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Mineralogy and deformation structures in components of clastic sediments from the Morasko meteorite lake (Poland)

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Agata Duczmal-Czernikiewicz* [1a], **Adam Choiński** [2b], **Mariusz Ptak** [2c], **Andrzej Muszyński** [1d]

Adam Mickiewicz University in Poznań, Poland

[1]* **Correspondence:** Institute of Geology, Adam Mickiewicz University in Poznań, Poland. E-mail: duczer@amu.edu.pl

[2] Department of Hydrology and Water Management, Adam Mickiewicz University in Poznań, Poland.

[a] https://orcid.org/0000-0002-8682-7513, [b] https://orcid.org/0000-0001-9006-0952, [c] https://orcid.org/0000-0003-1225-1686, [d] https://orcid.org/0000-0002-9746-0278

Abstract. The paper presents a mineralogical analysis of sediments of the biggest lake in the Morasko Meteorite Reserve (Poland). The lake is filled by phytogenic sediments at the top, while at the bottom there are Neogene clays. The main components are: clay minerals in fine fraction and quartz and feldspars in coarse sandy fractions. The presence of disturbed ferrous zones suggests the existence of a dynamic factor that caused deformations in the sediments. Cavities, crevices, cracks, and traces of parching or fragmentation of mineral material can be interpreted as deformations related to the impact of meteorite fragments in non-consolidated soft sediments in the Morasko meteorite nature reserve. Meteorite fragments that left numerous deformed structures were most probably consituted meteorite debris that originated from the fragmentation of the meteorite before its impact.

Key words:
meteorite Morasko,
lake,
sediments,
mineralogy,
microstructures

Introduction

Metorite craters developed from fine-grained unconsolidated sediments provide valuable data on the processes caused by the meteorite impact. The effects of the impact could be catastrophic (Veski et al. 2004), or may have caused only slight changes in rocks (Dypvik et al. 2003).Therefore, a detailed description of rocks directly related to the meteorite impact is useful in the reconstruction of the size and velocity of the cosmic body at the moment of impact. The features of sediments from craters are important for the determination of the crater's origin and development (e.g. Grieve 1991; Kenkmann et al. 2014). Micro-scale observations are among the principal methods used to determine the pressure the rock components were subjected to, and the metamorphic structures developed as a result of the shock (French, Koeberl 2010). Quartz grains, the most common components of the majority of rocks, are hard and resistant enough to preserve shock structures of different nature. In many craters, components of rocks other than quartz (e.g. feldspars and clay minerals) have been investigated in order to establish the origin of the craters (Nemeth et al. 2002; Jaret et al. 2014).

The Morasko meteorite (Fig. 1) left several craters. The largest has a diameter of approximately 90 m. The craters are surrounded by tills of the Vistula Glaciation (Stankowski and Muszyński 2008), and Neogene clay sediments (e.g. Duczmal-Czernikiewicz and Muszyński 2016, Szokaluk et al. 2016). The Morasko meteorite nature reserve in the north

