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Impact craters and the extraterrestrial matter in their surroundings: case of Morasko (Poland) and Kaali (Estonia)

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Abstract Investigations have been carried out in the area of meteorite impact craters within the Quaternary deposits in Morasko and the Silurian bedrock in Kaali. Both surface destructions occurred during the fall of cosmic bodies that induced formation of magnetic fine-grained material. The presence of extraterrestrial spherules in Morasko and Kaali and their cosmic origin state prove such a composition and character of the surface. Moreover, the amount of magnetic fraction is increased in the sediments in the environs of craters in relation to their surroundings. However, impact of similar meteorites under similar environmental conditions can generate various morphological, mineralogical and natural effects. Common features of the described areas are the occurrence of collateral craters, their formation in sedimentary rocks and presence of high amounts of extraterrestrial spherules in their environs.

Keywords • *impact craters* • *extraterrestrial matter* • *Kaali* • *Morasko*

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INTRODUCTION

Meteorite impacts generating craters on the Earth's surface appear to be a rare phenomenon. Meteorite fall has been and is a natural process happening throughout the existence of the Earth. In the Central and Eastern Europe there have been at least several of such events in the last ten thousand years (Stankowski 2001a, 2008; Raukas *et al.* 2001; Baillie 2007; Stankowski *et al.* 2007; Plado 2012). Such falls can create simple or multiple craters with different abilities to occur in morphology (Suuroja K., Suuroja S. 2010; Plado 2012). A special situation occurs when a meteorite falls onto a soft ground with a little potential of preservation. In that case, there are two possibilities. First, a recent, small crater can be rapidly eroded and may not leave any trace in the environment. Second, a fall can lead to establishing a bigger form recorded in suitable conditions enabling preservation. An object also undergoes denudation and may lead to difficulties of the interpretation. However, some traces enabling genetic identification always remain. Such indicator of meteoritic origin may present in the sediments forming crater and/or fine-grained forms – impact spherules. Spherules are mostly a magnetized fine-grained fraction, less than 1 mm. It can penetrate the Earth's atmosphere in two ways. Firstly, in its natural size (<1 mm), secondly, as a side product of disintegration of meteoroids which enter the Earth's atmosphere. Therefore, the place of meteorite fall exhibits strong enrichment of dusty material relatively to the environment. Despite its inconspicuous size, spherules are an important indicator of impact phenomena.

Well-known craters in Morasko can be regarded as craters formed in sediments of relatively young age. Craters in Kaali are formed in Silurian dolostones, covered with very thin till layer (Fig. 1). These are craters which genesis, form, structure and effects that they bring to the environment had previously been studied (Reinwaldt 1933; Karczewski 1976; Tiirmaa 1994; Aaloe, Tiirmaa 1981; Stankowski 2001a, 2008).

The aim of this paper is to acquaint with a new data on the presence of spherules in sediments and their role for the recognition of meteorite falls as well

Fig. 1 Location of the study areas; Morasko, Poland and Kaali, Estonia.

as their comparison with archive data. To achieve the objective it is necessary to understand precisely and describe the investigated objects. Hereby, author attempts to approach to recognition of the impact crater forms and the existence of extraterrestrial spherules in the sediments.

GEOLOGICAL SETTINGS

Kaali

Morphological description of the studied area is based on literature data and site survey conducted by the author.

The substrate of the Quaternary deposits of the Saaremaa Island is formed entirely by the carbonate rocks of early and late Silurian age. Within the Kaali crater field, under a thin layer of Quaternary sediments stratified, late Silurian dolostones occur. Directly on them the areas of Quaternary sediments are present – mainly basal till developed as clay till, sandy till and loamy sand classified as Järva Formation of the last glaciation (Raukas *et al.* 2004; Raukas, Stankowski 2005). The thickness of this cover, on the Saaremaa Island rarely exceeds 5 m. The occurrence of a thin layer of the last glaciation sediment indicates that older deposits were eroded before and during the last glacial ice sheet advance, and eventually came to depositing basal tills directly on the Silurian bedrock. After the deglaciation, the sea entered the area and relatively quickly retreated due to glacioisostatic movements (Raukas *et al*. 2004; Raukas, Stankowski 2005; Hoppe *et al*. 2002).

