Estonian meteorite craters

Väino Puura
University of Tartu

Alvar Soesoo
University of Tartu

Sten Suuroja
Geological Survey of Estonia

ESTONIAN
METEORITE CRATERS

Institute of Geology at Tallinn University of Technology
University of Turku, Department of Geology

ESTONIAN METEORITE CRATERS

Tallinn 2007

Estonian meteorite craters.
MTÜ GEOGuide Baltoscandia. Tallinn, 2007.

ISBN 978-9985-9834-1-6

Compiled:	Reet Tiirmaa Väino Puura Alvar Soesoo Sten Suuroja
Acknowledgements:	Enn Pirrus Kalle Suuroja OÜ Eesti Geoloogiakeskus
Edited:	MTÜ GEOGuide Baltoscandia
Layout:	Andres Abe
Figures redrawn:	Heikki Bauert
Photos:	Heikki Bauert
Front cover:	View of the Kaali main crater in Fall
Back cover:	Locations of craters in Scandinavia and in the Baltic States

KESKKONNAINVESTEERINGUTE KESKUS

Release of this booklet in English was co-financed by Environmental Investment Centre, Estonia. It was previously published in Estonian and Finnish languages under the INTERREG IIIA Southern Finland and Estonia programme.

ESTONIAN METEORITE CRATERS

A large number of meteorite craters have been discovered on the territory of Estonia. The geological setting of the region creates favourable conditions for preservation of craters of certain age, thus interest in discovering and investigating the craters has been and remains strong in Estonia. The investigations of Lake Kaali as a suspected meteorite crater began in the early 1920s, the first such undertaking in Europe.

Although meteorite craters occur everywhere on the Moon, Mercury and asteroids, and are common on Mars and several other celestial bodies, they are rare on Earth. The meteorite impacts (explosions of high-velocity falling celestial bodies) alter the planet's topography and structure of its upper beds, crush and melt the rocks, generate earthquakes and tsunamis in bodies of water, generate metamorphic signs in the rocks and signs of extraterrestrial matter in soils and rocks, and damage and destroy life and the environment. Meteorite craters are less visible in oceans and seas; craters are rapidly degraded and destroyed by geological and biological marine and oceanic processes and are not visible to the naked eye. The investigations of meteorites and their craters continue to be of interest, serving as a key for understanding the dangers proceeding from outer space, and for predicting and anticipating their possible impact.

As compared with other countries, the large number of young (postglacial age) small craters detected and investigated on Estonia's territory provides evidence of the success of the undertaking. Scientists continuously discuss and argue both the age and composition of meteorites, and their impact on the environment. The investigations of meteorite craters proceed, promising new discoveries in Estonia and the world over.

Meteoroids and meteorites, cosmic catastrophes and meteorite craters

The early history of the solar system planets was full of impact catastrophes, but in the following 4.5-billion-year development, falls of small celestial bodies (e.g. asteroids, comets, meteoroids) and cosmic dust were quite common. The surface of planets with very rare atmosphere and without hydrosphere, e.g. Moon and Mercury, is dissected by bowl-shaped craters and wide circular basins of crushed rocks, many of them 3–4 billion years in age. On Mars, craters of both meteoritic and volcanogenic origin are found. When meteorites hit the Earth's surface at cosmic velocity, they explode and form meteorite craters. When extremely large objects strike the Earth, the explosion caused by the collision forms basins of crushed rock. However, the number of visible craters on Earth is much smaller than on other planets and more are volcanogenic than meteoric. Due to the predominance of oceans over land, and geological and biological processes characteristic for Earth, craters are rapidly degraded and destroyed; only the most recent craters are easily recognisable. The majority of the almost

200 known meteorite craters are situated on the seafloor or are buried under rocks and/or deposits, or have been considerably eroded. Identifying their origin may take several decades.

The Emerging Science

Meteorites were the first extraterrestrial matter that was available for investigations, and launched Meteoritics, the science of meteorites, in the 19th century. Its aim is to detect meteorites on Earth's surface and investigate their composition and structure, applying methods and means of several other sciences, e.g. petrology, mineralogy, chemistry, physics, astrophysics, geochemistry. The material discovered is stored in scientific collections at natural history museums. Investigation of meteorites provides information on the structure and composition of solid extraterrestrial material, the conditions of its formation and the genesis and development of the solar system. It has been established that the composition of Earth's mantle (and that of other stony planets), resembles the composition of stony meteorites; it is supposed that the composition of Earth's core is similar to iron meteorites. Comparison of the composition of the planets' outer and deeper portions with that of meteorites enables the investigation of the development of rocks inside the planets, as well as on their surface, be these igneous, weathering or deposition processes.

A new discipline, planetology (planetary science), studies the comparative topogra-

Asteroid 951 Gaspra. Approximate size 19x12x11 km. Photographed from a distance of 5300 km during the mission of Galileo, October, 29, 1991.

Engraving of a leonid swarm on November, 13, 1833

The largest stone meteorite found from Estonia is the Pilistvere-Aukamäe meteorite that fell on August, 8, 1863 and weighs almost 11 kg. (Photo: G. Baranov)

phy and inner structure of planets, as well as their atmospheres and hydrospheres. Planetary science includes meteoritics in the classical sense, studying traces of meteorite explosions on other planets, the geology of meteorite craters and geology in general, theories and investigation methods of tectonic, igneous (including volcanogenic) and sedimentary processes. Space missions have created new possibilities for investigating the topography and composition of celestial bodies.

About Meteoroids

Vast numbers of meteoroids occur in interplanetary space; objects consisting of solid matter range from tiny particles to hundreds of kilometres in diameter. Meteoroids moving at cosmic velocity burn in the atmosphere; large ones lose their topmost layers, while smaller ones are often completely destroyed. However, those entering Earth's atmosphere are observable as bolides, meteors, or "meteorite showers." Those actually hitting the Earth's surface are called meteorites.

The larger meteoritic bodies explode when they penetrate the ground and are dispersed in the host rocks and sediments, leaving only fragments, or may be carried farther away with clouds of dust and gas. Only relatively small meteorites, which usually have slowed down when entering the atmosphere, are found on the ground surface as solid fragments. It was Estonian astronomer Ernst Öpik whose calculations proved that a celestial body hitting the Earth's surface at cosmic velocity vaporises due to the energy generated at the explosion.

Effects of Meteoritic Impacts

Meteorite impact explosions are rare and unpredictable; nevertheless, they are among the main processes of Earth's geological development, influencing the formation of the topography, environmental conditions and life activity. Modern astronomy observes the movement of asteroids, comets and bolides in space, thus serving as a tool for predicting both new discoveries and extraterrestrial threats.

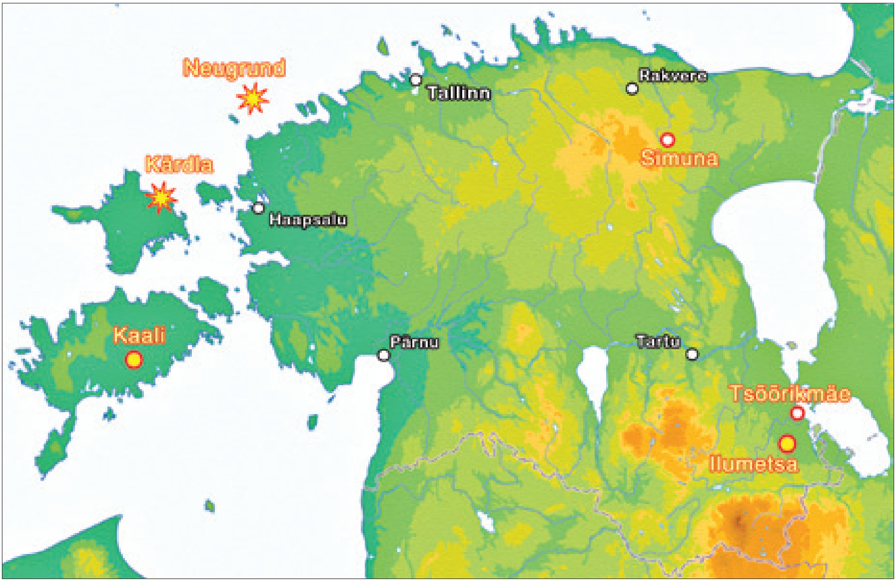
When huge meteorites strike a planet's surface, large craters are formed. Structures 100–300 km in diameter have been found on Earth, with zones of crushed rock reaching down to a depth of several and even tens of kilometres. Extremely powerful explosions are accompanied with ecological catastrophes – abrupt changes in the atmosphere and/or hydrosphere of the whole planet. Some turning points in the development of Earth's biosphere have been related to gigantic meteorite impacts.