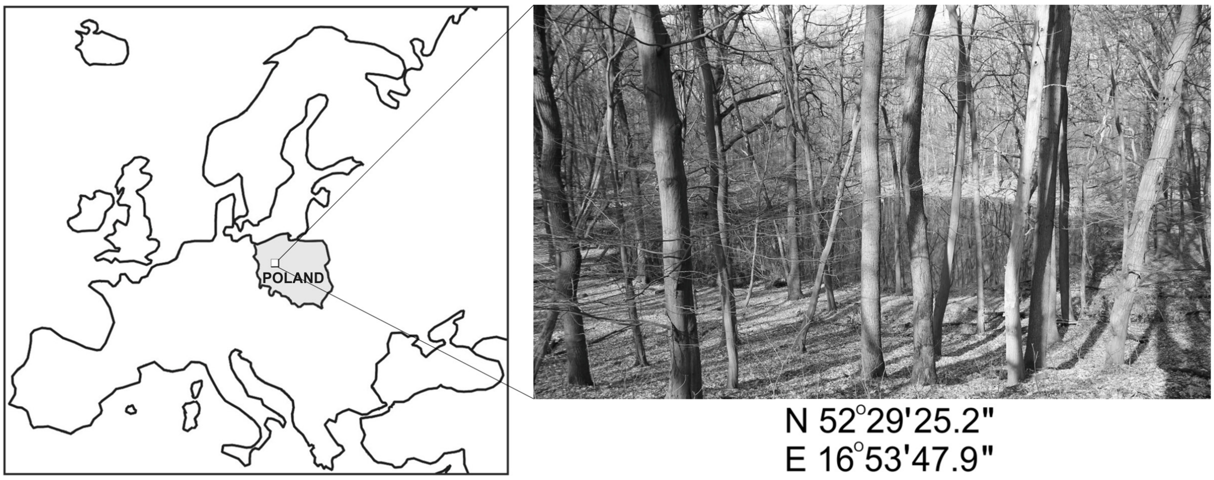

Fig. 1. Location of study object

of Poznań (West Poland, Wielkopolska) is an area where findings of meteorite fragments have been known for many years (Hurnik 1976; Karczewski 1976; Stankowski 2001; Stankowski et al. 2002; Stankowski and Muszyński 2008).

The activity of the ice sheet left a glacitectonically disturbed terminal moraine with fluvioglacial sediments (Stankowski et al. 2002). Several different meteorites each weighed more than 100 kg have been found in the reserve, as well as many small or very small fragments with a total weight of approximately 2000 kg. The largest fragments, weighing about 300 kg, were found within the Morasko meteorite nature reserve in 2012 (Muszyński et al. 2012) and in its vicinity in 2017. One of those two is included with other meteorite fragments in the collection of the Museum of the Earth at the Faculty of Geographic and Geological Sciences of the Adam Mickiewicz University in Poznań. The great majority of the findings are small or very small meteorite fragments ranging in size from several centimetres to less than on millimetre. The impact mechanism was recently described in a paper by Bronikowska et al. (2017) in which, based on modelling, the most probable input weight of the meteorite was determined to be approximately 1,000 tonnes, and impact velocity approximately 17 $km \cdot s^{-1}$. According to the authors of that study, before the space body reached the surface of the Earth, at a height of 25 km, it broke up into many smaller fragments. The time of impact was determined as approximately 5,000 years ago based on pollen analysis of peats from the bottom of the craters (Tobolski 1976) and ^{14}C isotope analysis of fossil soils occurring in sediments ejected by the formation of the crater (“ejecta”) (Szokaluk et al. 2016).

The investigated lake is filled by two lithological sorts of sediments: phytogenic sediments (peats) at the top of the profile, and non-organic sediments underneath. In this paper, the peats have been omitted because they were the latest and the youngest sediments filling the crater lake. In this paper the distribution of the non-organic sediments underlying the peats was studied, as well as the mineralogical and microstructural features of the sediments. Particular focus was placed on the mineralogy of the clays, which differ from the other Neogene clays known in other areas of Wielkopolska in terms of their mineralogy and grain components (Duczmal-Czernikiewicz 2013). Additionally, we would like discuss the origin of the investigated lake.

The objective of the paper was to provide a description of the bottom sediments from the biggest crater lake in the Morasko meteorite nature reserve. Moreover, an attempt was made to answer the question of whether non-organic sediments sampled from different parts of the crater show mineralogical and/or structural variability, in order to determine additional facts to contribute to reconstructing the meteorite impact and its record in sediments.

Materials and methods

Sampling

The largest crater is currently filled with water, forming a lake with an area of 1,695 m^2 and mean depth of 1.4 m (Choiński and Ptak 2017). Due to this, the corings necessary for sampling were performed from a pontoon by means of a manual "Dutch corer" (Fis. 2 and 3). Three cores were collected.

Mineralogical research

The mineralogical research concerned clay sediments. Analysis of sediments of a phytogenic character was omitted. Sediments from the cores were described macroscopically. Universal microscope thin sections from the available cores were prepared for research in transmitted and reflected light. The mineralogy of the sediments was analysed by means of an optical microscope Axipolan 2 (Zeiss) at the Institute of Geology at Adam Mickiewicz University in Poznań. Moreover, the mineral composition of the finest fractions was determined by means of an XRD Thermo Electron ALR X'tra at the Institute of Geology of the Adam Mickiewicz University. For this purpose, a fraction below 2 micrometres (preparation according to Jackson, 1975 and Moore and Reynolds, 1989) was isolated by means of a Polygen Sigma 4-15 centrifuge.

