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Ecological catastrophe in connection with the impact of the Kaali meteorite about 800–400 B.C. on the island of Saaremaa, Estonia

SIIM VESKI[1]*, ATKO HEINSALU[1], KALLE KIRSIMÄE[2,3], ANNELI POSKA[1,4] AND LEILI SAARSE[1]

[1]Institute of Geology at Tallinn Technical University, Estonia pst. 7, 10143 Tallinn, Estonia
[2]Institute of Geology, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia
[3]Institute of Geography, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia
[4]Department of Earth Sciences/Quaternary Geology, Villavägen 16, S-75236 Uppsala, Sweden
*Correspondence author's e-mail address: veski@gi.ee

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Abstract–A sequence of peat enriched with impact ejecta (allochthonous minerals and iridium) from Piila bog, 6 km away from the Kaali impact crater (island of Saaremaa, Estonia), was examined using pollen, radiocarbon, loss-on-ignition, and x-ray diffraction analyses to date and assess the environmental effect of the impact. The vegetation in the surroundings of the Piila bog before the Kaali impact was a fen surrounded by forest in natural conditions. Significant changes occur in pollen accumulation and composition of pollen in the depth interval 170–178 cm, which contains above background values of iridium (up to 0.53 ppb). Two samples from the basal silt layer inside the main crater at Kaali contain 0.8 ppb of iridium, showing that iridium was present in the impact ejecta. The impact explosion swept the surroundings clean of forest shown 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. Increased input of mineral matter measured by loss-on-ignition and the composition mineral matter (increased input of allochthonous minerals) together with an extensive layer of charcoal and wood stumps in Piila bog at the same depth interval points to an ecological catastrophe, with local impact-induced wildfires reaching at least 6 km northwest of the epicenter. The disappearance of cereals in the pollen record suggests that farming, cultivation and possibly human habitation in the region ceased for a period of ~100 years. The meteorite explosion at Kaali ranged between the effects of Hiroshima and Tunguska. The age of the Kaali impact event is placed between 800–400 B.C. based on radiocarbon dating of the peat enriched with impact ejecta in the Piila bog.

INTRODUCTION AND HISTORICAL BACKGROUND

There is a growing interest in the effects of impact events. Until recently extraterrestrial impacts were regarded as unimportant phenomena in geological processes. This attitude was changed through planetary exploration, which showed that all planets have been heavily bombarded by cosmic bodies throughout their history, although many craters on Earth have been erased by erosion, deposition, volcanism or tectonics (Grieve, 1990; Koeberl, 1997). Altogether ~160 impact craters have been identified on the Earth so far, most dated to prehistoric times. Terrestrial impact events have severely affected the geological and biological evolution on the Earth and they present a great danger to human populations. Such events are not just of scientific interest but intrigue a vast audience (Resolution 1080, 1996). Devastating examples of meteorite catastrophes are well known from the Cretaceous–Tertiary and possibly Permian–Triassic boundaries triggering the most massive extinctions recorded in the Earth's fossil record (Alvarez *et al*., 1980; Alvarez and O'Connor, 2000). More recent ecological disasters from smaller-scale meteorite blasts have been recorded in 1908 at Tunguska (Vasilyev, 1998) and in 1947 at Sikhote-Aline (Krinov, 1963).

About 800–400 B.C. a meteoroid hit a then relatively densely populated island, forming the Kaali meteorite impact craters. Unfortunately the people living at that time on the island of Saaremaa were illiterate and we have no direct written record of the impact event. Indirect written historical records interpreted as describing the Kaali meteorite blast event come from Tacitus (1942) and Pytheas from Massalia (see discussion below). Direct geological evidence of the Kaali impact (the impact craters, meteorite iron, and dust and the influence of the blast) must thus be studied by scientific methods to evaluate the strength of the impact and its ecological significance. The aim of this work is to describe the ecology, including the surrounding vegetation development, human habitation and prehistoric land-use before, during and after the impact event at Kaali.