A much studied example is the Chicxulub Crater on the present-day Yucatan Peninsula and Mexican Bay, formed 65 million years ago. The atmospheric pollution generated by this explosion caused climate changes globally, and the accompanying catastrophe led to the loss of a significant number of living organisms and the extinction of more than half the species. Palaeontologists investigating the fossils have detected a level of abrupt change in biota at the Palaeozoic/Cenozoic boundary. It was not until the end of the 20th century that scientists discovered that such catastrophic changes were launched by the Chicxulub explosion.

Like those scientists investigating Chicxulub, the astronomers of Tõravere Observatory in Estonia have also collected information about rare atmospheric phenomena – monitoring the dispersion of meteoric dust in outer space in connection with noctilucent clouds, etc. There findings are stored in the archives titled "Bolide."

Estonian meteorite craters

The topography of Estonia's territory and its subsurface has been thoroughly studied, leading to the discovery of several direct and indirect geological and topographical features. At first, some were categorized as simply "unusual" phenomenon but upon more detailed investigation, a few have been determined to be actual meteorite craters. These discoveries have been made under different circumstances and the craters have been variously exposed. The clearly observable Kaali meteorite craters on Saaremaa Island were formed in dolostone, while the Ilumetsa, Tsõõrikmäe and Simuna craters occur in soft sediments. By



Evidences of meteorite impacts in Estonia: structures under the surface (Kärdla) and under the sea (Neugrund), crater groups visible on landscape (Kaali and Ilumetsa), and single craters visible on landscape (Tsõõrikmäe and Simuna).

size, most are small craters 8.5 m (Simuna) to 110 m (Kaali main crater) in diameter.

The Kärdla crater on Hiiumaa Island (4 km in diameter) formed in the Ordovician rocks and the Neugrund multi-ring structure (diameter up to 9 km), presently underwater, near Osmussaar Island in the Cambrian period. At that time northwestern Estonia was submerged under a shallow epicontinental sea. Presently both craters are buried under younger sedimentary deposits, but the rocks covering the Neugrund structure have been eroded above the rim and it can be explored by underwater observations. In the world list of impact craters Kärdla and Neugrund craters are classified as small and medium structures.

The history of recording celestial bodies that have fallen on Estonia's territory dates back to the year 1821, when a stony meteorite roughly the size of a human head fell in Kaiavere village in northern Tartu County. Since then, seven more meteorite falls have been registered, five of which have been found and stored in collections. Luckily, these fragments were handed over to literate Baltic landlords and clergymen, who delivered them to scientific collections. Most falls are recorded in detail, and the resulting craters have been studied thoroughly and from different aspects by Estonian geologists and research students. The results of these studies are summarised in numerous publications.

The Kaali craters

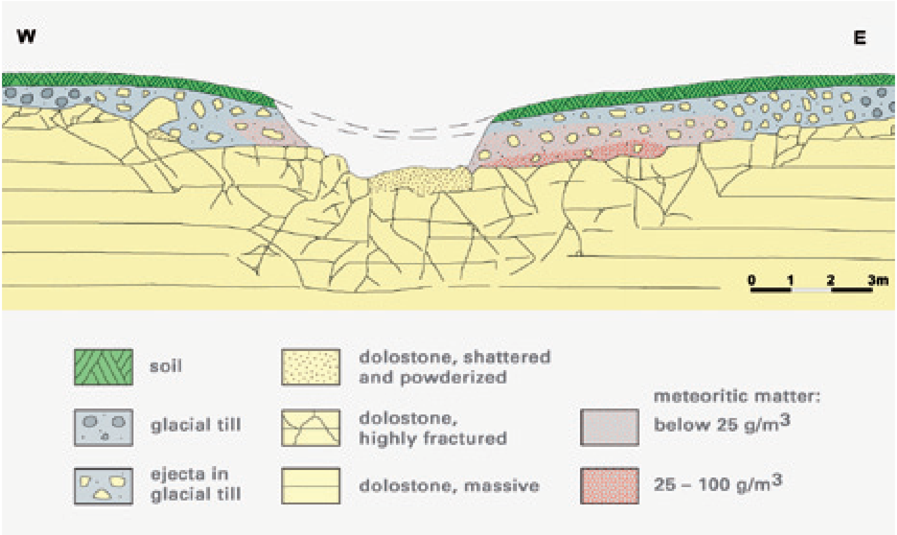
The history of the discovery of meteoritic craters in Estonia and Europe began with Lake Kaali (in Estonian Kaalijärv or Kaali). The Kaali crater field – a main crater surrounded by eight secondary craters – was formed as the result of a meteorite shower. The craters are an easily accessible and popular tourist attraction – all are located within a distance of 1 km^2 – however, most tourists visit only the main crater which is the largest and most impressive.

The interpreting of Lake Kaali as an unusual natural phenomenon began in 1827 and various hypotheses about its origin were presented:

- a volcanic eruption or abrupt emission of water, steam, gas and mud
- the collapse of a karst cave due to limestone fissures, or collapse of a salt dome
- an ancient stronghold, where the natural lake served as a well and the latter was surrounded by man-made walls;
- a meteorite crater.

The meteoritic origin of the Kaali main crater was suggested for the first time in 1922

Meteorite craters on the Kaali crater field: the main crater and the small craters (1-8)



Geological structure of crater 4 in Kaali (after R. Tiirmaa, 1994)

by Julius Kalkun-Kaljuvee (1869–1940). In 1927, geologist Ivan Reinwald (1878–1941) started investigations, including drilling, supported by the Estonian Government. Alfred Wegener (1880–1930, author of the continental drift hypothesis) visited Kaali in 1936 and he, too, considered the crater's impact origin possible. A year later, in 1937, Reinwald proved the impact origin of the Kaali craters, when a total of 30 fragments of iron meteorite were found in craters number 2 and 5. The Kaali meteorite represents the most common iron meteorite type – coarse octahedrite, which contains 91.5% Fe and 8.3%, with Co, Ge and Ir occurring as admixtures. The meteorite's polished cutting surface displays a typical Widmanstätten's structure and contains minerals characteristic of iron meteorites such as shreibersite, kamasite and taenite.

Kaali and its environs are located on a till plain eroded by the sea, where the clayey basal till is approximately 1 m thick. The latter has an underlay of thickly bedded dolostones of the Paadla Stage, Upper-Silurian. Investigations carried out by Ago Aaloe (1927–1980) in 1955–1978 showed that the well-defined shape of the craters formed in dolostone has remained intact for several thousand years.

At present the age of the Kaali craters is still argued; the data are inconsistent. It is agreed, however, that the craters were formed after the retreat of the Baltic Sea from this part of Saaremaa; sediments of marine origin have not been found in the craters. The crater bottom is covered with a characteristic mixture comprising fragments of dolostone crushed as the result of the explosion, plus till and humic soil. Fossils of terrestrial snails have been found on the bottom of the secondary craters, which indicates that the area under discussion has been a coppice-covered seaside area. The pollen found in the bottom deposits of Lake Kaali has been dated as ca 3700 years old. Radiocarbon dating of charcoal yielded an age of at least 4000 years. Based on the findings of supposed silicate explosion material from the peat layer of surrounding bogs, it can be assumed that the craters formed up to 7500–7600 years ago. The Ir-rich layer in a nearby bog was formed 800–400 years BC, which also indicates a possible age of the craters.

In the **Kaali main crater** there is a natural body of water known as Lake Kaali. The crater is almost circular and its rim-to-rim diameter is 105–110 m. The depth of the crater from the top of rim to the bottom is 22 m. The thickness of lacustrine deposits on the crater bottom is 6 m. The 4–7 m high crater rim is called Järvemägi (lake mountain in Estonian). The height of the rim may have varied naturally, but certainly it has been influenced by long-term human activity. The weathered surface of the dolostone blocks forming the rim is uneven. The lakelet, which is fed from groundwater and by precipitation, can be viewed from a small man-made terrace at the rim's lake-ward side. Depending on the level of water in Lake Kaali, its diameter ranges from 30 to 60 m and depth from 1 to 6 m. During summer droughts and dry autumns the lake almost dries up and the pile of stones in the centre becomes visible. In fact, a local landlord once planned to establish a small island with an arbour on that stone base.