Results

Crater sediment description

The microscopic research allowed two lithological types of sediments to be designated in the sampled cores: clays and organic sediments. The clays are greenish-grey in colour. In the moist state they show high plasticity. After drying, they form a compact rock. They are very fine-grained, and they contain unsorted sandy fraction (50–70 wt% of coarse grains). They are hard but brittle after drying. They split into small crumbs in which coarse-grained fragments of the grain skeleton are distinguishable. Organic formations are black and have a slightly laminar structure. The fine laminas in the organic sediments are emphasised by the presence of quartz grains. They contain small organic fragments, but are difficult to identify macroscopically.

Mineralogical results

The analysed sediments are composed of clays, and phytogenic sediments. The Neogene clays are primarily composed of clay minerals typical of the area, including smectite, illite and kaolinite, as well as mixed-packet smectite-illite phase, which were identified by means of X-ray analysis. The coarse fraction is composed mainly of quartz and feldspars cemented by a matrix. The bonding substance is stained brown or rusty in places, due to the presence of hydroxides and iron oxides. The matrix is black in places, which is caused by the presence of organic matter. Polycrystalline or monocrystalline

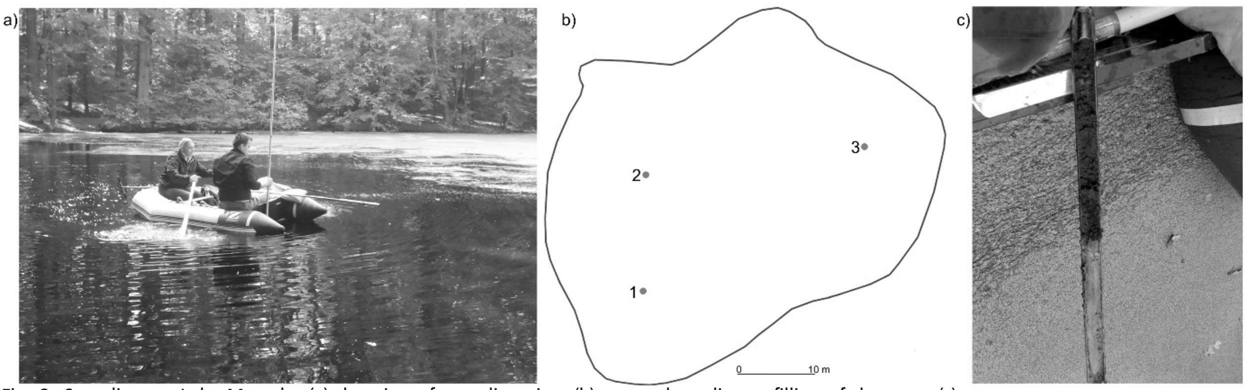

Fig. 2. Sampling on Lake Morasko (a), location of sampling sites (b), example sediment filling of the corer (c)

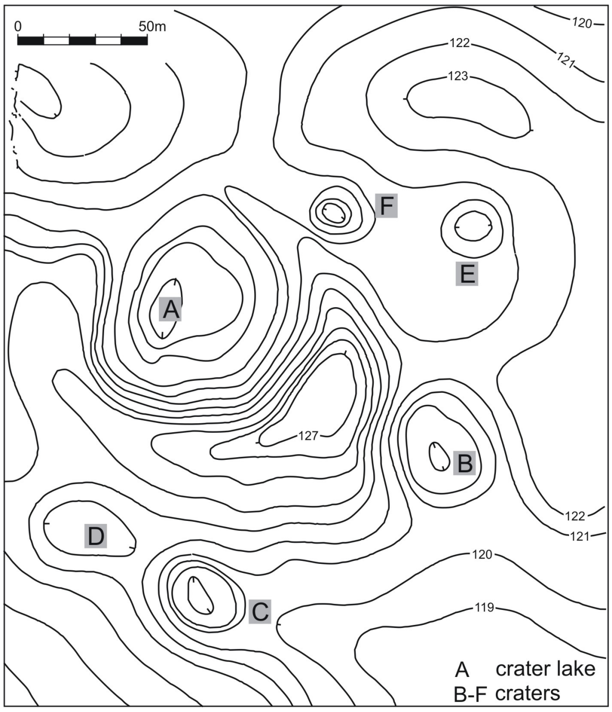

Fig. 3. Location of craters and crater lake in the Morasko Metorite Reserve, according to Karczewski et al. 1976 (from Duczmal-Czernikiewicz, and Muszyński 2016)

