Chapter 15

The Physical and Social Effects of the Kaali Meteorite Impact – a Review

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15.1
Introduction

There is a concern that the world we know today will end in a global ecological disaster and mass extinction of species caused by a meteorite impact (Chapman and Morrison 1994; Chapman 2004). We are aware that rare large impacts have changed the face of our planet as reflected by extinctions at the Permian/Triassic (~251 Ma; Becker et al. 2001), Triassic/Jurassic (~200 Ma; Olsen et al. 2002) and Cretaceous/Tertiary (~65 Ma; Alvarez et al. 1980) boundaries. Today astronomers can detect and predict the orbits of the asteroids/comets that can cause similar impacts. Yet, Tunguska, Meteor Crater-size and smaller meteorites that could cause local disasters are unforeseeable. However, while planning to avoid the next bombardment by cosmic bodies we can look at past interactions of human societies, environment and meteorite impacts to understand to what extent human cultures were influenced by meteorite impacts. The question is whether the past examples are relevant in the modern situation, but they are certainly useful. The Kaali crater field in Estonia, in that respect, is an excellent case study area for past human–meteorite interactions. Moreover, Kaali is not the only Holocene crater field in this region: in fact, during the last 10 000 years Estonia has been targeted at least by four crater forming impacts and there are five registered meteorite falls (Fig. 15.1). The two large craters, Neugrund and Kärdla, originate from 535 and 455 Ma, respectively (Suuroja and Suuroja 2000). The role of earth sciences combined with other natural sciences and archaeology in meteorite impact research is mainly to study the physical record of (pre)historic impacts (cratering), the evidence for past effects on biological organisms (extinction and disturbance events), causal effects of the impact such as the impact created tsunami damages and human cultures. The latter issue in Estonia is somewhat difficult to evaluate directly as unfortunately the possible people witnessing the Kaali impact were illiterate and there is no direct written record of the impact event, although there is a variety of indirect archaeological and oral material present. Considering that the Kaali meteorite impact had a wider reverberation in the contemporary world we may argue that some of the much-quoted early European written records possibly describe the event.

There are many ways a meteorite impact can influence societies, including changes in climate, tsunamis, earthquakes, wildfires, acid rain, greenhouse effects, the intensity of which depends on the size and target of the impact and the distance from it. But in the long run there are basically two options: (*1*) by extermination, and (*2*) when the impact is smaller by utilisation and worship. From the past, though, we seek the signal

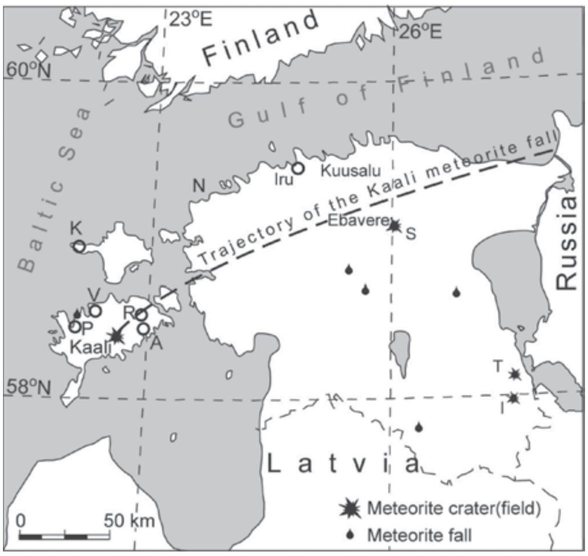

Fig. 15.1. Map of Estonia showing Holocene impact craters (Kaali on the Island of Saaremaa, *S* – Simuna, *T* – Tsõõrikmäe, *I* – Ilumetsa), registered meteorite falls and places mentioned in the text (*A* – Asva, *P* – Pidula, *R* – Ridala, *V* – Võhma, *K* – Kõivasoo bog, *N* – Neugrund)

