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DATING OF THE REO SITE (ISLAND OF SAAREMAA, ESTONIA) WITH SILICATE AND IRON MICROSPHERULES POINTS TO AN EXACT AGE OF THE FALL OF THE KAALI METEORITE

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Abstract: Pollen analyses and radiocarbon dates from the bottom sediments in the Kaali main crater suggested that the crater group is at least 4000-5000 years old. Investigations of silicate impact microspherules in surrounding mires (Raukas *et al.* 1995) put the age about 7500-7600 yr BP. Recently we found both silicate and iron microspherules from organic sediments below well-dated beach ridge in Reo site what supports the conclusions that the most realistic age of the Kaali craters is 7600±50 ^{14}C BP (8335-8537 cal BP) and the meteorite fall was from SSE to NNW.

Keywords: silicate and iron microspherules, meteorite fall, meteorite craters, radiocarbon and OSL dates.

1. INTRODUCTION

Investigation of Kaali impact craters (58º24'N, 22º40'E), 19 km NE of the town of Kuressaare on Saaremaa Island, has a long history. During last ten years the authors investigated the Kaali craters through the common project "Extraterrestrial material and impact structures in Poland and Estonia", coordinated by the Estonian Academy of Sciences and the Polish Academy of Sciences. Main attention was paid to find out the suitability of luminescence (TL and OSL) dating techniques for establishing a precise age of the impact craters in Estonia and Poland (Raukas and Stankowski, 2010, 2011; Stankowski *et al.*, 2007). Recently we reinvestigated and dated organic sediments with impact silicate and cosmic iron microspherules below a beach ridge in Reo, 7.5 km south from the Kaali main crater, pointing to an exact age of meteorite craters and indicating the meteorite fall from southeast to northwest. This direction can be concluded also on the base of dispersal ellipse of craters: small craters behind the main crater (**Fig. 1**).

2. BRIEF HISTORY OF FORMER STUDIES

Already the first investigator of craters Ivan Reinwald[1] (Reinvaldt, 1933) maintained that the Kaali craters were formed some 4000-5000 BP. The same opinion had in his first papers also Ago Aaloe (1958). The craters were formed after the retreat of the Baltic Sea from this part of Saaremaa because marine sediments in craters are absent. This implies that they must be younger than 9000 ^{14}C years (All ^{14}C dates we used, in lab. ages and relevant calibrated intervals – see **Table 1**).

[1] In the scientific literature the name Reinwald is written in different ways: Reinwald, Reinwaldt, Reinvalt. In this paper the first variant is used.

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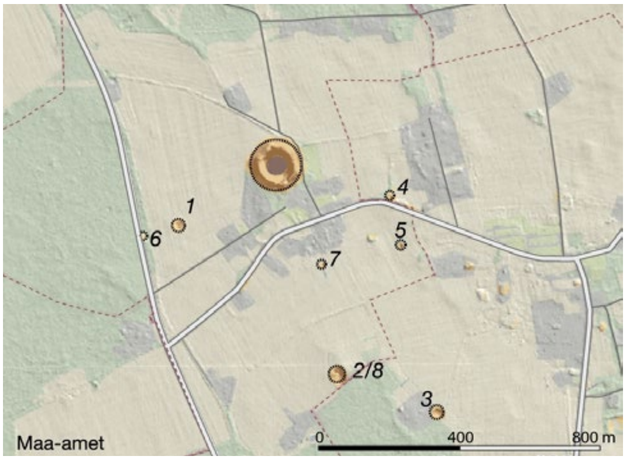

Fig. 1. *Location of the Kaali impact craters. Numbers indicate the location of small craters. Lidar projection of the Estonian Land Board.*

Based on an iridium content in peat Rasmussen *et al.* (2000) and Veski *et al.* (2001, 2002, 2004) concluded that the Kaali impact took place much later, about 800-400 BC (2800-2400 BP). This conclusion is clearly wrong. The pollen spectrum from the bottom deposits of Lake Kaali has been dated as approx. 3700 years old (Kessel, 1981) and the radiocarbon dating has yielded an age of about 4000 ^{14}C BP (Saarse *et al.*, 1991), but undoubtedly it is only the minimum age, because the accumulation of organic sediments in Lake Kaali started a rather long time after the impact. Already peat from a depth of 1.18-1.25 m gave the age of 2958±51 ^{14}C BP (Tln-2576), which after calibration is some 3220-3000 cal BP. Pollution is excluded, because a tree trunk from a nearby excavation yielded an age of 2673±47 ^{14}C BP (Tln-2573).

