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ORIGINAL ARTICLE

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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

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Abstract The Kaali meteorite impact crater field, which consists of a 110 m diameter main crater and eight satellite craters on the island of Saaremaa, Estonia is a unique object as its meteoritic origin is well proven, it lies in a densely populated area and fell in the relatively recent past. The precise age of the impact that generated the craters is still disputed. We investigated the basal sediment section from the main crater lake, Kaali järv, consisting of crushed and in-washed dolomite diamiction. AMS dating of terrestrial macrofossils from these sediment layers places the age of the impact at 1690–1510 B.C. The age is about 1000 years older than revealed from the impact marker-horizon in a contemporaneous peat sequence 6 km northwest of the Kaali crater. The pollen, diatom and chemical data suggest the instant formation of a shallow hard-water lake environment in the main crater depression after the impact, and a rapid post-impact sedimentation of crushed dolomite dust. Archaeological evidence on the crater slopes points to human activity around 700–200 B.C., indicating that the crater ring wall was inhabited by Bronze Age people soon after the impact event, and the structure of the main crater is mimicked in nearby archaeological sites.

Keywords Meteorite impact · Lake sediment · Radiocarbon dating · Pollen · Archaeology

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Introduction

Meteorite impacts are undoubtedly important phenomena in the evolution of the Earth (Grieve 1990). All planets have been heavily bombarded by cosmic bodies, although craters on Earth have been erased by different processes and only about 170 impact craters are recognised so far. Well known massive extinctions recorded in the Earth's fossil record at the Permian–Triassic (Becker et al. 2001), Triassic–Jurassic (Olsen et al. 2002) and Cretaceous–Tertiary (Alvarez et al. 1980) boundaries have been triggered by meteorite impacts. The environmental effects of smaller and more recent impacts range from about 20 km in diameter in Meteor Crater, Arizona 50000 years ago (Kring 1997) to fairly local disturbances at Sikhote-Aline in Siberia in 1947 (Krinov 1963). From the point of view of archaeology and vegetation history one may ask whether meteorite interactions with environment and human societies are traceable, and to what extent human cultures were influenced by meteorite impacts. The role of meteorite impacts has also been recognised in recent studies on ecosystem disturbances (Seppä and Bennett 2003).

There are dozens of examples from all over the world of meteorite utilisation, worship and legends (Hartmann 2001 and references within; Santilli et al. 2003). One of them is the voyage of Pytheas, a Greek explorer, who between 350–325 B.C. visited the island Ultima Thule far in the north, where the barbarians showed him "the grave where the Sun fell dead". According to one interpretation the place was the Kaali crater on the island of Saaremaa (Meri 1976; Blomqvist 1994). Kaali is not the only Holocene crater field in this region: in fact during the last 10000 years Estonia has been the target for four crater forming impacts and at least five registered smaller meteorite falls (Fig. 1).

The Kaali craters are among the most important geological, archaeological and cultural features in Estonia and the correct age of their formation is crucial to many scientific disciplines. The investigation is a logical extension to papers by Rasmussen et al. (2000) and Veski et

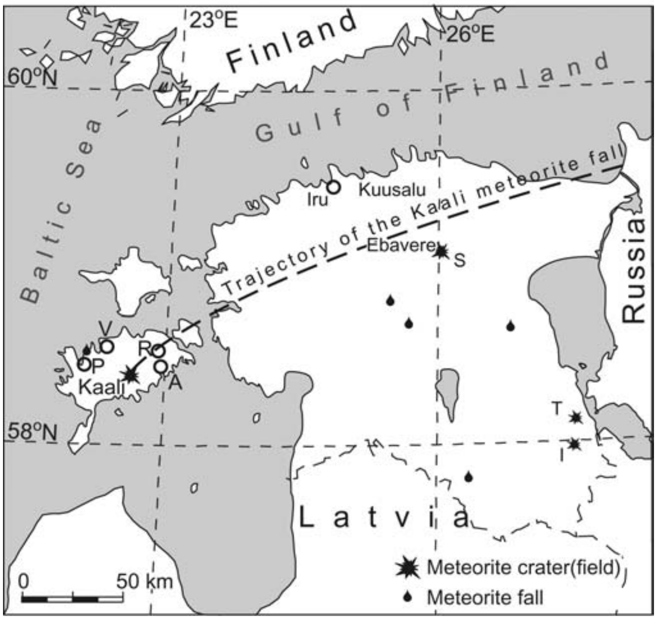

Fig. 1 Map of Estonia showing Holocene impact craters (Kaali on the island of Saaremaa, S – Simuna, T – Tsõõrikmäe, I – Ilumetsa), registered meteorite falls and places mentioned in the text (A – Asva, P – Pidula, R – Ridala, V – Võhma)

