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The age of the Kaalijärv meteorite craters

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Abstract–Precise radiometric age determination of the Kaalijärv meteorite craters on the island of Saaremaa in Estonia have so far proved inconclusive. Here we present trace element analyses of peat cores taken several kilometers away from the Kaalijärv craters that reveal a distinct Ir-enriched layer produced by the meteorite impact. By radiocarbon dating the peat cores, we have determined for the first time the precise age of the impact that generated the Kaalijärv craters. The calibrated date of the impact is 400–370 B.C. at $\pm 1\sigma$.

INTRODUCTION

The nine Kaalijärv craters on the Estonian island of Saaremaa (= Ösel, 58°24' N, 22°40' E; Fig. 1) are caused by the impact of a fragmented IAB iron meteorite, of which several masses have been recovered totalling ~2.5 kg. The largest piece recovered so far weighs 38.4 g (Raukas *et al.*, 1999). The craters were described already by von Luce in 1827 but were recognized as meteorite craters only in 1928 (Reinvald and Luha, 1928; Spencer, 1938; Krinov, 1966a). The primary crater is water filled and constitutes a lake, whereas the other eight smaller craters are dry. Small dolomitic scatter cones as well as highly shocked meteorite fragments have been recovered in the main crater (Dietz, 1968), and it is thus established without any doubt that the origin of the Kaalijärv craters is indeed by impact. The largest crater has a diameter of 105–110 m and a depth from rim to bottom of 22 m, the rim being raised 6–7 m above the surroundings. The other craters range in size from 12 to 40 m in diameter and in depth from 1 to 4 m (Tiirmaa, 1992; Hodge, 1994).

Pokrovskij (1963), Bronsten (1962), and Bronsten and Stanyukovich (1963) estimated an impactor mass of 400–450 tons