North-western Estonia emerged from the sea about 11,000 radiocarbon years ago (Hoppe *et al*. 2002). Through the constant uplift of the land in the Holocene the new islands appear: Saaremaa, Hiiumaa, and Muhu. The resultant of the changes in sea level and rate of uplift made the Kaali area completely raised above the sea level at least 7500 radiocarbon years ago (Tavast 2000). The terrain near the Kaali craters like in most parts of the island of Saaremaa is flat and the height difference does not exceed 4 m.

Kaali craters are composed of the main crater accompanied by eight smaller collateral craters (Fig. 2). At the bottom of the largest one, the main crater is a natural lake, subject to significant seasonal variations of water level. Its diameter varies seasonally from 30 to 60 m and its depth ranges from one to 6 m (Tiirmaa 1994; Veski *et al.* 2001; Veski *et al*. 2004). Minor craters are small depressions surrounded by a low rim. Some of them, for example crater No. 7, are re-filled with material from the denudation of the surroundings. Main crater takes far northern position in relation to other forms. The majority of minor craters (3, 4, 5, 7, 2/8) are located to the southeast of it while the other two (1, 6) are located on the southwest side. The largest of the minor craters (1, 3), of similar size, are located in different directions, and at different distances from the main crater.

Morasko

Morasko Hill (154 m a.s.l.) is located approximately 6 km north of Poznań. It is characteristic not only for the highest elevation in this part of Great Poland district but also for its highly varied terrain. The described area takes the form of an arc, open to the north and is a part of the moraines formed during the Poznan Phase, ca. 20 000 BP (Stankowski 2001a, 2008). At the back of Morasko Hill (north side), the area is gradually flattening, reaching the elevation of land approximately 100 m a.s.l. This area is limited from the east by meridionally extended Warta River valley, whereas a relatively flat area of sandurs limits the area from the south. Within the mentioned sandurs, there are small valleys of local streams and small depressions without outflow. A characteristic feature of this area is the occurrence of Neogene sedimentary rocks on the surface. Moraine elevation with culmination of Morasko Hill is built mainly of sand, loamy sand and till. To a lesser extent, locally there are Holocene sediments, mainly of organic origin. The fine-grained Neogene sediments occur as small-isolated outcrops. Under such conditions, the formation of meteorite crater took place (Stankowski 2001a; Stankowski