The Kaali craters are the result of a dramatic explosion. The meteorite pulverised momentarily and dispersed in the rising column of rock rubble, dust and gas. The eight small secondary craters are mostly dry; their diameter ranges from 12 to 40 m and their depth from 1 to 4 m.

Lake Kaali in springtime (Photo: R. Tiirmaa)

Crater 1 in Kaali

Crater 1 is located on a field and is surrounded by a circular grove. The crater has a diameter of 39 m and is 4 m deep. Erratic boulders from the field have been carried into the crater and onto the rim.

Craters 2 and 8 form a complex twin structure. The northern crater (no 2) is 27 m in diameter and 2 m deep, and the southern one (no 8) – 36 m and 3.5 m, respectively. I. Reinwald in 1937 found the first 28 meteorite fragments (total weight 102.4 g) in this twin crater. Excavations have considerably altered the craters' preliminary appearance; the crater rim is barely visible.

Crater 3 is the best preserved and clearly observable secondary crater. The crater

Crater 4 in Kaali altered by digging works

surrounded by hazel shrubs is 33 m in diameter and 3.5 m deep, and accumulates water in spring.

Crater 4 has been disfigured by geological excavations. Initially it was bowl-like, oval in shape and 14–20 m in diameter. On the distorted bedrock surface of its bottom, I. Reinwald discovered a funnel-shaped trace of the impact which provided valuable information about the parameters of meteorite fall. This trace, too, has been deformed as the result of later excavations. The largest number of meteorite fragments was found directly at the crater bottom, 3–4 m away from the impact trace.

Meteorite pieces from Kaali
(Photo: G. Baranov)

Crater 5 also has been disfigured by excavations and is presently overgrown with bushes. Its original shape resembled a flat bowl with a diameter of up to 13 m. In some places fragments of the crater rim have been preserved. On the bottom of this crater, too, there is a trace of impact. This crater yielded the biggest meteorite fragment (38.4 g including a lamina of rust).

Crater 6 was discovered near Masa–Putla Road, 450 m to the northwest of the main crater. Its diameter is 26 m and depth 0.6 m. It has been deformed due to its location near the road embankment, but meteorite fragments have been found.

Crater 7 is located south of the main crater. Its shape resembles an irregular quadrangle. Elderly people have told researchers that it was formerly used as the manor's liquid-manure depository. Excavations have been carried out in the crater and meteorite fragments have been found there.

Excavation works have revealed fragments of meteorites in the bottom layers of small secondary craters. The underwater bottom deposits of the main crater have not been investigated in detail. All Kaali craters are too big to have formed as the result of impact only, without an explosion. The fragments of meteorites found from secondary craters may originate from the exploded meteorites, but also from the falling of minor fragments which had slowed down in the atmosphere. A. Aaloe assumed that the craters were of complex "strike-and-explosion" origin. In principle, the meteorite fragments can be found in other places as well, but conditions for their preservation have been most favourable in the bottom layers of the craters.

The meteorite fragments found in Kaali are small, with uneven surface and sharp edges, normally 1–5 mm in diameter and weigh 0.5–2 g. The surface of the fragments has oxidised over time and is covered with rust. Presently, strict rules have been established for those searching the meteorite fragments, because the excavation works carried out to date have considerably impaired several craters. To avoid further damage, the Kaali craters have been taken under nature protection. The State geological reserve was established in 1959; in 1978 its area was enlarged and presently covers 50 hectares.

Beginning in 1976, archaeologists, too, have investigated the Kaali crater field. The archaeological excavations carried out by Vello Lõugas (1937–1998) on the outer slope of the main crater's eastern rim did not give the expected results, i.e. no objects dating from the Iron Age were discovered. However, archaeologists found silver objects, probably sacrifices or hidden property, as well as the remains of a stone fence which once bordered the crater in the west. It is possible that this fence once protected the stronghold and Lake Kaali, a prominent cult location. Historian and writer Lennart Meri (1929–2006, president of Estonia 1992-2001) has analysed various reflections on the Kaali catastrophe in his books "Hõbevalge" (1976) and "Hõbevalgem" (1983), combining the existing data and his imaginings about the events.

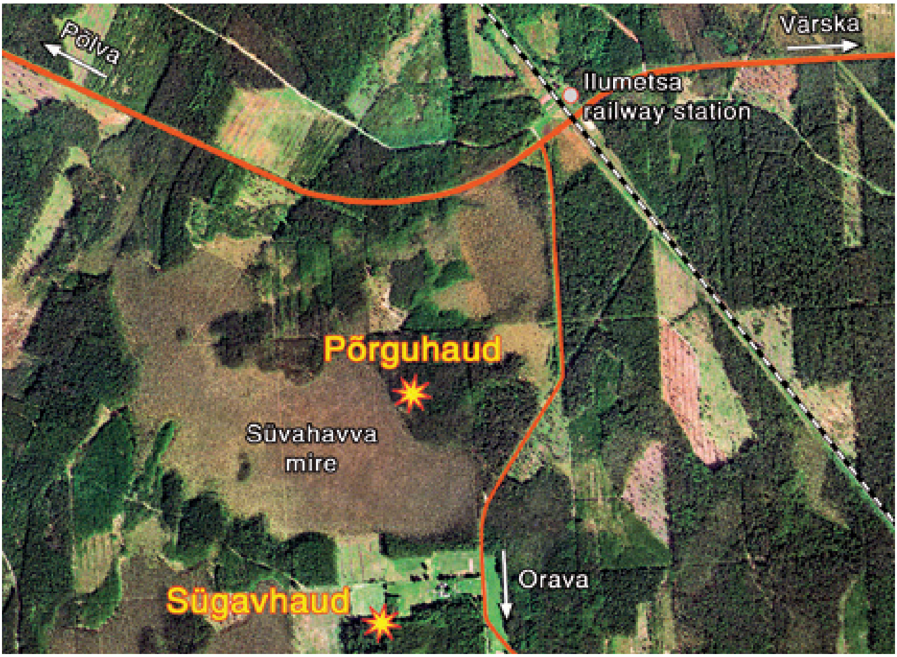
In recent years construction has been carried out in Kaali. Kaali Visitor Centre, including a museum of meteoritics and limestone, conference hall, guest rooms, souvenir shop, and employees' office, was opened in the summer of 2005.

The Ilumetsa craters

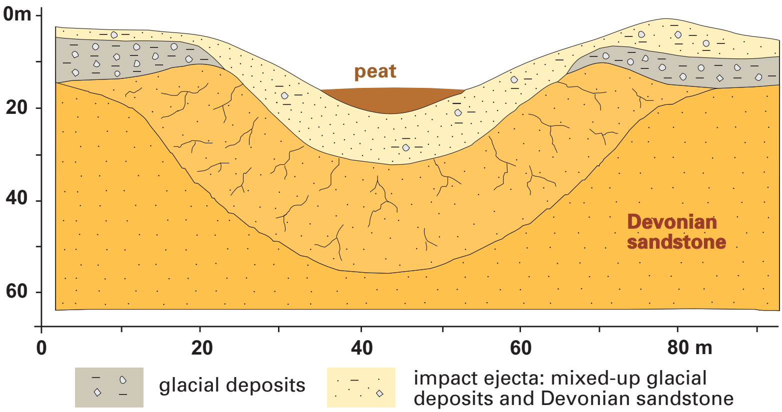
The Ilumetsa craters are located in Põlva County, approximately 1 km to the south-west of Ilumetsa railway station. At least two meteorite craters – Põrguhaud and Sügavhaud – are located in a beautiful pine forest. There are additional crater-like structures (Kuradihaud, Tondihaud and Inglihaud), but their impact origin has not yet been proved. Geologist Artur Luha (1892–1953) discovered these crater-like depressions in 1938 during geological mapping and initiated scientific investigations there. The Second World War interrupted the investigations, but A. Aaloe resumed the work in 1956. Based on the experience obtained in Kaali and on geological data, he proved the impact origin of these structures, although meteoritic matter was not found.

Põrguhaud, the biggest crater, has a rim-to-rim diameter of 80 m and a depth of 12.5 m. The crater bottom is covered with a layer of peat up to 2.5 m thick. The fragmentary crater rim is 1–4.5 m high. **Sügavhaud** is of similar shape, but is smaller in diameter – 50 m – and its depth reaches 4.5 m. Its height is 1.5 m. These rim-surrounded craters are much larger than the secondary craters in Kaali.

