

**On the age of the Kaali craters, Island of Saaremaa, Estonia**

***Anto Raukas, Wojciech Stankowski***

Raukas, A., Stankowski, W., 2011. On the age of the Kaali craters, Island of Saaremaa, Estonia. *Baltica*, 24 (1), 37-44. Vilnius. ISSN 0067-3064.

**Abstract** The meteoritic origin of the Kaali craters was proved in 1937. At that time these craters were the first in Europe clearly shown to be generated by extraterrestrial forces. Up to now there have been great disagreements about the age of the craters. Reinwald (Reinvaldt 1933) maintained that the Kaali craters were formed some 4000–5000 yr BP (before present). Pollen analyses and radiocarbon dates from the bottom sediments in the main crater suggest that the Kaali crater group is at least 4000 years old. Based on the iridium content in peat Rasmussen *et al.* (2000) and Veski *et al.* (2001, 2001a, 2002) concluded that this event took place much later, about 800–400 BC (before Christ) or 2800–2400 yr BP. An investigation of impact spherules in surrounding mires (Raukas *et al.* 1995) put the age at about 7500–7600 yr BP. Optically Stimulated Luminescence (OSL) dates from satellite craters samples indicate the craters' age to be about 7000 yr BP. The most realistic estimate of the craters age is 7600±50 yr BP; younger ages are not sufficiently supported.

**Keywords** Meteorite craters, explosive energy, iridium distribution, impact spherules, OSL dates, craters age, Saaremaa Island, Estonia.

*Anto Raukas [rauкас@gi.ee], Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn; Wojciech Stankowski [stawgeo@amu.edu.pl], Institute of Geology, Adam Mickiewicz University, Makow Polnych 16, 61-606 Poznan, Poland. Manuscript submitted 17 January 2011; accepted 15 March 2011.*

## INTRODUCTION

At least nine impact craters are located in an area of one square kilometre within the Kaali crater field (58°24'N, 22°40'E), 19 km NE of the town of Kuressaare on Saaremaa Island (Fig. 1). For the first time the craters were described more than 180 years ago (Luce 1827). Ivan Reinwald<sup>1</sup> (Reinvaldt 1933), having performed several drillings in the main crater with the diameter of 105–110 m reached the conclusion that the crater had a flat and symmetrical bottom. In later publications the depression was depicted as an asymmetrical hollow with a deepened central part (Saarse *et al.* 1991). Detail information on deposits and morphology of the main crater with 98 borings and several diggings is given by Moora *et al.* (2007, 2008).

<sup>1</sup> In the scientific literature the name Reinwald is written in different ways: Reinwald, Reinvaldt, Reinvaldt, Reinvald. In this paper the first variant is used.

The meteoritic origin of Kaali craters has been proved already in 1937, but up to now there are great disagreements about the age of the craters. Reinwald (Reinvaldt 1933) maintained that the Kaali craters were formed some 4000–5000 yr BP. Pollen analyses and radiocarbon dates from the bottom sediments in the main crater suggest that the Kaali crater group is at least 4000 years old (Kessel 1981; Saarse *et al.* 1991). Based on an iridium content in peat Rasmussen *et al.* (2000) and Veski *et al.* (2001, 2001a, 2002) concluded that this event took place much later, about 800–400 BC (2800–2400 yr BP). Investigation of impact spherules in surrounding mires (Raukas *et al.* 1995) put the age about 7500–7600 yr BP. Recent OSL dates give the craters age about 7000 yr BP (Stankowski 2007; Stankowski *et al.* 2007).

In Kaali area through decades worked many famous scientists from different countries. Promising new results in the dating of craters gave the common project *Extraterrestrial material and impact structures in Po-*

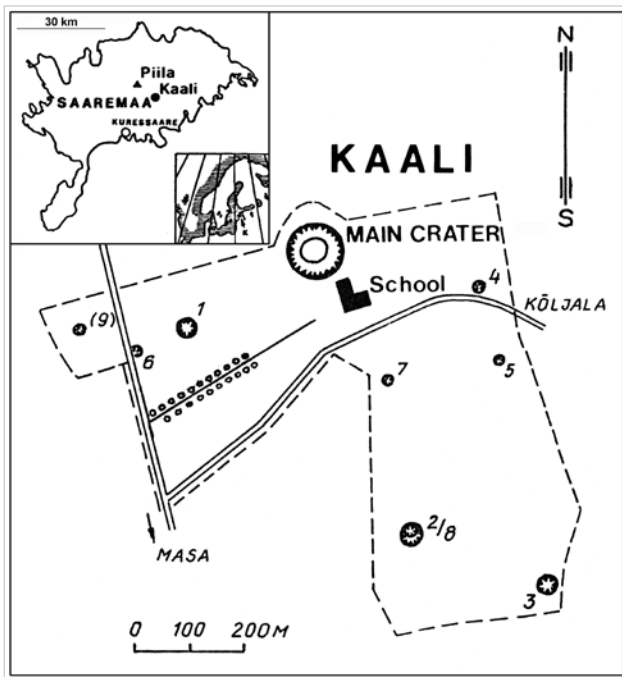


Fig. 1. Location of the Kaali impact craters and Piila mire in the central part of the Island of Saaremaa. Numbers on the map indicate the location of small craters.

land and Estonia, coordinated by Estonian Academy of Sciences (Institute of Geology at Tallinn University of Technology) and Polish Academy of Sciences (Institute of Geology, Adam Mickiewicz University). This paper is one of the results of this project.