quartz and feldspars (potassium and plagioclases) were determined among the grains of the grain skeleton, as were lower contributions of muscovite and chlorites, and accessory zirconium, titanite and ilmenite. To a lesser degree, the grain skeleton is also built of igneous rock pebbles. The clay fraction is composed of chlorites, illite and mixed-layered phases, probably of the smectite-illite or vermiculite-illite type.

Small fragments of iron oxides and hydroxides are visible in the clays. They are usually wither irregularly or regularly round or oval (Figs 4 and 5) and bind fragments of clays. Some of them have forms comprising elongated zones of microscopic size in which part of the grains of the grain skeleton are heavily damaged, transformed or crumbled, and the original structure of the matrix is strongly disturbed. Such ferrous zones occur together with other deformations of grains of the grain skeleton. Single crumbs also occur locally, of microscopic size and various sharp-edged shapes, and are composed of iron oxides or hydroxides.

In the clays, which are composed of grains of quartz and feldspars and a soft clayey matrix, different microstructures are unevenly distributed in the profiles of the analysed cores. The most common are characteristic cavities in – or on the edges of – grains, and most frequently inside quartz grains and feldspars ((Fig. 4 A, B and C; Fig. 5 A). The cavities are usually approximately 50 microns in size, and are usually round or approximately round in shape (Fig. 4 C, D, Fig. 5 E, F). In some grains, the edges of the cavities are sharp, with irregular shapes. The cavities develop local hollows in grains of quartz or feldspars.

Observations in reflected light show that the edges of the cavities are frequently uneven, deformed, or completely crumbled (Fig. 4 B) and are surrounded by cracks or chippings, which are most intensive in the zones adjacent to the cavities. In other places, the cavities are elongated, and deformed grains resemble cylindrical tunnels, looking like the trace of a micrometeorite sliding across the grain's surface. In this case, zones of optical properties that have been altered from those typical of quartz can also be seen (Fig. 4 B and C). Cavities and hollows also occur very commonly in the clayey matrix from core No. 3 (Fig. 5 E), with the highest intensity on the interface between clay formations and organic formations (peats).

The internal structure of the grains around the cavities, particularly in feldspars, shows disturbances not only in terms of mechanical crumbling of their edges, but also in the internal structure. This is exemplified by deformations of polysynthetic twinnings typical of feldspars (Fig. 4 F). In the most extreme cases they are bent or broken (Fig. 5 F). In some quartz grains, delicate cracks resembling planar fractures are also observed. They occur within the boundaries of the grains, and do not reach the edges, but are locally in contact with the edges. They also occur on grains in which no cavities or other deformations are found.

Another type of microstructure observed in quartz – the primary component of the grain skeleton – are sharp-edged, V-shaped cavities in grains (Fig. 5 A, B and C), and these are filled with a loamy or ferrous-loamy matrix. Moreover, there are microstructures that suggest damage to organic particles – their partial breaking, or parching. Such structures are commonly encountered on the interface between phytogenic formations and clays, and are accompanied by other traces of damage to organic or detritus components, such as