The Ilumetsa craters are located in the area where loose Devonian sandstones crop out. The meteorite explosion crushed the whole sequence and the characteristic raised blocks did not form in the rim core. Neither



The rim-to-rim diameter of the Põrguhaud crater at Ilumetsa
is 80 m and the depth until the base of the peat layer 12.5 m



Geological cross-section of the Põrguhaud crater in Ilumetsa (after R. Tiirmaa, 2002)

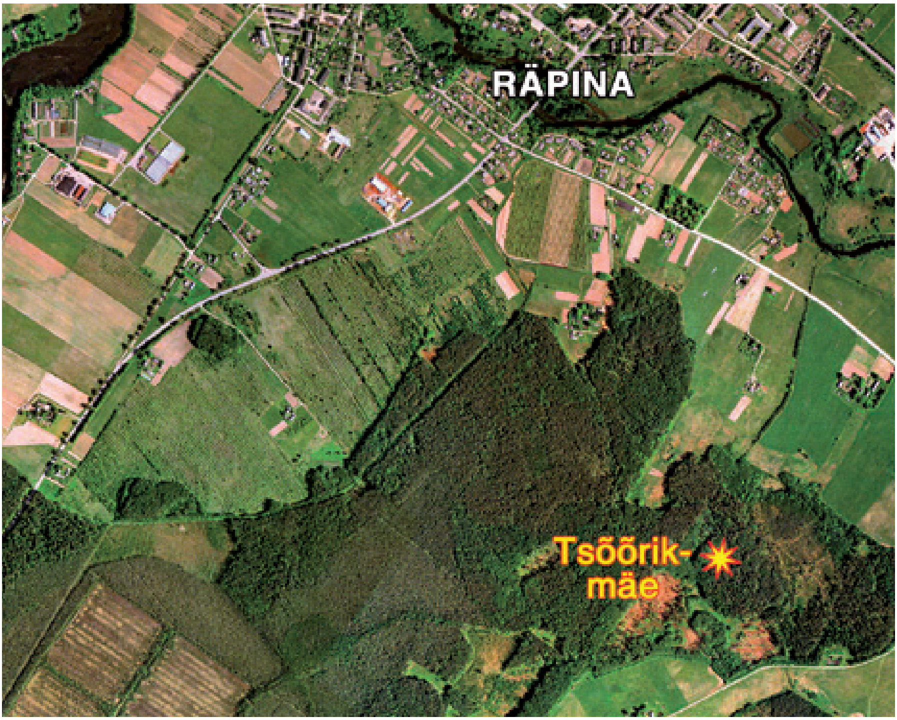
were fissure systems formed, thus geophysical investigations which would have provided valuable indirect data could not be conducted. In the beginning of 1970, the age of Põrguhaud was determined by radiocarbon dating and palynological analysis. It was established that accumulation of deposits containing organic matter began approximately 6000 years ago. In 1995, micro-impactites (dispersed matter formed at sites of meteorite explosion) were found in a 6600-year old layer in Meenikunno bog deposits; this seems to confirm the age of the craters determined earlier.

The Tsõõrikmägi Crater

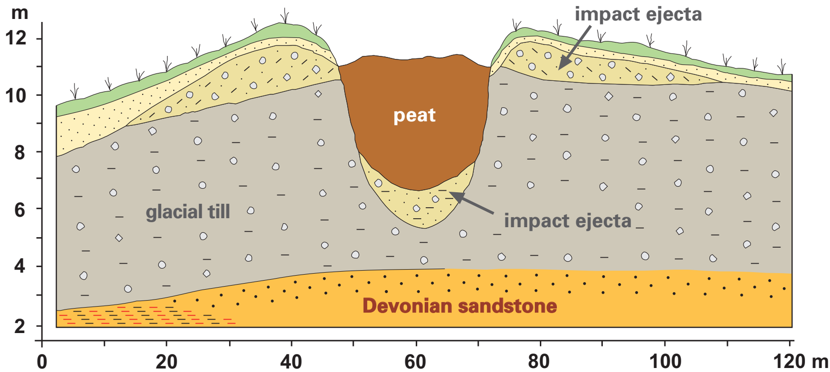
Tsõõrikmägi is a single crater – a circular depression surrounded with a barely perceptible rim – located at the southwestern boundary of Räpina settlement, ca 15 km to the east of the Ilumetsa craters. A. Aaloe gathered information about the crater from local residents.

The depression is filled with peat. At the rim's inner foot a circle of algae-rich water indicates that a lake has recently developed in the crater. The rim is 38–40 m in diameter, its top is wide (5–10 m) and gently sloping towards its outer side. Investigations including hand drilling, excavations and geophysical methods have been undertaken in the crater.

The following beds occur on the crater bottom (from the top): humus, sand, deposit resembling brown basal till, and Devonian sandstone. The peat filling the crater is up to 9500 years old; the depression was formed shortly after the termination of the last glaciation in southern Estonia. Some scientists have proposed that the depression may have formed as the result of the melting of a residual block of ice. However, all geological features (shape, relocated masses of target deposits, rock characteristics, and deformation of the rim's setting) suggest the impact origin of the crater. The



The diameter of the Tsõõrikmäe crater is almost 40 m and it was initially 6-8 m deep



Geological cross-section of the Tsõõrikmäe crater (after R. Tiirmaa, 2002)

age of the Tsõõrikmägi crater also refuted the assumption that it might belong to the group of craters created by the same meteorite shower as the Ilumetsa craters. The older age of Tsõõrikmägi compared to those at Ilumetsa proves that it is an independent crater. However, the primary natural appearance of the Tsõõrikmägi crater has changed as a result of former flax retting by area residents.

The Simuna Crater

On 1 June 1937, residents of northeastern Estonia witnessed a peculiar natural phenomenon – the flight of a bolide. This has been rapturously described by A. Kipper (1907–1984), a young astronomer who was sent to investigate this event. Almost 50 years later native researcher Heino Ross reported a small crater in the forest near Orguse village, northwest of Simuna. Karst phenomena are common in this region, therefore the crater's impact origin was questionable, but geologist Ülo Heinsalu (1928–1994) confirmed that the depression was not a karst funnel. The excavations carried out in 1986 confirmed the impact origin of the Simuna crater. Clear evidence is a humus layer buried under the rim and the position of particles in the material fallen on the latter. The rim-to-rim diameter of the crater is 8.5 m and its depth 1.9 m. The low rim around the crater is hardly visible, but is clearly circular and continuous. The crater was formed at the site with two layers of sediment: loose sand above and clayey till rich in cobbles and boulders below. In the rim the succession of the material is typical – the buried humic soil is covered with large boulders and pebbles, and fine sand occurs in the rim's upper part. Due to the presence of abundant household refuse (mostly scrap metal) the detection of meteoritic matter with a mine-hunter failed. Simuna crater might be one of the few impact craters formed on the Earth during our generation.

Location of the crater NW of Simuna village

The Simuna crater, 8.5 m in diameter and 1.3 m deep, is considered to be the youngest known meteorite crater in Estonia, likely formed in 1937

The Kärdla Crater

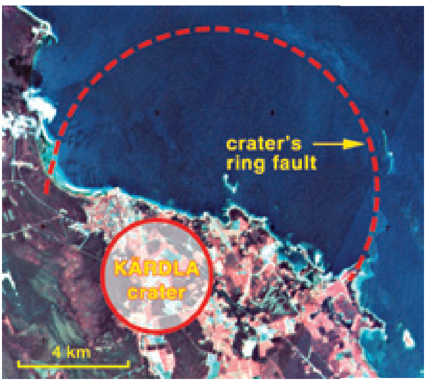
A prominent "star scar" is located deep in the Earth's bowels at the southeastern boundary of Kärdla on Hiiumaa Island. In contemporary topography it can be noticed only when one is familiar with its underground structure. The history of its discovery began in 1968, when a well was drilled in Paluküla. Surprisingly, the crystalline basement was reached at a depth of only about 20 meters instead of 240 m. After that, extensive geophysical investigations and drilling for geological mapping and exploration for minerals were launched.

In the 1970s very little was known in Estonia about large meteorite craters. At first, the geologists assumed that tectonic uplifts and depressions occur in the Soovälja area between Paluküla and Tubala, but in 1973 they discovered circular anomalies in the gravity and magnetic fields – a reflection of a buried crater-shaped structure. Some geologists proposed that the Kärdla crater is of volcanic origin. However, by 1980 it was apparent that the crushed rocks on the crater bottom (typical breccias characteristic of meteorite craters) bear metamorphic features characteristic of meteoritic impact explosions, primarily planar deformation elements (high pressure metamorphic deformation lamellae) in quartz grains.