## STUDY METHODS

Conventional radiocarbon dating of the bulk sediment samples was performed in the Institute of Geology at Tallinn University of Technology under E. Kaup management. Sampling interval for palynological analyses was 5 cm. To find impact spherules the samples of peat were burnt to ashes and after washing to remove the ash component, spherules were collected under a binocular microscope (Raukas *et al.* 1995). Samples for OSL analyses were taken by the second author from outcrops. All laboratory measurements were done in the Institute of Physics at the Silesian University of Technology under A. Bluszcz management. The laboratory procedures were described in detail in Raukas and Stankowski (2005). The meteorite impact must have been accompanied by high heat which must have turned the water in the rocks instantaneously into steam; it must also have heated the gases that formed so far that they must have caused burning of the rock not only to the depth reached by the impact, but also at much greater depths, thanks to the dense net of impact-generated cracks. The high temperatures and pressures occurring during the meteorite impact must have induced bleaching, and the luminescence ages should therefore coincide with the age of the craters.

## MORPHOLOGY AND FORMATION OF THE MAIN CRATER

The knowledge about the morphology and structure of the main crater is important for the age calculation on the base of pollen and radiocarbon studies because satellite craters are dry hollows with no datable sediments. It is important also for the calculation of the total mass of ejecta, necessary for the estimation of impact spherules distribution.

Johann Wilhelm Ludwig von Luce (1756–1842) is usually acknowledged as the discoverer of the Kaali craters as early as 1780 (Luce 1823). However, it is obvious that islanders were aware of the existence of the exotic hollows much earlier. The morphology of the main crater and uplifted dolostone rocks gave rise to several legends and tales. It was believed that the lake in the crater had no bottom and its waters were hiding an entrance to the hell. In reality the crater is 22 m deep and the water depth in the small lake is 5–6 metres during high-water periods (Fig. 2). During low-water periods the lake basin is almost dry.

Ernst Reinhold Hofman was the first to describe the structure of the Kaali main crater in 1837 (Hofman 1841). He noted that the Kaali depression bore an astonishing resemblance to maars—volcanic funnels on the Eifel plateau—and the tilt of the uplifted dolostone layers on the crater slopes indicated an explosion the force of which had been directed from bottom upwards.



Fig. 2. Lake Kaali in the main crater during the high stand of water in April 2000. Photo by R. Tiirmaa.

Hofman's theory suggesting an abrupt eruption of water, steam, gas and mud in the Kaali crater area was supported by Wangenheim von Qualen (1849), who presented a visual plan and assumable cross-section of the Kaali main crater. O. Linstow (1919), a supporter of gas eruption, presented also a scheme of the main crater, four smaller craters and the surroundings of the craters. As a source of gas eruption he considered the organic-rich *Dictyonema* argillite (alum shale) rocks well known in northern Estonia. In the area under consideration, their bedding depth is about 200 m.

In the autumn of 1927, following the order of the Mining Department of the Ministry of Trade and Industry of Estonia, Ivan Reinwald explored the solid bed in the craters by digging and boring (Reinwald 1928). One borehole was put down at the base of the main crater from outside to a depth of 63.14 m, and

two smaller ones were sunk inside the wall, the form and character of the lakebed were explored and water-level variations were studied. Reinwald mentioned huge dolostone blocks tilted upwards from inside at an angle of 30–40 degrees (Fig. 3).



Fig. 3. Dolostone blocks uplifted and destroyed during the Kaali impact about 7500 years ago. Photo by R. Tiirmaa.

Reinwald reached the conclusion that the craters were of meteoritic origin (Reinwald 1928). The same hypothesis had already been advanced in 1919 by Julius Kalkun-Kaljuvee (Kaljuvee 1933). In September 1927, E. Kraus and R. Meyer from Riga visited the Kaali area under the guidance of Reinwald. They were accompanied by Alfred Lothar Wegener (1880–1930), founder of the theory of continental drift. As a result of the short five-day field work Kraus, Meyer and Wegener (Kraus *et al.* 1928) more or less simultaneously with I. Reinwald persisted the idea of meteoritic origin of the Kaali craters. The same opinion was expressed by A. R. Hinks (1933), C. Fisher (1936, 1938) and W. Kranz (1937), but the last doubt about the genesis of the Kaali craters disappeared only in 1937 when I. Reinwald (1938) found meteoritic pieces containing nickel and iron (8.5 and 91.5 %, respectively). Thus, at that time the Kaali craters were the fourth extraterrestrial object in the world: after the Arizona (1906), Odessa (1922) and Haviland (1925) craters in the USA, which could have been generated by extraterrestrial forces.

According to Reinwald (Reinwaldt 1933), the meteorite had pierced the dolostone massif. The mighty impact caused an acute explosion which shattered the surrounding rock thereby crushing it partly into rock-flour, and throwing it upwards out of the formed crater. The focus of the explosion was presumably situated in the place of the greatest pressure, i. e. directly under the solid body. According to Reinwald, the meteorite that had produced the main crater had a diameter less than 3 m.