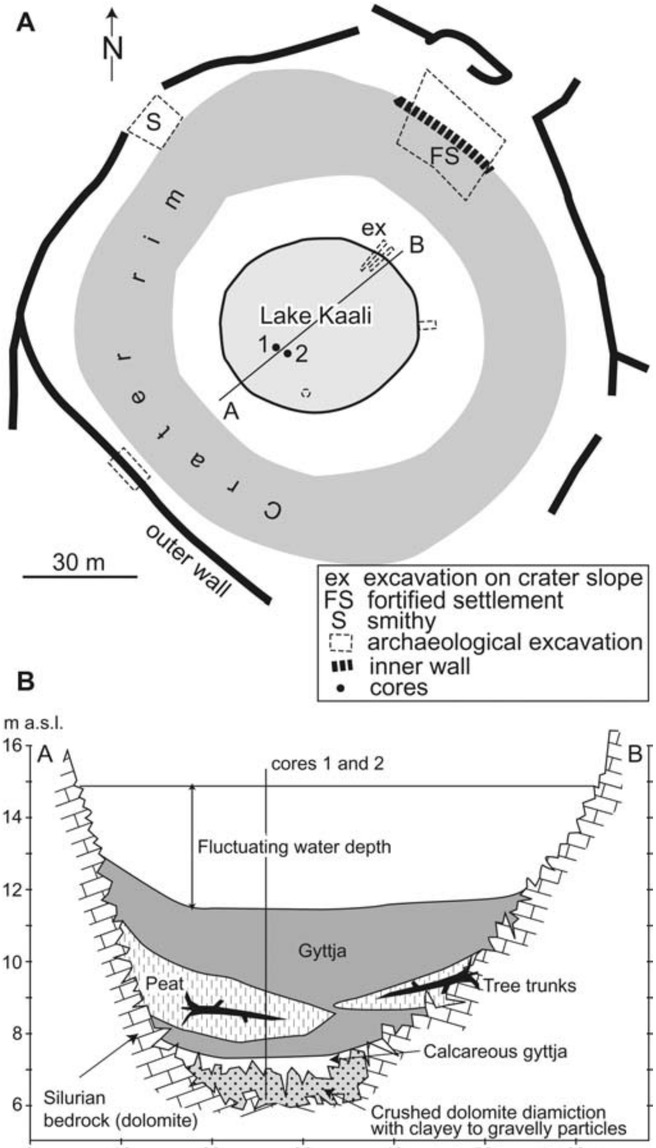

Fig. 2 A Schematic outlines of the main impact crater at Kaali, location of the cores and archaeological excavations and features discussed in the text (modified from Lõugas, 1996). **B** Geological cross-section A–B of the crater-lake showing lithological units and analysed cores

al. (2001), which focused on the evidence of the impact outside the crater area. Here we aim to investigate the Kaali craters with more traditional palaeolimnological and archaeological methods, to re-date the bottom sediments of the water-filled Kaali main crater by AMS radiocarbon dating of terrestrial macrofossils, discuss the age of the crater and the effect of the impact on the environment and contemporary people. To do that, we sampled and analysed, for the first time, the deepest minerogenic layers of the Kaali main crater (representing the meteorite impact fallback ejecta consisting of crushed dolomite debris and dolomite powder) indicating the initial post-impact filling of the crater and hence, the age of the impact.

Kaali meteorite impact craters

The Kaali meteorite impact crater field of a 110-m diameter main crater and eight satellite craters on the island of Saaremaa, Estonia (58°22’ N, 22°40’ E; Fig. 1) is a unique object as its meteoritic origin is well proven. It lies in a densely populated area and fell in the relatively recent past (Reinwald 1938; Veski et al. 2001). Kaali was an iron meteoroid of type IAB (Buchwald 1975), the resulting crater is 16 m deep (22 m from the top of the rim) and has a diameter of 105–110 m. The depression is filled with at least 5–6 m thick lake and bog deposits and a shallow crater lake (Fig. 2). The water depth of the lake fluctuates seasonally from 0.5–4 m and depends on the local groundwater level. The cluster of smaller meteoroids produced eight satellite craters with diameters ranging from 12 to 40 m and up to 4 m deep. Since the 1920s, when the craters were first described as potentially of meteoritic origin (Kalkun 1922; Kraus et al. 1928; Reinwaldt 1928), there have been discussions about their age. First Linstow (1919) estimated the age of the craters to be 8000–4000 B.C. Reinwald (1938) proved the meteoritic origin of the craters and concluded on the presence of land snails in satellite craters that the craters were young, possibly of postglacial time, and he also understood the need to perform pollen analysis on the lake sediments inside the crater for estimating the age of the meteorite fall (Reinwaldt 1933). Aaloe (1958) took into account the speed of the glacio-isostatic land uplift on the island of Saaremaa and suggested that the craters formed around

3000–2500 B.C., when the area emerged from the Litorina Sea stage of the Baltic basin. First radiocarbon dating of charcoal, wood and peat from the satellite craters suggested that they formed about 2900–2500 B.P. (1100–600 B.C.) (Aaloe et al. 1963). By interpolating the pollen evidence from a sedimentary core in the main crater, Kessel (1981) estimated the age of the impact as 3500 B.P. (around 1800 B.C.) Saarse et al. (1991) radiocarbon dated the near-bottom lake sediments of the Kaali main crater from a bulk sample of calcareous gyttja (organic mud) overlying the dolomite debris at 3390±35 B.P. (1740–1620 B.C.) and concluded the craters to be ca. 4000 ^{14}C years old. There are also several conventional ^{14}C dates obtained from different stratigraphic levels of the organic sediment sequence inside the crater yielding ages ranging from 500–1700 B.C. None of the investigators so far have dated the lowest contact of the basal minerogenic sediments in the Kaali crater.

The search for impact materials outside the crater and dating the impact by its signatures in the peat bogs next to the impact site was a new approach. ^{14}C dating of a peat layer containing glassy silicate microspherules (particles supposedly formed by melting and vaporization of impactor and target material during the impact) in bogs at various distances from the craters suggest that the impact took place much earlier (6500–6270 B.C., Raukas et al. 1995; Raukas 2000). Element analyses of peat from Piila raba (bog) 6 km northwest from the crater field, 1.5 m higher in the peat stratigraphy than previous investigators, reveal a distinct iridium-enriched layer attributed to the meteorite impact (Rasmussen et al. 2000). Radiocarbon dating of the upper surface of the peat layer enriched with Ir produced an age of the Kaali impact of 400–370 B.C. (Rasmussen et al. 2000). The research of Veski et al. (2001) was based on the results of Rasmussen et al. (2000) and using a variety of palaeoecological methods, evidence was found of distinct environmental change in the same Ir-rich layer in the area around the crater, which gave credence to interpret it in connection with the Kaali impact.