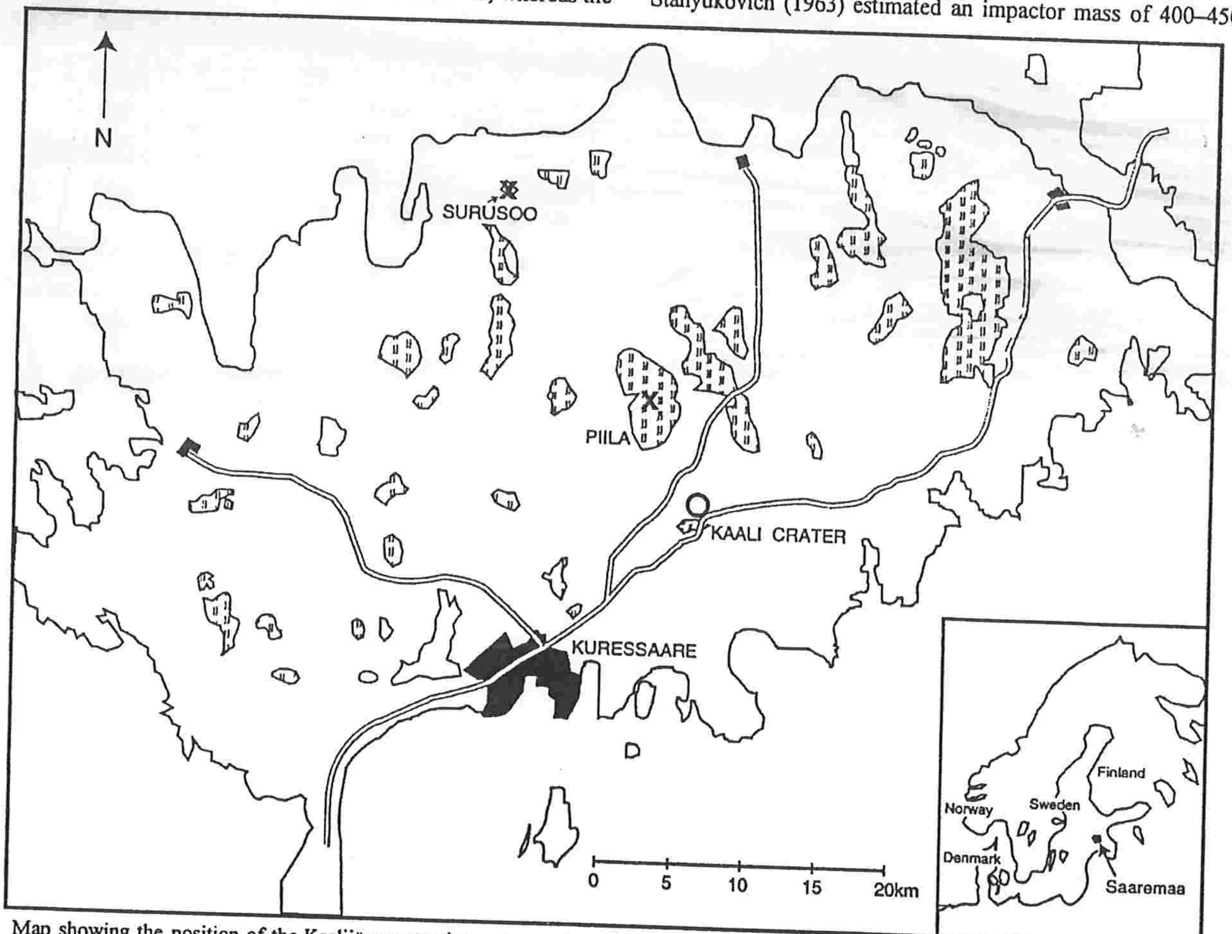

FIG. 1. Map showing the position of the Kaalijärv meteorite craters and positions of the peat sampling sites, the Piila and Surusoo mires on the Island of Saaremaa (Ösel), Estonia.

and an entry velocity of 10–21 km s^{-1}, corresponding to an impact energy release of about 2×10^{13} to 1×10^{14} J, which is equivalent to 5–25 ktons of TNT. Judging from the size of the primary crater, the energy released by the impact could, however, be less by up to a factor of 5 (Melosh, 1989). Judging from the distribution of the craters, the projectile approached the impact site from the northeast at an angle of ~35° to the ground (Aaloe, 1981; Bronsten, 1962).

EARLIER RADIOCARBON DATING

Previous attempts to date the Kaalijärv craters by the radiocarbon dating of samples from the lake sediments in the main crater resulted in widely varying ages (Kessel, 1981; Saarse *et al.*, 1991; see also discussion in Aaloe *et al.*, 1963; Krinov, 1966b; Aaloe, 1981). The oldest radiocarbon date found in the study of Saarse *et al.* (1991) was 3390 ± 35 ^{14}C-years B.P. (sample no., Tln-1353; the uncertainty is $\pm 1\sigma$), but this sample did not derive from the bottom of the lake sediments. This led, with much reservation, to the suggestion that the crater originated before 4000 years B.P. (Saarse *et al.*, 1991). There is, however, a general disturbance of the sediments in the main crater lake caused by timber that had been rammed down for a pavilion in the middle of the lake, deposition of large stones, and slumping sediments; and it is uncertain how much time has elapsed between the crater formation event and the onset of sedimentation in the crater lake. Because of these factors, no conclusive radiocarbon age for the beginning of the sedimentation has been found. Considering the magnitude of the disturbances in the lake sediments it is unlikely that a secure radiocarbon age for the onset of sedimentation will ever be determined.

In this context, it should also be noted that the target rock underneath the loess cover was Silurian dolomite (the Paadla formation), which contains ^{14}C-free carbon. The dolomite bedrock is lying flat in the undisturbed surrounding area, but it is raised 60° at the crater rim. This target rock was highly fractured and crushed to stone flour in the crater, and it is likely that this has resulted in a hard-water effect (Mook and Waterbolk 1985; Fontes 1992) in the crater lake, which could make the radiocarbon ages of the lake sediments appear older by an unknown amount.

Aaloe (1958) found shells of land molluscs in one of the smaller craters. The shells were never radiocarbon dated, but Aaloe (1958) interprets this find to indicate that the craters were formed in or before the Litorina period, 3000–4000 B.C. This evidence is, however, very circumstantial because the shells could as well have been brought into the crater at a later date by exactly the same process that is supposed to have brought them in in the Litorina period. It is also odd that the Litorina type molluscs were found only in one crater.

Raukas *et al.* (1995, 1999) studied three mires near the Kaalijärv crater at Piila, Pelisoo, and Pitkasoo, and one from the island of Hiiumaa (Koivasoo), and found a layer containing silicate spherules in all of them. The spherules, which were interpreted as "micro-impactites" (Raukas *et al.*, 1999), were found in the Piila mire at a depth of 300 to 310 cm and radiocarbon dated to 7586 ± 67 ^{14}C-years B.P. (uncertainty $\pm 1\sigma$; sample no., Tln-1972).