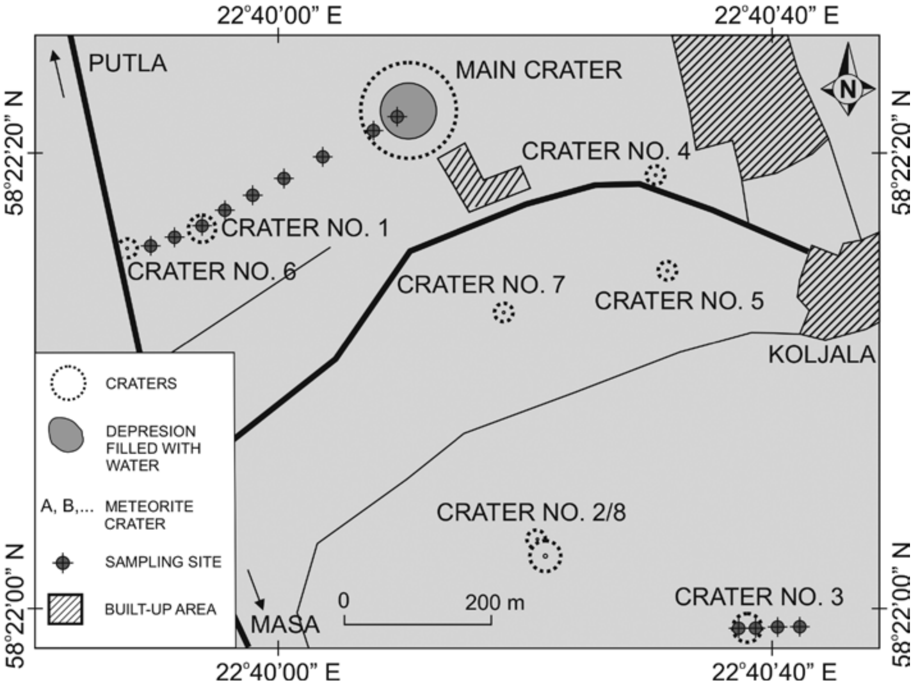

Fig. 2 Areal distribution of the Kaali craters.

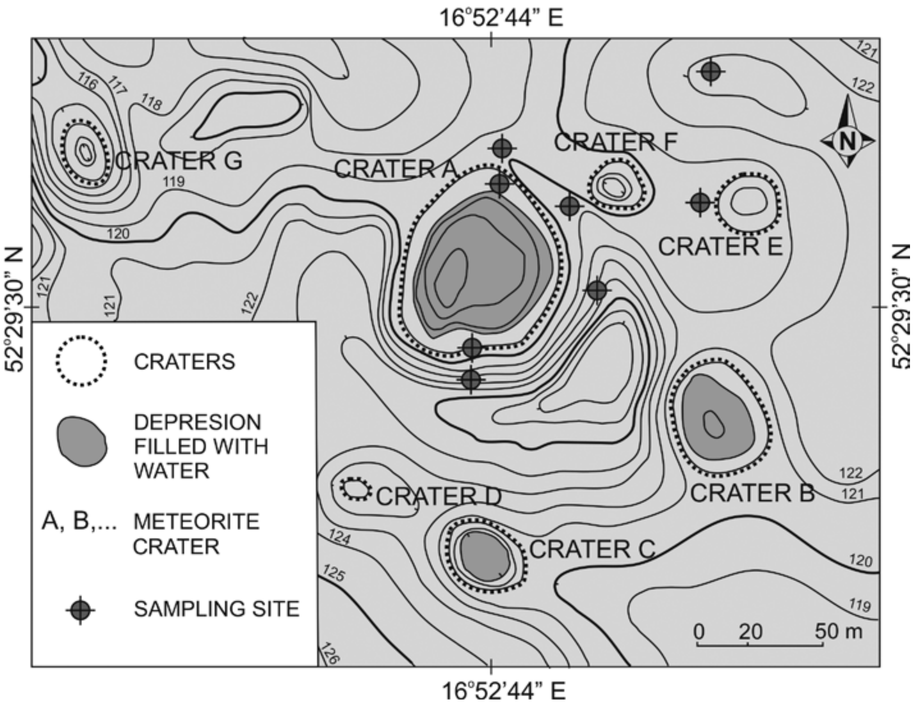

Fig. 3 Schematic outline of the Morasko craters field. Compiled by G. Uścinowicz, 2013; hypsometric drawing after Karczewski 1976, with changes,

et al. 2007; Stankowski, Muszyński 2008).

The Morasko Natural Reserve has seven closed, circular depressions (Fig. 3). The two biggest craters, marked as A and B, have a diameter of 90 and 50 metres. These craters are constantly filled by water with a depth of up to 2.5 m. Both craters are filled with thick organic material layers. The third biggest crater C (with a diameter of 30 m) is also filled by water. However, during dry years it reveals its organic bottom. Two slightly smaller craters D and E (diameter 25–20 m) gain a thin layer of water only during hydrologically moist years. They are filled with thin-layered mineral and organic-mineral sediments. The smallest crater F (diameter of 20 m) is permanently dry (Karczewski 1976; Stankowski *et al.* 2007; Stankowski 2008).