of the meteorite in meteorite utilisation, worship and cultic activity, but today we would assess the impact damage and put it all into an economic framework. There are dozens of examples from all over the world of meteorite utilisation, worship and legends (e.g. Blomqvist 1994, Hartmann 2001, and references within; Santilli et al. 2003). One of the legends is the voyage of Pytheas, a Greek explorer, who between 350–325 BC visited the island Ultima Thule far in the north, where the barbarians showed him "the grave where the Sun fell dead". According to the interpretation of Meri (1976) the place was the Kaali crater on the Island of Saaremaa. The reason he suggested that Lake Kaali and the meteorite impact 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 (Rhea), is associated with meteorites (Burke 1986). Also Phaeton is connected with celestial bodies and more precisely with Kaali (Blomqvist 1994). The Argonautica of Apollonius of Rhodes (295–215 BC) may describe the Kaali crater lake: "… where once, smitten on the breast by the blazing bolt, Phaethon half-consumed fell from the chariot of Helios into the opening of that deep lake; and even now it belcheth up heavy steam clouds from the smouldering wound" (Seaton 1912). Apart from classical literature the Kaali phenomenon may be reflected in the Estonian and Finnish folklore and eposes (Jaakola 1988).

15.2
The Meteorite

The Kaali meteorite impact site (main crater 58° 22' 22" N, 22° 40' 08" E) with nine identified craters is located on the Island of Saaremaa, Estonia (Fig. 15.2). Geological and chemical studies in the area suggest that an iron meteoroid of type IAB, weighing

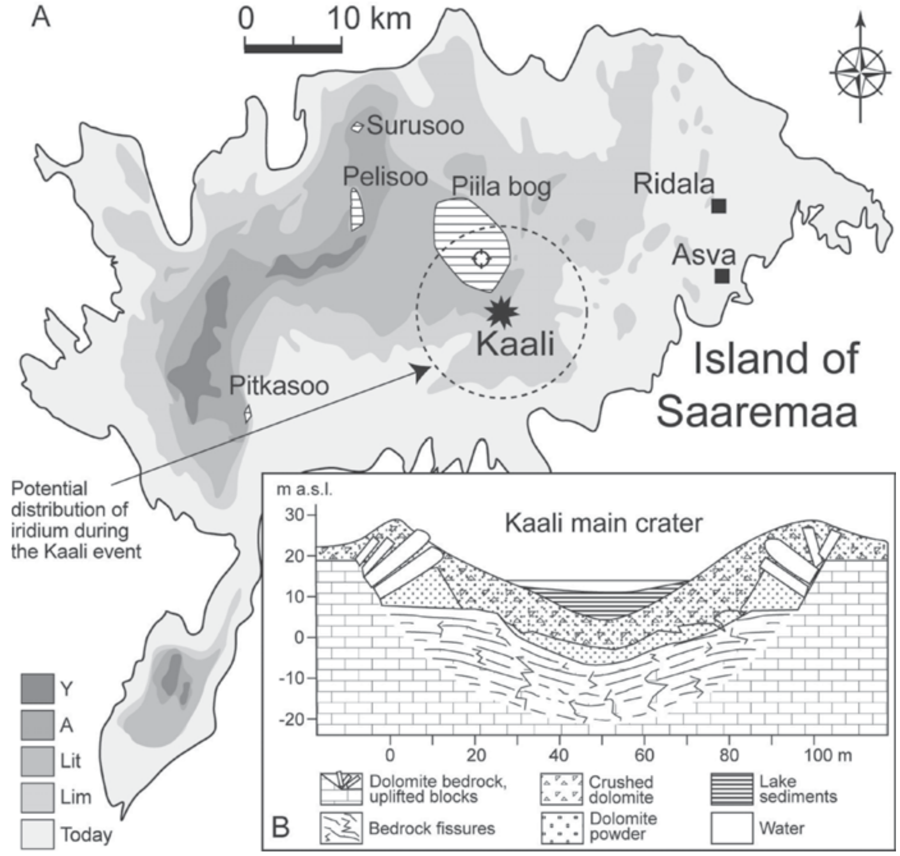

Fig. 15.2. a Map showing the Island of Saaremaa, Estonia, location of the investigated sites, Kaali meteorite crater field, and Piila, Surusoo, Pelisoo and Pitkasoo bogs. The map displays the location of the shoreline during the different stages of the Baltic Sea (*Y* – Yoldia Sea 9000 BC, *A* – Ancylus Lake 8000 BC, *Lit* – Litorina Sea 6000 BC, *Lim* – Limnea Sea 2000 BC). **b** Geological cross-section of the main crater at Kaali (modified from Aaloe 1968)