SAMPLE PREPARATION AND RESULTS

In order to circumvent the problems of sampling the disturbed and hard-water affected crater lake itself, we decided to sample the Piila peat bog ~8 km northwest of the craters. Here we achieved an undisturbed and uninterrupted stratigraphic sequence of ombrotrophic peat for radiocarbon dating. The peat sequence was also analyzed for Ir, and a distinct Ir-enriched layer was found. The top of the Ir-rich layer marks the precise time of the impact. We also sampled the Surusoo peat bog 25 km northwest of the craters, but this proved too far away from the impact site to detect Ir.

Peat monoliths were taken from open sections excavated for sampling purposes at Piila (58°25' N, 22°36' E), 8 km northwest of Kaalijärv, and at Surusoo (58°33' N, 22°24' E), 25 km northwest of Kaalijärv (see Fig. 1). The Piila peat section and the monoliths (horizontal area: 10 × 10 cm) did not indicate disturbances in the peat stratigraphy in the interesting range, 160 to 190 cm below the surface.

The monoliths were dissected vertically and half of each monolith used for instrumental neutron activation analysis (INAA), the other half for radiocarbon dating and stable isotope analysis (δ^{13}C). The samples used for INAA were incinerated at 450 °C leaving ~5 wt% of ash for analysis. Samples of ~100 mg ash were irradiated for 48 h in the Danish heavy water reactor DR-3 in a neutron flux of about 1×10^{13} n cm^{-2} s^{-1} and counted on a high-purity Ge-detector. Samples of Allende and our Cretaceous-Tertiary (KT) boundary standard (Gwozdz *et al.*, 1992) were also analyzed in the same irradiation. The uncertainties for the Ir contents are generally better than ±10%. Iridium concentrations were achieved for some of the samples; for the rest, only upper limits could be determined. The results of the Ir analyses are listed in Table 1 and shown in Fig. 2.

TABLE 1. Results of the instrumental neutron activation analysis.*

Lab. No.	Locality	Depth (top) (cm)	Depth (bottom) (cm)	Ir in ash (ng/g)	Ash 450 °C (wt%)	Ir in dry peat (pg/g)	IAB material (μg/cm^2)
KLR-329	Piila	170	171.5	<0.245	5.66	<13.7	<0.41
KLR-330	Piila	171.5	173	2.2	5.85	128.7	4.63
KLR-331	Piila	173	174.5	7.2	6.06	436.6	14.89
KLR-332	Piila	174.5	176	8.29	6.37	527.0	19.71
KLR-333	Piila	176	177.5	7.72	6.91	533.6	20.11
KLR-334	Piila	177.5	179	<0.324	6.98	<22.6	<0.91
KLR-335	Piila	179	180.5	<0.411	7.04	<28.9	<1.17
KLR-336	Piila	180.5	182	5.05	8.56	432.1	21.00
KLR-337	Piila	182	183.5	<0.497	9.74	<48.4	<2.10
KLR-338	Piila	183.5	185	<0.522	7.27	<37.9	<1.82
KLR-339	Piila	185	186.5	<0.473	5.64	<26.7	<1.12
KLR-340	Piila	186.5	188	<0.764	7.87	<60.1	<2.58

*Depth is measured below the 1994 peat bog surface. Iridium is given in ng/g in the ash. The amount of ash produced when incinerating at 450 °C is listed as wt% of the original dry weight. The calculated Ir content in dry peat is given in pg/g. The calculated deposition rate of IAB material assumes a 10 × 10 cm sample size and an IAB Ir content of 2.8 μg/g following Kracher *et al.* (1980).