Material and methods

In winter 2001 sediment cores were collected inside the main crater at Kaali using a Russian type sampler (core 2, Fig. 2). Attention was paid to get the lower contact between minerogenic and organic sediments and to penetrate as deep as possible into the underlying minerogenic sediments. Cores were wrapped in plastic film and transported to the lab for subsampling and analyses.

Samples for pollen analysis were taken as 4 mm thick slices of sediment (volume 1 cm^3) and were prepared following the standard acetolysis procedure (Bennett and Willis 2001). Samples were treated with cold concentrated HF to remove inorganic matter. *Lycopodium* spores were added to a known volume of sediment to estimate pollen concentration and influx (Stockmarr 1971). More than 500 pollen grains were counted in each sample. Charcoal particles were counted from pollen slides and measured along the longest axis. Pollen data are expressed as percentages of the total pollen sum, concentration (pollen grains cm^{-3}) and influx values (pollen grains cm^{-2} year^{-1}). Counts of spores, algae, charcoal and other microfossils were calculated as percentages of the total pollen sum. For diatom analysis sediment samples were subjected to sequential treatment with 10% HCl and 30% H_2O_2 in order to remove carbonates and organic matter respectively, and thereafter fine and coarse mineral particles were removed by repeated decantation (Battarbee et al. 2001).

The relationship between dolomite and calcite in the sediment was analysed titrimetrically by estimating the percentage of CaO, MgO and CO_2 and calculating the percentage of dolomite $CaMg(CO_3)_2$ and calcite $CaCO_3$.

One cm thick subsamples for AMS ^{14}C dating from the basal minerogenic/organic contact and the overlying calcareous lake sediments were sieved on a 0.5 mm mesh, extracted macrofossils were identified under a binocular microscope and suitable terrestrial macrofossils were selected for radiocarbon dating at Uppsala University. Radiocarbon years were calibrated using OxCal 3.8 (Stuiver and Reimer 1993; Bronk Ramsey 2001).

Results

Sediment stratigraphy

Coring the lake and bog sediments inside the main crater of Kaali is complicated, as trees from the crater rim have fallen into the water, forming an almost impenetrable timber floor. One has to try tens of times to find a place between the tree trunks to core through the whole lake sediment sequence. The description of the studied core from the main crater is as shown in Table 1.

Mineralogy

Based on sediment mineralogical composition, the basal minerogenic sediment unit is characterised with high dolomite content (Table 2), while the calcareous gyttja overlying the crushed dolomite layer contains 83–85% of authigenic calcite (biochemically in-lake precipitated calcareous material).

Chronology

There are altogether 34 dates from inside the Kaali craters (Table 3, Fig. 3). Dates 1–4 are AMS dates on terrestrial macrofossils processed in the course of this study. Dates

Table 1 Sediment core description (depth from sediment surface, cm)

Depth, cm	Lithology
0–38	Gyttja, brown, loose, with plant debris and single grains of pebbles and gravel
38–190	Calcareous gyttja, brown, with wood debris
190–203	Coarse detritus calcareous gyttja, brown
203–280	Calcareous gyttja, brown, with plant debris
280–400	Woody fen peat (timber at 318–343 cm)
400–480	Coarse detritus calcareous gyttja, brown (timber at 433–435 cm)
480–487	Calcareous gyttja, yellow
487–547	Crushed dolomite diamiction (unsorted sediment that contains a wide range of particle sizes from clayey to gravelly particles)

Table 2 Mineralogical composition of the bottom sediments of Kaali järv (depth from sediment surface, cm)

Depth	Dolomite	Calcite
cm	$CaMg(CO_3)_2$, %	$CaCO_3$, %
485	5.87	85.23
487	8.01	83.57
488	73.23	6.70
500	79.00	4.00
525	79.50	5.40
542	75.70	6.90

1–3 are taken from core 2 (Fig. 2) and dates 4 and 5–10 were taken from an excavation in the crater slope (Fig. 2, ex), the sample depths are from ground surface (Raukas et al. 2003). Dates 11–23 (Saarse et al. 1991) were taken from a core (Fig. 2, core 1) in the SWW part of the crater lake (water depth 110 cm) of which date no 23 was taken from the basal peat layer corresponding approximately to our date no 3. Dates 24–31 come from archaeological excavations in the Kaali main crater (Saarse et al. 1991; Lang 1996) and dates 32–34 from the bottom of the dry satellite craters 2/8 and 4 at Kaali.