~1000 tons (estimations range from 400 to 10 000 t) fell at an angle estimated to be ~35° from the northeast (Bronshten 1962; Aaloe 1968). Others suggest that the meteorite fell from the southeast (Reinwaldt 1937) or south (Krinov 1961). The target rock consisted of Silurian dolomites covered by a thin layer of Quaternary till (Fig. 15.2b). Altogether 3.5 kg of meteorite iron of coarse octahedrite class (Buchwald 1975) has been collected in Kaali (Raukas 2004). The largest piece weighs ~30 g (Saarse et al. 1991), but the bulk consists of small, less than a gram, particles (Marini et al. 2004). The iron contains 7.25% of Ni, 2.8 $\mu g\ g^{-1}$ of Ir, 75 $\mu g\ g^{-1}$ of Ga and 293 $\mu g\ g^{-1}$ of Ge (Yavnel 1976). While penetrating the atmosphere, the meteoroid heated and broke into pieces. It is estimated that the largest fragment was ~450 tons, and struck the ground surface with an energy of ca. 4×10^{12} J, corresponding to an impact velocity of ~15 $km\ s^{-1}$ (Bronshten and Stanyukovich 1963). The resulting crater is 16 m deep (rim-to-floor depth is

Fig. 15.3. Kaali main crater from air. Photo by Ants Kraut (Estonian National Heritage Board)

22 m) and has a diameter of 105–110 m (Fig. 15.3). The depression is today filled with water and at least 5–6 m of lake and bog deposits (Fig. 15.2b). The cluster of smaller meteoroids produced eight satellite craters with diameters ranging from 12 to 40 m and up to 4 m deep scattered over an area of 1 km^2. The total energy of all nine impacts was $\sim 4.7 \times 10^{12}$ J, which is equivalent to about 5–20 kilotons of TNT (calculated from Bronshten and Stanyukovich 1963). Raukas (2004) estimated the energy forming the main crater at Kaali to be 1–2 kT TNT.

15.3
Age of the Impact

Kaali craters were not always regarded to be of cosmic origin. Rauch (1794) suggested that the crater was a fossil volcano (Raukas 2002). Subsequently, the peculiar Kaali landform was also considered as created by eruption, karst phenomena, gypsum or salt tectonics (Raukas et al. 1995). Since the 1920s, when the craters were first described as potentially of meteoritic origin (Kalkun 1922; Kraus et al. 1928; Reinwaldt 1928), discussions about their age were initiated. First, Linstow (1919) estimated the age of the craters to be 8000–4000 BC. Reinwald (1938) proved the meteoritic origin of the craters by collecting 30 fragments of meteoritic iron from satellite craters and further concluded, based on the presence of land snails, that the craters were young, possibly of postglacial time. He also understood the need to perform pollen analysis on the lake sediments inside the crater to estimate the age of impact (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 BC, when the area had emerged during the Litorina Sea stage from the Baltic basin. First conventional radiocarbon dating of charcoal, wood and peat from the satellite craters suggested that they may have formed about 1100–600 BC (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 around 1800 BC. Saarse et al. (1991) radiocarbon dated the near-bottom lake sediments of the Kaali main crater from a bulk sample of calcareous gyttja overlying the dolomite debris and proposed an age of 1740–1620 BC. Raukas et al. (2003) acquired several wood samples from excavations on the crater slope obtaining ages ranging from 760 to 390 BC. Veski et al. (2004) re-dated terrestrial macrofossils in the bottom sediments of the water-filled Kaali main crater by AMS radiocarbon method by sampling 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. The obtained age of the crater is 1690–1510 BC using traditional paleolimnological approaches, though Rasmussen et al. (2000) and Veski et al. (2004) put forward some doubts on the possibility of ^{14}C dating inside the Kaali craters. Sediment disturbance by falling trees, mixing with in washed old humus and/or hard-water effects could have influenced the radiocarbon determinations from sediments of shallow hard-water lakes such as Kaali.

