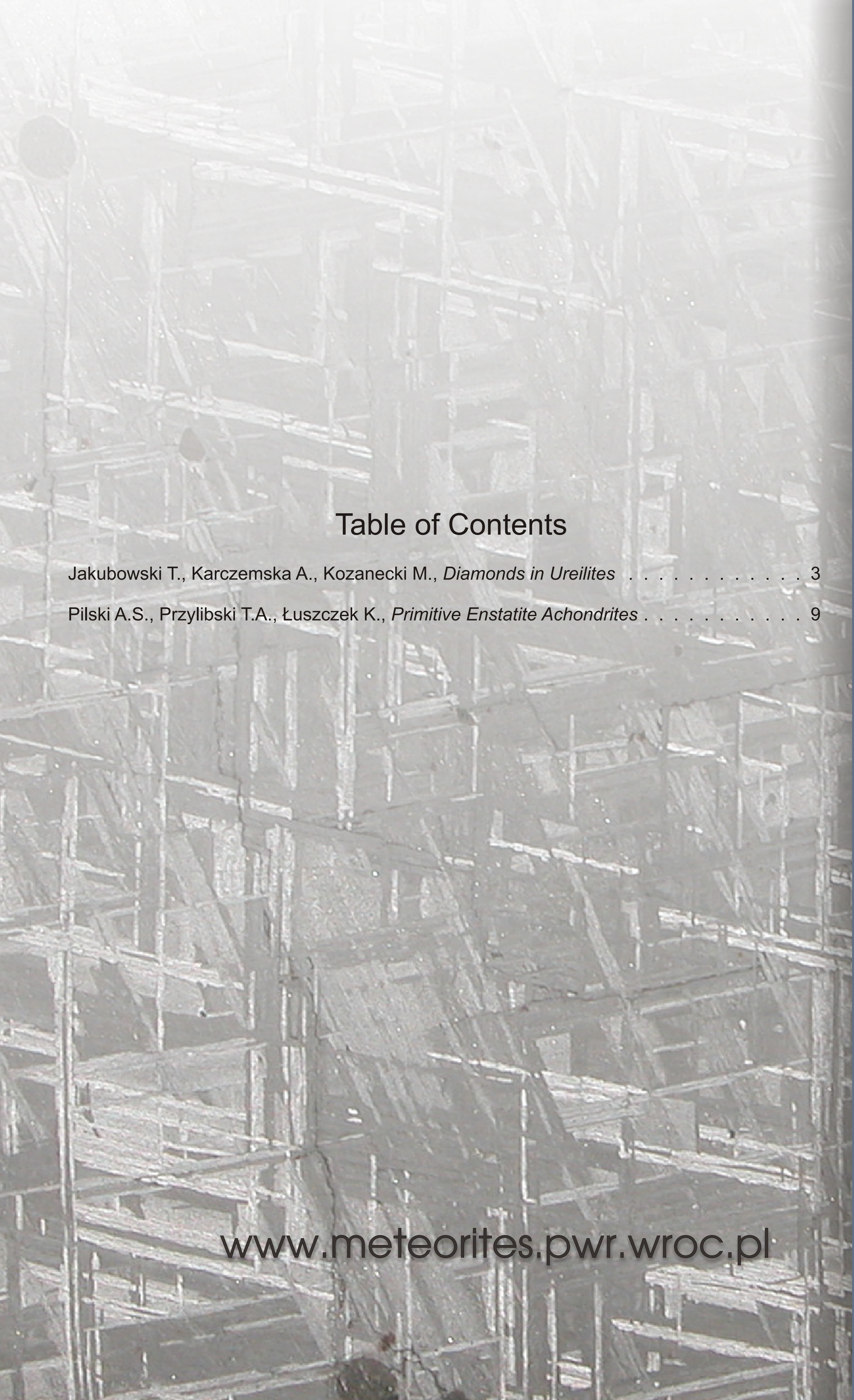

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