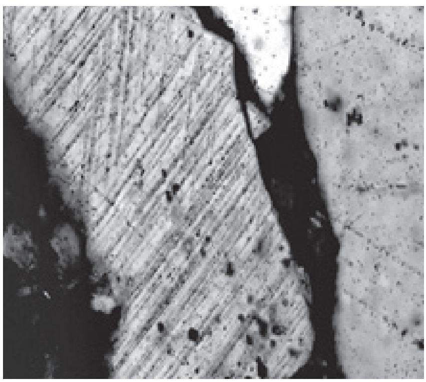
During more than 30 years of geological mapping 300 boreholes have been drilled. The processed results of these investigations have been published in numerous manuscripts and papers. The well preserved Kärdla structure is known worldwide as one of the most thoroughly investigated meteorite craters.

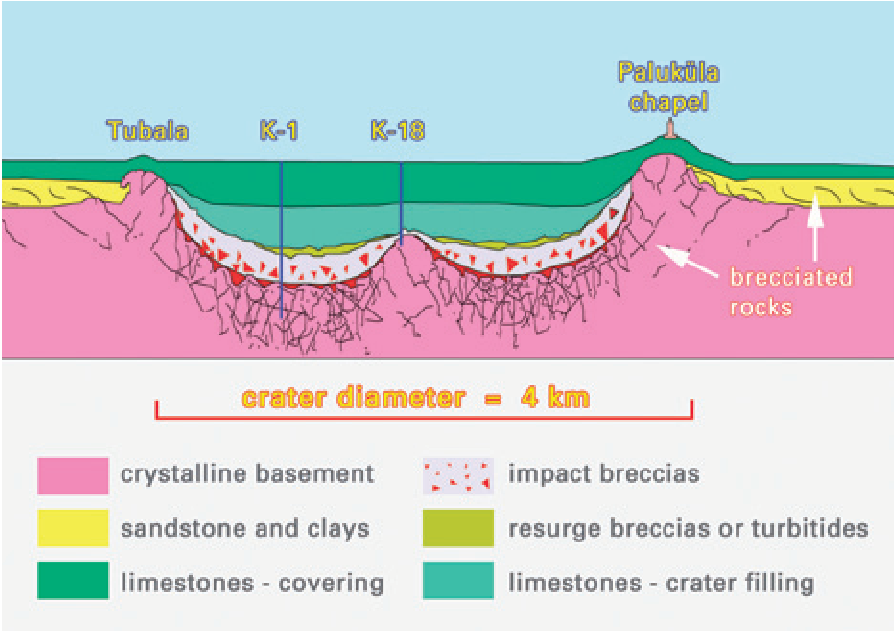
The Kärdla meteorite crater was formed in the Ordovician period, almost 455 million years ago when a huge meteorite struck Earth's surface in shallow sea. The crater's

The position of the Kärdla meteorite crater in northwestern Hiiumaa, south-west of the town of Kärdla (after K. & S. Suuroja).



Quartz grains in the impact-breccia of the Kärdla crater. Two systems of cracks indicate planar deformations, the evidences of shock metamorphism. x 100. Photo: S. Suuroja





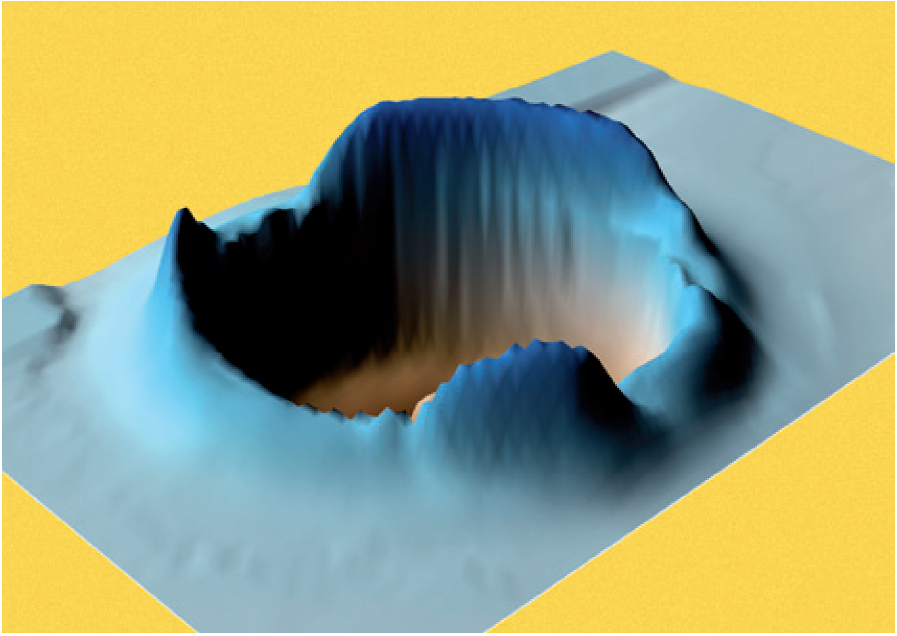
The geological cross-section of the Kärdla meteorite crater (after K. and S. Suuroja)

shape, although slightly angular, is rather regular. Its diameter at the top of the rim is almost 4 km. The crater rim is buried only under thin Upper- and Middle-Ordovician rocks, and these in turn are covered by a thin Quaternary layer. The 10–15 m high ridge-like formation running over Paluküla-Lõpe and several smaller bedrock elevations mark the crater rim at a depth of approximately 15–150 m below ground surface. The low plain above the crater deep between Tubala and Paluküla has been drained and is presently used as arable land.

The crater is easily observable in the crystalline basement topography: in some places, up to 250 m high and a 1 km wide rim with a wavy top surrounds the flattish crater deep 3.5 km in diameter and 400–500 m deep.

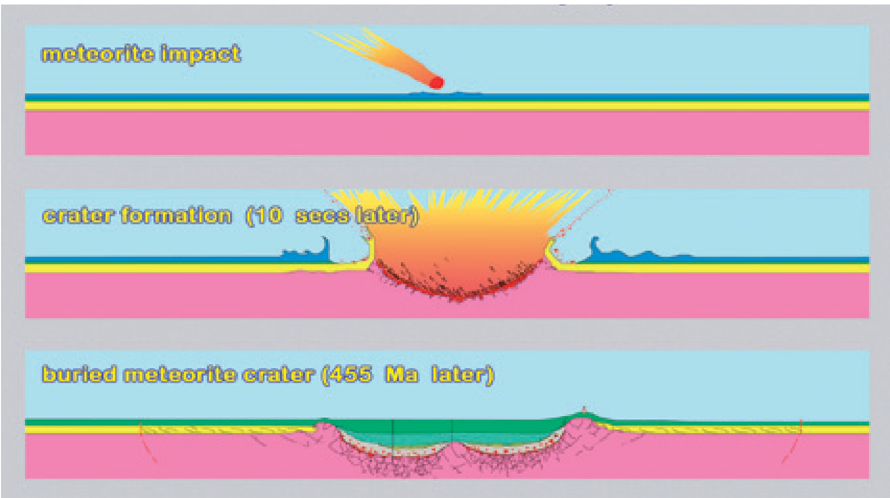
In 1984, a central uplift characteristic of a meteorite crater was discovered in the process of drilling a borehole. The deepest borehole in Estonia, K-1 Soovälja (815.2 m) was drilled in 1989–1990 to investigate the Kärdla Crater. Mineral water was extracted from the deeper layers in the central part of the crater, and was bottled and marketed under the trade mark "Kärdla".

The crater is surrounded by a characteristic ring fault 12–15 km in diameter, which can be traced even on space photos. The sedimentary bedrocks outside this fault are intact.



