GEOLOGOS 5 (2000)

PL ISSN 1426-8981 • ISBN 83-86682-45-0

Study of meteoritic matter for precise regional stratigraphy

ANTO RAUKAS
Institute of Geology at Tallinn Technical University, 7 Estonia Avenue, 10143 Tallinn, Estonia
e-mail: Raukas@gi.ee

Abstract: New physical and isotope-geochemical methods and improvement of old classical methods have considerably enlarged our knowledge not only of the physical age of the deposits but also of the palaeogeographic situation in the past. During the last hundred years, microscopic glassy and ferrous spheroids of different origin have often been found in various geological formations. In 1996, IGCP project 384 "Impact and Extraterrestrial Spherules: New Tools for Global Correlation" with a duration of five years (1996–2000) was launched. Estonia with its two well-known astroblems (Kärdla, Neugrund) and three groups of Holocene craters (Kaali, Ilumetsa, Tsôôrikmäe) serves as a key region for this kind of studies. The concentration of magnetite-silicate microimpactites in certain layers of peat in the surroundings of the Kaali and Ilumetsa craters suggests that the Holocene impact events can be precisely dated on the basis of ^{14}C dates and pollen evidence, and serve as good regional chronostratigraphical markers. The age of the Kaali craters is approximately 7500 and Ilumetsa craters about 6600 years BP.

Key words: meteorite impact, microimpactites, spherules, chronostratigraphical markers.

Introduction

It is well known that meteorites make up only an insignificant part of the extraterrestrial matter reaching the Earth. Mostly, it is in the form of extraterrestrial dust, the varieties of which are meteoritic, meteoric and cosmic dust. Glassy spherules, formed by partial melting and evaporation of the terrestrial and extraterrestrial matter during the impact explosion, are abundant. We have carefully studied the surroundings of the Kaali and Ilumetsa craters (Fig. 1). The Kaali craters, 9 in all, in an area of 1 sq km are located in the SE part of Saaremaa Island, Estonia. The soil both in the craters and around them contains

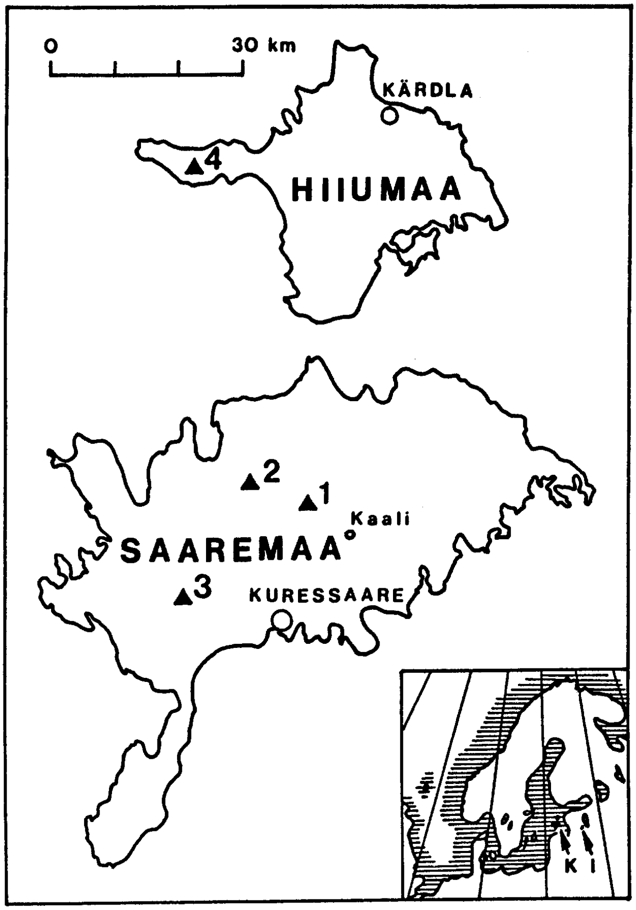


Fig. 1. Investigated sites on the islands of Hiiumaa and Saaremaa and the location of Kaali (K) and Ilumetsa (I) craters:
1 – Piila Mire, **2** – Pelisoo Mire, **3** – Pitkasoo Mire, **4** – Kôivasoo Mire.

a large number of micrometeorites and pulverized impactite matter. The energy needed for the formation of the main crater with a diameter of 110 m in the Kaali crater field has been estimated at 4×10^{19} ergs. The initial velocity of the meteorite upon entering the atmosphere was 15 to 45 km/sec and at the time of impact 10 to 20 km/sec (Tiirmaa 1994). The mighty explosion with accompanying high temperature led to the formation of glassy silicate microimpactites, which distributed over a large area and deposited in different sediments. On their basis, it is possible to estimate the age of the impact and to correlate rather far-lying sequences.