Apart from estimating the age of the meteorite impact from inside the crater one can detect the signature of the meteorite shower and impact ejecta in peat bogs near the crater. Different groups of researchers have used ^{14}C dating of peat layers with extraterrestrial material or particles supposedly formed by melting and vaporisation of impactor and target material during the impact. A horizon with glassy siliceous microspherules in the peat of Piila bog (6 km northwest from Kaali craters and 310–300 cm below bog surface; Fig. 15.2a) is dated radiometrically back to ~6400 BC (Raukas et al. 1995; Raukas 2000, Raukas 2004). Similar microspherules have been found in the Early Atlantic layers of peat at the Pelisoo and Pitkasoo mires some 18 km NW and 30 km SW from Kaali, respectively (Fig. 15.2a) as well as in the peat of Kõivasoo bog on Hiiumaa Island (Fig. 15.1) ~70 km NW from Kaali (Raukas 2004). However, the early Holocene age of the impact can be ruled out given the local Quaternary geology and history of the Baltic Sea. At 6400 BC (see Raukas et al. 1995), the water level of the Baltic Sea basin, whose shore was situated about 2 km away from Kaali at that time, was approximately 16 m above the present sea level and was still rising (Fig. 15.4). 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, 2004). Moreover, the initial sediments of the crater contain pollen of spruce (Veski et al. 2004) that immigrated and established on Saaremaa Island starting only about 3800 BC (Saarse et al. 1999).

In the abovementioned Piila bog Rasmussen et al. (2000) found a peat layer at 172–177 cm below peat surface that has an elevated Ir content (up to 0.53 ppb) and is dated to about 800–400 BC (Fig. 15.5). This marker horizon has been considered to represent the signal of the Kaali iron meteorite outside the crater area (Rasmussen et al. 2000; Veski et al. 2001). Thus, currently there are three contradicting hypotheses about the age of the Kaali meteorite impact. Two of them rely on ^{14}C dating of peat

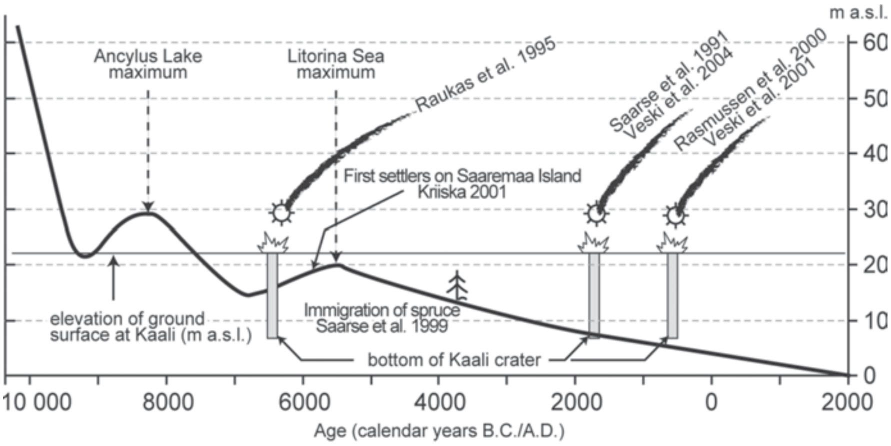

Fig. 15.4. The altitude of the Kaali meteorite target area (22 m a.s.l.) projected to the shore displacement curve for the Kaali area (after the database of Saarse et al. 2002) and three hypotheses of the age of the Kaali meteorite fall

