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HIGH RESOLUTION X-RAY MICROTOMOGRAPHY ANALYSIS IN NON-DESTRUCTIVE INVESTIGATION OF INTERNAL STRUCTURE IN TWO CHONDRITES

Abstract. A comparison of the internal structure of two stony meteorites has been carried out using computer-aided X-ray microtomography (X-ray CT). The meteorites are both chondrites of the petrological type 5 with one (Baszkowka) being a group L chondrite and the other (Pultusk) being a group H chondrite. The volume of metal grains in the Pultusk meteorite (7.7 vol.%) is larger than that in the Baszkowka meteorite (5.1 vol.%). The metal grains in the Baszkowka meteorite are generally larger than those in the Pultusk meteorite. The Baszkowka meteorite has a much higher void volume (8.7 vol.%) than the Pultusk meteorite (3.4 vol.%). The voids in the Pultusk meteorite are generally much smaller than the voids in the Baszkowka meteorite. X-ray CT shows that the two meteorites, despite being structurally different, reveal in each similar correlations between the structural characteristics of the metal grains and voids. From an analysis of the structural features of both meteorites it is postulated that more regularly shaped intergranular voids were formed at the same time as the regularly shaped metal and silicate grains. It means they had formed when the meteorite parent body had been assembled, i.e. before metamorphism inside the meteorite parent bodies. It is also postulated that the less porous, high aspect ratio void systems seen in the Pultusk meteorite (elongated, fissures) formed after pressure metamorphic period and during a shock event that fragmented the parent body of this meteorite.

Key-words: Pultusk meteorite, Baszkowka meteorite, chondrite, X-ray microtomography

INTRODUCTION

Until recently, to study the internal structure of a rock fragment it was necessary to embed the fragment in a resin, cut and polish a thin section of the rock fragment and then make observations on the structure of the rock using optical or electron microscopy. This method of specimen preparation is destructive as the specimen has to be partly destroyed to obtain information on its internal structure. Cutting and other methods of surface preparing may create artefacts that are difficult to quantify (for

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example grains may be removed creating false voids). Such specimen sacrifice is tolerable for the investigation of common rocks but not in the case of meteorites which are precious in scientific and commercial terms. In such circumstances non-destructive methods are preferable.

New non-destructive technology in form of computed-aided X-ray microtomography (X-ray CT) has been successfully introduced to the examination of meteorites in a limited number of studies (Masuda et al. 1986; Hirano et al. 1990; Kondo et al. 1997; Tsuchiyama et al. 1998; Hanamoto et al. 1999; Kawabata et al. 1999). Masuda et al. (1986) and Hanamoto et al. (1999) were unable to obtain detailed information on textures because of poor spatial resolution (~0.25–0.8 mm). Tsuchiyama et al. (1998) studied mineral grains in epoxy as a meteorite analog. Voids in chondrules separated from a meteorite were studied by Kawabata et al. (1999). Kondo et al. (1997) studied chondrite structure using X-ray CT by cutting meteorites into cylinders 8 and 10 mm in diameter to remove artefacts that are common when an irregularly shaped sample is studied by X-ray CT. Such a sample preparation may help avoid artefacts but cannot be strictly classified as a non-destructive technique. Furthermore, after X-ray CT examination polished thin sections of the specimens were prepared to compare the internal structure observed by X-ray CT with optical microscopy observations.

In the present study irregular fragments of two meteorites, Baszkowka and Pultusk, were studied. Both meteorites are chondrites of petrological type 5 according to Van Schmus and Wood (1967). The meteorites belong to chemically distinct groups with the Baszkowka meteorite belonging to group L (Przylibski et al. 2003) and the Pultusk meteorite belonging to group H according to the classification of Keil and Fredriksson (1964). A fragment of the Baszkowka L5 meteorite was obtained from Dr. M. Stępniewski from the Polish Academy of Sciences, Warsaw. This meteorite is a recent fall (1994) and the fragment studied was probably cut from a larger specimen. The fragment studied weighs 4.86 g and has an irregular shape being about 2 cm long and with a maximum thickness of 1 cm as shown in the X-ray projection image of Figure 1A. This

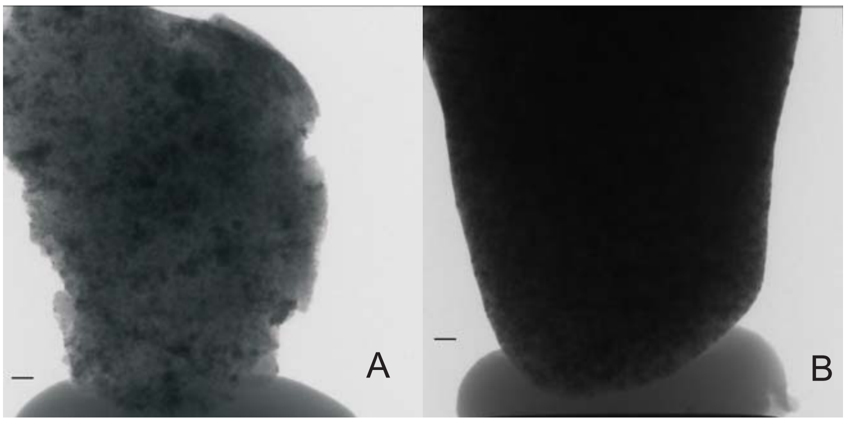

Fig. 1. X-ray projection images of meteorite fragments
A — Baszkowka meteorite; B — Pultusk meteorite. Scale bar: 1 mm

meteorite fragment is partly covered by black fusion crust as seen at the top right of the specimen shown in Figure 1A. Chondrules are easily distinguished by eye in the specimen as well as in X-ray projection images.