Investigation of silicate impact spherules in surrounding peat bogs (Raukas *et al.* 1995, Raukas 2000) put the age about 7500-7600 ^{14}C BP and it was supported by luminescent dating. Stankowski concluded (Raukas and Stankowski, 2010; 2011) that the luminescent dates about 7000 years BP indicate the moment of sedimentary infilling which must have started almost immediately after the creation of craters (data from no. 7 crater infilling material – two indicators for semi-bottom and middle section part, about 7 ka).

Until a few years ago we have found in the surroundings of Kaali only buried silicate microspherules. But recently a long search of iron spherules has been richly rewarded in Reo site, where the first author found both silicate and iron microspherules from the peaty histosol below a well-dated beach ridge.

3. INVESTIGATION OF SILICATE AND IRON FINES IN KAALI AREA

The Kaali iron meteorite belongs to the IA group of coarse octahedrites and its fragments in the Kaali crater field are rich in forms, colours and composition (Raukas, 2004, Marini *et al.*, 2004). According to Aaloe and Tiirmaa (1981), with some later modifications (Shymanovich *et al.*, 1993), the following main types of extraterrestrial matter occur in the Kaali crater field and surroundings:

1) Meteoritic iron formed as a result of the break-up of the meteorite in the atmosphere and its disintegration at the moment of impact. It occurs in the form of irregular tiny meteorite fragments and fine (mainly less than 1 mm) pulverized particles with a variety of shapes.
2) Meteoritic dust formed as a result of melting and evaporation of the rapidly upheated meteoroid during its entering of the Earth's atmosphere. The products of evaporation are represented by magnetite globules and platelets, varying in shape, internal structure and microsculpture. Globules may be spherical, rounded elliptic, ovatetubercular or drop-like.
3) Microimpactites formed on the melting and vaporization of meteoritic matter and target rocks during the impact. Both magnetite-silicate and silicate formations have been discovered.

In the second half of the 1970-s, to elaborate the direction of the meteorite fall, a systematic study of the fragments of meteors and diffuse material from satellite craters and surface sediments was carried out in the crater field (Aaloe and Tiirmaa, 1981). The work was extended on Muhu Island and also on the mainland (Tiirmaa, 1988). The first results showed that the meteorite fall was from east or northeast. The study of spherules from surface sediments met critical opponents who did not consider it possible to tell the difference between the ancient meteorite material and the pollution coming from con-

Table 1. *Results of radiocarbon dating. Dates were calibrated with using OxCal programme (Bronk Ramsey, 2009) and InCal09 calibration curve (Reimer* et al., *2009).*

No.	Lab. code	^{14}C age (BP±1σ)	Calibrated age 68.2% conf. intervals (cal BP)
1	Tln-2576	2958±51	3220-3000
2	Tln-2573	2673±47	2850-2820 (15.3%) 2800-2740 (52.9%)
3	Tln-1972	7586±67	8450-8330
4	Tln-1973	7669±46	8520-8410
5	Tln-2278	7558±65	8430-8310
6	Tln-254	7350±70	8290-8260 (8.0%) 8210-8040 (60.2%)
7	Tln-253	7165±70	8050-7930 (63.4%) 7900-7870 (4.8%)
8	Tln-3246	9498±70	11070-10950 (25.9%) 10870-10840 (3.3%) 10810-10650 (37.9%) 10620-10600 (1.1%)
9	Tln-2558	7368±68	8320-8150 (54,2%) 8120-8050 (13.9%)
10	Tln-2554	7730±120	8640-8390

temporary smithery, welding and from the chimneys of factories, located in eastern direction. Thanks to justified critics the second author got the idea of looking for meteorite diffuse material in the vicinity of Kaali in the mire deposits not having industrial influence (**Fig. 2**).

Glassy silicate microspherules (microimpactites) were found in the Lower Atlantic peat of Piila mire about 10 km northwest of the Kaali craters in the layer at a depth of 300-310 cm dated at 7586±67 (Tln-1972), 7669±46 (Tln-1973) and 7558±65 (Tln-2278) ^{14}C BP (Raukas *et al.,* 1995, 1999). Microspherules of the same age were discovered also in the Peli mire, ca. 18 km northwest of the Kaali craters, in the Pitkasoo mire in the western part of Saaremaa, about 27 km southwest of Kaali and in the Kõivasoo mire on the Hiiumaa Island ca. 65 km from the craters (**Fig. 2**, Raukas, 1997). The chemical composition of glassy microimpactites is diverse, being controlled by the character of the target rocks (Raukas, 2004). Some spherules consist mainly of silica and calcium, others from calcium and iron, and a third set of silica with a small quantity of calcium. They contain an admixture of iron and nickel, sometimes also cobalt, specific for iron meteorites. In all the above-mentioned mires, silicate microspherules were detected only in one layer showing the exact age of the meteorite impact. As a result of the Kaali impact, the heated gas stream reached a height of 6.8-7.9 km (Raukas and Laigna, 2005) and the distribution of small glassy silicate microimpactites over a vast area was a normal process. In 2000 the age of Ilumetsa meteorite fall in South-East Estonia was established (Raukas *et al.,* 2001) using the same method. No iron spherules were found in mire deposits to the W and NW from Kaali.