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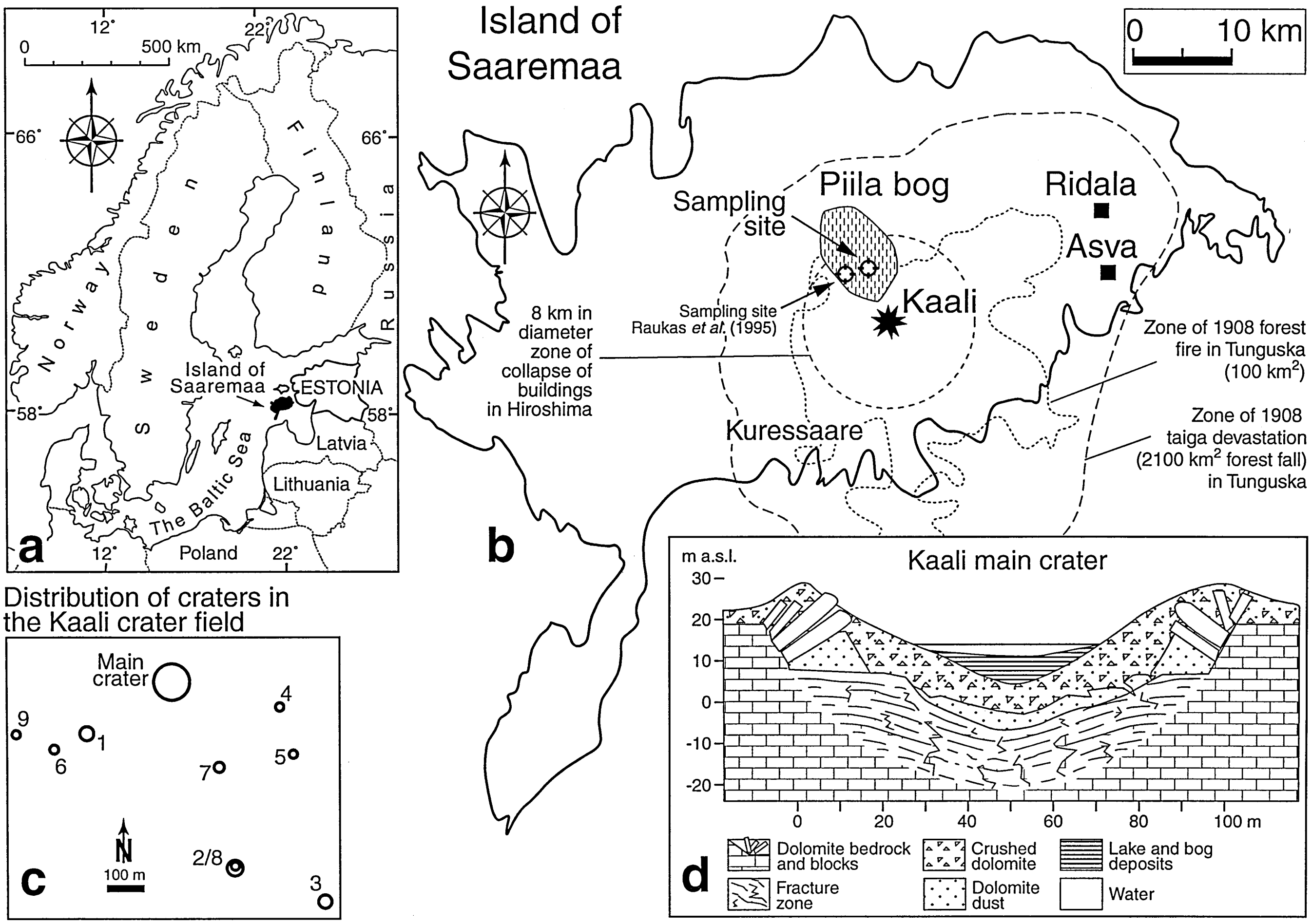

FIG. 1. (a) Map showing the position of the island of Saaremaa, Estonia; (b) the location of investigated sites, Kaali meteorite crater and Piila bog. Areas of impact at the Tunguska meteorite site and the Hiroshima atomic bomb are superimposed (The Manhattan Engineer District, 1946; Vasilyev, 1998); (c) configuration of the Kaali crater field (modified from Aaloe, 1968); (d) geological cross-section of the main crater at Kaali (modified from Aaloe, 1968).

Kaali Meteorite Impact Craters

The meteorite impact site of Kaali (58°22' N, 22°40' E) and the eight associated smaller meteorite craters are located on the island of Saaremaa, Estonia (Fig. 1a,b). Geological and chemical studies in the crater area suggest that an iron meteoroid of type IAB, weighing some 1000 tons fell to the Earth at an angle estimated to be ~35° (Bronshten, 1962; Aaloe, 1968). The meteorite iron found at Kaali contains 7.25% of Ni, 2.8 μg/g of Ir, 75 μg/g of Ga and 293 μg/g of Ge (Yavnel, 1976). Altogether 2.5 kg of meteorite iron of coarse octahedrite class (Buchwald, 1975) has been collected in Kaali, the largest piece weighting ~30 g (Saarse *et al.*, 1991). While penetrating the atmosphere, the meteoroid heated up and broke into pieces. It is estimated that the largest fragment was ~450 tons, and struck the ground surface, consisting of Silurian dolomites with an energy of 4×10^{12} J, corresponding to an impact velocity of ~15 km/s (Bronshten and Stanyukovich, 1963). The resulting crater is 16 m deep and has a diameter of 105–110 m. The depression is today a shallow lake filled with water and at least 5–6 m of lake and bog deposits (Fig. 1d). The cluster of smaller meteoroids produced eight satellite craters with diameters ranging from 12 to 40 m and up to 4 m deep (Fig. 1c). The total energy of all nine impacts was ~4.7×10^{12} J, which is equivalent to ~20 kilotons of TNT. For comparison, the energy released from the Hiroshima atomic bomb was 15–20 kilotons of TNT (The Manhattan Engineer District, 1946).

Since the 1920s, when the craters were first described as of meteoritic origin (Kalkun, 1922; Kraus *et al.*, 1928; Reinwaldt, 1928), there have been discussions about their age. Confirmation of the meteoritic origin of Kaali craters came in 1937, with the finding of ~100 g of meteoritic iron in satellite crater 2 (Reinwald, 1938). Reinwald (1939) concluded that the craters formed 4500–5000 years ago considering the speed of the glacio-isostatic land-uplift on the island of Saaremaa. First radiocarbon (^{14}C) dating of charcoal, wood and peat from the satellite craters suggested that they formed about 2500–2900 ^{14}C years B.P. (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 ^{14}C years B.P. Saarse *et al.* (1991) radiocarbon dated bulk organic matter from the near-bottom lake sediments (calcareous gyttja) of the Kaali main crater at 3390 ± 35 ^{14}C years B.P. and concluded the craters to be ~4000 ^{14}C years old. ^{14}C dating of a time-synchronous 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 around 7500–7600 ^{14}C years B.P. (Raukas *et al.*, 1995; Raukas, 2000). Element analyses of peat from Piila bog reveal a distinct Ir-enriched layer attributed to the meteorite impact (Rasmussen *et al.*, 2000). Radiocarbon dating of the upper surface of the peat layer enriched with Ir produces an age 2305 ± 20 ^{14}C years B.P. (calibrated date is 400–370 B.C. at $\pm 1\sigma$) of the Kaali impact (Rasmussen *et al.*, 2000).