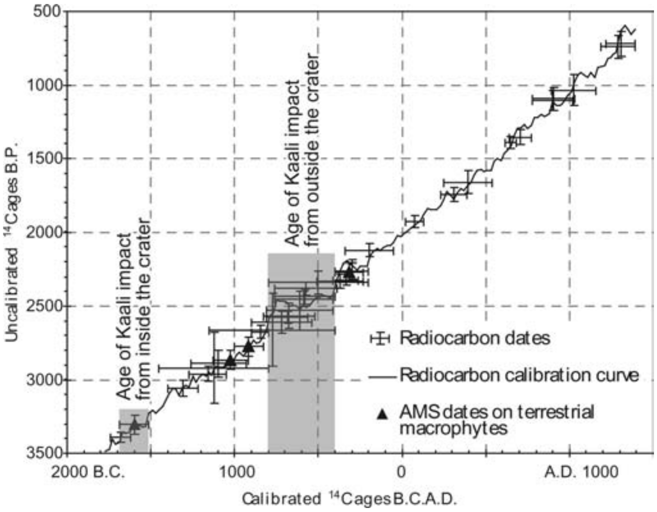

Fig. 3 ^{14}C dates from Kaali plotted on a radiocarbon calibration curve showing the 1000 year age difference of the Kaali impact event dated from inside and outside the crater area

Table 3 Radiocarbon dates from the bottom deposits of Kaali järv (No 1–23), from archaeological material on the crater rim (No 24–31) and from charcoal found inside satellite craters (No 32–33 from 2/8, No 34 from 4); depths from sediment surface

No	Crater	Depth, (cm)	Lab no.	^{14}C age B.P.	Calibrated age 1σ B.C./A.D.	$\delta^{13}C$‰ PDB	Material dated
1.	Main	487	Ua-17964	3305±65	1690–1510 B.C.	−31.0	Beetle (*Carabidae*)
2.		483	Ua-17965	2865±65	1130–920 B.C.	−28.8	*Betula* seeds+catkin scales, *Picea* needles
3.		479	Ua-17966	2775±65	1000–830 B.C.	−30.1	*Picea* needles, *Pinus* needles
4.		170	Ua-17967	2270±65	400–230 B.C.	−26.9	*Fraxinus* twig
5.		40	Tln-2571	1745±45	A.D. 230–390		Wood
6.		95	Tln-2574	2125±45	340–50 B.C.		Wood
7.		115	Tln-2573	2675±45	900–795 B.C.		Wood
8.		122	Tln-2576	2960±50	1270–1050 B.C.		Peat
9.		122	Tln-2582	2260±55	400–200 B.C.		Wood
10.		150	Tln-2575	2380±45	760–390 B.C.		Wood
11.		145	Tln-1430	720±85	A.D. 1220–1390		Gyttja (fraction >0.5 mm)
12.		145	Tln-1428	1035±105	A.D. 890–1160		Gyttja (fraction <0.5 mm)
13.		145	Tln-1402	1095±80	A.D. 780–1030		Wood
14.		155	Tln-1433	1105±70	A.D. 780–1020		Gyttja (fraction >0.5 mm)
15.		155	Tln-1401	1660±80	A.D. 250–540		Gyttja (fraction <0.5 mm)
16.		185	Tln-1502	1355±50	A.D. 640–770		Gyttja (fraction <0.5 mm)
17.		185	Tln-1503	740±80	A.D. 1190–1390		Wood
18.		365	Tln-1431	2610±75	900–540 B.C.		Gyttja (fraction >0.5 mm)
19.		365	Tln-1427	3055±55	1400–1220 B.C.		Gyttja (fraction <0.5 mm)
20.		375	Tln-1426	2260±75	400–200 B.C.		Gyttja (fraction >0.5 mm)
21.		375	Tln-1424	2565±85	830–520 B.C.		Gyttja (fraction <0.5 mm)
22.		455	Tln-1354	2575±40	810–560 B.C.		Calcareous gyttja, bulk organic matter
23.		485	Tln-1359	3390±35	1740–1620 B.C.		Peat, bulk organic matter
24.			Tln-237	2890±90	1260–930 B.C.		Wood
25.			Tln-286	2340±80	800–200 B.C.		Wood
26.			Tln-330	2330±50	510–230 B.C.		Charcoal
27.			Tln-412	1930±40	A.D. 20–130		Wood
28.			Tln-422	1390±40	A.D. 615–680		Wood
29.			Tln-288	2320±40	410–260 B.C.		Settlement layer
30.			TA-1075	2450±50	760–410 B.C.		Charcoal
31.			TA-1149	2435±50	760–400 B.C.		Charcoal
32.	2/8		TA-19	2530±130	810–410 B.C.		Charcoal
33.	2/8		TA-22	2660±250	1150–400 B.C.		Charcoal
34.	4		TA-769	2920±240	1450–800 B.C.		Charcoal

Pollen evidence

The deepest minerogenic layers of the Kaali main crater contain pollen grains and green algae. Pollen is dominated by *Betula*, *Pinus*, *Alnus* and *Quercus*, and to a lesser extent by *Picea*, *Corylus*, *Ulmus*, *Tilia*, *Fagus*, *Carpinus* and *Salix* (Fig. 4) There is about 15% of NAP pollen of which Ericaceae, Poaceae and *Artemisia* dominate. At 532 cm there is a find of *Secale* pollen. In the lowermost minerogenic sediment are indications of algae (*Pediastrum* and *Botryococcus*), water fleas (Cladocera) and water plants (*Nymphaea* hairs – intracellular branched filaments in leaves and other parts of the plant). Pollen concentration is about 150 times less than in the overlying calcareous gyttja. The four samples taken from the basal minerogenic sediments contain up to $7 \cdot 10^6$ grains of charcoal dust (particles 10–100μm) and 10^5 grains of larger charcoal particles (>100μm) per cm^3. The concentration of pollen is 50–350 times less compared to charcoal particles and ranges between 1000–3000 grains per cm^3. There is no major change in the pollen composition of the calcareous gyttja compared with the underlying sediment unit, only the pollen concentration is higher and there are apparently fewer charcoal particles in the calcareous gyttja.