The energy needed for the formation of the Kaali main crater is estimated as  $4 \times 10^{19}$  ergs, and approximately two orders of magnitude less for the formation of small craters (Bronšten, Stanyukovich 1963). The

initial velocity of the meteorite with an initial mass of 400–10 000 t (most probably  $\sim 1000$  t upon entering the atmosphere) is estimated as 15–45 km/s. At the time of impact, its weight was probably 20–80 t and its velocity was 10–20 km/s (Bronšten, Stanyukovich 1963). According to G. Pokrovski (1963), the diameter of the Kaali meteorite was probably 4.8 m, its mass 450 t, and its impact velocity 21 km/s. V. I. Koval (1974) suggested a somewhat lower velocity ( $\sim 13$  km/s) of the Kaali meteorite at impact. His calculations showed that the mass of the meteorite, which produced the main crater, must have been about 40–50 t. According to Koval, the meteorites that formed the small craters may have weighed between 1 and 6 t. Thus, the force of the Kaali meteorite was too small to induce thus great environmental consequences as maintained by S. Veski *et al.* (2001, 2001a, 2002). To our mind, its explosion did not cause any serious ecological catastrophe in the surroundings (Raukas 2002; Raukas *et al.* 2003; Raukas, Laigna 2005).

If considering the main crater as a segment of a sphere with a radius  $R = 55$  m and height  $h = 18$  m, the calculated amount of the material ejected from the crater is about 81 300 m<sup>3</sup>. A hypervelocity three-dimensional gas flow ejected from the crater had a high temperature gradient with respect to the surrounding environment. The height of the velocity turbulent flow should be treated according to the equivalent heat transmission. Crater formation by a hypervelocity impact is a relatively well studied and mathematically modelled process (Melosh 1989). For comparison, data on artificial explosions could be taken. During a meteoritic impact, most of the impactor's genetic energy is transferred to the target rocks, giving rise to a short pulse of high pressure and to particle motions and ejection (Deutsch, Schärer 1994). According to calculations of A. Raukas and K.-O. Laigna (2005), some 60% of the



Fig. 4. Glassy spherules are small and light and can easily distribute to long distances. Photo by G. Baranov.

crater forming energy (ca  $1.85 \times 10^{11}$  J) was transferred to the formation of the crater and mound, as well as to

the deformation of the surrounding rocks, consisting of Upper Silurian dolostones of the Paadla Regional Stage with a thin cover of till of the last, Weichselian glaciation. According to seismic and electrometric measurements, the area of the shattered rocks surpasses the dimensions of the crater at least twice, covering about 0.1 sq. km (Aaloe *et al.* 1976.).

Taking the initial parameters of the gas flow as follows: initial temperature 2500–3000 K, initial speed 6–9 km/s, initial density 1.02 kg/m<sup>3</sup>, initial pressure  $5.6 \times 10^4$  atm, initial diameter 4.8 m, and solving the corresponding equation system, was obtained 6.8–7.9 km for the height of the gas flow (Raukas, Laigna 2005). The gas streams ejected into the atmosphere as a result of the Kaali impact could easily distribute small (mainly less than 1 mm) glassy silicate spherules over a vast area (Fig. 4). It gives good possibilities for the estimation of exact time of the impact on the base of spherules studies in lake and bog sediments (Raukas 2000, 2000a, 2004).

## ON THE AGE OF THE IMPACT

### Early age estimations

As in craters marine sediments are absent, I. Reinwald (Reinvaldt 1933) maintained that the Kaali craters were formed some 4000–5000 yr BP. The same age was mentioned in early papers of Ago Aaloe (1958). On the basis of very scanty and contradictory archaeological evidence obtained from the burning of ancient strongholds at Asva and Ridala on the Island of Saaremaa, some archaeologists reached the conclusion that the Kaali meteorite could not have fallen before the turn of the seventh to the eighth centuries BC, i.e. about 2600 years ago. History of archaeological studies is summarised in the monograph of V. Lõugas (1996).

Aaloe also changed his former opinion and started to support this incomprehensible idea. He (Aaloe *et al.* 1963, 1975; Aaloe 1981) justified his conclusion on radiocarbon dates of charcoal from the bottom of the twin craters 2 and 8 (2530±130 BP, TA-19, and 2660±250 BP, TA-22), and from the bottom of crater 4 (2920±240 BP, TA-769). He concluded that the age of the craters is 2800±100 yr BP (Aaloe 1981). A bit earlier he mentioned (Aaloe *et al.* 1975) that the “final age” of the craters is 2660±200 yr BP. With no doubts charcoal in small craters is much younger than the craters themselves, but unfortunately this very young age of craters is repeated in later publications (Lõugas 1995; Kello 2003).