Indirect written evidence of the impact age has been investigated by Meri (1976). Meri analyzed the voyage of Pytheas from Massalia (Marseilles), who between 350–325 B.C. visited Britain and possibly also the island of Saaremaa (Ultima Thule) to get information on the Baltic Sea (Metuonis) and its amber. Pytheas wrote in his book on the "Earth Sea" —"the barbarian showed me the grave where the Sun fell dead". The same metaphor was repeated in the epic "Argonautics" of Rhodos Appolonios (295–215 B.C.) where a sailor found a "deep lake in the far north—the burial of the Sun, from which still fog rose as from the glowing wound." This gave Meri (1976) the reason to suggest that Lake Kaali and the meteorite catastrophe were known among the geographers and philosophers before Cornelius Tacitus, who in his book *De Origine et Situ Germanorum Liber* wrote "Upon the right of the Suevian Sea [the Baltic] the Aestyan nations [Estonians] reside, who use the same customs and attire with the Suevians [Swedes]. They worship the Mother of the Gods." (Tacitus, 1942). The Mother of Gods, Cybele, is associated with meteorites (Burke, 1986).

The island of Saaremaa has been inhabited since the Mesolithic (5800 B.C.; Kriiska, 2000). During the Neolithic and Bronze Age, Saaremaa was densely populated; indeed, half of the bronze artefacts of Estonia come from this island (Ligi, 1992). Three Late Bronze Age fortified settlements (Asva, Ridala and Kaali) are known from Saaremaa (Aaloe *et al.*, 1977) (Fig. 1b). The main economy was cattle rearing and agriculture. Archaeological evidence around, inside, and on the Kaali crater slopes suggests human habitation since 700–500 B.C. (Lõugas, 1978). This conclusion is based on artifacts and a radiocarbon date of 2320 ± 40 ^{14}C years B.P. (410–350 B.C.) from an archaeological setting (a stronghold) on the crater rim. In this context it is interesting to point out that the fortified settlement of Asva (20 km east from the main crater) burned down according to the radiocarbon dating of charcoal from a ~30 cm charred settlement layer between 2585 ± 50 and 2520 ± 60 ^{14}C years B.P. (800–400 B.C.; Aaloe *et al.*, 1977), which is close to the age of the Kaali impact (Rasmussen *et al.*, 2000).

METHODS

To evaluate the results of the meteorite explosion on the surroundings, a sampling site was selected in the peatbog closest to the impact crater (Piila bog, 6 km northwest; Fig. 1b). Sampling for pollen, radiocarbon, loss-on-ignition and x-ray diffraction analyses was carried out in the Piila bog by extracting a monolith from the vertical peat-wall of an excavation (Fig. 2a). The sampling site is exactly where Rasmussen *et al.* (2000) found the Ir-enriched layer and dated the Kaali impact (the monoliths were taken side by side).

Pollen Analysis–Pollen samples were taken continuously from the peat sequence between 185 and 164 cm as 5 mm slices of material, and prepared following the standard acetolysis procedure (Berglund and Ralska-Jasiewiczowa, 1986). *Lycopodium* spores (Stockmarr, 1971) were added to a known volume of sediment to estimate pollen concentration and influx. One thousand tree pollen grains were counted in each sample. Pollen data is expressed as influx values (pollen grains cm^{-2} year^{-1}) and percentages of the total pollen sum. Influx values are shown smoothed with a running mean of 5. The pollen diagram of 21 levels is subdivided into 3 pollen zones using optimal splitting by information content method (using the "psimpoll 3.10" program; Bennett, 1996). The statistical significance of each split is tested against the portion expected

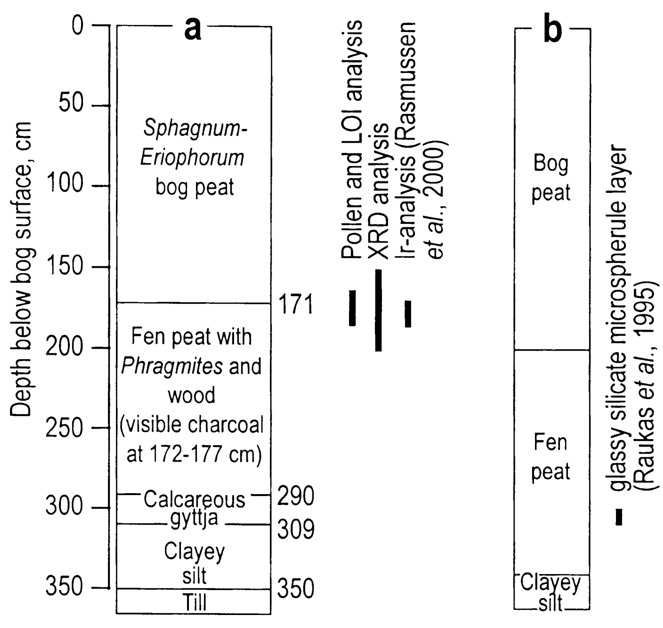

FIG. 2. (a) Lithology of the investigated section at Piila bog. The position of the analyzed in detail intervals (pollen, loss-on-ignition, x-ray diffraction and iridium analysis by Rasmussen *et al.*, 2000) is shown. (b) Position of the layer containing glassy silicate microspherules detected by Raukas *et al.* (1995). The location of the sections is shown on Fig. 1b.

from a broken-stick model, no further division can be justified (Bennett, 1996). Psimpoll software is specially designed for numerical analysis of biostratigraphical data in order to obtain statistically significant zone boundaries from a large matrix of pollen data.