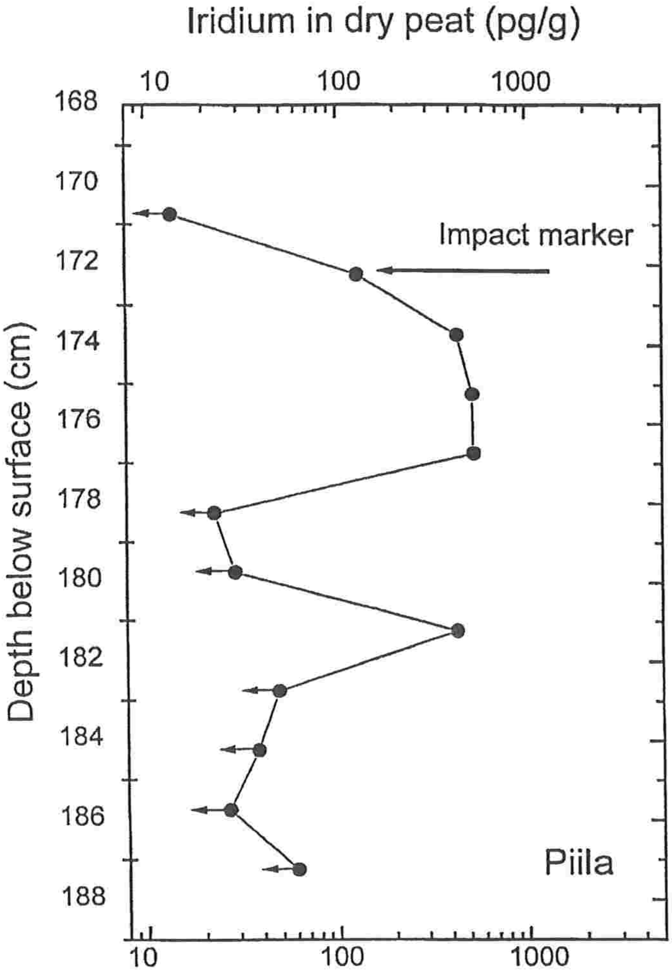

FIG. 2. Iridium concentration as a function of depth determined in the ash fraction of the peat core from Piila. Arrows indicate upper limits. The top of the Ir-enriched layer marks the impact.

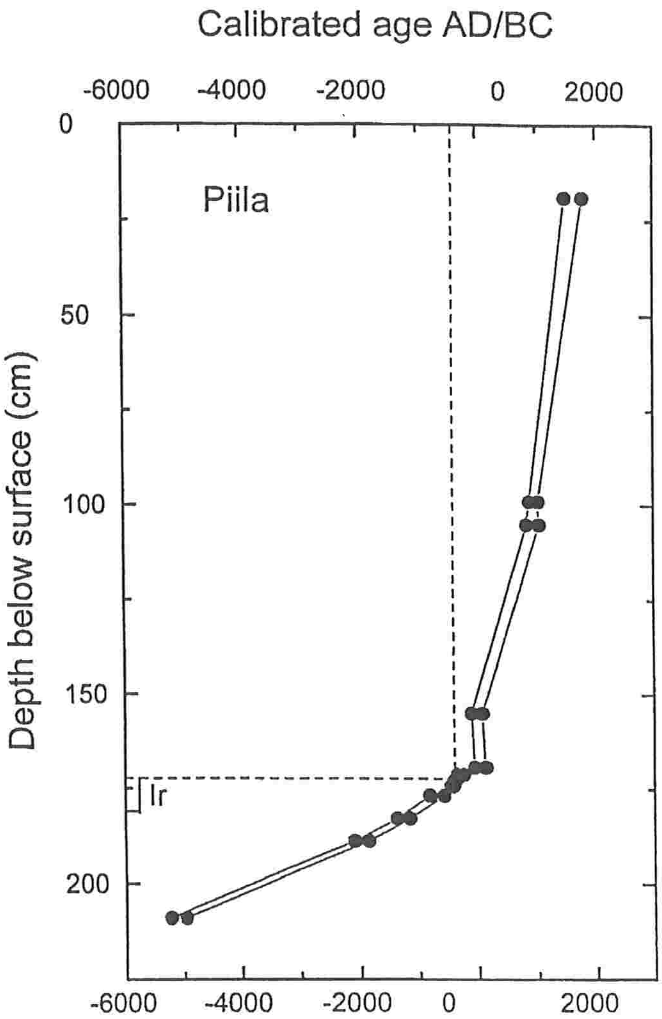

FIG. 3. Calibrated age *vs.* depth for the peat core at Piila. The interval of $\pm 1\sigma$ is shown for each date. The top of the Ir-enriched layer and its age is marked.

The samples subjected to radiocarbon dating were boiled in 1% HCl in order to remove any carbonate, followed by boiling in demineralized water and drying at 120 °C. The samples were then burned in pure O_2 to produce CO_2, and after purification in a $CaCO_3$-oven, counted in a 2 L 1.5 atm pressure conventional proportional counter equipped with a proportional guard counter. Calibration was performed with the University of Washington calibration program Calib v.4.1, using between 20 and 300 years averages of the atmospheric curve (Stuiver *et al.*, 1998). The radiocarbon dates are given in Table 2 and the age of the cores shown as a function of depth in Fig. 3.