Crater elements in subsurface: buried crater rim and other features are reflected in the topography of the surface of the crystalline basement. These structures are buried under Cambrian and Ordovician sedimentary rocks. (3-D image after S. Suuroja)

The origin of the Kärdla meteorite crater (after K. Suuroja)

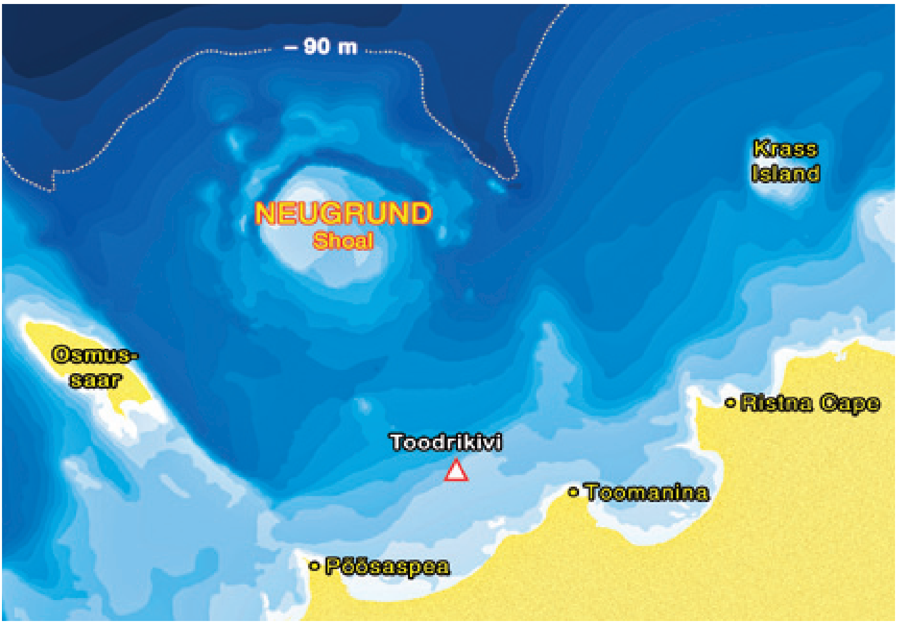


The Neugrund Crater

The multi-ring Neugrund crater is the biggest meteorite crater in Estonia. By the beginning of the 20th century geologists were familiar with a peculiar rock type – "gneiss breccias" – which was found on Osmussaar Island and elsewhere in northwestern Estonia. The experience gained while investigating the Kärdla impact breccias helped to elucidate the origin of the gneiss breccias. The problem was solved by investigating the seafloor landforms on Neugrund Bank (Nygrund, Uusmadalik) located near the mouth of the Gulf of Finland. The bank morphologically resembled crater structures. The samples of gneiss breccias from the crater rim were obtained by diving. And again, characteristic metamorphic deformation lamellae were found in quartz grains.

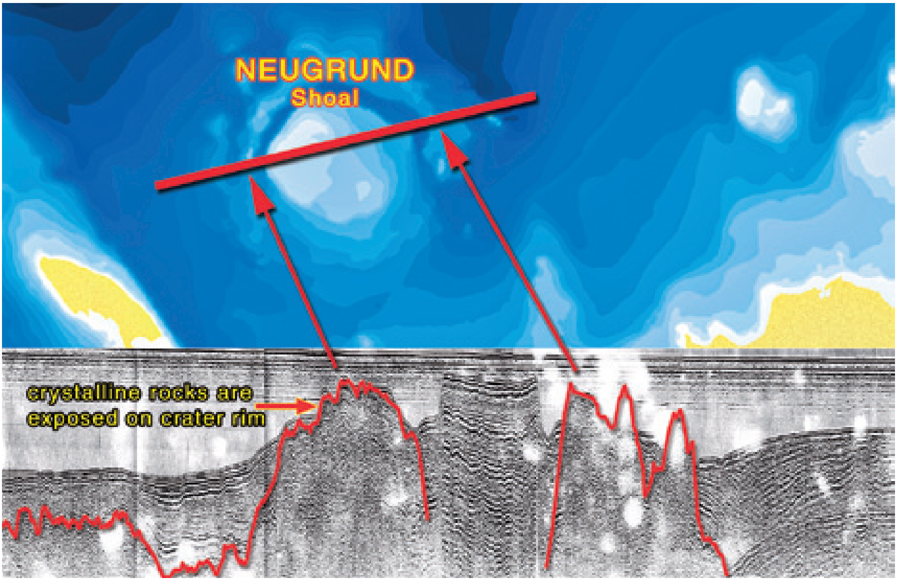
On Neugrund Bank, located east of Osmussaar Island, extensive geophysical and underwater geological works were launched. In the summer of 1996, during a joint Estonian-Swedish expedition, the Neugrund structure and its environs were investigated by seismoacoustic sounding from on board the r/v Strombus. The drillcores from Osmussaar Island and northwestern Estonia were revised and some new ones were made.

The Neugrund structure proved to be of much older age than the Kärdla Crater – approximately 535 million years old. The structure is concentric; around the crater deep there are at least three rims consisting of crystalline rocks. The Neugrund



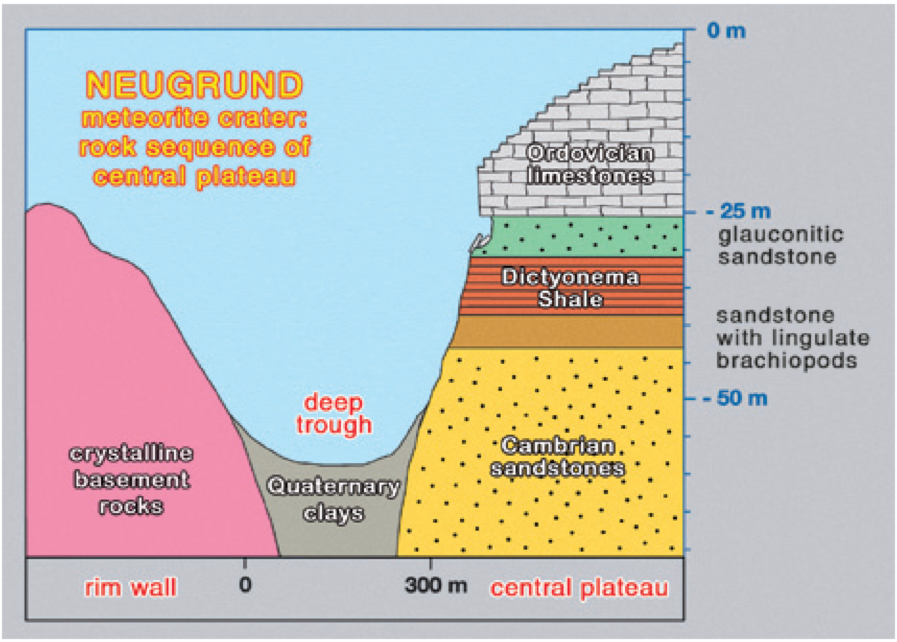
The erratic boulder of Neugrund-breccia at the coast of Toomanina

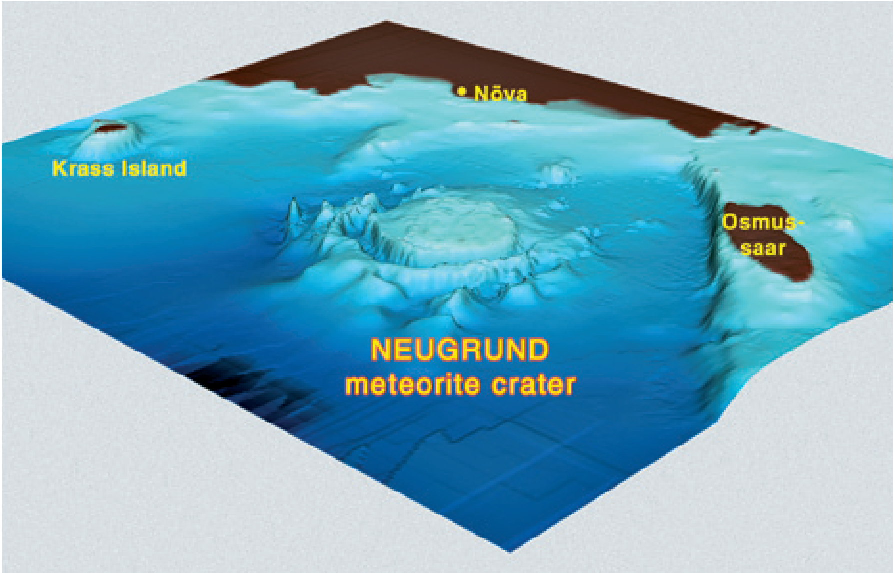
An erratic bolder of Neugrund-breccia among the erratic boulders originating from the crystalline basement of Finland