Loss-on-Ignition–The organic, $CaCO_3$ and terrigenous contents in the sediment were estimated by loss-on-ignition from 1 cm samples at 550 and 825 °C, respectively (Bengtson and Enell, 1986).

Radiocarbon Dating (Carbon-14 Dating)–A 2 cm sample was taken from the sediment monolith and ^{14}C dated at the Institute of Geology, Tallinn Technical University, Estonia using the conventional liquid scintillation counting method (Gupta and Polach, 1985). Radiocarbon dates of Rasmussen *et al.* (2000), with a lab index K are also used in the discussion.

The radiocarbon method (Libby, 1955) is based on the rate of decay of the unstable carbon isotope (^{14}C), which is formed in the upper atmosphere through the effect of cosmic-ray neutrons upon nitrogen (^{14}N). Plants and animals which utilize carbon in biological foodchains take up ^{14}C during their lifetimes and they cease this metabolic function of carbon uptake as soon as they die, there is no replenishment of radioactive carbon, only decay at a constant rate (half-life $t_{1/2}$ = 5568 years). Radiocarbon ages are reported as ^{14}C years B.P. (before present, before year 1950). Radiocarbon years are not equivalent to calendar years, because the atmospheric concentration of ^{14}C is not constant, but varies according to changes in solar radiation and in the intensity of the Earth's magnetic shield. Radiocarbon years are calibrated to reflect calendar years (expressed as calendar years B.C./A.D.) using dendrochronology, which has provided a direct comparison between ^{14}C and calendar years (Stuiver and Reimer, 1993).

X-Ray Diffraction–The mineralogical composition was investigated in eleven 1 cm peat samples. The samples were ignited at 450 °C for 3 h to remove organic material. The ash was homogenized and unoriented air-dry preparations were analyzed using a Dron-3M diffractometer with Ni filtered Cu$K\alpha$ radiation according to standard techniques (Klug and Alexander, 1974). Scanning steps of 0.02 °2θ from 2 to 50 °2θ with time steps of 10 s were used. X-ray diffraction patterns were then decomposed into elementary peaks in the 20 to 40 °2θ region using Axes-19a code (Mändar *et al.*, 1996). The diffraction peaks were assumed fitting with symmetrical pseudo-Voigt function shape curve doublets (Jones, 1989). The relative abundance of the mineral phases was estimated from the integral intensities of selected type peaks. Peaks at 3.47, 3.34, 3.24, 3.19 and 3.04 Å corresponding to anhydrite, quartz, K-feldspar, plagioclase, and calcite were used, respectively (Davis and Johnson, 1989; Nakamura, 1988).

Trace Elements–Additional samples for trace element analysis were taken from the basal sediment unit of the main crater at Kaali (Fig. 1d). The mixture of the clayey-to-gravelly material represents the layer of inwashed fallback ejecta on top of the crushed and broken dolomite blocks at the crater bottom. Iridium was measured from two 50 g sediment samples at the XRAL laboratories (Toronto, Canada) by nickel sulphide collection followed by inductively coupled mass spectrometry. The detection limit is 0.1 ppb.

Principal Component Analysis–In order to reduce multidimensional data to a two-dimensional plot displaying the major directions of variation within the data set, and to facilitate correlation of the results of different methods, the principal component analysis, a multivariate correlation analysis, was applied (using Canoco 4.02; Ter Braak and Šmilauer, 1997–1999 and CanoDraw 3.10; Šmilauer 1997). The principal component analysis was carried out on the joint analyzed data set of the Piila bog, pollen influx values, iridium concentration, loss-on-ignition values and mineral composition of peat ash