Diatom evidence

The base of the core with dolomite diamiction (unsorted sediment that contains a wide range of particle sizes from clay to gravel) contains very few diatoms. The most common taxon is the epipsammic diatom, which lives attached to silty grains, *Fragilaria brevistriata*. Other species present are mostly diatoms common in shallow hard-water lakes, for example *Navicula oblonga*, *Cymbella ehrenbergii* and *Caloneis silicula*. Diatom valves are well preserved and no signs of dissolution were observed. The absolute abundance of diatoms is extraordinary low, with 1900–2200 valves gr^{-1} sediment. In the calcareous gyttja overlaying the minerogenic sediment section, diatoms are very sparsely distributed and the diatom valves observed are highly degraded and bear clear traces of dissolution. In a few cases the remains are better preserved and epiphytic diatoms such as *Cocconeis placentula* and *Epithemia adnata*, as well as epipsammic *Fragilaria pinnata* and *F. brevistriata* were recognised. Due to dissolution, the absolute abundance of microfossils was not calculated for this sediment section.

Archaeological evidence

The island of Saaremaa has been inhabited since the Mesolithic period, around 5800 B.C. (Kriiska 2000). During the Neolithic and Bronze Ages, Saaremaa was densely populated, and half of the bronze artefacts of Estonia originate from this island (Ligi 1992). Three late Bronze Age fortified settlements, Asva, Ridala and Kaali, are known from Saaremaa. The main economy was cattle rearing and agriculture. Continuous signs of crop cultivation on the island of Saaremaa appear approximately 2300 B.C. (Poska and Saarse 2002). Archaeological evidence around, inside, and on the Kaali crater slopes (Lõugas 1978b) suggests human habitation since 700–200 B.C. This conclusion is based on artefacts and three radiocarbon dates from an archaeological setting, a late Bronze Age fortified settlement or ceremonial site on the north-eastern part of the crater rim (Fig. 2). The site was defended by a ~110 m long, 2 m wide and at least 2.2 m high stone wall on the outside. The surface area of the site was small, ca. 600–800 m^2. Another 2.3–2.8 m wide and 470 m long stone wall consisting of granite blocks up to 1.8 m in diameter embraces the whole main crater. Thus the Kaali archaeological monument consists of a lake surrounded by two concentric circles: the rim formed as a result of the meteorite impact, and a man-made stone wall. The site (135 m^2) was archaeologically investigated by Vello Lõugas in 1976–1979 (Lõugas 1978a, 1978b, 1980). Remains of at least two rectangular buildings or platforms were partly excavated, yet their function was unclear. By the side of the inner wall there was a burnt layer together with remains of burnt logs. Radiocarbon samples date this site from the late Bronze Age to early pre-Roman Iron Age (Table 3; dates 29–31). Archaeological find assemblage (AI 4915)[1] of the site is rich in pottery characteristic of other fortified sites of that period on the island of Saaremaa and northern Estonia, for example Asva, Ridala and Iru (Lang 1996, Plates IV–VII). In addition, 20 fragments of clay moulds and crucibles for bronze casting, 8 pieces of amber, a double-button and arrowhead of bone, and several bone awls and fragments of other bone artefacts were discovered. All this material is likewise characteristic of the other fortified sites. An interesting find was a silver hoard consisting of a neck-ring, a spiral bracelet and a finger-ring. The hoard was found in the uppermost horizon of the cultural layer and is obviously of later, Iron Age date. There is no data about the time of the erection of the outer wall of massive stones, although a length of 10 m was archaeologically excavated. The stone wall consists of two layers, an obviously much older lower part and a narrower wall covering partly the older one. The excavations yielded large amounts of animal bone (cattle, horse, pig, dog, and sheep) found by the innermost side of the wall: no finds were observed outside the wall. The bones could be connected with sacrifice. One single sherd of a hand-moulded pot from the uppermost wall-layer confirms that the construction took place in prehistoric times, perhaps contemporary with the fortification on the crater rim. In addition, remains of a smithy (A.D. 17th–18th century) were discovered inside the outer stone wall (Fig. 2).

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[1] AI – Archaeological collections of the Institute of History, Tallinn.