MATERIAL AND METHODS

Field work

In May 2004, the author undertook research in the area of Kaali craters. A number of boreholes (a total of eleven) and two excavations were made, from which more than 60 sediment samples were taken. The range of the fieldwork covered outside and inside rims of the main crater and craters Nos. 1, and 3. In addition, samples were taken from boreholes between the main crater, crater No. 1 and southwest from the edge of the crater No. 1. Moreover, boreholes were drilled inside the crater No. 3, and 35 m and 110 m east of its border. In addition, two excavations were performed in the rim of the main crater.

Fieldwork in the area of Morasko meteorite craters was complementary to previous studies and was conducted in the fall of 2008. The nine boreholes were drilled, primarily in the environs of the main crater and on its north–eastern borderland. The borehole depths were up to 1.5 m. Sediment samples weighing ~ 200–450 g were taken from each hole at the intervals of 0.5 m below ground surface, from the depths of 0.5, 1.0, 1.5 m, respectively. Drilling has primarily been focused on the north-east of the crater A. This refers to the earlier study of the distribution of cosmic dust, carried out in the 1970s (Hurnik 1976). In addition, several holes were made in the immediate surrounds of the secondary craters, C and E and the rims of the largest crater A.

Position of research points in Kaali has been designated in the rims of craters and in their margin. This brought satisfactory results in the form of acquired magnetic material of meteoritic origin. Application of similar method in Morasko was to bring satisfactory research material.

Methods

Samples of mineral deposits represented mainly by till and sand are characterized by relatively high solidity. Therefore, they were disintegrated in a solution of water and sodium hexametaphosphate ($Na_6O_{18}P_6$) for dispersing the particles in suspension. Then samples were washed on a sieve with a mesh size 0.063 mm. This was to get rid of dust and clay fractions. The rest of material was dried at 30° C. Dry samples from both analyzed positions, after the separation of mineral fractions, were tested with a magnet. The fine magnetic particles from the dried samples were studied using a stereomicroscope. Colour, transparency and glitter were recorded.

Scanning electron microscopy (SEM) and energy dispersive spectrometer (EDS) studies of the particles were undertaken at the Didactic Laboratory of Scanning Microscopy at Poznań Adam Mickiewicz University, Faculty of Geographical and Geological Science and at the Laboratory of Scanning Microscopy at Kraków Jagiellonian University, Department of Biology and Earth Sciences. In both cases, the samples were carbon-coated and the EDS analyses were carried out on the surfaces of the spherules. The results from these laboratories are fully comparable.

RESULTS

Kaali

The results of the research, including studies of chemical composition using microprobe analyzer allowed distinguishing four groups of the matter (Fig. 4).

Group 1: Spherules with the highest iron oxide content and with additions of nickel. The nickel content in the spheres of group 1 varies from 10% to almost total absence of this element. The predominant form is almost perfectly spherical. These spherules have dark colour and their surface is shiny with a metallic luster. Their surface texture varies from diverse, highly fractured to smooth, fine, dendritic pattern.

Group 2: Spherules with the high carbon content (from 68 to 95%). There are also admixtures of other elements: CaO (up to 18%), Fe_2O_3 (up to 9%), SiO_2 (up to 3%), CuO (up to 2%), and ZnO (up to 2%). The size of spherules ranges from 50 to 100 µm. Their form is spherical, while their surface is usually opaque and cracked.

Group 3: Spherules with different contents of oxides such as SiO_2 (from 31% to 57%), Al_2O_3 (up to 36%), Fe_2O_3 (up to 29%), MgO (up to 6%), and MnO (up to 1%). The size of spheres ranges from 50 to 200 µm. Their shape is spherical with diversified surface texture.

Group 4: Plates containing 98% of Fe_2O_3 with admixtures of titanium. These objects are black tiles with irregular, sharp edges.