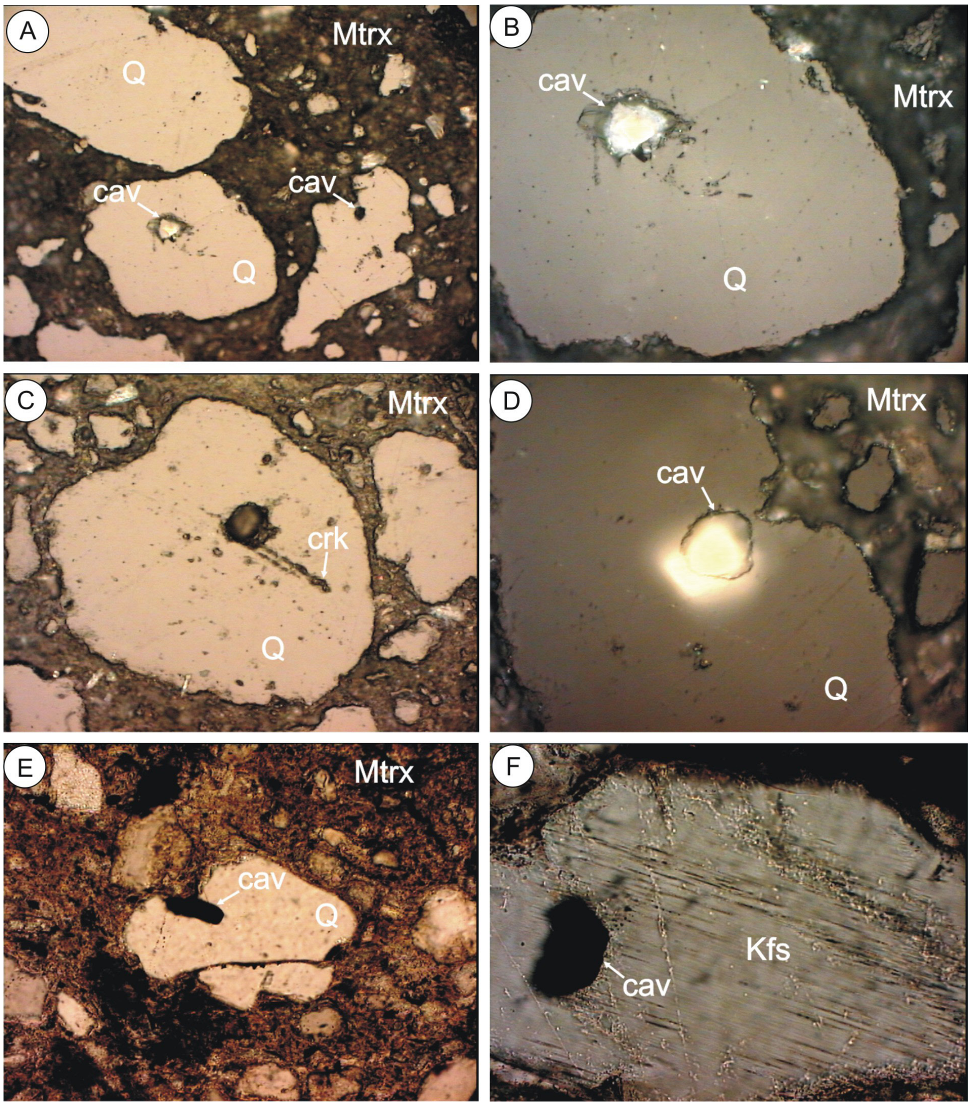

Fig. 4. Microphotograph of sediments from the largest crater of the Morasko meteorite (cores 1 and 2). A. quartz grains (light grey) with strongly variable sizes, surrounded by loamy matrix (dark grey), visible quartz grains with cavities in the middle (the middle of the photograph, yellow; right and down from the middle of the photograph, black), reflected light, 1 polar, magn. approx. 200x. B. Enlargement of Fig. 4 A, edges of the cavity have sharp outlines, a part of the grain shows crumbling around the cavity, reflected light, 1 polar, magn. approx. 500x. C. Quartz grain with a cavity with sharp edges and cracks within the cavity, reflected light, 1 polar, magn. approx. 500x. D. Quartz grain with a cavity with an approximately round shape, hollow inside (shines through in yellow), reflected light, 1 polar, magn. approx. 500x. E. Quartz grain with a cavity with an elongated shape, no cracks around, in clayey matrix transmitted light, 1 polar, magn. approx. 500 x. F. K-feldspar grain with a visible cavity with sharp edges, transmitted light, 1 polar, magn. approx. 500x. Abbreviations: Q – quartz, Kfs – K-feldspar, Mtrx – matrix, crk – cracks, cav – cavity, magn. – magnification, approx. – approximately.

fragmentation of the material and partial crumbling of grains and grain edges.