Already the palynological analyses by Helgi Kessel (1981) showed that the basal sediments in the Kaali main crater are at least 3500 years old. L. Saarse *et al.* (1991) obtained a <sup>14</sup>C age of 3390±35 BP (Tln-1353) for the bottom sediments in the main Kaali crater. However, there is no proof that the sediments studied actually originated from the base of the section. The

time interval between crater formation and the age of the lowermost radiocarbon-dated sample from the crater-lake deposit is also uncertain. Undoubtedly, the heavily crushed crater bottom was for a long time dry and the sediments which accumulated during a high stand of water were washed away via cracks like in typical karst hollows. Considering all the above, there is no doubt that the Kaali craters are older than 4000 years.

### Iridium studies

But strivings to verify young age for Kaali craters are still alive (Kello 2003 a.o.) and developed even by geologists and geochemists (Rasmussen *et al.* 2000; Veski *et al.* 2001, 2001a, 2002, 2004). The analysis of trace elements in peat cores taken from the Piila mire (58°25'N, 22°36'E), 8 km northwest of the craters (Fig. 5), suggested for the impact an age of 400–370 calibrated years BC, or 2800–2400 yr BP (Rasmussen *et al.* 2000).

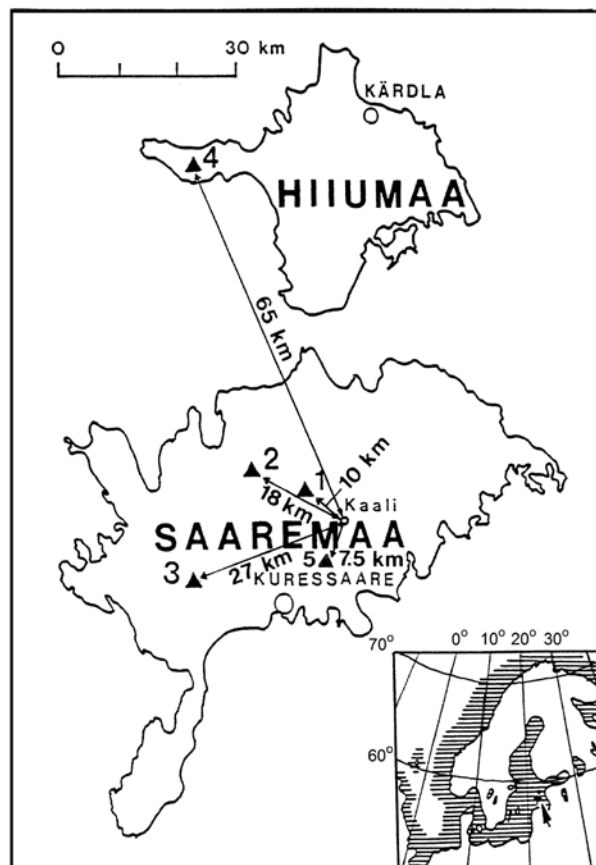


Fig. 5. Distances from Kaali to investigated sites: 1 – Piila; 2 – Pelisoo; 3 – Pitkasoo; 4 – Kõivasoo; 5 – Reo.

This weakly grounded idea was supported by Siim Veski with co-authors (Veski *et al.* 2001, 2001a, 2002, 2004). In these papers the authors assumed that the impact comparable with Hiroshima bomb caused serious geochemical (Rasmussen *et al.* 2000) and ecological changes (Veski *et al.* 2001, 2001a, 2002, 2004) in the

surrounding environment. Distinct Ir-enriched layer in Piila mire produced the age of  $2305 \pm 20$   $^{14}\text{C}$  years BP (the calibrated date, as already mentioned, is 400–370 years BC at  $\pm 1\sigma$ ). After dendrochronological calibration Veski *et al.* (2001) changed the age of enrichment ( $2560 \pm 85$   $^{14}\text{C}$  years BP) and the impact to about 800–400 years BC (2800–2400 yr BP). These conclusions are clearly wrong, because according to direct dates from the bottom of Lake Kaali, the age of the impact is undoubtedly more than 3500 years (Raukas *et al.* 2003). Already peat from a depth of 1.18–1.25 m gave the  $^{14}\text{C}$  age of  $2958 \pm 51$  BP (Tln-2576), which after dendrochronological calibration is some 3260–3050 years BP. Heavy pollution is excluded, because a tree trunk from a nearby excavation (Fig. 6) yielded the age of  $2673 \pm 47$   $^{14}\text{C}$  years BP (Tln-2573). We would



Fig. 6. Lake Kaali during low stand of water in 14 October 2000. In the excavation it can be seen big dated tree trunks. Photo by T. Moora.

like to underline that our excavations were far from the bottommost part of the main crater (Raukas *et al.* 2003; Moora *et al.* 2007). As sedimentation in the crater started long after the event, indirect methods are needed to estimate the real age of the impact. For this purposes we used OSL dating and impact spherule studies.

### Optically stimulated luminescence (OSL) dating

The first luminescence investigations in the Kaali main crater—two samples from the upper part of crater rim

dating ( $5.8 \pm 0.6$ , UG 5913; and  $5.6 \pm 0.9$ , UG 5914 ka thermoluminescent (TL) years; Stankowski 2007; Stankowski *et al.* 2007) were very promising. They were enlarged on the smaller craters dating. It should be added here that powdered dolomite at the bottom (some 20 cm beneath the impact niche) of crater 4 have given the similar TL date  $5.4 \pm 0.6$  ka BP (UG 5915).