Morasko

The mineral deposits that build Morasko craters and their surroundings are source of two types of spherules: dissected non-transparent, opaque, brown spherules, but also gray-black spherules with a characteristic metallic luster.

Type 1: Surface of brown spherules is clearly corroded. High degree of weathering cover is noted in the description of micrometeorites and meteorite balls drawn by previous researchers (Stankowski 2008). The size of these spherules ranged from 50 µm to 300 µm. Their surface structure is secondary and does not represent original features. It indicates its highly diverse, rough and coarse structure of the surface. The composition of the spherules is dominated by Fe_2O_3 (from 62 to 94%); also occur in a significant amount, SiO_2 (from 3 to 24%), Al_2O_3 (from 2 to 10%) and compounds such as P_2O_5, K_2O, MnO, MgO, Cr_2O_3, CaO, TiO_2. These latter are present in small quantities not exceeding 2%.

Type 2: Dark-grey spherules have a clear, smooth surface. A grain structure is visible in high magnification. This type of spherules is characterized by a smaller size, of approximately 50 µm. Their composition is characterized by the overwhelming dominance of Fe_2O_3 (ca. 96%), while a negligible share of SiO_2 (ca. 2%) and Al_2O_3 (ca. 1%). Significant is the absence of other accessory compounds.

DISCUSSION

Geological conditions at the time of fall of meteorites in Morasko (about 5000 BP) and Kaali (about 7600 BP) were similar but not without significant differences (Raukas 2000a,b; Stankowski 2008; Raukas, Stankowski 2011; Moora *et al.* 2012). Quaternary deposits, which are common in the mentioned areas, have been exposed to the factors that lead to a huge environmental transformation. In the case of Morasko craters, the morphological expression can be ambiguous. In the area of young post-glacial landscape, a similar form to relatively small craters can take hollows resulted in processes of dead ice melting, evorsion or degradation of pingos (Rutkowski *et al.* 1998; Stankowski 2001b).