Interpretation and discussion

The mineralogy of the Neogene clays from the investigated lake should be described separately for the fine fraction and for the coarse fraction. The coarse fraction indicate differences in mineralogy and texture, as revealed by the disporportionate quantity of sandy grains (up to 70 wt %) compared to typical Neogene clays (which usually contain up to 30 %) (Wichrowski 1981; Duczmal-Czernikiewicz 2013). Therefore, the investigated sediments could be classified in petrography as muds or silts. It should be pointed out that in earlier studies, among the non-organic sediments, both tills and clays have been described (Stankowski and Muszyński 2008)

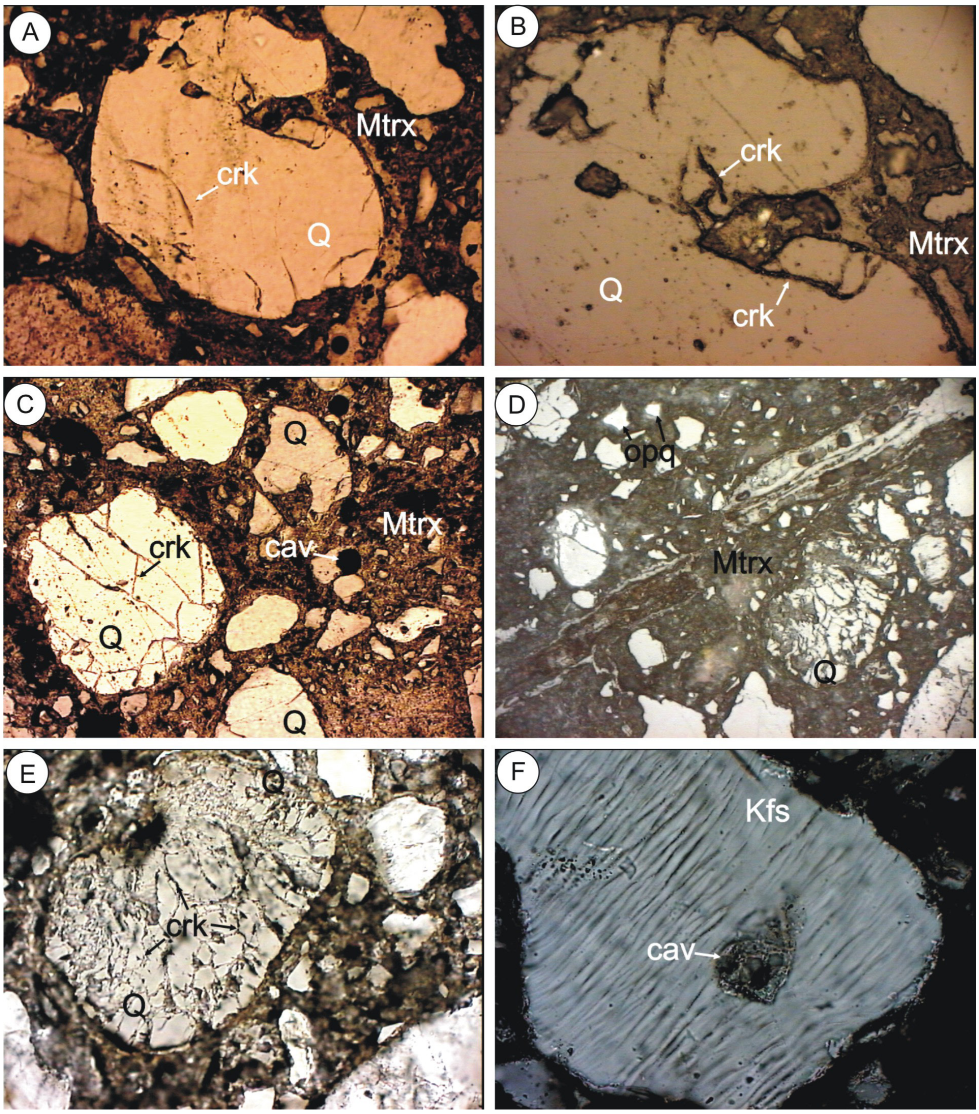

Fig. 5. Microphotograph of sediments from the largest crater of the Morasko meteorite (core 3). A. Quartz grain with a visible microcrater structure, filled with damaged and deformed matrix, a round opening inside the microcrater; quartz grain cracked on the sides (on the bottom of the grain and on the side opposite to the microcrater), transmitted light, 1 polar, magn. approx. 200x. B. Enlargement of Fig. 5 A, edges of the cavity in the form of a microcrater with sharp outlines, parts of the quartz grain cracked around the cavity, reflected light, 1 polar, magn. approx. 500x. C. Strongly cracked quartz grain (yellowish) surrounded by non-cracked grains, round or oval microstructures (black) visible in the matrix, transmitted light, 1 polar, magn. approx. 200x. D. Strongly cracked and deformed component of the grain, a microcrater visible on the left side of the grain, transmitted light, 1 polar, magn. approx. 200x. E. Quartz grain with a cavity in the middle, deformed matrix, very fine quartz grains, and opaque minerals visible among components of the matrix (upper part of the photograph), reflected light, 1 polar, magn. approx. 500x. F. K-feldspar grain with a visible micro cavity, disturbed internal structure observed around it (polysynthetic twinnings), transmitted light, 1 polar, magn. approx. 500 x. Abbreviations: Q – quartz, Kfs – K-feldspar, Mtrx – matrix, crk – cracks, cav – cavity, opq – opaque minerals.

in the crater lakes. The genesis of the Neogene clays described in this work could be related to the deformation and reworking of the primary clayey material, possibly with the mixing in of another kind of sandy sediments. These features could be caused by a meteorite impact.

The research on clay fractions from the matrix of sediments shows a mineral composition typical of post-glacial areas in the Polish Lowland (e.g. Wichrowski 1981; Walkiewicz 1984; Duczmal-Czernikiewicz 2010). The former contain smectite, illite-smectite, and kaolinite, and the latter – illite, kaolinite, and mixed-layered minerals of the vermiculite-smectite type with an admixture of chlorites. No other clay minerals have been found so far that could originate from higher-than-average pressures and temperatures probably caused by extra-terrestrial phenomena over a short time, or as a result of a permanent change in physical and chemical conditions (Duczmal-Czernikiewicz and Muszyński 2016).