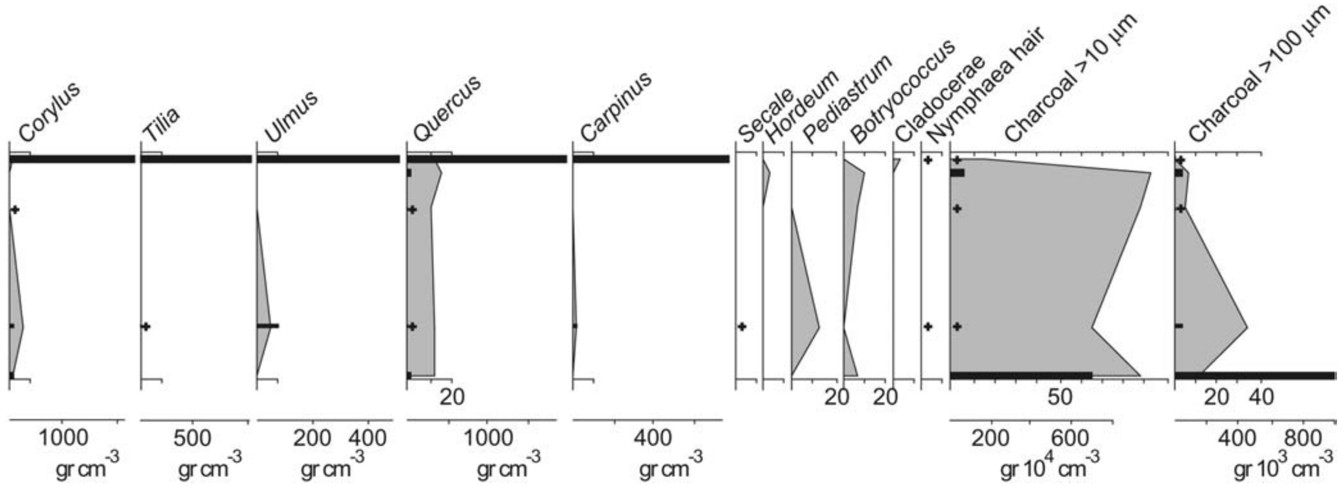


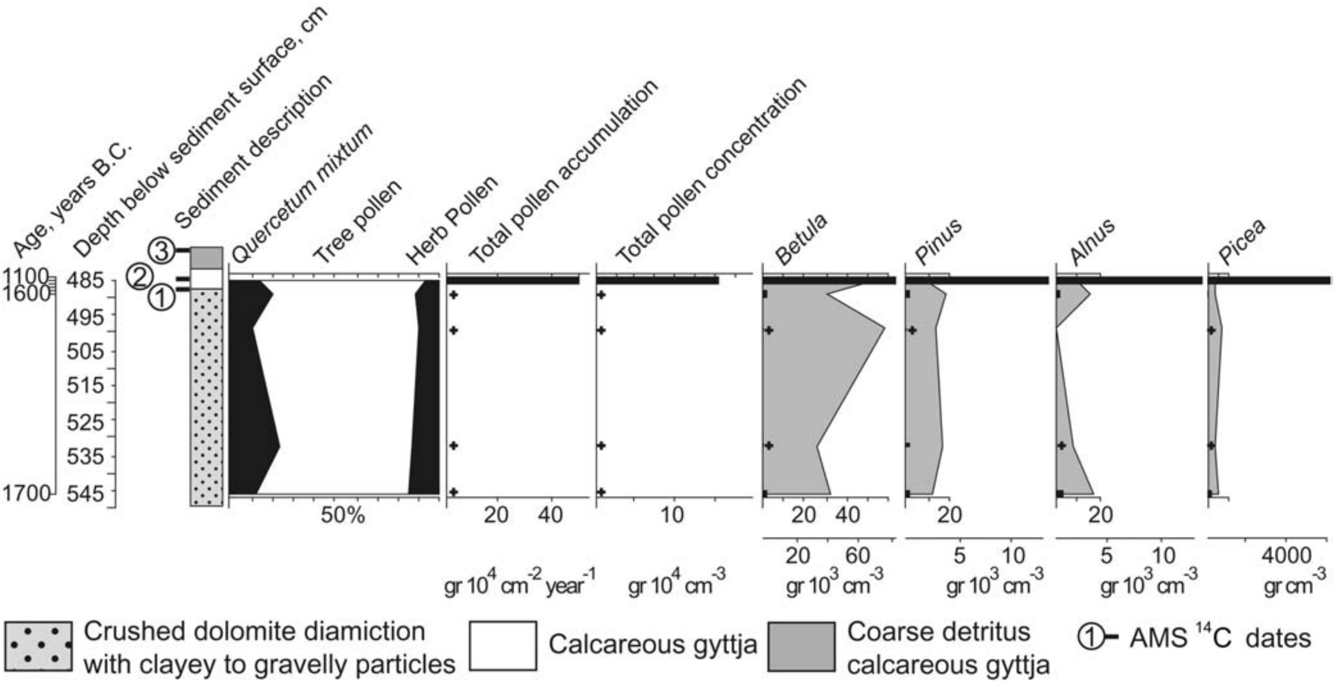
Fig. 4 Pollen diagram from the basal sediments of Kaali järv (core 2) showing pollen percentages (curves) and pollen concentration (grains · cm^{-3}), (bars and crosses) of selected taxa and the total accumulation of pollen (grains · cm^{-2} · yr^{-1}). Crosses indicate low concentration values not able to be seen on the diagram due to vast differences in concentration. Numbers of the AMS radiocarbon dates correspond to Table 3

Discussion

Age of the craters and their early environment

Currently there are three contradicting hypotheses about the age of the Kaali meteorite impact. Two rely on ^{14}C dating of peat layers with extraterrestrial material and impact ejecta found in nearby bogs. The horizon with siliceous microspherules in the peat of Piila raba (bog) is dated back to about 6400 B.C. (Raukas 2000), and the one with elevated cosmic Ir to about 800–400 B.C. (Rasmussen et al. 2000; Veski et al. 2001). The third, more classic approach radiocarbon dated a bulk sediment sample from the near-bottom lake sediments of the Kaali main crater to 1740–1620 B.C. (Saarse et al. 1991). We do not go into details in discussing all of these approaches, but maybe just mention that the results scatter greatly and the rather early date of the impact put forward by Raukas (2000) has been debated in several occasions (Rasmussen et al. 2000; Veski et al. 2001, 2002).