The small secondary craters in Kaali are mostly dry and easy to investigate. Their diameter ranges from 12 to 40 m and depth from 1 to 4 m. Crater 1 is a hollow, overgrown with shrubs. The crater has a diameter of 39 m and is of 4 m deep. Uplifted dolostone layers are exposed here as in the main crater. Erratic boulders from the field have been carried into the crater and onto the rim. The crater is easily visible in the middle of cultivated land as an evenly rounded grove of trees. Two TL dates  $5.8 \pm 0.9$  ka years (UG 5916) – bleaching connected to impact and  $11.4 \pm 2.6$  ka years (UG 5917) – sediments origin time, not bleaching – have been received from the proximal slope of rim, segment S.

Twin craters 2 and 8 were formed at the impact of two separate meteorites. The traces left behind are located very close to each other, forming thus one hollow with a somewhat more complicated outline. The northern crater (No 2) is 27 m in diameter and 2 m deep, and the southern one (No 8) – 36 m and 3.5 m, respectively. The longitudinal axis of the twin crater is up to 53 m. I. Reinwald found in 1937 the first 28 meteorite fragments (total weight 102.4 g) in this twin crater (Reinwald 1938). Excavations have considerably altered the craters' preliminary appearance; the crater rim is barely visible. From the top part of rim, segment S a TL date  $9.8 \pm 2.3$  ka BP (UG 5918) and OSL date  $8.7 \pm 0.78$  ka BP (Gd TL 879) were obtained. Out of rim about 40 m to south at a depth of 60 cm an OSL date  $4.25 \pm 0.32$  ka BP (Gd TL 878) was received.

Crater 3 is the best preserved and clearly observable secondary crater. The crater surrounded by hazel shrubs is 33 m in diameter and 3.5 m deep, with a gently sloping bottom. Excavations and sampling are not allowed here.

Crater 4 has been strongly disfigured by geological excavations. Initially it was bowl like, oval in shape and 14–20 m in diameter. On the distorted bedrock surface of its bottom, I. Reinwald (Reinwald 1928) discovered a funnel-shaped trace of the impact which provided valuable information about the parameters of meteorite fall. This trace, too, has been deformed as the result of later excavations. The largest number of meteorite fragments was found directly at the crater bottom, 3–4 m away from the impact trace. In the crater bottom from powdered dolomite at a depth of 20 cm OSL age  $5.4 \pm 0.6$  ka BP (UG 5915) was obtained.

Crater 5 in its original shape resembled a flat bowl with a diameter of up to 13 m and depth up to 3 m. On the bottom of the crater is a trace of impact. This crater yielded the biggest meteorite fragment (38.4 g including a lamina of rust). The crater was not sampled for the TL dating.

Crater 6 has a diameter of 26 m and depth only 0.6 m. A lot of meteorite fragments have been found here. The crater was not sampled for the TL dating.

Crater 7 is located south of the main crater and is intensively filled in with younger man-made sediments. The diameter of the crater is 15 m, and it is about 2 m deep. Its shape resembles an irregular quadrangle. Excavations have been carried out in the crater and abundant meteorite fragments have been found there. Three samples of crater infilling material were taken for dating. The obtained result for thin layer of silty-loamy sediment from depth ~210 cm, immediately covering the solid Silurian dolostone, is 10.20±0.46 ka BP (Gd TL 929). The luminescence data of two samples of mixture the Silurian dolomite shatter and Quaternary sediments crater infilling, from depth ~175 cm, 7.09±0.34 (Gd TL 928), and from depth ~140 cm, 7.16±0.41 (Gd TL 927), seems to be a good proof of crater age.

Author's conclusion is that the dates ~7000 years BP indicate the moment of sedimentary infilling, which must have started almost immediately after the creation of craters.

### Investigation of impact spherules

During the studies of 1994 the first author with co-workers found a high concentration of glassy spherules (microimpactites) in the Lower Atlantic peat of Piila mire, about 10 km northwest of the Kaali craters. A clear concentration of silicate spherules was established in the layer at a depth of 300–310 cm (Fig. 7) dated at 7586±67 (Tln-1972), 7669±46 ((Tln-1973), and 7558±65 (Tln-2278) years BP by the <sup>14</sup>C method (Raukas *et al.* 1995). In next years, spherules of the same age were discovered in Peli mire, ca 18 km northwest of the Kaali craters, in Pitkasoo mire in the

western part of Saaremaa, about 27 km southwest of Kaali, and in Kõivasoo mire on Hiiumaa Island ca 65 km from the craters (see Fig. 5) (Raukas 1997).

Since in all the above mentioned mires silicate spherules were detected only in one layer, we proposed a new precise correlation method for Holocene sequences, based on microimpactites. The method was successfully used also in the age determinations of the Ilumetsa craters in southeast Estonia (Raukas *et al.* 2001).

For establishing of the age of Kaali impact an outcrop was recently investigated on the Island of Saaremaa between the villages of Ilpla and Reo 7.5 km to south from Kaali main crater, where buried under coastal ridge organic sediments with microimpactites were dated (see Fig. 5). Upper part of the layer gave an age 7368±70 BP (Tln-2558), and lower 10 cm an age 7773±120 BP (Tln-2554), well coinciding with Kaali impact.