Microstructures determined within quartz grains, feldspars and the clayey-ferrous matrix are unevenly distributed in the analysed sediments. They are most numerous in profiles 1 and 3, and less abundant in the remaining profiles. Just as cavities in grain sides have very characteristic shapes and edges and are relatively uniform in size (generally varying from 25 to 50 micrometres), so too do openings within the grains and the matrix. The sizes of openings correspond to the diameters of micrometeorites described in sediments around the craters in the analysed sediments (Dworzyńska and Muszyński 2012; Muszyński et al. 2012). The development of micro-cavities of up to 0.5 mm in diameter in hard grains of quartz and feldspars is difficult to explain with anything other than the strong impact of fine dust into sediments containing grains of quartz and feldspars. Such processes could have occurred after sediment was ejected from the crater in the "curtain" falling into the crater. The "curtain" could have been created by sediments thrown away from the Earth's surface at the moment of impact (at the compact-compression stage, according to Melosh, 1989 and French, 1998), immediately after the fall of the meteorite. At the next stage (the excavation stage), minerals from the Earth's surface occur in the ejected dust, and then the ejected minerals slide back into the crater (the modification stage).

Because some cavities have folded edges (partially isotropic), the quartz grains were probably subject not only to pressure, but also to a local increase in temperature. The impact resulted not only in the appearance of a cavity in the grain of quartz or feldspar, but also cracking in the immediate vicinity of the cavity. The appearance of microcracks in quartz grains could also be the result of an increase in directional and rapidly changing pressure. Moreover, traces of incineration or parching of fragments of organic matter may be related to an impact and local temperature increase caused by particles hitting the grains.

Quartz, feldspars, and other minerals described from many craters worldwide commonly show deformations from shock metamorphism, allowing for the determination of the pressure and temperature at the time of impact (Langenhorst et al. 1991; French 1998). Such diagnostic structures in investigated sediments (e.g. planar fractures), however, are missing.

Traces of damage and deformation of the clayey matrix also suggest the effect of a sudden factor affecting temperature and pressure that at the moment of impact was massively in excess of normal PT conditions on the surface of sediments in post-glacial formations. The presence of sharp-edged ferrous fragments that do not correspond with natural components of clay tend towards the conclusion that microshrapnels appeared in the sediments as a result of the fragmentation of the meteorite and its falling into the sediments. Similarly, the presence of disturbed ferrous zones suggests the existence of a sudden factor having caused deformations in the sediments. The meteorite impact could have been such a factor. It is very unlikely that any other potential origin of these ferrous structures is responsible.