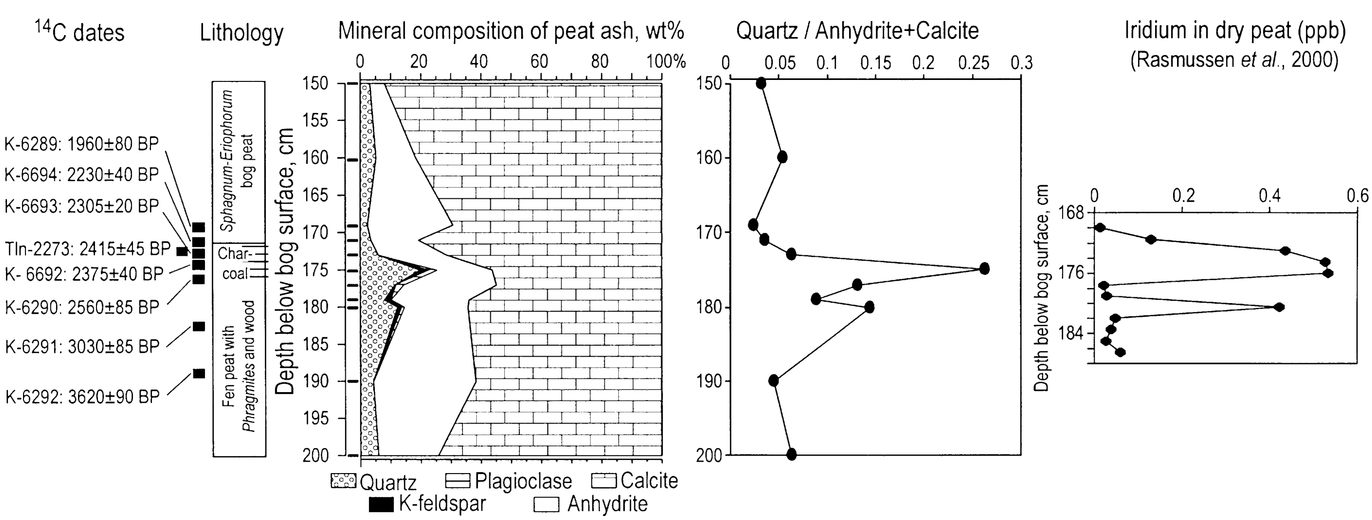

FIG. 3. Diagram showing the lithology of the investigated section at Piila bog, ^{14}C dates, mineral composition of peat ash, the ratio of quartz/anhydrite + calcite and the iridium concentration in the peat ash (Rasmussen *et al.*, 2000).

were combined by levels. The analysis was performed on a covariance matrix (centered by variables) using un-transformed data (Chatfield and Collins, 1980). Scaling in correlation biplots was focused on inter-sample distances. Principal component analysis is used to reduce the overall dimensionality in the data, to identify a small set of factors that define the interrelationship among a group of variables, and to define subgroups of variables that are highly correlated (Birks and Gordon, 1985). The resulting dimension reduction permits graphical representation of the data so that significant relationships among observations or samples can be identified. The first principal component (principal component analysis axis 1) is the combination of variables that explains the greatest amount of variation. The second principal component (principal component analysis axis 2) defines the next largest amount of variation and is independent to the first principal component.

RESULTS

The sediment column at the sampling site in Piila bog is described on Fig. 2a. Rasmussen *et al.* (2000) showed a well-developed peak/plateau in the content of iridium (up to 0.5 ppb) in the peat of Piila bog at 172 to 177 cm below the bog surface (Fig. 3). The upper part of this sediment unit (172–173.5 cm) was radiocarbon dated to 2305 ± 20 ^{14}C years B.P. (K-6693; which corresponds approximately 400–370 B.C.). This iridium-rich layer is considered to be the marker horizon for the impact event by Rasmussen *et al.* (2000). They explained the Ir double peak by simple mechanical falling of particles through the bog surface. We radiocarbon dated the same horizon at 172 cm below the bogs surface to 2415 ± 45 ^{14}C years B.P. (Tln-2273; approximately 400–520 B.C.). Associated with the Ir-enriched horizon is a marked layer of charcoal, charred wood, and wood stumps (generally less than 10 cm in diameter). This charred layer is found over an area of 5 km^2 across the Piila bog. Loss-on-ignition analyses of peat show two levels of increased input of inorganic allochthonous material (terrigenous fraction; Fig. 4). These levels coincide with the iridium and x-ray diffraction data and visual observations of charcoal and mineral particles (quartz and feldspar grains were found in pollen samples at the 169 cm level).

The x-ray diffraction analyses reveal that the main mineral phases in the peat ash are calcite, anhydrite, and quartz, with traces of K-feldspar and plagioclase (Fig. 3). The relative abundance of calcite in the ignition residue gradually increases upward through the section, whereas the content of anhydrite decreases. Calcite ($CaCO_3$) and anhydrite ($CaSO_4$) are common authigenic phases in peat ash that form during ignition at the expense of Ca, S and C present in organic material (Nakamura, 1988). The amount and ratio of calcite and anhydrite depends on the availability of Ca and S in local material. Quartz and feldspars are allochthonous phases. The content of quartz varies between 3 and 5% in the upper and lower part of the section, whereas in the middle of the section, at depths around 173–180 cm, it reaches up