DISCUSSION

A pronounced Ir plateau of ~5 cm is observed over several samples in the Piila core starting at a depth of ~172 cm below the surface and extending down to ~177 cm (see Fig. 2). We interpret the highest stratigraphic level in the Ir-rich plateau as the marker for the impact. It seems likely that some of the fine-grained Ir-rich meteoritic dust originating from the impact was either initially distributed over a couple of centimeters because of the surface topography of the mire or that it was transported a few centimeters downwards in the sediment. This transport, which probably took place in the immediate weeks or months after the impact, could have been caused by simple mechanical falling of particles through the relatively porous surface peat layer or it could have been facilitated by percolating rain water. In either case, the top of the Ir-enriched zone marks the precise time of the impact. From our observations on the peat, we believe that centimeter-scale convective folding in the compacting peat layer is not likely to have taken place as new peat was accumulated on top of the impact layer. We rather think that the compaction preserved the stratigraphic sequence, at least on a centimeter-scale, as is also demonstrated by numerable examples of radiocarbon datings in similar sediments at these latitudes (*e.g.*, Andersen and Rasmussen, 1993; Odgaard, 1994). Cryoturbation is not a likely agent in changing the Ir-profile, because the Ir-enriched material is very finely divided. The progressive compaction of the peat eventually led to a sediment completely impermeable to fine meteoritic dust. This closure happened in a rather short time span, probably in much less than a hundred years. There seems to be no way that the Ir-rich dust could have been transported upwards in the peat at any stage in the compaction process.

The impact marker sample was subjected to high-precision radiocarbon dating. The sedimentation rate in this portion of the core is ~100 years cm^{-1} (see Fig. 3), and the 1.5 cm thick sample

TABLE 2. Radiocarbon dates.*

Lab. No.	Locality	Depth (cm below ground)	Internal age (years)	^{14}C-age B.P. ($\pm 1\sigma$)	Calculated date at $\pm 1\sigma$ (Stuiver *et al.*, 1998)	δ^{13}C (‰) VPDB
K-6166	Piila	18–20	20	285 ± 70	A.D. 1490–1790	–22.8
K-6167	Piila	98–100	20	1100 ± 75	A.D. 880–1020	–24.8
K-6168	Piila	104–106	20	1110 ± 75	A.D. 830–1010	–25.5
K-6169	Piila	154–156	20	2000 ± 80	100 B.C.– A.D. 80	–28.9
K-6289	Piila	168.5–170	150	1960 ± 80	50 B.C.– A.D. 130	–27.7
K-6694	Piila	170.5–172	150	2228 ± 39	340–240 B.C.	–28.0
K-6693	Piila	172–173.5	150	2307 ± 22	400–370 B.C.	–27.9
K-6692	Piila	173.5–175	150	2377 ± 38	460–410 B.C.	–28.0
K-6290	Piila	176–177.5	150	2560 ± 85	820–570 B.C.	–27.6
K-6291	Piila	182–183.5	150	3030 ± 85	1380–1160 B.C.	–28.3
K-6292	Piila	188–189.5	150	3620 ± 90	2100–1860 B.C.	–28.0
K-6170	Piila	208–210	200	6150 ± 105	5240–4920 B.C.	–27.5
K-6595	Surusoo	30.5–32	300	575 ± 33	A.D. 1350–1370	–27.0
K-6596	Surusoo	36.5–38	300	1167 ± 42	A.D. 820–910	–26.4
K-6597	Surusoo	39.5–41	300	1810 ± 35	A.D. 180–260	–28.1
K-6598	Surusoo	42.5–44	80	2275 ± 40	390–240 B.C.	–27.0
K-6599	Surusoo	48–49.5	80	2592 ± 34	800–780 B.C.	–28.0
K-6174	Surusoo	60–62	100	3060 ± 85	1410–1200 B.C.	–27.1
K-6434	Surusoo	63.9–65.2	60	2990 ± 65	1310–1110 B.C.	–23.7
K-6293	Surusoo	68–70	100	3220 ± 85	1580–1400 B.C.	–27.7
K-6294	Surusoo	91–93	100	3990 ± 90	2620–2360 B.C.	–24.8
K-6175	Surusoo	118–120	100	5590 ± 100	4520–4330 B.C.	–28.3

VPDB stands for Vienna Pee Dee Bellemnite and is measured in per mille.
*The internal age is calculated on the basis of the sedimentation rate (see Fig. 3). The internal age is taken into account when calculating the calibrated age using the University of Washington Calibration Program ver. 4.1 and the curves of Stuiver *et al.* (1998).

thus has an internal age of ~150 years. The result of the radiocarbon date of the impact marker sample is 2307 ± 22 ^{14}C B.P., and the calibrated age is 400–370 B.C. at $\pm 1\sigma$ and an internal age of 150 years, and 420–350 B.C. at $\pm 2\sigma$ (Stuiver *et al.*, 1998).