The Pultusk H5 meteorite (Manecki 1972) fell on 30 January 1868 and a single stone from the Pultusk shower-producing fall was obtained from Dr. Jakubowski from the Museum of the Earth, Polish Academy of Sciences. The specimen weighs 18.33 g and is elongated in shape being 3 cm long and 1.5 cm thick (Fig. 1B). The meteorite is covered by a secondary black fusion crust. In one section of the meteorite the fusion crust has broken away exposing the grey coloured interior of the meteorite. In this fragment separate metal grains are observed but chondrules are not distinguishable. This meteorite fragment looks more solid and compact in comparison to the more fragile and less compact Baszkowka meteorite.

EXPERIMENTAL

The Baszkowka and Pultusk meteorite samples were examined in their as-received states. A Skyscan 1072 (100 kV) high-resolution X-ray tomographic system was used to obtain X-ray tomographs of the two meteorite samples. The X-ray source in this instrument has a tungsten target with a source diameter of approximately 3 μm. For the examination of the meteorite samples the X-ray source was operated at 100 kV and an Al filter was used to increase absorption contrast. To generate X-ray tomographs, the specimens were rotated through 180° with X-ray projection images taken at 0.90° intervals. The imaging system of the Skyscan 1072 uses a 1024 by 1024 pixel CCD camera assembly allowing X-ray tomographs of 1024 by 1024 pixels to be computed. The pixel size in the tomographs is determined by the size of the sample and for the meteorite samples the pixel size in the X-ray tomographs was 18.95 μm.

Properties such as total 3D volumes and surface areas of components within a sample can be calculated in a straightforward manner by thresholding X-ray tomographs. The calculation of more complex sample properties such as particle-size distributions and particle shapes requires the use of sophisticated image analysis software. For the meteorite samples the Skyscan™ CT-analyser software was used (www.skyscan.be).

To mimic the SEM investigation of the metal grain content in meteorites without destroying the meteorite samples' integrity, two X-ray two-dimensional images were chosen and processed using STIMAN image analysis program (Sergieyev et al. 1983). This program was designed primarily for the analysis of scanning electron microscopy images of oil-bearing rock formations but can also be readily extended to a wide range of analyses. The results obtained from STIMAN give overall information on sample microstructure, including size and shape of structural elements (e.g. particles), the spatial orientation of structural elements and the integral characteristics of the microstructure (Sokolov, Kuzmin 1993). STIMAN includes a special statistical-processing program developed to graph structure-element distribution histograms according to various parameters, such as the area, perimeter, equivalent diameter and shape (or form) index. This information gives the dependence of particle shapes on their areas.

The program provides the possibility of changing the number of intervals on distribution histograms so as to highlight changes in an investigated parameter and to delineate separate groups of structural elements. Definitions of the main parameters determined by STIMAN are:

- ➢ relative particle area; particle coverage in % (the opposite of porosity);
- ➢ form index (K_f); the reciprocal of the aspect ratio which indicates how the particle shape differs from a circular particle (for circular shaped particles $K_f = 1$ and for elongated, high-aspect-ratio particles K_f is close to 0).

RESULTS

Metal grains

X-ray projection images of the Baszkowka meteorite (Fig. 1A) reveal an internal structure where numerous metal grains (dark) are randomly distributed throughout the meteorite. A few grey spherical objects, probably chondrules, are visible at the specimen surface. A fusion crust fragment about 1 mm thick can be seen at the top right corner of the specimen. Figure 1B shows an X-ray projection image of the larger and more compacted Pultusk meteorite. The relatively high density of the Pultusk meteorite is indicated by the low transparency of the meteorite fragment in the X-ray projection image.

Figure 2 shows X-ray tomographs of 19 μm thick slices (cross sections) of the Baszkowka (Fig. 2A) and Pultusk (Fig. 2B) meteorites. Metal grains (black in tomographs) are less numerous in the Baszkowka meteorite than in the Pultusk meteorite. However, the Baszkowka meteorite appears to contain metal grains of a larger size than the Pultusk meteorite. An idea of the distribution of the metal grains throughout the meteorites can be obtained from 3D visualisations created from the X-ray tomographs