The Ilumetsa craters are located in SE Estonia, and reach Devonian sandstones (Fig. 2). As meteoritic iron had not been found in the craters, their impact origin was until recently questionable. On the basis of spherules, not only the meteoritic origin of the craters, but also the age of the impact could be established.

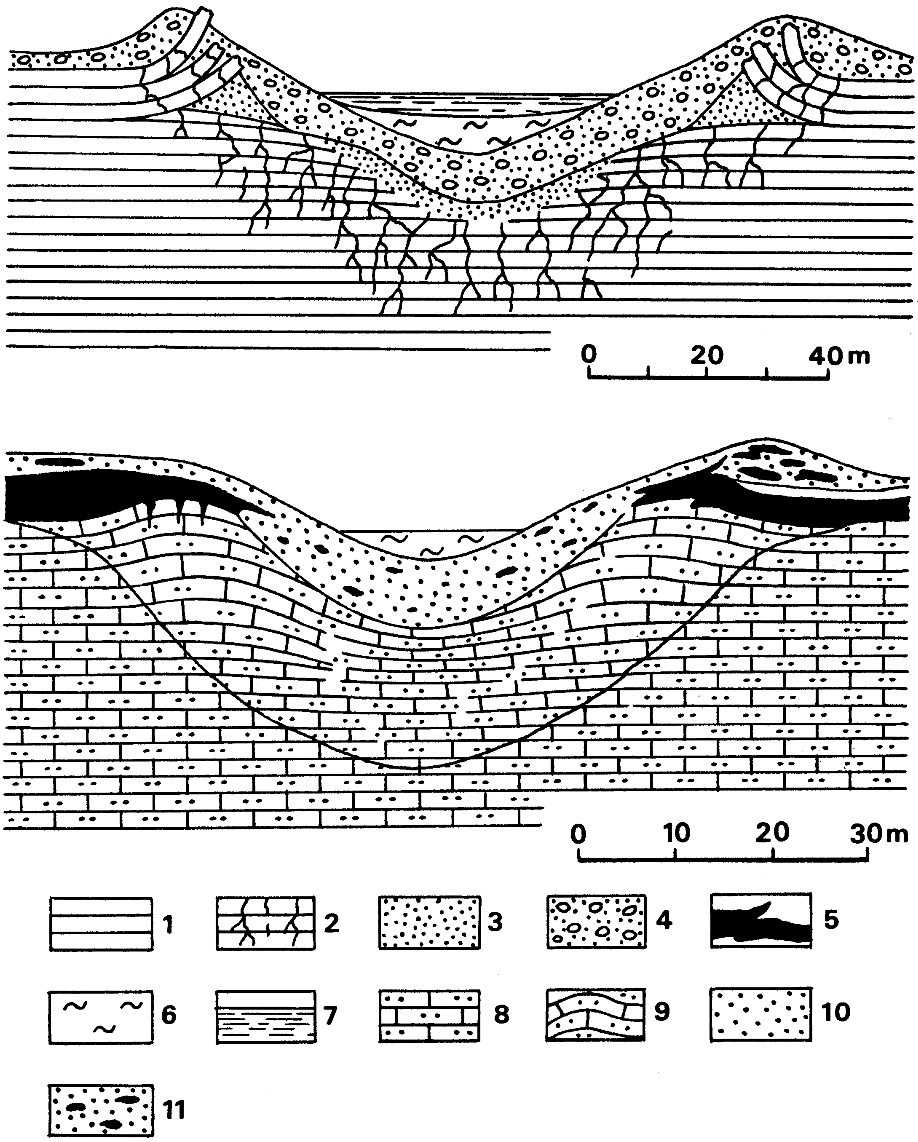


Fig. 2. Geological structure of the Kaali main crater (above) and Ilumetsa Pôrguhaud crater (below) after A. Aaloe:

1 – Silurian dolomites, **2** – dolomites destroyed during the impact, **3** – dolomite powder, **4** – dolomite breccia with till inclusions, **5** – till, 6 – peat and gyttja, **7** – water, **8** – Devonian sandstone, **9** – destroyed sandstone, **10** – glaciofluvial sand, **11** – glaciofluvial sand with nests of till.

Material and methods

Different magnetic and glassy spherules have been recovered from various terrestrial and marine environments, most notably from deep-sea sediments and glacial ice. Part of spherules originate from the meteorites exploded high in the atmosphere, others issued from impacts of crater producing meteorites. Spherules of volcanic and industrial origin are also rather frequent. Both, extraterrestrial and explosive spherules can be used in stratigraphical correlations over large areas.