### DISCUSSION

Up to the mid-70's of the 20<sup>th</sup> century, the Kaali craters were investigated mainly by geologists. Later, historians and botanists joined them. Lennart Meri, writer and former president of Estonia, analysed in his books the possible influence of the Kaali catastrophe on human recollections. He tied together disputed historical tidbits, linguistic expressions and his own thoughts into an interesting whole (Meri 1976). In the 1970s, archaeological excavations were began in the old fortification that was discovered on the outside slope of the northern wall of the main crater. Most artefacts date from the Iron Age. During the 1976–1978 excavations, archaeologists found animal bones in Lake Kaali in peat layers of over 1500–2000 years old; these bones are believed to be remnants of religious sacrifices (Lõugas 1996).

This implies many interesting legends about the origin and age of the craters (Veski *et al.* 2001), like the burning of ancient strongholds of Asva and Ridala due to an impact at about 2600 years ago. They are scientifically not tenable, as well as iridium studies, showing very young age of craters.

It is agreed, that the craters were formed after the retreat of the Baltic Sea from Saaremaa. This implies that they are younger than 8500 years. The pollen spectrum from the bottom deposits of Lake Kaali has been dated as about 3700 years old. Radio-

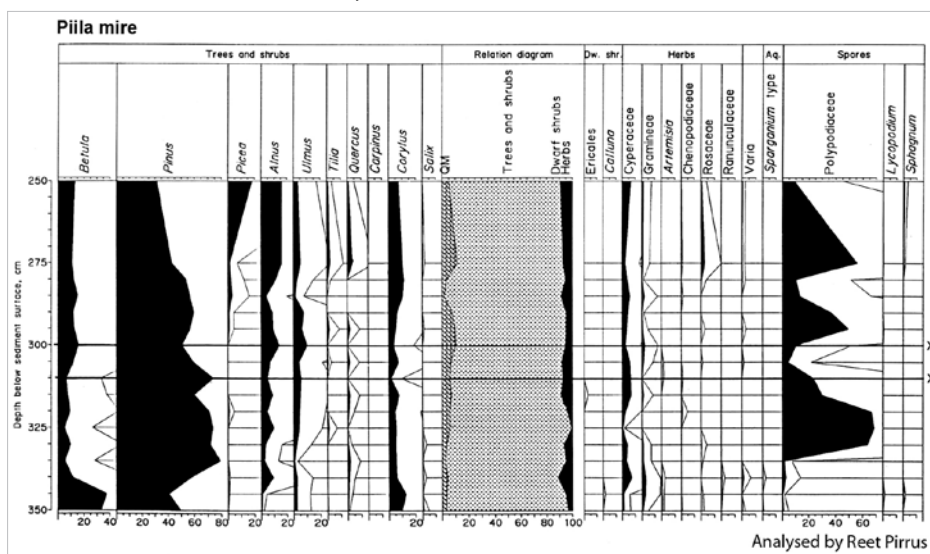


Fig. 7. Palynological diagram of Piila mire, showing the exact age of impact. A clear concentration of silicate spherules was established in the layer at a depth of 300–310 cm shown between two lines dated at 7586±67, 7669±46 and 7558±65 years BP by the <sup>14</sup>C method. Abbreviations: QM – broad-leaved trees, Aq – aquatic plants, water plants.

carbon dating has yielded an age of about 4000 years, but undoubtedly it is only minimum age, because the accumulation of sediments in the Lake Kaali started rather long time after the impact. Based on the findings of silicate spherules in the peat layer in the mires surrounding the crater field, it might be deduced that the craters formed 7500–7600 <sup>14</sup>C years ago, most probably 7600±50 years BP.

## CONCLUSIONS

The performed interdisciplinary studies, mainly in luminescence techniques and investigation of impact spherules assert that Kaali craters are most probably of 7600±50 <sup>14</sup>C years old. The time resolution of spherules studies seems to be higher than in the case of the palynological method, because in all the mires studied some local differences in pollen spectra occurred. Precise radiocarbon dating is also somewhat difficult, due to differences between dated material and variable carbonate contents. Hopefully, we could predict the age of Kaali impact with the precision of ±50 years.

## Acknowledgements

The authors thank Mrs Reet Tiirmaa for separating impact spherules and fruitful discussions. We are thankful to reviewers Dr. Francesco Nicolodi and Dr. Kalle Suuroja for careful reading of submitted paper and useful advises. The authors are most grateful to Prof. Algimantas Grigelis for constructive comments and improving the paper.