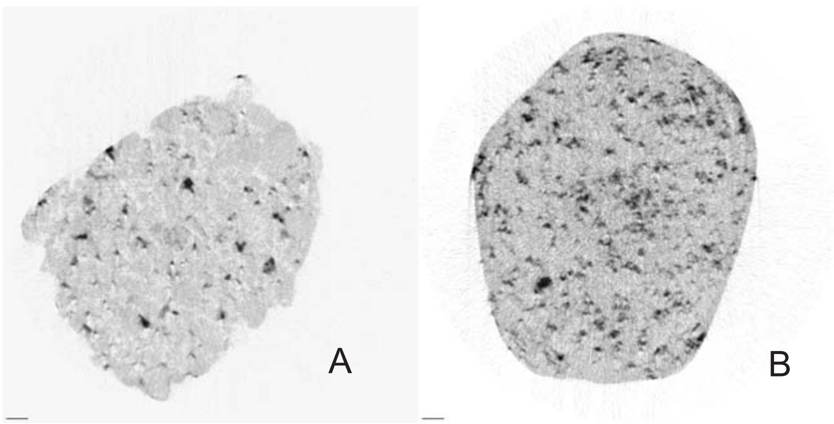

Fig. 2. Examples of the X-ray tomographs
A — Baszkowka meteorite; B — Pultusk meteorite. Scale bar: 1 mm

(Fig. 3). A large, irregular metal grain in the Baszkowka meteorite is visible in the right wall of the virtually-cut section of the visualisation (Fig. 3A). The generally smaller and more numerous metal grains in the Pultusk meteorite are readily apparent (compare Fig. 3A with Fig. 3B).

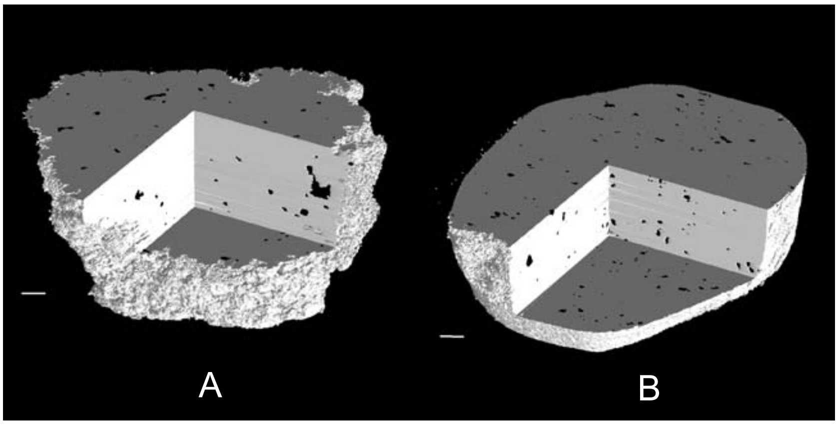

Fig. 3. Three-dimensional reconstruction of metal grain incorporation
A — Baszkowka meteorite; B — Pultusk meteorite. Scale bar 1 mm

Measurements obtained by thresholding the X-ray tomographs with the Skyscan^{TM} CT-analyser software give the volume occupied by metal to be 5.1 vol.% in the Baszkowka L5 chondrite and 7.7 vol.% in the Pultusk H5 chondrite (Fig. 4A). Given that the metal inclusions are iron, the volume fractions give the metal abundances of 11.6 wt.% in the Baszkowka meteorite and 17 wt.% for and the Pultusk meteorite. This abundance is consistent with the iron present within chemical groups of the meteorites studied and is similar to the data obtained by Sears (1998). The average metal grain equivalent spherical diameters are 248 µm for the Baszkowka meteorite and 180 µm for the Pultusk meteorite.

The metal grain distribution versus diameter for the Baszkowka meteorite (Fig. 5A) shows broad distribution between 100 and 400 µm with extension towards larger diameters up to 700 µm. The largest grain measured in the examined fragment of the Baszkowka meteorite has a diameter of 1.32 mm. In the Pultusk meteorite the metal grains are narrowly distributed with maximum grain diameter around 200 µm (Fig. 5B). The largest grain measured in the examined fragment of the Pultusk meteorite has a diameter of 2.14 mm. The grain diameter distribution show that the smallest metal grains are the most numerous with the distributions peaked at diameters below 0.2 mm. Generally, for the Pultusk meteorite the metal grain distribution according to equivalent spherical diameter falls uniformly with increasing diameter. For the Baszkowka meteorite the distribution is generally wider and has a small secondary peak centred on a diameter of approximately 0.5 mm and within the intermediate group of grains for this meteorite. Correspondingly, the average equivalent diameter for the Baszkowka meteorite is larger than the average equivalent diameter for the Pultusk meteorite.