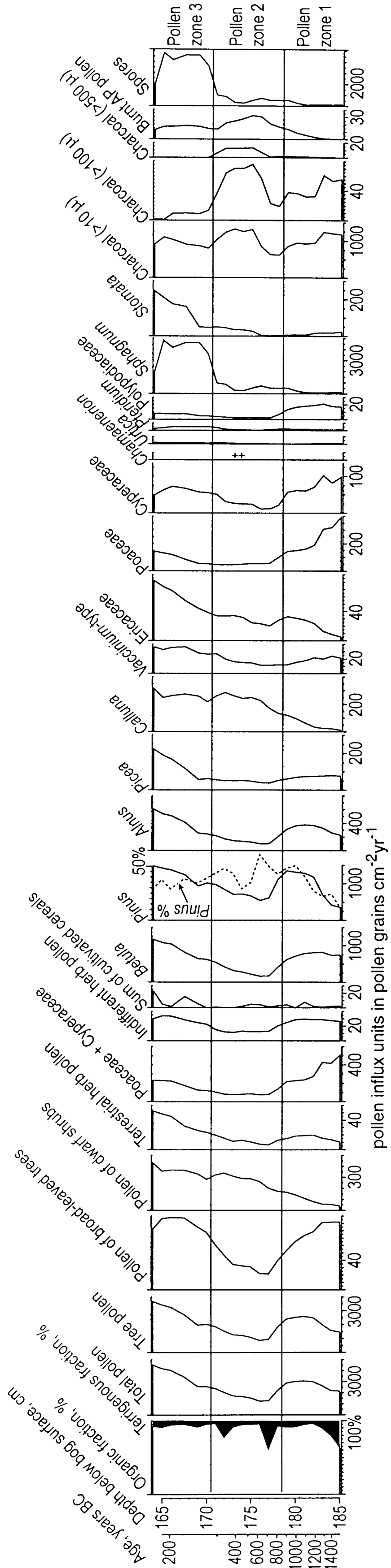

FIG. 4. Loss-on-ignition and selected pollen and spore influx (pollen grains cm^{-2} year^{-1}) diagram from the investigated section at Piila bog. Percentage values of *Pinus* (dotted line) are given together with influx of *Pinus* pollen.

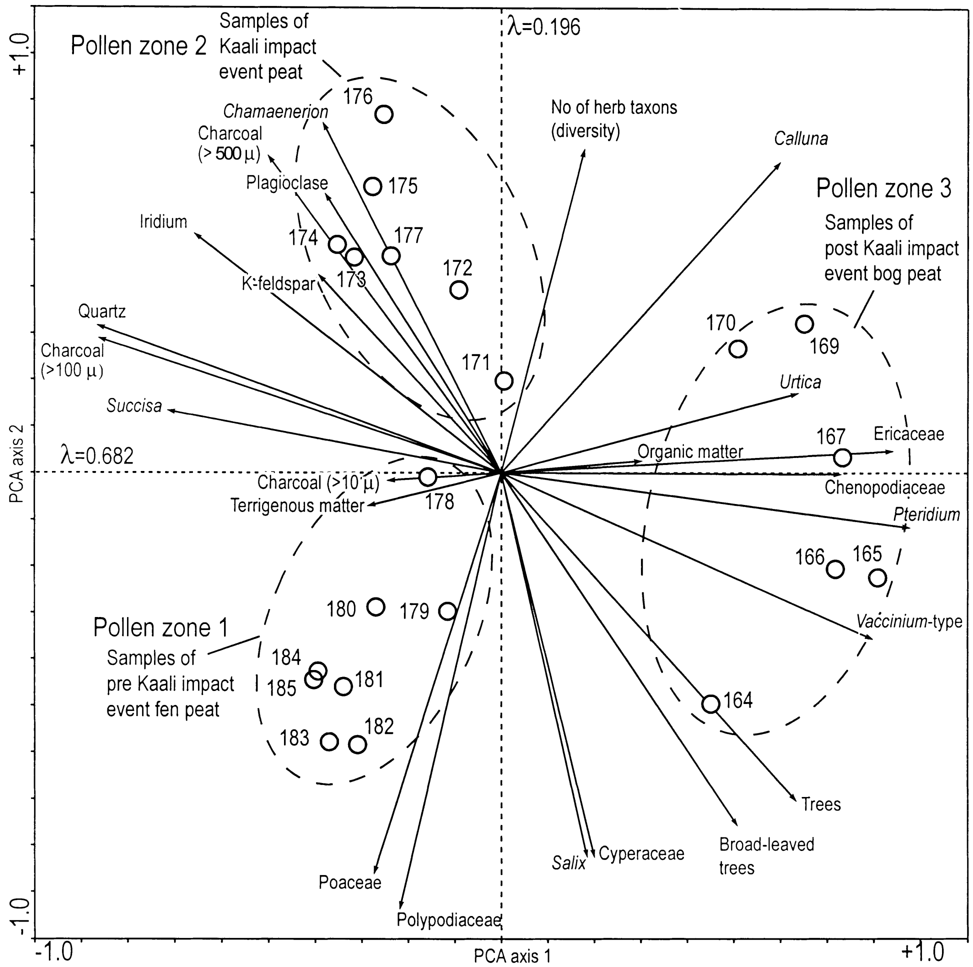

FIG. 5. Principal component analysis biplot of the joint Piila data set of pollen influx values, iridium concentration, loss-on ignition values and mineral composition of peat ash, combined by levels. The variable loadings (arrows) and the position of samples (circles) are plotted as scores on the first two principal component axes. The sample levels are in stratigraphical order from bottom to top of the investigated sequence. Clusters of samples comprising pollen zones have been independently delimited on the basis of numerical zonation (psimpoll 3.10 software; Bennett, 1996), circled and labeled. The first principal component analysis axis explains 68.2% and the second principal component analysis axis a further 19.6% of the variation in the data set. Principal component analysis was applied in order to reduce multidimensional data to a two-dimensional plot displaying the major directions of variation within the data set, to define subgroups of variables that are highly correlated, and to facilitate correlation of the results of different methods. The resulting dimension reduction permits graphical representation of the data so that significant relationships among observations or samples can be identified.

to 20% of the mineral composition of the ash. In the same interval small amounts of K-feldspar and plagioclase were found. This abrupt change in the composition of peat ash at depth 173–180 cm is better expressed in a quartz/(calcite + anhydrite) relative abundance curve, which shows the clear increase of quartz compared to calcite + anhydrite in this interval (Fig. 3).