Three main types of extraterrestrial matter – meteoritic iron, meteoritic dust and microimpactites – have been found in and around the Kaali craters. In lakes and bogs around the Ilumetsa and Kaali crater fields, in an area of several hundred square kilometres, mainly glassy impactites with diverse morphology and chemical composition have been found and studied by means of scanning electron microscope and microsond analysis (Shymanovich *et al.* 1993; Raukas & Tiirmaa 1998).

Peat samples were taken from dug holes and by means of a Belarus peat corer. The sampling interval was 5 cm. The collected samples were divided and used for palynological, radiocarbon and spherule studies. In the latter case, the samples were burnt to ashes at the temperature of 700 ± 25^0C. Ash was removed and the spherules were collected under a binocular microscope.

The pollen slides were prepared according to the conventional method. All samples were boiled in 10% KOH for 5 min. Thereafter they were treated with 10% HCl, washed, treated with acetic acid and heated in acetic acid/H_2SO_4 solution (9:1). After being treated once more with acetic acid, they were washed several times with distilled water.

Radiocarbon dating of sediments was performed at the laboratory of the Institute of Geology at Tallinn Technical University (Tallinn Laboratory – Tln) by means of the conventional liquid scintillation technique. Sample material was subject to normal acid – alkaline – acid pretreatment to remove carbonates and humic matter having enhanced mobility.

Types of extraterrestrial matter

Spherules of different type have been found in the crater field and surroundings (Fig. 3). According to Aaloe & Tiirmaa (1981) with some later modifications (Shymanovich *et al.* 1993), three main types of spherules occur in the Kaali crater field:

1. Meteoritic iron, formed as a result of the break-up of meteoritic masses at the moment of their impact, is represented with irregular tiny meteorite fragments and fine (less than 1mm) pulverized matter. All meteorite pieces found are small (diameter 1–5 mm, weight 0.5–2 g). Large fragments, over 5 g in weight, are rare. The fragments display a variety of shapes, in most cases they have

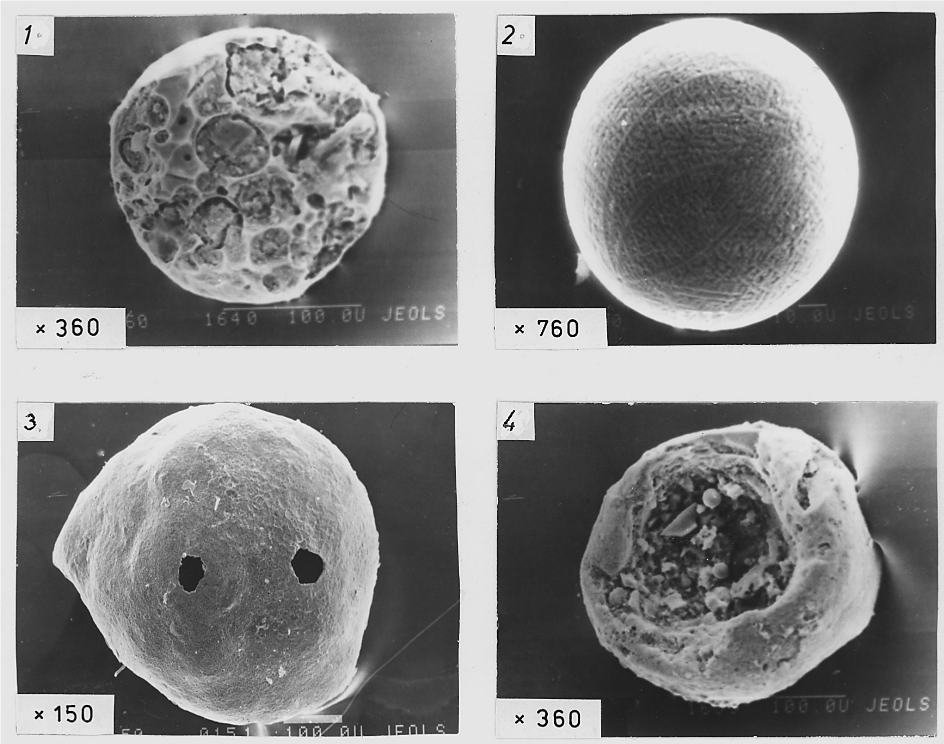


Fig. 3. Some of multiple varieties of magnetite spherules (1–4) with post-depositional coatings (1 and 4). Photos by S. Shymanovich.

bumpy surfaces, sharp edges, are highly oxidized and crusted with a thin layer of loamy material.