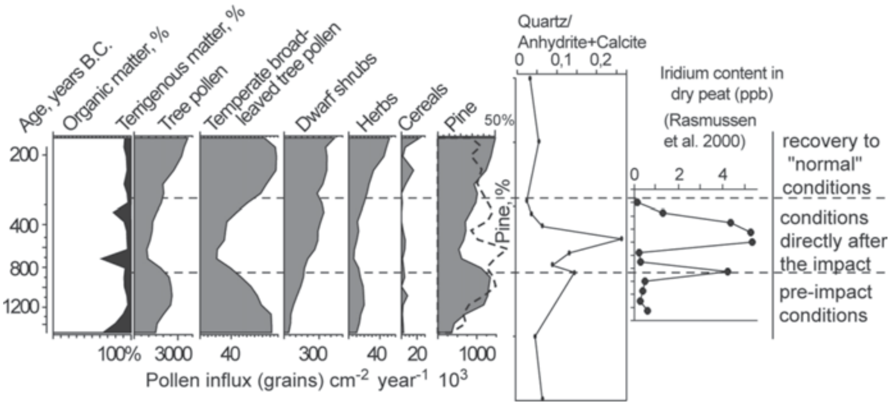

Fig. 15.5. Loss-on-ignition (LOI) and selected pollen accumulation rates (pollen grains $\text{cm}^{-2}\,\text{yr}^{-1}$) diagram from the investigated section at Piila bog. Percentage values of *Pinus* (*dotted line*) are given together with influx of *Pinus* pollen. Generalised mineral composition of peat ash, the ratio of quartz / anhydrite + calcite and the iridium concentration (ppb) in the peat ash (Rasmussen et al. 2000)

layers with impact ejecta found in nearby bogs and the third, more classic approach, on radiocarbon dated terrestrial macrofossils from the near-bottom lake sediments of the Kaali main crater. The relevance of these dates is more thoroughly assessed in Veski et al. (2004). Briefly, the age of the impact estimated inside the crater is 1690–1510 BC which is about 1000 years older from that revealed from the Ir-rich marker-horizon in a contemporaneous peat sequence. The microspherules discovered by Raukas et al. (1995) could indicate another much older event not connected with the Kaali impact.

15.4
Effects of the Meteorite Impact

The statistical frequency of impacts by bodies of various sizes is fairly well known, less well understood are the physical and environmental consequences of impacts of various sizes (Chapman 2004). Impact hazard studies tend to focus on Tunguska-size and larger bodies (Chapman and Morrison 1994), but as far as we know the only crater forming impact that fell into a relatively densely inhabited region was Kaali, which is a magnitude smaller than Tunguska. Nevertheless, even smaller meteorites disturb the local environment for a long time period. Effects of the impact vary from the initial deposition of meteoritic matter during the entrance of the meteoroid, the impact explosion, deformation of the target rock, blast and heat wave, and cratering. After the impact the crater and its nearest vicinity is a classic primary succession habitat (Cockell and Blaustein 2002), at sufficient distances from the crater the blast wave may fell trees and destroy vegetation (Kring 1997) leaving a secondary succession habitat with damages similar of tornadoes and hurricanes. Cockell and Lee (2002) divide the post-impact biology of craters into three phases: phase of thermal biology, phase of impact succession and climax, and phase of ecological assimilation.

The physical effects of the impact, apart from the crater field itself, may be recorded in the surrounding sedimentary archives – the bogs. The above-mentioned peat horizon with elevated Ir contents in the Piila bog combines additional multiple evidence that may be connected to the Kaali event. Significant changes occur in loss-on-ignition (LOI), pollen accumulation, composition of pollen and mineral matter in the 8-cm peat layer, that contains iridium (Fig. 15.5). Enriched Ir values in the peat are possibly primarily formed as a result of atmospheric dispersion of Ir during the entrance and break-up of the meteoroid. The Ir signal is present at Piila bog, but was not found at Surusoo bog 25 km NW from Kaali (Fig. 15.2a), which sets a limit to the effect of the meteorite impact. Associated with the Ir-enriched horizon in Piila is a marked charred layer of peat spread over the entire bog basin and indicating that the whole bog probably suffered from a severe burn. LOI and X-ray diffraction analysis of the same peat layer show increased input of inorganic allochthonous material (up to 20% of quartz and feldspars). Above-mentioned mineral matter accumulated in the peat as impact ejecta during the explosion and/or later, as post-impact aeolian dust during the period of increased erosion of the fire-destroyed topsoil in the surroundings. Pollen evidence reveals that the impact swept the surroundings clean of forest, which is shown by the threefold decrease in pollen influx (especially tree pollen influx), increase in influx and diversity of herb taxa and the relative dominance of pine (Fig. 15.5). Over representation of *Pinus* percentages is a common feature for barren landscapes. The temperate broad-leaved trees on fertile soils outside the bog were most affected, which indicates that the disruptions in vegetation were not just local features around the sampling site in the bog. Pollen evidence indicates a gradual recovery of vegetation from the impact, thus, the effect of the Kaali impact on landscape is hidden by new generations of vegetation.