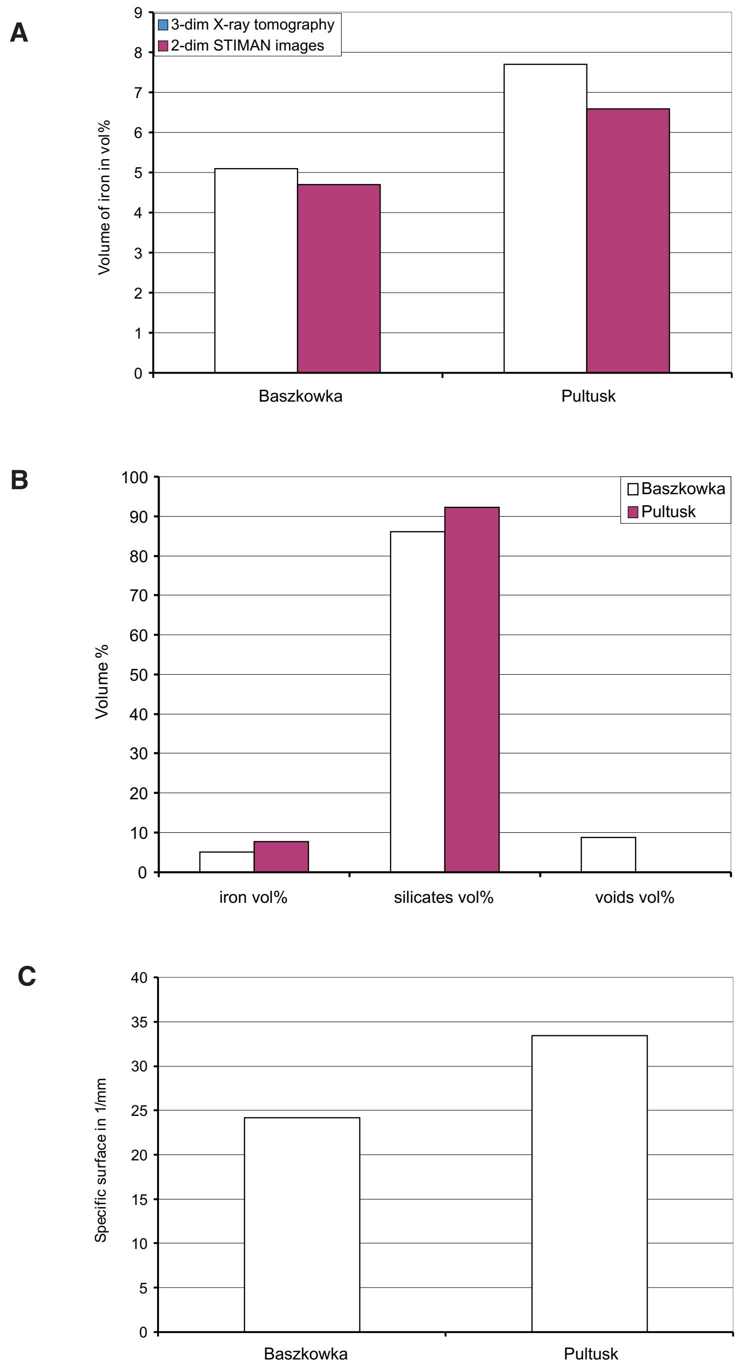

Fig. 4. Analysis of meteorite properties
A — volume of metal grains in the meteorites studied from thresholding the X-ray tomographs;
B — volumes of voids, metal grains and silicate phases in the meteorites studied;
C — metal grain surface to volume ratio (specific surface) in the meteorites studied

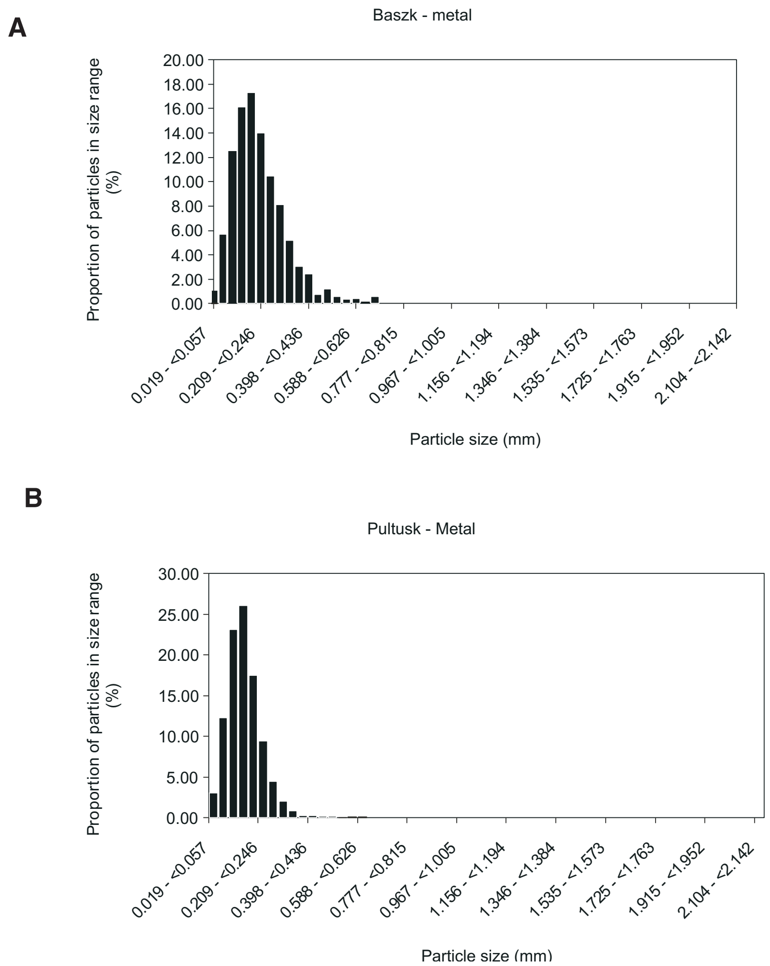

Fig. 5. Distribution of metal grain sizes
A — Baszkowka meteorite; B — Pultusk meteorite

X-ray section images analysed using STIMAN determine the iron volumes to be 4.7% in the Baszkowka meteorite and 6.6% in the Pultusk meteorite (Fig. 4A). The average metal grain diameter calculated by STIMAN is 0.148 mm for the Baszkowka meteorite and 0.169 mm for the Pultusk meteorite. The average metal grain area and perimeter follow similar trends.