## References

- Aaloe, A., 1958. Kaalijärve meteoriidikraatri nr. 5 uurimised 1955. aastal. *ENSV TA Geoloogia Instituudi Uurimused* 2, 105–117. [Studies of Kaali meteorite crater No.5 in 1955; in Estonian, with English and Russian summaries].
- Aaloe, A., 1981. Erinevused Kaali kraatrite vanuse määran-gutes [Discrepancies in dating the Kaali meteorite craters]. *Eesti Loodus* 4, 236–237. [In Estonian, with English and Russian summaries].
- Aaloe, A., Eelsalu, H., Liiva, A., Lõugas, V., 1975. Võimalusi Kaali kraatrite vanuse täpsustamiseks [On the correction of the age of the Kaali meteorite craters]. *Eesti Loodus*, 12, 706–709. [In Estonian, with English and Russian summaries].
- Aaloe, A., Liiva, A., Ilves, E., 1963. Kaali meteoriidikraatrite vanusest [The Age of the Kaali Meteorite Craters]. *Eesti Loodus*, 5, 262–265. [In Estonian, with English and Russian summaries].
- Aaloe, A., Dabizha, B., Karnaukh, B., Starodubtsev, V., 1976. Geophysical investigations of Kaali crater. *Eesti NSV Teaduste Akadeemia Toimetised, Keemia, Geoloogia* 25 (1), 58–65. [In Russian, with English and Estonian summaries].
- Bronšten, V., Stanyukovich, K., 1963. On the fall of the Kaali meteorite. *Eesti NSV Teaduste Akadeemia Geoloogia Instituudi Uurimused* 11, 78–83. [In Russian, with English and Estonian summaries].
- Deutsch, A., Schärer, U., 1994. Dating terrestrial impact events. *Meteoritics* 29, 301–322.
- Fisher, C., 1936. The meteor crater in Estonia. *Natural History* 38 (4), 292–299.
- Fisher, C., 1938. Exploring Estonian meteor craters. *Sky Magazine of Cosmic News* 2 (5), 8–9.
- Hinks, A. R., 1933. Kurznotiz oder Überschrift. *Geographical Journal* 82, 375.
- Hofman, E., 1841. Geognostische Beobachtung auf einer Reise von Dorpat bis Abo, 1837. *Beiträge zur Kenntniss des russischen Reichs und der angrenzenden Länder Asiens* 4, 97–142.
- Kaljuvee, J., 1933. *Die Grossprobleme der Geologie*. Tallinn (Reval), F. Wassermann, 162 S.
- Kello, K., 2003. *Kaali Crater-Lake in Saaremaa. Origin, myths and legends*. Tallinn, Muinsuskaitseamet, 32 pp.
- Kessel, H., 1981. Kui vanad on Kaali järvi põhjasetted? [How old are the bottom deposits of Lake Kaali?]. *Eesti Loodus* 4, 150–155. [In Estonian, with English and Russian summaries].
- Koval, V. I., 1974. About the mass and composition of the Kaali meteorite. *Astronomicheskiye vesti* 8 (3), 169–176. [In Russian].
- Kranz, W., 1937. “Krater von Sall” auf Ösel Wahrscheinlich “Meteoritenkrater”. *Gerlands Beiträge zur Geophysik* 51, 50–55.
- Kraus, E., Meyer, R., Wegener, A., 1928. Untersuchungen über den Krater von Sall auf Ösel. *Gerlands Beiträge zur Geophysik* 20, 312–378.
- Linstow, O., 1919. Der Krater von Sall auf Oesel. *Zentralblatt für Mineralogie und Geologie* 21/22, 326–339.
- Luce, J. W. von, 1823. *Topographische Nachrichten von der Insel Oesel in medizinischer und oekonomischer Hinsicht*. Riga, Reliktenfauna XVI, 384 S.
- Lõugas, V., 1995. Must auk Saaremaa ajaloo. [Black hole in the history of Saaremaa]. *Luup* 2, 52–56. [In Estonian].
- Lõugas, V., 1996. *Kaali kraatriväljal Phaetonit otsimas*. [Investigating of the Phaeton in the Kaali crater field]. Tallinn, Eesti Entsüklopeediakirjastus, 175 pp.
- Melosh, H. J., 1989. *Impact Cratering. A Geologic Progress*. Oxford University Press, New York, 245 pp.
- Meri, L., 1976. *Hõbevalge*. [Silver white]. Tallinn, Eesti Raamat, 488 pp. [In Estonian].
- Moora, T., Raukas, A., Kestlane Ü., 2007. Kaali peakraatri setetest. [On deposits of the Kaali main crater]. *Eesti Geograafia Seltsi aastaraamat*, 36 kd., 128–143. [In Estonian].
- Moora, T., Raukas, A., Kestlane, Ü., 2008. Kaali meteoriidi peakraatri setetest. [On deposits of the Kaali meteorite main crater]. In V. Lang (Ed.), *Muinasaja teadus* 17, *Loodus, inimene ja tehnoloogia* 2, Tallinn–Tartu, 209–229. [In Estonian].
- Pokrovski, G., 1963. Computation of the parameters of a meteorite according to the crater caused by its fall.