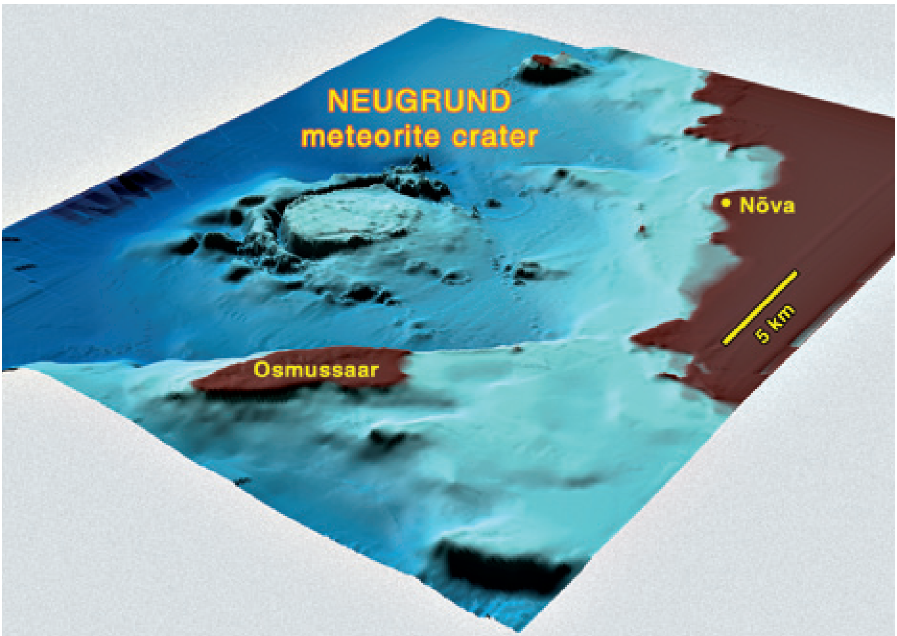
The seismic section of the Neugrund crater (after S. Suuroja)

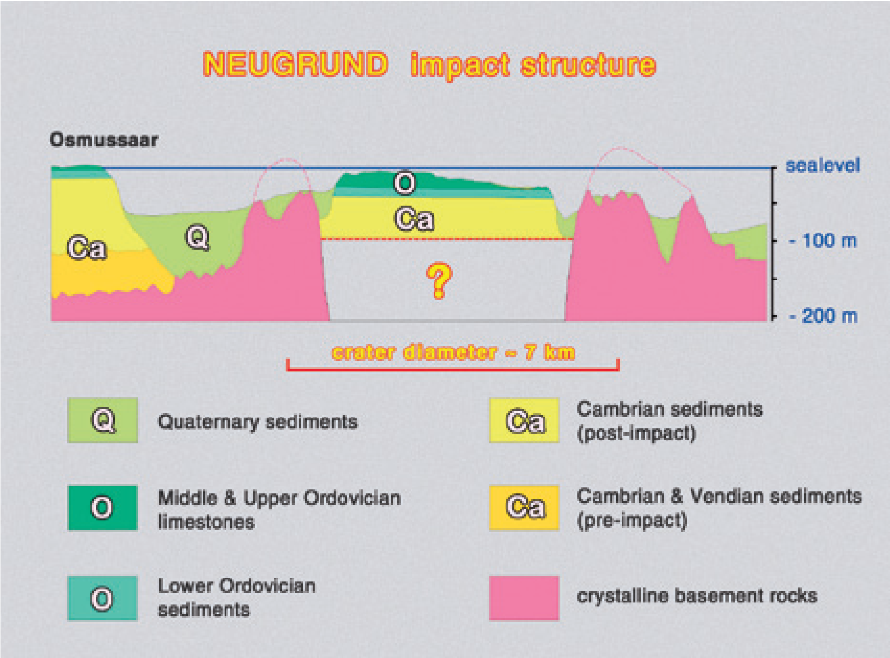
The geological section of the Neugrund central plateau (after S. Suuroja)





The 3-D models of seabed topography in the surroundings of the Neugrund crater (after S. Suuroja)





The cross-section of the Neugrund structure (after K. and S. Suuroja)

structure was buried under sedimentary rocks for hundreds of millions of years, but the continental glacier eroded the stone matter and carried the gneiss breccia blocks torn off the crater rim to Osmussaar Island and to the Estonian mainland. The rim closest to the crater deep is the highest and best preserved, and also the most accessible for underwater observations and investigations. The breccias occurring on the bottom of the crater deep are covered by the so-called "cap" – i.e. what has remained from the sedimentary beds which once filled and covered the crater. The Neugrund central bank is formed primarily of this post-impact limestone, deposited in the Early and Middle-Ordovician seas. The outer crater rim is 9 km in diameter, but the diameter of the ring fault surrounding the whole structure reaches 21 km. Between the central bank (depth of water 2–20 m) and the surrounding rim there is a circular canyon up to 70 m deep and 200–500 m wide, formed during glacial erosion. The southern part the canyon is filled with Quaternary deposits. The crater rims consisting of crushed crystalline basement rocks have been considerably eroded by the continental glacier. The recorded changes through the geologic epochs demonstrate the role of Pleistocene glacial erosion in exposing the upper part of the Neugrund structure and formation of the present dissected topography.

The Estonian Commission of Meteoritics

Scientists and researchers of Estonian universities, scientific institutions and the Geological Survey of Estonia belong to the Estonian Commission of Meteoritics. Several amateurs have investigated meteorites and meteorite craters, as well. The Commission of Meteoritics was established in 1954 at the Institute of Geology of the Estonian Academy of Sciences and was led by Karl Orviku (1903–1981). Its first aim was to continue the investigations of the Kaali crater field and the problematic depressions at Ilumetsa, which were discovered in 1938. Conditions for investigation of meteorites were favourable, since the valuable collection of meteorites was stored at the Geological Museum of Tartu University and the present Institute of Geology at the Tallinn University of Technology. The collection of meteorites was established in 1803 when three specimens of the famous Pallas Iron (found in 1749 on the bank of the Yenissei River) were purchased together with a collection of minerals. In the beginning of the 19th century all meteorites which had fallen on the territory of Estonia and Latvia were gathered in this collection and investigations of their mineral and chemical composition were begun. Later on, the collection was supplemented with donated, purchased and exchanged specimens. Presently, the collection comprises 225 meteorites.

Among the members of the Estonian Commission of Meteoritics – including geologists, astronomers, physicists, botanists, historians, and amateurs – an especially active commission member was Ago Aaloe (1928–1980). Beginning in 1955, he initiated excavations in the Kaali (Saaremaa) and Ilumetsa (Põlvamaa) crater fields, applying geophysical methods to identify the extensive zone of crushed rocks around the Kaali craters. He discovered two new craters in Kaali and registered the problematic Tsõõrikmäe depression near Räpina. The Commission cooperated with the Meteorite Commission of the Academy of Sciences of the USSR and scientists of the Chair of Geophysics of the Moscow State University. Mineral investigations of Estonian meteorites were carried out jointly with science centres of Moscow, Kiev and Sverdlovsk. Estonian geologists participated in the expeditions organised by the former Academy of Sciences of the USSR in the areas of meteorite falls in Sihhote-Alin and Tuva; numerous specimens were contributed to the meteorite collection.

The Commission of Meteoritics has established relations with scientific institutions in Estonia and abroad, organising conferences, meteoritic study days and workshops for wider audiences. The results of investigations of meteorite craters have been made available in international scientific journals and presentations.

Selected popular and scientific papers and publications

Aaloe, A., Liiva A., Ilves, E. 1963. About the age of Kaali meteorite craters. Eesti Loodus, 5, 262-265.

Bauert, H., Männil, R. & Suuroja, K. 1987. The age of the Kärdla crater. Local structures in Belarus and Baltic Region. Thesis of the meteoritic conference. Vilnius (in Russian).

Kala, E,. Puura, V. & Suuroja, K. 1984. Main features of the Kärdla buried crater. Proceedings of the Estonian Academy of Sciences. Geology. 33, 1–7 (in Russian).

Lehtinen, M. 1998. Meteoriittitörmäyskraaterit. Suomen Kallioperä. M. Lehtinen, P. Nurmi, T. Rämö (ed.). Suomen Geol. Seura, 327-341.

Kipper, A. 1937. About the meteorite of 1 June 1937. Eesti Loodus, 4, 150-155.

Lõugas, V. 1996. Looking for Phaeton in the Kaali crater field. Tallinn (in Estonian), 174 s.

Orviku, K. 1935. Gneiss-breccia erratic boulders. Eesti Loodus, 4, 98–99.

Pirrus, E. & Tiirmaa, R. 1984. Tsõõrikmägi – is it a meteorite crater? Eesti Loodus, 9, 566-571; 10, 638-642.

Pirrus, E. & Tiirmaa, R. 1991. Did the Virumaa bolite reach the Earth? Eesti Loodus, 4, 210-214.