We assume that the impact crater forming process was very short, a matter of seconds. After the “smoke cleared” the crater was a conical empty hole in the Silurian dolomite bedrock coated with loose crushed dolomite and dolomite powder. The loose material was gradually washed to the bottom of the crater where it formed the lowest sedimentary unit, the allochtonous dolomite diamiction. The lowest sedimentary unit in the crater clearly represents the local dolomite bedrock as shown by sediment composition (Table 2) with an admixture of meteoritic matter suggested by the elevated content 0.8±0.1 ppb of Iridium at 563–572 cm (Veski et al 2001). This replacement and accumulation of the loose material must have been a rather rapid process, years, maybe tens of years but certainly a shorter period than the radiocarbon analysis error margins. So the contact between the upper surface of the dolomite powder and the overlying calcareous gyttja possibly tells us about the age of the crater. We dated a complete terrestrial beetle (*Carabidae*) from the contact at 487 cm to 3305±65 B.P. 1690–1510 B.C. (date no 1, Table 3). The age is consistent with an earlier near-bottom age 1740–1620 B.C. (date no 23, Table 3), but the latter was processed from a bulk sample of organic matter. It is always possible that sediment disturbances, mixing with inwashed old humus and/or hard-water effect can influence radiocarbon measurements from sediments of shallow hard-water lakes such as Kaali järv. Anyhow, the 1690–1510 B.C. age of the Kaali crater is up to now the best age estimate from inside the main crater. One can argue that there is a possibility that AMS dates on terrestrial macrofossils from extremely calcareous environments can suffer from old carbon error. Meaning that, in a fresh gravel-pit in completely calcareous material (as the young crater was), the plants started to grow on broken-up dolomite. Might this have affected the pine and spruce needles and the organisms we dated? Could a small new pine/spruce tree growing inside the Kaali crater during the first years after the impact incorporate infinitely old CO_2 into their needles from the Silurian dolomite rock powder? The release of CO_2 gas could take place when rock powder and the acid of decaying plant material react. Since spruce and pine have a CO_2 uptake from the atmosphere for the formation of cellulose, the only way the ^{14}C values could have been affected by old carbon should have been by an enhanced atmospheric concentration of old CO_2 released from the calcareous soil. The 22 m deep crater pit could act as a local CO_2 anomaly, comparable to active volcanic areas. Radiocarbon dating of plants growing near hot springs in active volcanic areas in western Germany yielded radiocarbon ages 1500 years too old (Bruns et al. 1980). The same authors found that 200 m away from the volcanic source, plants yielded an age in agreement with that expected. Estonia is not a volcanic area, however, the fresh crater could have acted as a CO_2



anomaly emanating ^{14}C-free CO$_2$ assimilated by plants growing in the crater and leading to considerably older radiocarbon ages similar to samples affected by reservoir and hard-water effects.

Very low pollen concentration in the dolomite dust shows that the sedimentation rate in the crater after the impact was high, estimated to be about 3 cm y^{-1}. The AMS dates from the same sequence show that, compared to the underlying sediment unit, the sedimentation rate of the calcareous gyttja in the young crater lake was low 0.01–0.04 cm y^{-1}, accelerating to 0.04 cm y^{-1} in the overlying peat.

The basal sedimentary unit in the crater is not devoid of microfossil evidence as may be thought. Apart from a large number of 10–100 μm charcoal particles ($7 \cdot 10^6$ grains cm^{-3}), which can be expected inside the meteorite crater, there are pollen grains (10^3 grains cm^{-3}), green algae and diatoms in the sediment. Pollen may have originated from the pre-impact target soil and redeposited into the crater, but diatoms and the green algae *Pediastrum* and *Botryococcus*, remains of water fleas (Cladocera) and water plants (*Nymphaea* hairs) show that the lowermost minerogenic sediments accumulated in the water of a crater lake. Pollen concentration is about 150 times lower than in the overlying calcareous gyttja. As noted earlier (Saarse et al. 1991) the basal pollen spectra are very difficult to attach to a certain time period. Considering the immigration of *Picea* to Saaremaa (Saarse et al. 1999) the basal layers of the Kaali crater must be younger than 3800 B.C. A find of *Secale* pollen at 532 cm also supports the relatively young age of the crater as sparse grains of rye pollen appear about 1000 B.C. in Estonia (not necessarily meaning the start of rye cultivation). There is no major change in the pollen composition of the calcareous gyttja compared with the underlying sediment, only the pollen concentration is larger and there is less charcoal in the sediment indicating no hiatuses in the sedimentation. All that speaks in favour of the Bronze Age/pre-Roman Iron Age date of the craters.

The signal of the impact explosion in Piila raba (bog), outside the target area, shows that the surroundings were swept clean of woodland indicated by the threefold decrease in the total pollen influx (especially tree pollen influx), increase in influx and diversity of herb taxa, and the relative dominance of pine (Veski et al. 2001). Increased input of mineral matter measured by loss-on-ignition and the composition of mineral matter (increased input of allochthonous minerals) together with an extensive layer of burnt peat in Piila raba (bog) at the same depth interval points to an ecological catastrophe, with local impact-induced wildfires reaching at least 6 km northwest of the epicentre at Kaali. The disappearance of cereals from the pollen record suggests that farming, cultivation and possibly human habitation in the region ceased for a time.

To support his theory that the Kaali meteorite fell around 6400 B.C. Raukas et al. (1995, 2003) suggest that the crater had been dry for several thousand years or due to fractured bedrock around and in the crater it was not dry but intensive groundwater flow in the dolomite fissures precluded the formation of a stable water table and accumulation of sediments inside the crater itself. Biostratigraphic evidence such as diatoms, green algae and pollen of water plants from the basal minerogenic sediments underlying the calcareous gyttja clearly indicates accumulation in a small lake, though the concentration of microfossils in the minerogenic sediment is very low. The reason for that can be a very low productivity. We, however, suggest that immediately after the crater formation ejected material from the steep slopes of the crater and from its nearest vicinity was rapidly transported into the small basin, which had formed inside the crater. Thus a low concentration of pollen and diatoms can be attributed to the high sedimentation rates causing a pronounced dilution effect in the sediment. Moreover, if the crater was formed at 6400 B.C., the water level of the Baltic Sea basin situated about 2 km away from Kaali at that time was approximately 16 m a.s.l. This means that the bottom of the Kaali main crater had to be at least 9 m below the contemporary sea-level and consequently filled with water as the groundwater level cannot be lower than the sea-level (Veski et al. 2002). If that holds true it is very difficult to explain the lack of sediments in Kaali järv between 6400–1600 B.C., the difference of the age estimation of Raukas et al. (1995) and Rasmussen et al. (2000) and Veski et al. (2001) respectively.