Indicators of cultivated land, such as the pollen of cereals *Triticum*, *Hordeum* and *Secale*, which were continuously present in pre-impact conditions, disappear after the impact. The disappearance of cereals suggests that farming, cultivation and possibly human habitation in the region was disturbed 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 BC; Lõugas 1980), indicating that people did not abandon the area, but, on the contrary, soon after used the rim of the crater as part of their fortification and/or ceremonial purposes. We do not possess many examples of human societies interacting with crater forming meteorites and these very few should be studied thoroughly. Currently, archaeological evidence does not tell much about the imprint of meteorite impacts nor may we with certainty associate the legends and folk songs with these impacts. One, however, provides a relatively clear picture. The Island of Saaremaa was inhabited since the Mesolithic period, around 5800 BC (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 (Fig. 15.2a). The main economy was cattle rearing and agriculture. Continuous signs of crop cultivation (cereal pollen grains in sediments) on the island of Saaremaa appear at approximately 2300 BC (Poska and Saarse 2002). Archaeological evidence around, inside, and on the Kaali crater slopes suggests human habitation since about 700–200 BC. The impact must have been witnessed and most probably worshipped in some way as the archaeological record at Kaali suggests primarily a ceremonial purpose for the complex (Veski et al. 2004). Although there is a record that small meteorites have caused human casualties (Yau et al. 1994 and references within) we may say nothing of the kind in the case of Kaali. Some archaeological sites on Saaremaa seem to mirror the shape of the Kaali complex, consisting of two concentric circles built of stones. The best examples come from Võhma and Pidula (Fig. 15.6). There is evidence of impact craters utilisation by humans in other different parts of the world. For instance, the Tswaing impact crater in South Africa appears to have been visited by Stone Age people to collect salt (Reimold et al. 1999). Several other craters have been preferentially used as agricultural land (Cockell and Lee 2002).

The ethnographic material that has been related to the Kaali impact is wide and outside the expertise of environmental scientists. The Kaali phenomenon supposedly had a major impact on Estonian-Finnish mythology, folklore, involvement in iron-making and trade (Meri 1976; Jaakola 1988; Raukas 2002; Haas et al. 2003). Particularly

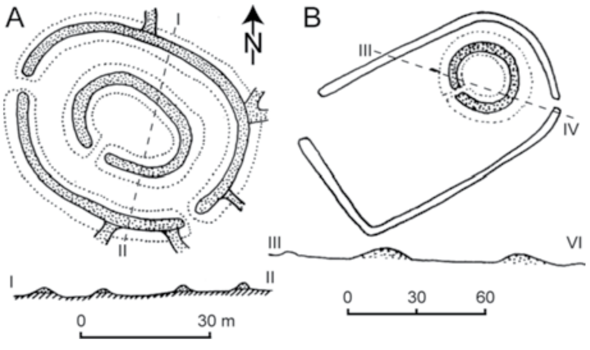

Fig. 15.6. Archaeological sites on the island of Saaremaa that seem to mirror the Kaali complex, having two concentric circles built of stones. *A* – Võhma. *B* – Pidula. Both from north-west Saaremaa, see Fig. 15.1

the natural phenomena such as the birth of fire, the giant figures, the blind archer and the role of iron is believed to originate from the Kaali event (Jaakola 1988). The epics refer to the birth of iron in a lake. The legend written down in the chronicle of Henry the Livonian (*Heinrici Chronicon Livoniae*, early 13th century, in Tarvel and Kleis 1982) about the god Tharapita (Taara), who was born on the hill of Ebavere (located in northeast Estonia, on the trajectory of the meteorite, see Fig. 15.1) and flew to the island of Saaremaa from there may be a reflection of this event. Songs in north Estonian (Kuusalu) folklore describe the burning of the Island of Saaremaa, etc. Outside the Baltic area, the legend of Phaeton is connected with celestial bodies and more precisely with Kaali (Blomqvist 1994; Raukas 2002). There can be no scientific verification that all these tales are reflections of the Kaali meteorite explosion, but we cannot exclude the possibility. Even today the craters at Kaali are a major tourist attraction and part of ceremonial traditions.

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