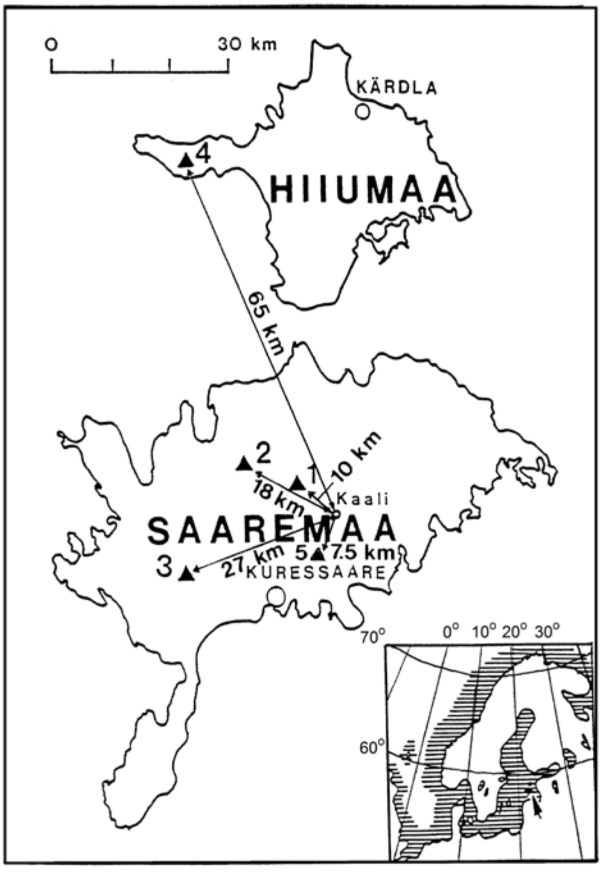

Fig. 2. *Location of investigated sites: 1 – Piila; 2 – Pelisoo; 3 – Pitkasoo; 4 – Kõivasoo; 5 – Reo.*

Magnetic fines from the Kaali impact site (Marini *et al.,* 2004) and Reo section were carefully investigated by Dr. Francois Marini. He performed SEM examinations on carbon-coated, 3D particles, coupling classical SE and BSE imaging, and systematic EDS qualitative analysis. Several grains were checked for quantitative study, using standardless XPP quantitation. He found, that Kaali fines record a wide range of air-flight-, impact-, and post-impact processes. All grains contained nickel, the highest Ni contents appear to have been directly inherited from oxidation of preexisted taenite and schreibersite. In mineral composition kamacite, taenite, schreibersite, hematite, magnetite, goethite, maghemite and wüstite were found, in coated fragments also quartz, feldspars, micas, dolomite, clay minerals and wads; organic coatings always contain Si, Ca, Mg, C, Cl, K, Na, P and S. Organic matter most probably originates from organic compounds in the surrounding sediments and from recent soils.

4. REO – A KEY SECTION FOR THE ESTABLISHING OF THE PRECISE AGE OF KAALI CRATERS

For the establishing of additional proof for the age of the Kaali impact we reinvestigated Reo-Ilpla outcrop (old gravel pit which was exhausted in 1976) between the villages of Ilpla and Reo (58º19'N, 22º40'E) 7.5 km south from the Kaali main crater (**Fig. 2**). The section is described in detail in Reintam *et al.* (2008). This paper contains also chemical, agrochemical and grain-size analyses of all layers.

In 1976, Helgi Kessel took several samples from the Kilbumäe gravel pit, which were analysed by her palynologically and dated by J.- M. Punning who received an age of 7350±70 ^{14}C BP (Tln-254) for the lower part and 7165±70 ^{14}C BP (Tln-253) for the upper part of the organic-rich layer. On the 14 m contour line marked in **Fig. 5**, in the gravel pit near the Reo graveyard there is a layer rich in birch and pine trunks. The oldest of these were recently dated to 9498±70 BP ^{14}C BP (Tln-3246).