The pollen diagram was divided into three statistically significant pollen zones using psimpoll software (Bennett, 1996). The same zones independently show up in the principal component analysis plot (Fig. 5). The total influx of pollen diminishes abruptly for an order of three at ~178 cm (boundary between pollen zone 1 and 2), then gradually recovers upwards (Fig. 4). The decrease in zone 2 is seen in tree pollen, pollen of broad-leaved trees and herb pollen influx. The influx of dwarf shrubs, on the other hand, increases. The percentage diagram shows an increase of *Pinus* (dotted line) in pollen zone 2 (Fig. 4). At the same time there is an increase in the influx of *Calluna*, Ericaceae and *Vaccinium*-type. The influx diagram shows noticeably greater accumulation of charcoal of all sizes in pollen zone 2, where findings of *Chamaenerion*, *Urtica* and *Pteridium* are more frequent. Indicators of cultivated land, such as the cereals *Triticum*, *Hordeum* and *Secale* ("sum of cultivated cereals" profile) are present in pollen zones 1 and 3, but almost disappear in zone 2. The influx of *Sphagnum* increases from about 172 cm upwards. In pollen zone 3 the total pollen accumulation is again comparable to that of zone 1.

Two samples from the basal silt unit representing the layer of post-impact inwash of dolomite dust of the main crater at

Kaali at the depth 563–572 cm below the present-day sediment surface contain 0.8 ± 0.1 ppb of iridium.

DISCUSSION

The Age of the Kaali Craters

There are currently two contradicting hypotheses about the age of the Kaali meteorite impact (Raukas, 2000; Rasmussen *et al*., 2000). Both rely on ^{14}C dating of peat layers with a minor content of extraterrestrial material and possible impact ejecta found in nearby bogs. The peat horizon with glassy silicate microspherules (Fig. 2b) is ^{14}C dated back to about 6270–6500 B.C. (7500–7600 ^{14}C years B.P.) by Raukas *et al*. (1995) and Raukas (2000). The authors insist that this is the true age of the Kaali meteorite impact. Element analysis of peat revealed a distinct Ir-enrichment in Piila bog, most likely produced by the meteorite impact (Rasmussen *et al*., 2000), which is radiocarbon dated at 400–370 B.C. They believe this is the date of the impact. Our data seems to speak in favor of the latter date, with some corrections. Rasmussen *et al.* (2000) interpreted the highest stratigraphic level in the Ir-rich plateau as the marker for the impact. They suggested that iridium particles were partly transported downwards in the sediment. The pollen evidence in zone 2 suggests disturbances in vegetation at 178 cm. The change in vegetation occurred simultaneously with the impact. So we may consider the 400–370 B.C. age of the impact as "not later than" and propose placing the impact marker level inside pollen zone 2 at 178–176 cm, which is approximately 820–570 B.C. (2560 ± 85 B.P., K-6290). At this stage of research the precision of dating the time of the Kaali impact crater lies within zone 2 and between 800–400 B.C. Our conclusion is mainly based on the fact that a bog surface is not a horizontal solid surface—the fine-grained impact ejecta and the pollen grains were originally distributed over some centimeters in the sediment, as also pointed out by Rasmussen *et al*. (2000).

Several lines of evidence support the Ir theory of Rasmussen *et al*. (2000) and our observations *vs.* the theory of Raukas *et al*. (1995). (1) Two samples from the basal silt layer inside the main crater at Kaali contain 0.8 ppb of iridium. This shows that iridium, an element typically enhanced in meteorites, was present in the Kaali meteorite impact ejecta. Part of it fell back into the crater and/or was washed in from the crater slopes. The bulk of iridium, though, was deposited in the neighborhood, and can today be found as an iridium-marker-horizon in the Piila bog. (2) Although the dating of the sediments in the Kaali main crater is difficult owing to various disturbances, such as inwash of old humus and hard-water effect, the ^{14}C dates and pollen analysis indicate the start of organic accumulation around 1730–1630 B.C. If the meteorite fell ~6400 B.C. it is hard to believe that no sediments accumulated in the water-filled 16 m deep crater during the following 5000 years. (3) Microspherules of 6270–6500 B.C. age have been found also 70 km north of Kaali, in Kõivasoo bog, island of Hiiumaa. This contradicts by far the estimates of amount and distance of the impact ejecta from the Kaali craters (Bronshten, 1962; Rasmussen *et al*., 2000). (4) The composition of the glassy silicate microspherules found in peat (Raukas, 2000) differs chemically from those discovered in the craters, the latter containing 20–30 vol% of magnetite (Judin and Smyshlyayev, 1963).

Based on these disagreements the 6270–6500 B.C. microspherule horizon should be considered to represent a different event, not even necessarily an impact event, as pointed out also by Rasmussen *et al*. (2000).

The Effect of the Impact

As mentioned before, the total energy of the Kaali impact event, 20 kilotons of TNT, is comparable to the energy released from the Hiroshima atomic bomb. For comparison, the Tunguska event was about three orders of magnitude stronger (15 megatons of TNT), but the explosion took place at an altitude of 5–10 km above the Earth's surface. As a result, the Tunguska shock wave reached the ground producing a 4.5–5 magnitude earthquake (Pasechnik, 1986), equivalent to 5–32 kilotons of TNT, therefore comparable to the Kaali impact. The Tunguska explosion devastated ~2100 km^2 of forest (Fig. 1b) and produced a radial burn of flora at more than 100 km^2 (Vasilyev, 1998). The devastation in Hiroshima was smaller and roughly circular in shape. Almost all life and constructions up to about 1.5 km from the epicenter were wiped out, collapse of buildings was observed up to 8 km away and flash ignition of dry combustible material was observed as far as 3 km from the epicenter (The Manhattan Engineer District, 1946).