The distribution as determined by 2D analysis of metal grain area versus diameter for the Baszkowka meteorite shows steady increase in the larger metal grain abundance in this meteorite sample (Fig. 8A). The largest grain in the Baszkowka meteorite has a diameter of 1.32 mm. For the Pultusk meteorite the metal grain area distribution shows a broad distribution centred on a diameter of approximately 0.27 mm (Fig. 8B). The largest grain in the Pultusk meteorite has a diameter of 2.14 mm. The distributions as determined by 2D analysis of metal grains according to equivalent diameter (Fig. 9A, B) show that the smallest metal grains are the most numerous in both meteorites with the distributions peaked at diameters below 0.05 mm. Correspondingly, the average equivalent diameter for the Baszkowka meteorite (0.148 mm) is smaller than that for the Pultusk meteorite (0.169 mm). From the metal grain distribution according to form index (Fig. 10A, B) it can be seen that grain shape factor maximum is similar for the two meteorites (K_f – 0.44). In the Baszkowka meteorite the shape factor of metal grains is more broadly spread into the lowest and highest possible values. These extreme grains represent these of high aspect ratio, very thin and long grains (K_f up to 0.12) and these with spherical regular shape (K_f more than 0.88). When the form index of metal grains in both meteorites is classified according to grain equivalent diameter (not shown here) it can be seen that, in general terms, the large metal grains in the Baszkowka meteorite are more circular in cross section (high form index) than the large metal grains in the Pultusk meteorite in which the large metal grains have a relatively low form index.

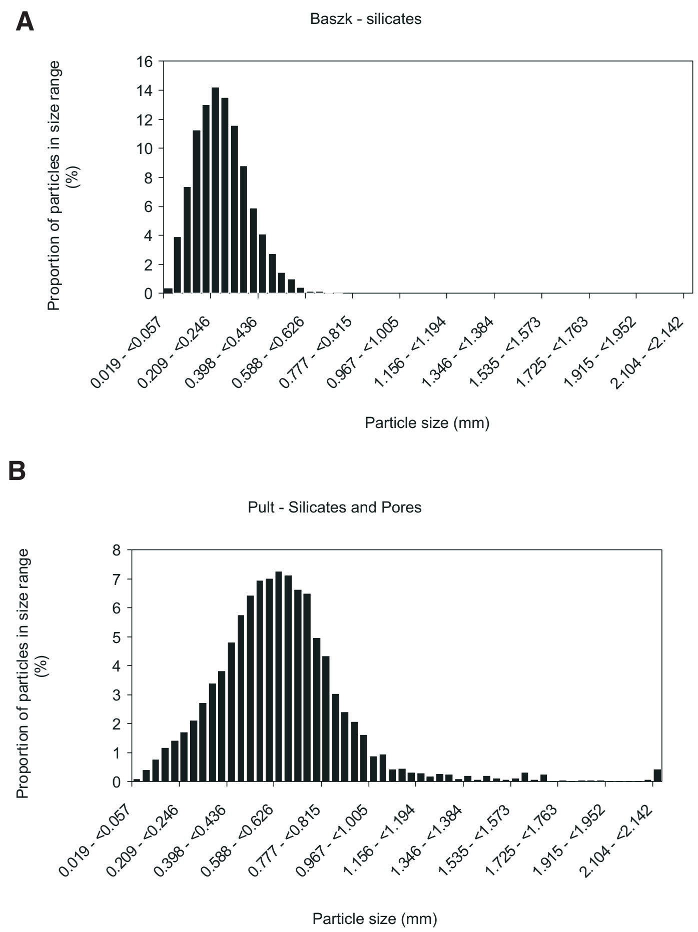

Fig. 6. Distribution of silicate grain sizes
A — Baszkowka meteorite; B — Pultusk meteorite

Although 2D analysis performed by programs such as STIMAN is not as accurate as will 3D analysis, the data obtained by 2D analysis on individual tomographic sections is still useful for determine the properties of meteorites at the local micro level.

Silicates

Measurements obtained by thresholding grey colored regions in X-ray tomographs with the Skyscan^{TM} CT-analyser software give the volume occupied by silicates as 86.1 vol.% in the Baszkowka meteorite and 92.3 vol.% in the Pultusk meteorite. The silicate--grain distribution versus diameter for the Baszkowka meteorite (Fig. 6A) shows normal distribution between 50 and 700 μm with gentle extension towards larger diameters. The maximum silicate grains aggregate between 200 and 350 μm in diameter. The silicate-grain distribution versus diameter for the Pultusk meteorite (Fig. 6B) is much wider than in the Baszkowka meteorite (100 to 1000 μm) with broad extension to the end of the scale at 2000 μm.