Between 1999 and 2008, the section was thoroughly investigated by the first author who tried to find impact spherules. First iron spherule was picked up by R. Tiirmaa in 2003. In 2008 at the Reo site both silica and iron microspherules were found. Buried under coastal ridge organic material (**Fig. 3**) was dated in the radiocarbon laboratory of the Institute of Geology at Tallinn University of Technology by E. Kaup. The upper part of the layer gave an age of 7368±68 BP ^{14}C BP (Tln-2558) and lower 10 cm an age of

7730±120 ^{14}C BP (Tln-2554), well coinciding with the age of spherules from the mire sections. Silica microimpactites and cosmic iron microspherules (**Fig. 4**) were mineralogically and chemically investigated by F. Marini from National Research Center in Vandoeuvre-les-Nancy Cedex, France. Pedogenetic analysis of the layer was done by L. Reintam (Reintam *et al*., 2008).

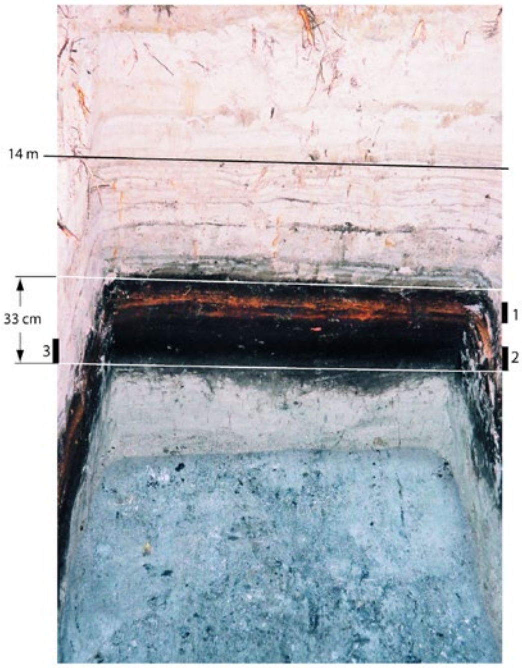

Fig. 3. *Buried organic layer with iron and silicate spherules between marine sands. Black piles from the right hand of the layer show the sampling points for the ^{14}C dating. The age of the lower part of the layer yielded 7350±70 (Tln-254) and that of the upper part 7165±70 (Tln-253) ^{14}C BP. Photo by T. Moora.*

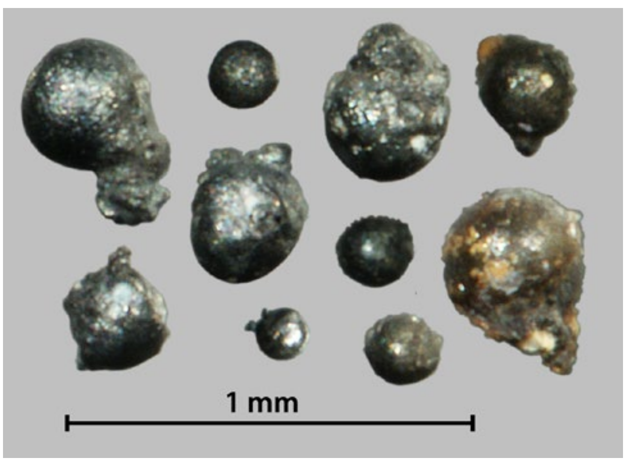

Fig. 4. *Iron spherules from the Reo Kilbumägi section. Photo by G. Baranov.*

The Holocene history of Reo-Ilpla area (**Fig. 5**) is typical for the Island of Saaremaa (Raukas, 1997; Raukas *et al.,* 1995). During the regressions of the Baltic Ice Lake and the Yoldia Sea the study area was dry land in the situation of islands or islets. In Pre-Boreal about 9300 ^{14}C BP thin silty-sandy sediments of the Ancylus Lake transgression covered the limestone surface here. If it is assumed that shallow water of the Ancylus Lake rapidly retreated from islet-like bedrock and tilly hillocks, the duration of hydromorphic pedogenesis must have been at least 2000 years until Litorina transgression once again buried the formed soil profiles under the sandy carpet. The Late Ancylus pedogenesis in Boreal Chronozone resulted in the formation of Eutric Histosol during about two millennia or even for some hundred years less.