Glacitectonic disturbances related to the movement of an ice sheet occur both in clays and in tills (Hurnik 1976; Karczewski 1976; Stankowski and Muszyński 2008). Clays containing swelling minerals could show plasticity as a result of a change in the arrangement of the ice sheet. Therefore, structural properties such as folding and cracks in the matrix in clays could be shaped by pressures related to glacigenic processes approximately 21,000–18,000 years ago – considerably earlier than the meteorite impact (Stankowski 2011). The effects of the ice sheet cannot currently be clearly separated from the effects of folding deformations related to the impact. Later processes observed in the macro- and micro-scale, such as weathering, probably also overlapped. The appearance of micro-cavities in grains of quartz and feldspars is possible to interpret as having been caused by the activity of the ice sheet. They could, however, have been caused by a sudden impact of matter fragments of approximately 100 microns in diameter into the surface of grains of the grain skeleton. The impact mechanism can be compared to the impact of many small-diameter, round or oval bullets hitting from a relatively close distance. It cannot be excluded, however, that some of the deformations of grains of feldspars or quartz, which manifest in the occurrence of microinclusions or microcracks, might have developed in a very distant time and place, in magmatic or metamorphic processes recorded in grains of the grain skeleton much earlier than the material migrated with the movement of the ice sheet from the north.

The paper attempts to associate characteristic microstructures in sediments with effects of the impact of the Morasko meteorite. The probable interpretation seems to be that involving the impact of meteorite fragments, related to the explosion of the fragments in the surface ground layers, hitting the sediments with high velocity (called a "curtain"). The movement of glacier sediments was affected by the impact due to the following stages of crater development (described by Melosh 1989 and French 1998): contact/compression stage, excavation stage, and modification stage. The meteorite impact was related to the explosion of sediments, triggered by the shock wave pressure, and associated with temperature at the contact/compression stage of creating the curtain.

The development of such a curtain containing mixed material could cause damage and deformation both to grains of the grain skeleton and the original structure of the mineral matrix of the sediments. Such an interpretation is also confirmed in other studies previously conducted, for example concerning "pancake" modelling (Bronikowska et al. 2017) that determined that the meteorite fragmented and different parts of it impacted with different forces and velocities depending on the sizes of the falling particles. Charcoal can be scattered in such a curtain comprising sediments ejected from the ground surface mixed with fragments of space matter (Łosiak et al. 2017). These processes were also very probable in the case of the Morasko impact, although charcoal were found in the "ejecta" layer in traces (Szokaluk et al. 2016).

Due to a number of processes that can obscure the original structural and textural features of formations changed by a meteorite impact, all traces left by small impacts should be treated with particular attention.

Conclusions

1. Two lithological types of sediments occur within the largest crater from the Morasko meteorite nature reserve, namely clays and phytogenic formations. The mineral composition of the clays primarily included smectite, illite and kaolinite, as well as mixed-layered phases of the illite-smectite type, which are typical components of clay fractions in the area. The mineral composition of coarse fraction primarily included quartz and feldspars as components of the grain composition, and clay minerals and iron hydroxides as components of the matrix. The sediments from the three investigated cores are similar in their mineralogy and textures.

2. The investigated Neogene clay sediments are different from the Neogene clays of other Polish regions in terms of grain size and matrix deformation. These textural differences could be interpreted as processes of reworking caused by impact cratering.

3. Some grains of quartz and feldspars, and the matrix of sediments from the crater include cavities, openings, crevices and cracks. They can be interpreted as deformations related to the impact of a meteorite into the non-consolidated sediments of the crater in the Morasko meteorite nature reserve. Small fragments of meteorites probably constituted meteorite dust resulting from the fragmentation of the meteorite during or after its fall. The development of micro-cavities in hard grains of quartz and feldspars, with sizes reaching a maximum of 0.5 mm in diameter, is difficult to explain by anything other than impacts of fine dust into the sediments containing the grains.

4. According to the study conducted in this work, the lake in Morasko meteorite reserve is very probably of impact origin. However, although typical micrometeorites were not found in the sediments, the microstructures described in the quartz in this work do not exclude their impact origin.

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