Pores

Pore space in the Baszkowka and Pultusk meteorites (white regions in X-ray tomographs) shows considerably large values in the L5 Baszkowka meteorite (8.7 vol.%). In the Pultusk meteorite this value has not been measured because most pores were below the equipment resolution, however voids observed in X-ray micrographs seems to be of elongated fissures with high aspect ratio. In the first ever study of pore spaces in stony meteorites (Zbik 1982), the porosity in the Pultusk meteorite was determined as 4.4 vol.% using mercury porosimeter. According to Zbik (1982), the equivalent diameters of the voids fall mostly between 0.1 and 10 μm. Consolmagno and Britt (1998) determined a slightly larger porosity (5±1.5 vol.%) from their much larger Pultusk meteorite fragment (860 g). Their results were obtained using volume and density

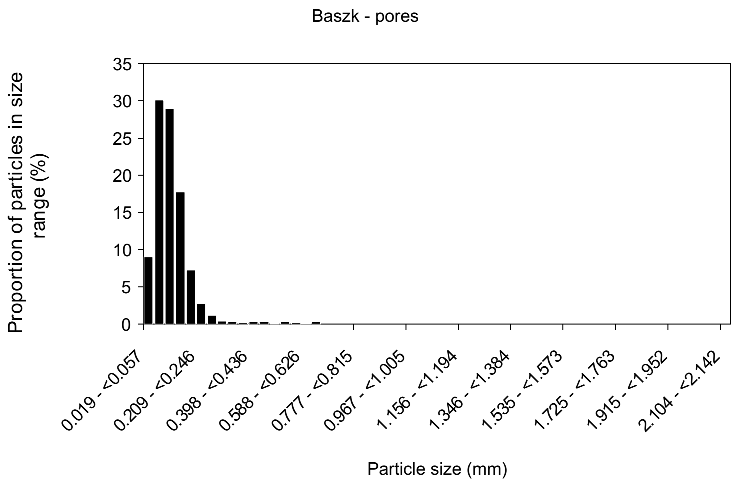

Fig. 7. Distribution of void sizes in the Baszkowka meteorite

method. As the Pultusk meteorite has lain for about 135 years in museum collections its porosity may be reduced due to aging and may vary from specimen to specimen according to the climatic conditions of storage.

The Baszkowka meteorite is a recent meteorite that fell in 1994 (Stępniewski 1995a, b). This fall was witnessed and the meteorite immediately recovered. Porosity data for this meteorite has not yet been published and our fragment was too small for reliable porosity measurements using standard density and volume methods. In such situations, when only a small sample is available, X-ray microtomography examination seems to be invaluable.

Graphs presenting pore equivalent spherical diameter distribution (Fig. 7) show a rather uniform void distribution across diameters 20 to 300 µm with steady extension to 700 µm. The average pore equivalent spherical diameter in the Baszkowka meteorite is 108 µm. The largest pore measured in Baszkowka meteorite was approximately 2.4 mm. The pore surface to volume ratio (specific surface) in this meteorite is 55.7 mm^{-1} which is much higher than calculated for the metal grains. This value may suggest much more developed void surface in comparison to more equidimensional metal grains.

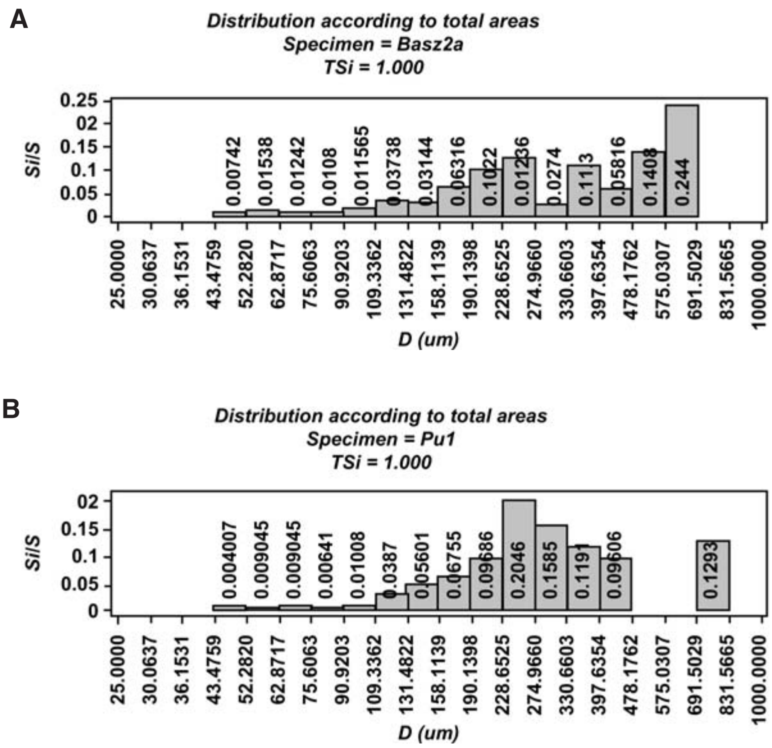

Fig. 8. Distribution of metal grains according to total areas from two-dimensional X-ray micrographs with aid of STIMAN image analysing program
A — Baszkowka meteorite; B — Pultusk meteorite