Up to now, opinions differ as to the direction from south to northeast and angle of incidence of the Kaali meteorite. On the basis of the size and location of the craters, Reinwald (1937) and Krinov (1961) came to the conclusion that the direction of movement was from the SSE to NNW and according to Kovalevski (1954) from south to north. The morphology of the wall of the main crater, sparse geophysical data available in the destruction zones of the main and secondary craters 1 and 6 (Aaloe *et al.,* 1982) and the distribution of dispersed

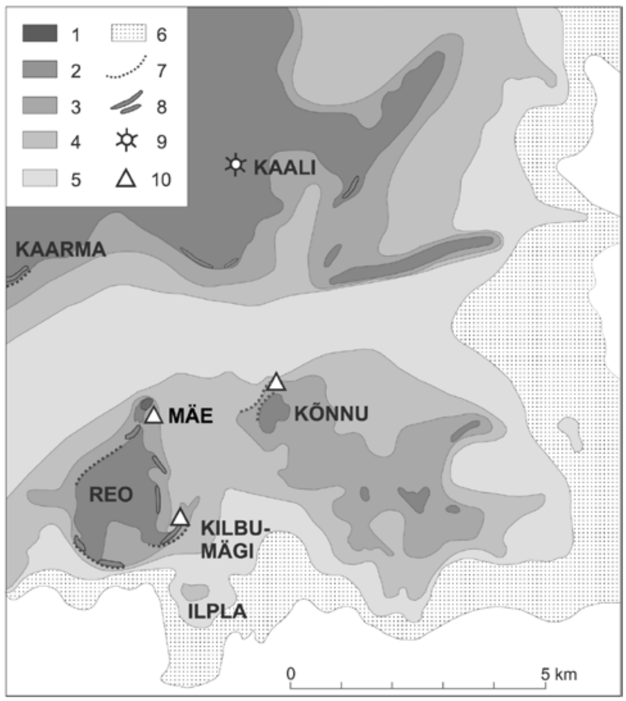

Fig. 5. *Palaeogeographical map of the Reo-Ilpla area: 1 and 2 – phases of the retreat of the Ancylus Lake; 3 – area of the maximum transgression of the Litorina Sea; 4, 5 and 6 – most important shorelines of the retreating Litorina Sea and the shoreline of the Limnea Sea; 7 – coastal scarps of the Litorina Sea maximum; 8 – beach barriers of the Litorina Sea maximum transgression; 9 – Kaali craters; 10 – early Neolithic Kõnnu settlement. Buried organic layers were found at Kilbumägi and Mäe.*

material in the craters and outside of the crater field (Aaloe and Tiirmaa, 1981, 1982, Tiirmaa, 1988) suggested that the meteorite probably fell from the east-northeast over the Pandivere elevation. This idea was strongly supported by archaeologists (Lõugas, 1996) and the former president of Estonia Lennart Meri (Meri, 1976). As we already mentioned, the magnetic spherules in surficial layers of the Estonian mainland, which according to Aaloe and Tiirmaa (1982) show the fall trajectory, are mostly industrial in origin and were probably transported to Saaremaa and western Estonia by winds from the industrial region of northeastern Estonia and Tallinn. Therefore, the explanation by Reinwald (1937), Krinov (1961) and Kovalevski (1954) is much more reasonable and now supported also by factual data from Reo.

5. CONCLUSIONS

In the Reo section we found cosmic iron globules for the first time. It allows to draw two important conclusions: 1) the most realistic age of the Kaali craters is 7600±50 yr BP (8335-8537 calibrated years in OxCal) and 2) the metorite fall was probably from SSE to NNW, because meteorite with a greater mass maintains its initial cosmic velocity for a longer time than smaller ones (**Fig. 1**). Therefore, the larger one should be in front of the dispersal ellipse, and the smaller ones behind it in decreasing order (Krinov, 1961). It explains the content of pulverised and melted iron meteoritic particles (mainly less than 1 mm in diameter) in the organic matter to the south of craters. During the impact, much silicate matter from the Earth was thrown into the air as well and glassy silicate spherules mixed with the iron particles. Other our investigated sites were to the west or north-west from the craters (**Fig. 2**) and therefore they contained only silicate spherules. The performed interdisciplinary studies assert, that Kaali craters are most probably 7600±50 radiocarbon years old (Raukas and Stankowski, 2011). In this paper we used conventional radiocarbon dates. In calibrated radiocarbon years the impact took place some 8440 years ago.

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The authors thank Mrs Reet Tiirmaa for separating impact spherules, Dr. Francois Marini for complex studies of different types of spherules in the Kaali crater field and surroundings and Prof. Loit Reintam for common field studies in Reo section. Our sincere thanks belong to reviewers of the manuscript. We are much obliged to the editor of the manuscript Dr Danuta Michczyńska for the improving our text and adding the **Table 1**, which helps the using of ^{14}C dates.

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