Plado, J., Pesonen, L.J., Elo, S., Puura, V., Suuroja, K. 1996. Geophysical research of the Kärdla impact structure, Hiiumaa Island, Estonia. Meteoritics & Planetary Science 31, 289–298.

Puura, V., Huber, H., Kirs, J., Kärki, A., Suuroja, K., Kirsimäe, K., Kivisilla, J., Kleesment, A., Konsa, M., Preeden, U., Suuroja, S & Koeberl, C. 2004. Geology, petrography, shock petrography, and geochemisty of impactites and target rocks from the Kärdla crater, Estonia. Meteoritics & Planetary Science 39/3, 425–451.

Puura, V. & Plado, J. 2005. Settings of meteorite impact structures in the Svecofennian Crustal Domain. Impact Tectonics. Springer-Verlag Berlin Heidelberg, 211–245.

Puura, V. & Suuroja, K. 1984. Kärdla crater – a unique structure in the bowels of the Earth. Eesti Loodus, 8, 553–565.

Raukas, A., Pirrus, R., Rajamäe, R. & Tiirma, R. 1995. On the age of the meteorite craters at Kaali (Saaremaa Island, Estonia). Proceedings of the Estonian Academy of Sciences, 4, 177-183.

Reinwald, I. 1937. Meteor craters in Saaremaa. Looduskaitse, 1. 118-131.

Suuroja, K. 1998. Neugrundi meteoriidikraater. Loodus, November, 16-20.

Suuroja, K., Puura, V., Kirs, J., Niin, M. & Põldvere, A. 2002. Geological setting of the Kärdla area. Soovälja (K-1) drill core. Geological Survey of Estonia. 6–10.

Suuroja, K. & Suuroja, S. 1999. Neugrund structure - a submarine meteorite crater at the entrance to the Gulf of Finland. Estonia Maritima 4, 161–189.

Suuroja, K., Suuroja, S. & Puurmann, T. 1997. Neugrund structure as an impact crater. Bulletin of the Estonian Geological Society, 2/96, 32-41.

Tiirmaa, R. 1984. Meteorites behind the glass and in the boxes. Eesti Loodus, 8, 490-495.

Tiirmaa, R. 1994. Kaali meteorite. Tallinn. Institute of Geology at the Estonian Academy of Sciences. 125 s.

Tiirmaa, R. 2002. Meteorites and meteorite craters. Tallinn. TTÜ Geoloogia Instituut. 108 s.

Tiirmaa, R. 2005. Star scars in Kaali. Tallinn. Institute of Geology at Tallinn University of Technology. 24 s.

Veski, S., Heinsalu, A., Kirsimäe K., Poska, A. & Saarse, L. 2005. Ecological catastrophe in connection with the impact of the Kaali meteorite about 800-400 B.C. on Saaremaa Island, Estonia. Meteoritics and Planetary Science 36, 1367-1375.

Some explanations of terms

Asteroid – a minor planet that orbits the Sun between Mars and Jupiter, normally with a diameter less than 1000 km

Basement – also crystalline basement, part of Earth's crust consisting of folded igneous and metamorphic rocks, which are overlain by sedimentary cover

Bolide – a huge meteoric body, brighter than Venus

Breccia – rock composed of angular fragments of minerals or rocks

Comet – a small body in the solar system that orbits the Sun and exhibits a coma (or atmosphere) and/or a tail. The comet's solid nucleus is 0.5–50 km in diameter and is composed of rock, dust, and ice. When approaching the Sun, the nucleus begins to vaporize and the volatile compounds form a tail, which is turned away from the nucleus

Dolomite – both carbonate rock and a mineral consisting of calcium magnesium carbonate, formula: $CaMg(CO_3)_2$

Dolostone – rock composed predominantly of the mineral dolomite

Erratic boulder – a boulder dislocated by a glacier or a continental glacier

Iron meteorites – siderites, are largely composed of metallic iron-nickel; carbides, nitrides, phosphides, sulphides, oxides, phosphates and silicates occur as admixture

Karst – an area of irregular limestone in which erosion has produced fissures, sinkholes, underground steams, and caverns

Mantle rock – or regolith, the layer of loose rock resting on bedrock, constituting the surface of most land

Meteorite – an extraterrestrial body that survives its impact with the Earth's surface without being completely destroyed. Primary material of meteorites originates from the asteroids and comets circling in the solar system. The material of most meteorites is 4.5–4.8 billion years old, which is similar to the Earth's geological age. Meteorites have traditionally been divided into three categories: stony meteorites, iron meteorites and stony-iron meteorites. Huge meteorites with a mass of more than 100 tons and velocity of more than 3–4 km/s create an explosion crater at collision due to enormous kinetic energy

Radiocarbon dating method – a radiometric dating method that uses the naturally occurring isotope carbon-14 to determine the age up to ca 50,000 years

Stony-iron meteorites – contain large amounts of both metallic and rocky material; silicate minerals olivine, pyroxene and plagioclase occur as inclusions

Stony meteorites – also aerolites; their composition is similar to Earth's mantle rock, primarily of silicate minerals olivine and pyroxene. That makes them difficult to identify, even though they are the most common type of meteorites, accounting for 93% of all known falls

Widmanstätten pattern – a characteristic cross-hatched pattern that becomes visible on the polished surface of meteorites. It is named after its discoverer, the Austrian mineralogist Alois von Widmanstätten and is observed in most iron meteorites. The structure is formed in a solid body by diffusion at a temperature below 700 ^{o}C in the process of slow cooling, e.g. inside a huge celestial body

IUGS ICS Geological Time Scale 2004 (www. stratigraphy.org)

adapted and modified by Estonian Commission on Stratigraphy (www.gi.ee/ESK/)

EON	ERA	SYSTEM	SERIES	AGE (Ma)
				0,00
Phanerozoic	Cenozoic	QUATERNARY	Holocene	0,0115
			Pleistocene	1,806
		NEOGENE	Pliocene	5,332
			Miocene	23,03
		PALEOGENE	Oligocene	33,9 ± 0,1
			Eocene	55,8 ± 0,2
			Paleocene	65,5 ± 0,3
	Mesozoic	CRETACEOUS	Upper Cretaceous	99,6 ± 0,9
			Lower Cretaceous	145,5 ± 4,0
		JURASSIC	Upper Jurassic	161,2 ± 4,0
			Middle Jurassic	175,6 ± 2,0
			Lower Jurassic	199,6 ± 0,6
		TRIASSIC	Upper Triassic	228,0 ± 2,0
			Middle Triassic	245,0 ± 1,5
			Lower Triassic	251,0 ± 0,4
	Paleozoic	PERMIAN	Lopingian	260,4 ± 0,7
			Guadalupian	270,6 ± 0,7
			Cisuralian	299,0 ± 0,8
		CARBONIFEROUS	Pennsylvanian	318,1 ± 1,3
			Mississipian	359,2 ± 2,5
		DEVONIAN	Upper Devonian	385,3 ± 2,6
			Middle Devonian	397,5 ± 2,7
			Lower Devonian	416,0 ± 2,8
		SILURIAN	Přidoli	418,7 ± 2,7
			Ludlow	422,9 ± 2,5
			Wenlock	428,2 ± 2,3
			Llandovery	443,7 ± 1,5
		ORDOVICIAN	Upper Ordovician	460,9 ± 1,6
			Middle Ordovician	471,8 ± 1,6
			Lower Ordovician	488,3±1,7
		CAMBRIAN	Furongian	501,0±2,0
			Middle Cambrian	513,0±2,0
			Lower Cambrian	542,0±1,0
Proterozoic	Neoproterozoic	EDIACARAN		630
		CRYOGENIAN		850
		TONIAN		1000
	Mesoproterozoic	STENIAN		1200
		ECTASIAN		1400
		CALYMMIAN		1600
	Paleoproterozoic	STATHERIAN		1800
		OROSIRIAN		2050
		RHYACIAN		2300
		SIDERIAN		2500
Archean	Neoarchean			2800
	Mesoarchean			3200
	Paleoarchean			3600
	Eoarchean			~4500

ISBN 978-9985-9834-1-6

Scientists believe that only a small number of craters have been discovered so far. The discovery and preservation of craters depends on the geological setting and history of the region. A precondition, of course, is the purposeful activity of geologists. In Estonia conditions are more favourable for preservation of the craters formed in the end of the Proterozoic, in the Palaeozoic, and in the end of the Cenozoic – in the Holocene period. The main task of astronomers is to discover possible extraterrestrial threats and to provide warnings about them.