- Eesti NSV Teaduste Akadeemia Geoloogia Instituudi Uurimused II*, 61–71. [In Russian, with English and Estonian summaries].
- Rasmussen, L. K., Aaby, B., Gwóźdz, R., 2000. The age of the Kaali meteorite craters. *Meteoritics and Planetary Science* 35, 1067–1071.
- Raukas, A., 1997. An attempt to use microimpactites in establishing the age of impact events on the example of the Kaali crater field (Estonia). *Sphaerula* 1, 32–41.
- Raukas, A., 2000. Investigation of impact spherules – a new promising method for the correlation of Quaternary deposits. *Quaternary International* 68–71, 241–242.
- Raukas, A., 2000a. Study of meteoritic matter for precise regional stratigraphy. *Geologos* 5, 77–86.
- Raukas, A., 2002. Postglacial impact events in Estonia and their influence on people and the environment. In C. Koeberl, KG MacLeod (eds), *Catastrophic events and mass extinctions: impacts and beyond*. Boulder, Colorado, Geological Society of America Special Paper 356, 563–569.
- Raukas, A., 2004. Distribution and composition of impact and extraterrestrial spherules in the Kaali area (Island of Saaremaa, Estonia). *Geochemical Journal* 38, 101–106.
- Raukas, A., Laigna, K.-O., 2005. Height of the turbulent gas flow and transport distance of glassy spherules on the example of the Kaali impact, Estonia. *Proceedings of the Estonian Academy of Sciences, Geology* 54 (3), 145–152.
- Raukas, A., Laigna, K., Moora, T., 2003. Olematu looduskatastroof Saaremaal 800–400 aastat enne Kristust. [Non-existing natural catastrophe in Saaremaa 800–400 years before Christ]. *Eesti Loodus* 1, 12–15. [In Estonian].
- Raukas, A., Pirrus, R., Rajamäe, R., Tiirmaa, R., 1995. On the age of meteorite craters at Kaali (Saaremaa Island, Estonia). *Proceedings of the Estonian Academy of Sciences, Geology* 44, 177–183.
- Raukas, A., Pirrus, R., Rajamäe, R., Tiirmaa, R., 1999. Tracing the age of the catastrophic impact event in sedimentary sequences around the Kaali meteorite craters on the Island of Saaremaa, Estonia. *Journal of the European Network of Scientific and Technical Cooperation for the Cultural Heritage (PACT)* 57, 435–453.
- Raukas, A., Stankowski, W., 2005. Influence of sedimentological composition on OSL dating of glaciofluvial deposits: examples from Estonia. *Geological Quarterly* 49 (4), 463–470.
- Raukas, A., Tiirmaa, R., Kaup, E., Kimmel, K., 2001. The age of the Ilumetsa meteorite craters in southeast Estonia. *Meteoritics and Planetary Science* 36, 1507–1514.
- Reinvald, I., 1928. Bericht über geologische Untersuchungen am Kaali järv (Krater von Sall) auf Ösel. *Loodusuurijate Seltsi Aruanded* 35, 30–70.
- Reinvald, I., 1933. Kaali järv – the Meteorite Craters on the Island of Ösel (Estonia). *Loodusuurijate Seltsi Aruanded* 39, 183–202.
- Reinwald, I., 1938. The finding of meteoritic iron in Estonian craters. A long search richly awarded. *The Sky Magazine of Cosmic News* 2 (6), 6–7.
- Saarse, L., Rajamäe, R., Heinsalu, A., Vassiljev, J., 1991. The biostratigraphy of sediments deposited in the Lake Kaali meteorite impact structure, Saaremaa Island, Estonia. *Bulletin of the Geological Society of Finland* 63, 129–139.
- Stankowski, W. T. J., 2007. Luminescence dating as a diagnostic criterion for the recognition of Quaternary impact craters. *Planetary and Space Science* 55, 871–875.
- Stankowski, W. T. J., Raukas, A., Bluszcz, A., Fedorowicz, S., 2007. Luminescence dating of the Morasko (Poland), Kaali, Ilumetsa and Tsõõrikmäe (Estonia) meteorite craters. *Geochronometria* 28, 25–29.
- Veski, S., Heinsalu, A., Kirsimäe, K., Poska, A., Saarse, L., 2001. Kaali meteorite impact induced ecological catastrophe 800–400 BC, as revealed by pollen, XRD, LOI and <sup>14</sup>C analyses of peat containing impact ejecta. In *6<sup>th</sup> ESF-IMPACT Workshop Impact Markers in the Stratigraphic Record, Abstract Book, Granada (Spain), May 19–25, 2001*, 132–135.
- Veski, S., Heinsalu, A., Kirsimäe, K., Poska, A., Saarse, L., 2001a. Ecological catastrophe in connection with the impact of the Kaali meteorite about 800–400 BC on the island of Saaremaa, Estonia. *Meteoritics and Planetary Science* 36, 1367–1375.
- Veski, S., Heinsalu, A., Kirsimäe, K., 2002. Kaali meteoriidi vanus ja mõju looduskeskkonnale Saaremaa Piila raba turbaläbilõike uuringu põhjal. [The age of the Kaali meteorite and the effect of the impact on the environment: evidence from Piila bog, Island of Saaremaa, Estonia]. *Eesti Arheoloogia Ajakiri* 6 (2), 3–20. [In Estonian with English summary].
- Veski, S., Heinsalu, A., Lang, V., Kestlane, Ü., Possnert, G., 2004. The age of the Kaali meteorite craters and the effect of the impact on the environment and man: evidence from inside the Kaali craters, island of Saaremaa, Estonia. *Vegetation History and Archaeobotany* 13, 197–206.
- Wangenheim von Qualen, F., 1849. Der Krater bei Sall auf der Insel Oesel. *Korrespondenzblatt des Naturforscher-Vereins zu Riga* 3, 48–68.