Effect of the impact on the contemporary people

The Kaali archaeological site has for years been connected with the phenomenon of Estonian and east Baltic fortified settlements of the late Bronze and (early) pre-Roman Iron Ages (Jaanits et al. 1982). The characteristic features of the fortifications are 1) location close to main water routes (sea, rivers), 2) either natural or modest manmade fortifications, 3) large occupation areas indicating that numerous people lived there, 4) traces of agricultural activities and bronze casting. The Kaali complex, however, was located 7–10 km away from the Bronze Age sea coast – so, its “strategic position” differed remarkably from the other fortified sites. The surface area of the Kaali enclosure is tens of times smaller than that of the other fortified sites; hence, the population which could live there had to be very small. At the same time, the amount of labour put into the erection of these fortifications was tens of times larger than in the case of the other fortified settlement sites. As there is also clear evidence of sacrifices and reports from medieval written sources that Kaalijärv was considered holy, the function of this ancient complex should be regarded as primarily ceremonial.

When people started to regard this crater and lake as holy is not clear, but it probably happened rather soon after the fall of the meteorite when human memory about the impact event was still alive. It is highly possible that the legend written down in the chronicle of Henry the Livonian (*Heinrici Chronicon Livoniae*, early 13th century, in Kleis and Tarvel 1982) about god Tharapita (Taara) who was born on the hill of Ebavere (located in northeast Estonia, on the trajectory of the meteorite, see Fig. 1) and flew to the island of Saaremaa from there is a reflection of this event. In the Finnish epic Kalevala there is a song about the Sun which fell to the earth into the lake called Alue, burning everything on its way (Kalevala, ILVII, in Lönnrot 1985). In addition, songs in north Estonian (Kuusalu) folklore describe the burning of the island of Saaremaa. Of course, there is no scientific verification that all these tales are reflections of the Kaali meteorite explosion but we cannot exclude the possibility.

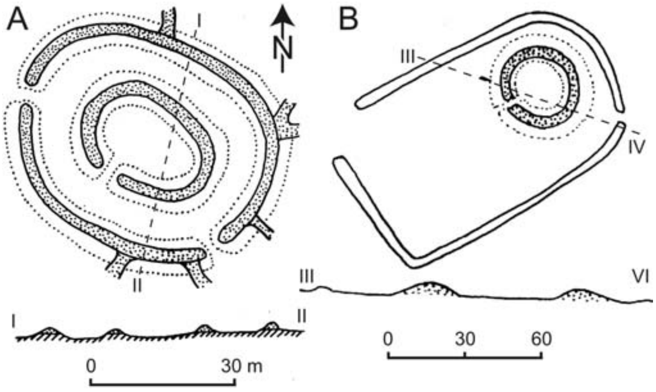


Fig. 5 Archaeological sites on the island of Saaremaa that seem to mirror the Kaali complex, having two concentric circles built of stones. A – Võhma. B – Pidula. Both from northwest Saaremaa, see Fig. 1

It is also noteworthy that there are some archaeological sites on Saaremaa the structure of which seem to mirror that of the Kaali complex, consisting of two concentric circles built of stones. The best example comes from Võhma and Pidula (Fig. 5). Small-scale excavations at Võhma in 1986 by V. Lõugas yielded finds from the late Neolithic and early Iron Age (AI 5370); yet, the stratigraphy and building period of this site is unclear. As the amount of labour put into the building of such a small site (the interior area measures 30×15 m) had to be large, the Võhma site is a place erected for ceremonial purposes rather than for ordinary defence. A sign consisting of either two concentric circles or a central point surrounded with one circle is a common symbol of the sun. In Estonia, this symbol is widely reflected in the structure of stone-cist graves dated from the late Bronze and early pre-Roman Iron Ages (ca 1000–200 B.C.), that is from more or less the same period when the fortified ceremonial site by the Kaali crater was used. Such graves are also known in the surroundings of Kaali, especially a couple of kilometres northwest of the lake; yet, they have not been investigated so far.

Conclusions

1. AMS dating of terrestrial macrofossils from the deepest part of the meteorite impact crater-lake at Kaali, island of Saaremaa, Estonia places the age of the impact at 1690–1510 B.C. The age agrees with previous research inside the crater, but is about 1000 years older than revealed from impact marker-horizon radiocarbon dating in a contemporaneous peat sequence, yet those two signatures reflect the same impact event. The microspherules discovered by Raukas et al. (1995) could indicate another much older event not connected with the Kaali impact.

2. Chemical, pollen and diatom analyses from the bottom sediments of Kaali järv indicate that post-impact rapid sedimentation of loose crushed dolomite debris took place in a shallow lake and that there seem to be no hiatuses in the sedimentation. Consequently the lowermost sediment contact of Kaali järv can be used for radiocarbon dating of the impact event.
3. Biostratigraphic material is difficult to interprete in terms of impact age, but pollen grains of *Secale* and *Picea* in the bottom sediments of Kaali järv indicate that the impact was not earlier than 3800 B.C.
4. Archaeological evidence on the crater slopes points to ceremonial activity since 700–200 B.C., and the structure of the main impact crater is mimicked in nearby archaeological sites. Some other evidence as well points towards the importance of meteorite impacts to prehistoric societies.

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