DISCUSSION

Britt and Consolmagno (2003) and Consolmagno and Britt (1998) using results from a large database of meteorites have concluded that no correlation exists between meteorite chemical and petrological types and porosity. They admit some influence of impact metamorphism and terrestrial weathering on enclosed pore space. Our results from only two different meteorite samples do not allow us to draw any encompassing conclusions about chondrite evolution. However, our results show some correlation between the metal grain size, void size and their equivalent spherical diameter distributions. In the Baszkowka L5 chondrite void volume percentage is larger than metal grain volume percentage. The diameter of metal grains in the Baszkowka meteorite is much larger than calculated void diameter. This may suggests that the some voids, most probably the intergranular voids (Zbik 1982) developed alongside metal and silicate grains in an early stage of meteorite formation (primordial accretion). The intergranular voids are irregular in shape, which is reflected in the high surface to volume ratio (specific surface) of the metal grains in this meteorite. The morphology of voids and metal grains in the Baszkowka meteorite seen in 3-dimensional images

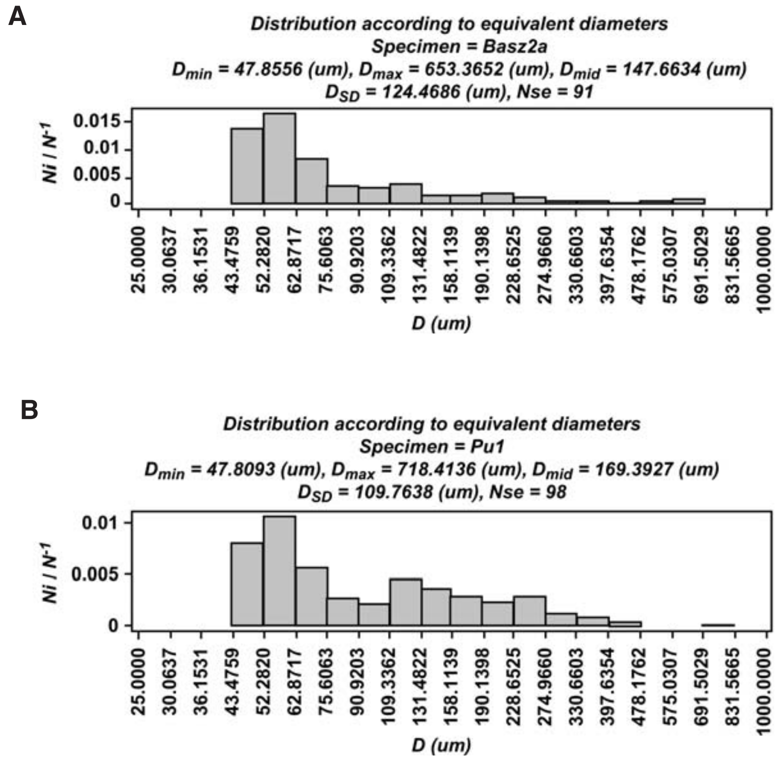

Fig. 9. Distribution of metal grains according to equivalent diameters from two-dimensional X-ray micrographs with aid of STIMAN image analysing program
A — Baszkowka meteorite; B — Pultusk meteorite

confirms that metal grains are regular in shape with respect to the shape of the open intergranular voids. Because of their irregularity voids have an overall larger aspect ratio than metal grains. The high aspect ratio, smaller voids may represent fissures which occurred during impact events well after the cooling of the meteorite parent body.

In the Pultusk H5 chondrite metal grain volume is larger than void volume. Many of the voids in the Pultusk meteorite are below the resolution of the X-ray tomography instrument used in this study. From direct study of X-ray micrographs and other sources we know that voids in Pultusk meteorite are up to 10 μm in size, have a large aspect ratio and appear fissure-like (SEM observations in Zbik, 1982). Such compact meteorite structure in Pultusk meteorite is in contrast to more porous Baszkowka meteorite. Both meteorites belong to the same petrologic type and the large difference in structure once again shows the lack of coordination between petrologic type, which reflects meteorite metamorphism and physical properties. In the Pultusk meteorite fissure-like voids may form due of rapid relaxation during the shock event that triggered parent body fragmentation. The metal grains in the Baszkowka meteorite are more regular in shape than voids. These observations suggest that metal grains accreted