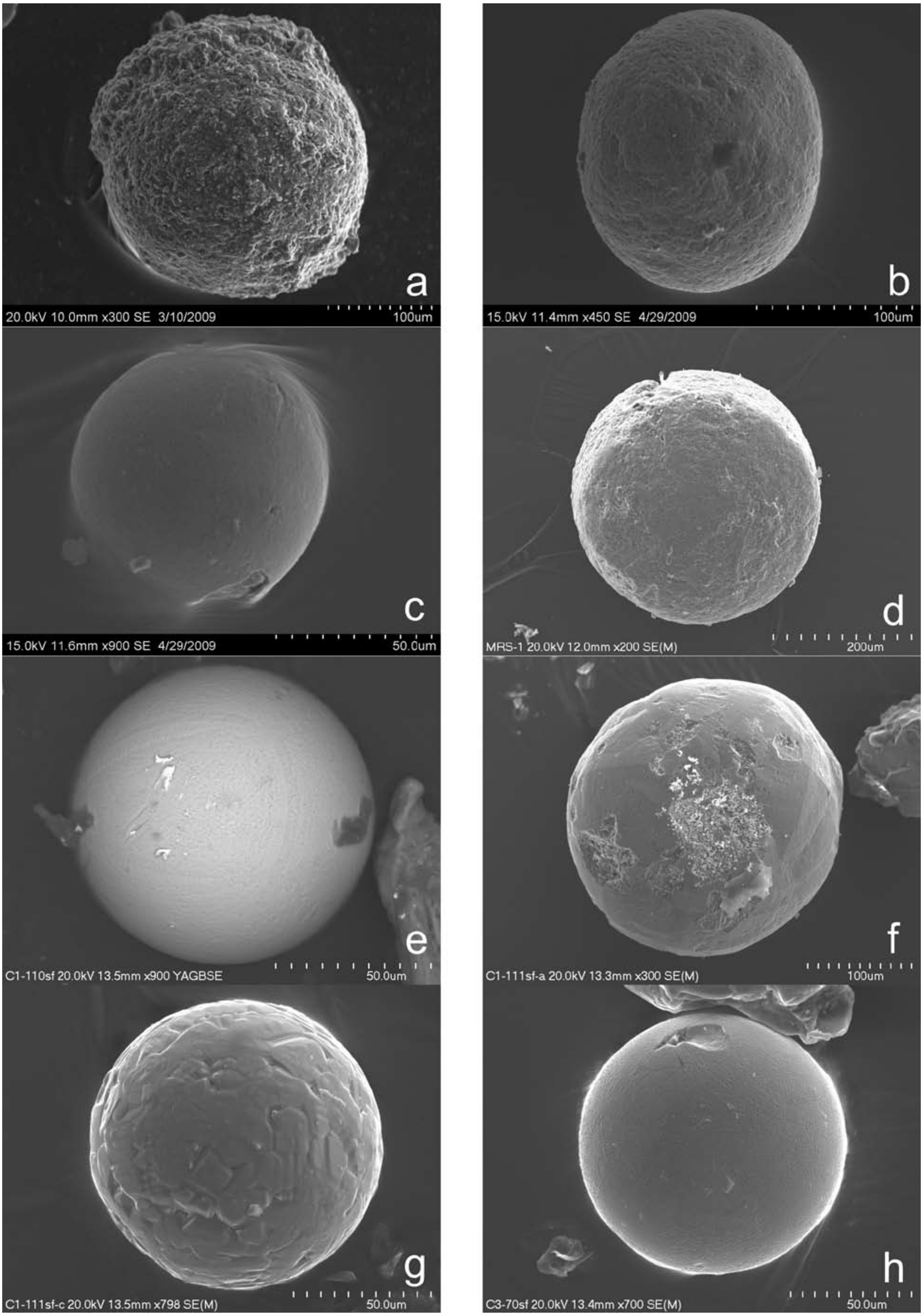

Fig. 4 Extraterrestrial spherules from the Morasko Natural Reserve: a, b, c – spherules from the rims of a crater A; d – spherule from the vicinity of the craters and Kaali crater field; e, f, g – spherules from the rims of the crater number 1; h – spherule from the crater number 3.

In the case of Kaali crater, geological situation is favourable that the thin cover of Quaternary deposits lies over the solid rocks of the Silurian age (which is significantly different from Morasko conditions). This has ensured the preservation of meteorite impact. Deflected from its original position (Fig. 5), a layer of dolostone is a tangible evidence of the forces deforming the ground (Uścinowicz 2008). In this context, the main crater appears to be a unique object in terms of preservation. However, for the practical aspect of the identification of craters of the relatively young age and those established in unconsolidated sediments, more relevant are studies of collateral craters. The study of collateral craters which genesis is clear will provide the methodological assumptions allowing the identification of depressions of unknown origin. Without a doubt, beside crater forms, they are important because of the presence of extraterrestrial matter.

As for the Morasko, the quantity of cosmic matter in the block fraction is abundant (hundreds of kilograms [kg] or even tons [t]) (Fig. 6), while there is a small number of such material in Kaali (Tiirmaa 1994; Raukas 2000b; Stankowski, Muszyński 2008). Such a situation may be caused by the dynamics and the character of a meteorite as well as the type of bedrock. However, not only a body of a meteorite testifies the rank of an event. Equally important, if not more important, is the presence of fine-grained matter in the sediment of craters and its surroundings. This kind of matter reflects the effects of the processes taking place since the meteorite has been entering the atmosphere until the fall of the object (Marini *et al*. 2004). For example, the spherules from Kaali (Group 1, mentioned above) reflect the transformation of the meteorite original material in high temperature conditions. When a meteorite enters the atmosphere, it undergoes rapid heating. This leads to partial melting and vaporization of the surface. Afterwards, this matter, upon cooling and freezing, condenses. This leads to the precipitation of metallic, condensed matter on the surface of the Earth (Raukas 2004; Uścinowicz 2008). Probably in the same phase, plates classified to Group 4 were formed, but their form suggests that they were not subjected to such intense melting as smaller fragments. Probably it resulted from fragmentation. However, spherules classified in Group 3 are likely to be a record of post-impact processes. The high temperature and pressure created favourable conditions for the penetration of terrestrial (Si, Al) and extraterrestrial (mainly Fe) elements (Raukas 2004; Uścinowicz 2008).