We have calculated the total amount of Ir deposited at the Piila core location to be 2.06 ng of Ir per gram of dry peat. Assuming an Ir concentration of 2.8 μg/g in the Kaalijärv IAB iron projectile (Kracher *et al.*, 1980), this corresponds to a deposition of 80.3 μg/cm^2 of Kaalijärv projectile material at the Piila site. With this deposition, a circular area 8 km in radius would have received 160 tons of IAB material, a very rough estimate, but in good agreement with the estimated 400–450 tons impactor mentioned above.

In the core from Surusoo, 25 km away from the crater, no significant Ir signals were detected in our continuous INA analysis of the core that covers a time span from A.D. 1360 to 2500 B.C. Cal. So the Surusoo site proved too far away from the impact crater to contain measurable amounts of Ir-rich material at our present detection limit, about 10–60 pg Ir g^{-1} of dry peat (corresponding to a detection limit of 0.4–2.6 μg IAB material per cm^2).

Our identification of the Kaalijärv impact material with the Ir-rich layer at 400–370 B.C. Cal. is in contradiction with the interpretation of Raukas *et al.* (1995, 1999) that the silicate-spherule-containing layer at 6500–6270 B.C. Cal. is correlated to the Kaalijärv impact event. In our opinion two questions remain, however, concerning the spherule-rich layer. The first is whether the silicate spherules found by Raukas *et al.* (1995, 1999) are indeed impactites, and the second is whether they originate from the Kaalijärv impact. A trace element study of the spherule layer at ~6400 B.C. is called for, because at all localities where impactites are present, there should be plenty of Ir-rich impactor material. An explanation reconciling the two opposed views could be that there are two impact layers in the Estonian mires, one at 400 B.C. and one at 6400 B.C. In the present work, we have by the Ir measurements proven beyond any doubt that there certainly is one at 400 B.C.

Our estimate of the impactor mass, 160 tons, is in very good agreement with that expected from the size of the craters and therefore speaks in favor of our identification of the 400–370 B.C. Ir-rich layer as the impact layer corresponding to the Kaalijärv impact.

Apart from radiocarbon dating a Holocene meteorite crater precisely, this crater and its age are interesting from a historical point of view. The Roman historian Tacitus is widely known for his description of the Germanic tribes, that is, those Europeans living north and east of the Roman frontier, called the *Limes*. In his work *Germanica*, Tacitus wrote in A.D. 98 that:

> On the right (Eastern) side of the Swedish Ocean live the Estonians, their habits and clothings are similar to the Suedes, but their language is nearer to English. They worship the mother of gods. ("*matrem deum venerantur*") (Tacitus 98).

In Greek and Roman mythology, the mother of gods is usually identified with the Phrygian goddess Cybele (Μήτηρ ϑεων; see Simon, 1997). The Cybele cult at Pessinus in Asia Minor was renowned for the transfer of a meteorite to Rome in 204 (or 205) B.C. (Simon, 1997; Kron, 1992). So there can be little doubt that the mother of gods, Cybele, to Tacitus was associated with meteorites.

It is conceivable that the witnessing of a large crater-forming meteorite impact event releasing an amount of energy comparable to that of the Hiroshima bomb could induce this kind of worship. This possibility is substantiated by archaeological excavations at the main crater that have revealed a wall-like or alter-like construction right at the crater rim. Unfortunately, no material suited for radiocarbon dating has been retrieved from the archaeological excavations. However, judging from the pottery found near the site, habitation seems to have started in either Early Iron age or Late Bronze age (from about 700 to 600 B.C.; Lougas, 1980). Also, from ancient times until A.D. 1800, the name of Kaalijärv was Pühha Järw (Treumann, 1963), which means "the sacred lake". In the vicinity of the Kaalijärv craters, there are several settlements, which implies that this part of the world was inhabited before and after the time of the impact. There is, of course, no way we can prove that the worshiping at Kaalijärv had any connection with the fall of the meteorite, but it is not an unlikely hypothesis.

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