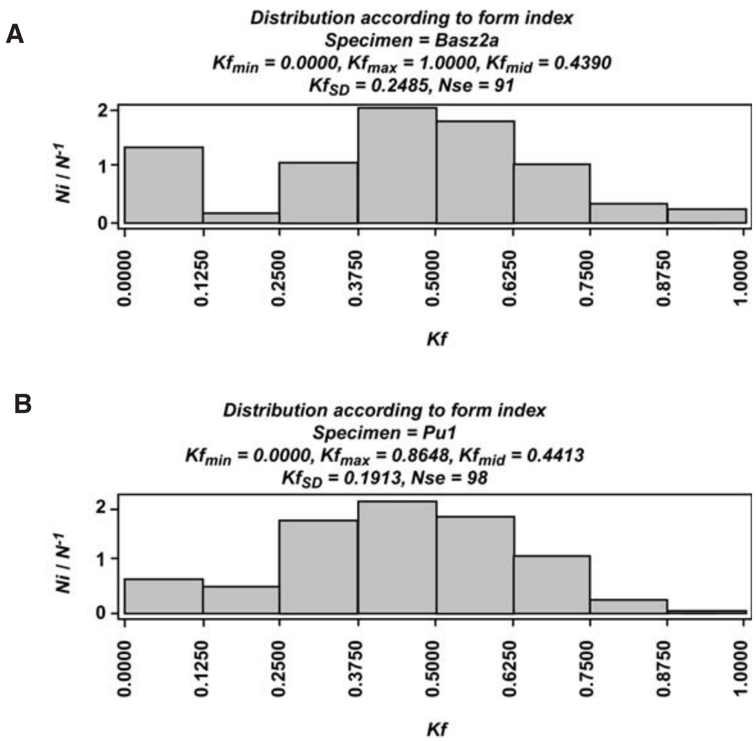

Fig. 10. Distribution of metal grains according to form index from two-dimensional X-ray micrographs with aid of STIMAN image analysing program
A — Baszkowka meteorite; B — Pultusk meteorite

alongside silicates and voids formed spanned network like in the regolithes observed in our planet and the surfaces of the Moon and Mars. The primordial regolith from which Baszkowka meteorite has been formed seems to never been compacted to such a degree as the Pultusk meteorite whose primordial porosity system have been obliterated.

CONCLUSIONS

The X-ray CT technique combined with subsequent image analysis of X-ray tomographs is useful in the study of the internal structure of small meteorite samples that after investigation may be returned to the precious meteorite collection. The two-dimensional cross sections and three-dimensional reconstructions obtained from the X-ray CT analysis reveal the internal structure of the rock sample with high accuracy. However, computed tomography is a time-consuming task and should follow petrologic studies to actually identify the objects imaged in CT.

The L5 ordinary chondrite Baszkowka has a large porosity (8.7%) and a low volume of metal grains (5.1%). The H5 ordinary chondrite Pultusk has low porosity (3.4%) and displays more than twice the volume metal grains (7.7%) than the Baszkowka meteorite. This is consistent with the observations of Consolmagno et al. (1998) that H chondrites typically have higher bulk densities than L chondrites (Yomogida, Takafumi 1983).

The median metal grain and pore diameters are larger in the Baszkowka meteorite in comparison to the Pultusk meteorite. Similarities in the form index in metal grains in both meteorites inherit their genetic similarities. Morphology indicates that the Pultusk meteorite has higher aspect ratio voids (judged from specific surface and morphological observations) compared to voids in the Baszkowka meteorite. This may suggests that in the Pultusk meteorite most of the primordial pore system formed during parent-body assemblage has been obliterated during pressure metamorphism and shock fragmentation subsequent to the cooling of the parent body. Grain size, pore size and morphology suggest a genetic distinction between metal grains and voids in each of the meteorites as well as major structural differences between both meteorites. The voids and metal grains co-formed.

The average metal grain and pore diameters are larger in the Baszkowka meteorite in comparison to the Pultusk meteorite. Also metal grain form index and pore appearance indicate that in primordial space sediments assembled to form both meteorites. Both meteorites have undergone the metamorphic processes as confirmed by their identical petrological type but probably less pressure metamorphosed Baszkowka meteorite has never been compacted to the same extent as the Pultusk meteorite.

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MIKROTOMOGRAFIA RENTGENOWSKA WYSOKIEJ ROZDZIELCZOŚCI W NIENISZCZĄCEJ ANALIZIE STRUKTURY WEWNĘTRZNEJ DWÓCH CHONDRYTÓW

Streszczenie

Autorzy porównali wewnętrzną strukturę dwóch meteorytów kamiennych przy zastosowaniu wspomaganej komputerowo, nieniszczącej mikrotomografii rentgenowskiej (ang. *X-ray CT*). Oba meteoryty są chondrytami typu 5, przy czym jeden z nich (Baszkówka) jest chondrytem grupy L, a drugi (Pułtusk) — chondrytem grupy H. Stwierdzono, że całkowita objętość ziaren faz metalicznych w meteorycie Pułtusk (7,7% obj.) jest większa niż w meteorycie Baszkówka (5,1% obj.). Ziarna faz metalicznych w meteorycie Baszkówka są z kolei generalnie większe niż takie same ziarna w meteorycie Pułtusk. Objętość porów w meteorycie Baszkówka (8,7% obj.) jest znacznie większa niż w meteorycie Pułtusk (3,4% obj.), podobnie jak wielkość porów.

Przekroje wykonane metodą tomografii rentgenowskiej wykazują, że oba meteoryty, jakkolwiek strukturalnie różne, cechują się podobną charakterystyką stosunków między ziarnami faz metalicznych i porów. Komputerowa analiza strukturalna pozwoliła stwierdzić, że bardziej regularne pory utworzyły się w tym samym czasie jak regularnie ukształtowane ziarna faz metalicznych i krzemianowych. Oznacza to, że utworzyły się one, gdy powstawały macierzyste ciała meteorytów, czyli jeszcze przed przemianami metamorficznymi wewnątrz tych ciał. Autorzy sugerują również, że mniej porowaty system meteorytu Pułtusk, cechujący się porami o kształcie wydłużonych spękań, utworzył się po okresie metamorfizmu ciśnieniowego, tzn. dopiero wtedy gdy macierzyste ciało tego meteorytu uległo rozpadowi w wyniku jakiejś kolizji.