Fig. 5 The slope of the Kaali main crater and deflected layers of dolomite. Photo by G. Uścinowicz.

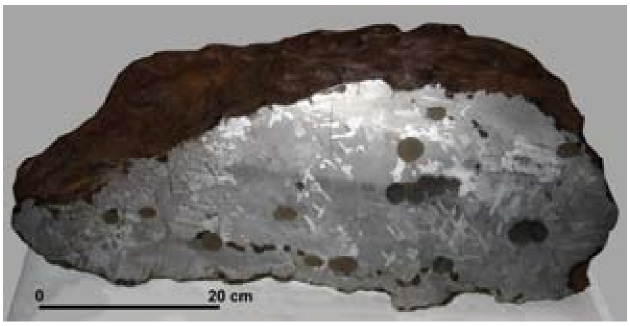

Fig. 6 The piece (weight ~ 164 kg) of meteorite Morasko found in 2006. Photo by G. Uścinowicz.

Similarly, in Morasko different types of spherules can be distinguished. The main difference lies in the fact that most of the spherules from Morasko are corroded and do not represent original features. This situation could be caused at least by two factors. Firstly, these spherules were formed in the same phase, which influenced their broad character. Secondly, the homogeneity of the forms could be due to secondary factors, which occurred after precipitation of dust on the surface of the Earth. Long-term weathering processes could lead to blurring of the original diverse structures (Lougheed 1966). It appears that the second concept is closer to the truth. This is because during the previous studies the full spectrum of distinguished ablation, fine-grained material had been found (Hurnik 1976; Stankowski *et al*. 2006). The fact that spherules are abundant in the area of craters and at the same time, there are not many of them in a wider surrounding is a strong indicator of their extraterrestrial origin. This means that the spherules get into sediment during the impact, when sediment movement occurred.

CONCLUSIONS

The conducted studies and analysis of archival materials allow for the following statements and conclusions:

The impacts of meteorites in Morasko and Kaali are comparable in terms of morphological (craters) and mineralogical (spherules) effects but not without important differences resulting from the geological structure.

Kaali craters appeared because of the impact of meteorites on the surface of solid rock, lying under the thin cover of unconsolidated sediments. This has ensured the preservation of meteorite impact and gave assumption to studying this phenomenon.

The morphological expression of Morasko craters is ambiguous. However, their meteoritic genesis has been confirmed, based on prevalence of cosmic matter.

Results of this study confirm previous data; moreover, they bring new aspects in terms of identifying the extraterrestrial spherules in the relatively young Quaternary sediments. The data obtained from the Kaali craters has been used as a comparison to the recognition of extraterrestrial matter in the Morasko sediments.

The study in Kaali made it possible to describe the four groups of magnetic matter. This kind of matter reflects the effects of the processes taking place since the meteorite has been entering the atmosphere (ablation spherules) until the fall of the object (derivative products accompanying the fall of a meteorite).

The presence of two groups of spherules of undoubtedly cosmic origin in the Morasko area has been better stated. Their extraterrestrial origin provides features such as composition, form or nature of the surface. At the same time, the amount of magnetic fraction in the sediments of a crater and its vicinity is increased in relation to the broader surrounding.

Thus, impact of similar meteorites under similar environmental conditions can generate various morphological, mineralogical and natural effects. A common point for described areas is the occurrence of secondary craters. It is important because of their formation in soft/young sediments and presence of higher amounts of extraterrestrial spherules in relation to their surroundings.

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