The meteorite explosion at Kaali must have had at least a similar impact on the surroundings, ranging between the effects of Hiroshima and Tunguska. It must have induced wildfires, which reached at least 6 km northwest from the epicenter (*i.e.*, to the Piila bog). The whole bog probably suffered from a severe burn, judging from the extent of charcoal and wood layer. The burn brought on a change in peat accumulation and a shift from a *Phragmites*–*Carex*–fern–wood fen peat to a *Sphagnum*–*Eriophorum* ombrotrophic bog peat. We can not exclude, of course, the possibility that the charred layer in Piila bog was a result of natural fires. Soot particles at the Cretaceous–Tertiary boundary are explained as possibly the result of a global fire triggered by heat from an impact by a meteorite or asteroid (Wolbach *et al*., 1988). Small meteorites are not able to start global wildfires (Jones and Lim, 2000), but they certainly produce some burning in the vicinity of the impact. Svetsov (1996) showed that the radiation energy from the Tunguska explosion was sufficient to set fires within ~20 km. The impact of Kaali must have ignited vegetation in its target area, the fire then probably spread in the devastated forest in different directions. An intriguing topic in connection with the fires is the burning of the Asva fortified settlement around 800–400 B.C., already pointed out by Aaloe *et al.* (1977). Although this hypothesis is in need of further detailed investigation, it is clear that the end of Asva and the impact of Kaali overlap in time and maybe in space.

The explosion also felled forests and the resulting cleared landscape is shown by the presence of wood stumps, a decrease in tree pollen influx, and a greater influx of *stomata* in pollen samples (Fig. 4). The loss-on-ignition and detailed pollen influx data from the Piila bog indicate disturbances in the vegetation history and peat accumulation. Terrigenous matter accumulated in the peat during the explosion and/or later during the period of increased aeolian erosion of the fire-destroyed field layer and topsoil in the surroundings.

The three zones identified from pollen evidence roughly correspond to: pollen zone (1) pre-impact conditions, pollen zone (2) conditions directly after the impact and pollen zone (3) the recovery to "normal" conditions. The ecological development is best summarized on the principal component analysis plot (Fig. 5). The pre-impact vegetation conditions around Kaali produced ~3000 pollen grains cm^{-2} $year^{-1}$ (Fig. 4). The vegetation in the surroundings of the Piila bog before the Kaali impact was Poaceae–Polypodiaceae–Cyperaceae–*Salix* dominated fen in natural conditions as shown by pollen influx data and the cluster of sample levels (pollen zone 1; samples in between 185–178 cm) and the loadings of the above-mentioned taxa (Fig. 5). The impact explosion swept the surroundings clean of forest shown by the threefold decrease in the total pollen influx and the relative dominance of *Pinus* on the percentage diagram (Fig. 4). Over-representation of *Pinus* percentages is a common feature of barren landscapes. The broad-leaved forest outside the bog on fertile soils was most affected, indicating that the disruptions in vegetation were not just local features around the sampling site in the bog.

Sample levels of pollen zone 2 (samples 177–171) on the principal component analysis plot are positively correlated with iridium, larger fractions of charcoal, allochthonous minerals (quartz, K-feldspar and plagioclase) and pollen types indicating burning (*Chamaenerion*). The correlation is negative with tree pollen and pollen of the broad-leaved forest (*e.g.*, "normal woodland conditions") indicating open landscapes around the bog. Indicators of cultivated land, such as the cereals *Triticum*, *Hordeum*, and *Secale*, which were present in pre-impact conditions, disappear in pollen zone 2. Continuous signs of field cultivation on Saaremaa appear after 2300–2150 B.C. (Veski, 1998; Poska and Saarse, 2001). The disappearance of cereals in pollen zone 2 suggests that farming, cultivation and possibly human habitation in the region ceased for a period. However, archaeological evidence from the ring-wall of the main crater at Kaali displays signs of habitation in the Late Bronze Age–Pre-Roman Iron Age (approximately 500–700 years B.C.; Lõugas, 1980), indicating that people did not abandon the area, but, on the contrary, immediately used the rim of the crater as a part of their fortification.

The transition from pollen zone 2 to 3 is interpreted as a gradual recovery of vegetation from the impact of the meteorite. The herb diversity is larger due to open landscape and the sample levels at 169–170 cm show good correlation with *Calluna* (Fig. 5). The effect of fire in Estonian bogs has been thoroughly studied by Masing (1960). One of his case studies was carried out in the Piila bog, which severely burned in the 1950s. *Calluna*, typical to vegetation recoveries after bogfires (in this case with an untypical trigger), flourishes directly after the fire for up to 50 years (Masing, 1960) and is then taken over by Ericaceae (*Andromeda*, *Ledum*) and *Vaccinium*. The pollen evidence reveals a similar pattern (transition from sample levels 170 to 164 cm). Pollen and spore types such as *Urtica*, Chenopodiaceae, and *Pteridium* show disturbed vegetation. Finally, the vegetation around Kaali reaches "normal" woody conditions, the upper sample levels of pollen zone 3 (samples 166–164) correlate positively with tree pollen influx and broad-leaved forest. The effect of the Kaali impact event on the landscape is covered by new generations of vegetation, but its impact on people may be discussed by analyzing the archaeological material from the island of Saaremaa, the epics of the Finno-Ugrians (Meri, 1976), the voyage of Pytheas, or the works of Tacitus.

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