2. Meteoritic dust, formed on the melting of meteoritic matter during the impact of condensed metal vapor, is represented with spherical and subspherical magnetite globules, platelets and crusts. Magnetite globules vary in roundness, internal structure and microsculpture. They may be spherical, elliptic, ovatetubercular, oolitic or drop-like, resembling a lemon. Occasionally, strongly crushed forms are encountered. On the surface of some spherules, the clear Widmanstätten structures occur. Magnetite platelets are usually less than 1000 μm (occasionally up to 2000 μm) in diameter, and 100... 200 μm thick. They are dull grey, sometimes with a metallic lustre. Most frequently, they are irregular in outline and have kidney-shaped striated or imbricate surfaces displaying a pattern of rhombs, quadrangels and polyhedrons.

3. Microimpactites formed by partial melting and evaporation of terrestrial and extraterrestrial matter by reactions on target rock. These forms are usually brownish-yellow with smooth lustrous surfaces, pitted with odd furrows. Both magnetite-silicate and silicate formations have been discovered. The largest sub-

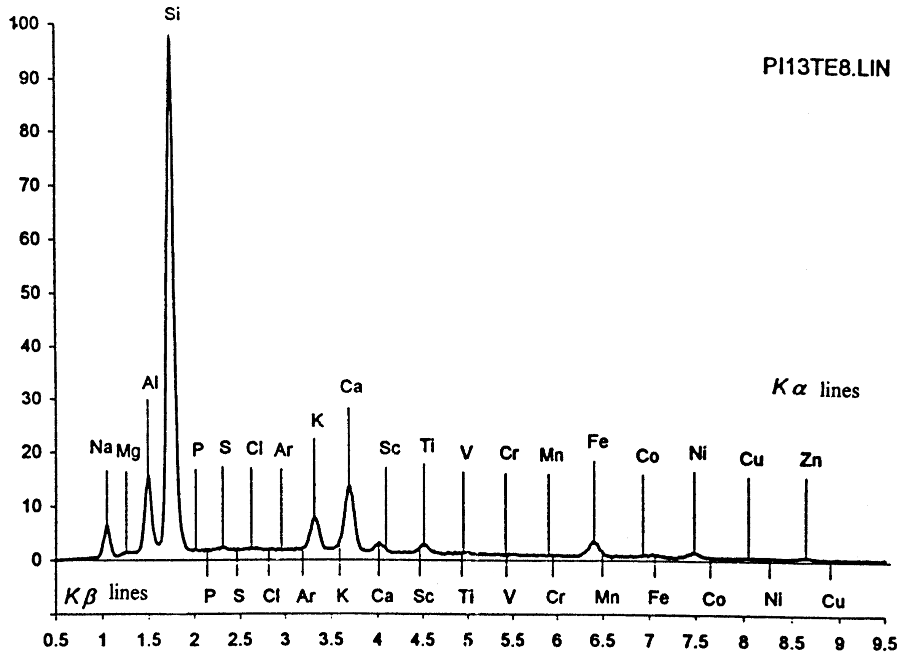


Fig. 4. Chemical composition of the brownish-yellow kidney-shaped spherule from the peat layer of the Piila Mire, consisting mainly from silica with small quantities of calcium, iron and nickel.

spherical magnetite-silicate formations have a diameter of 600 µm. The silicate globules range from 5 to 20 µm in diameter. These forms are ellipsoidal and drop-like, usually brownish-yellow with smooth lustrous (occasionally dull) surfaces, pitted with odd furrows, creating an impression of rock paintings. Sometimes, there are crater-like funnels on the surface of silicate microimpactites.

After a mighty explosion, which was accompanied by high temperature, both magnetite and silicate spherules accumulated in the surroundings of the Kaali and Ilumetsa craters. Silicate spherules are strongly prevailing. Mainly ellipsoidal, drop-like or rounded well-shaped white, grey or light-beige to dark-brown globules have been found. Half of these are multicoloured, porcellain, opale or marble like. The spherules have smooth lustrous surfaces, and are sometimes hollow from inside (about 10% of all spherules). The platelets of spherule pieces with conchoidal structure display abundant hollows indicating gas eruption (70% of glassy spherules). Positive tubercles on the planes consist mostly of magnetite crystals.

The chemical composition of glassy microimpactites is diverse. On the carbonate bedrock at Kaali, part of spherules consists mainly of silica and calcium with a small admixture of iron and nickel (Fig. 4), while in others calcium and iron prevail. Some spherules are extremely rich in nickel, containing at the same time also Co and Ti.

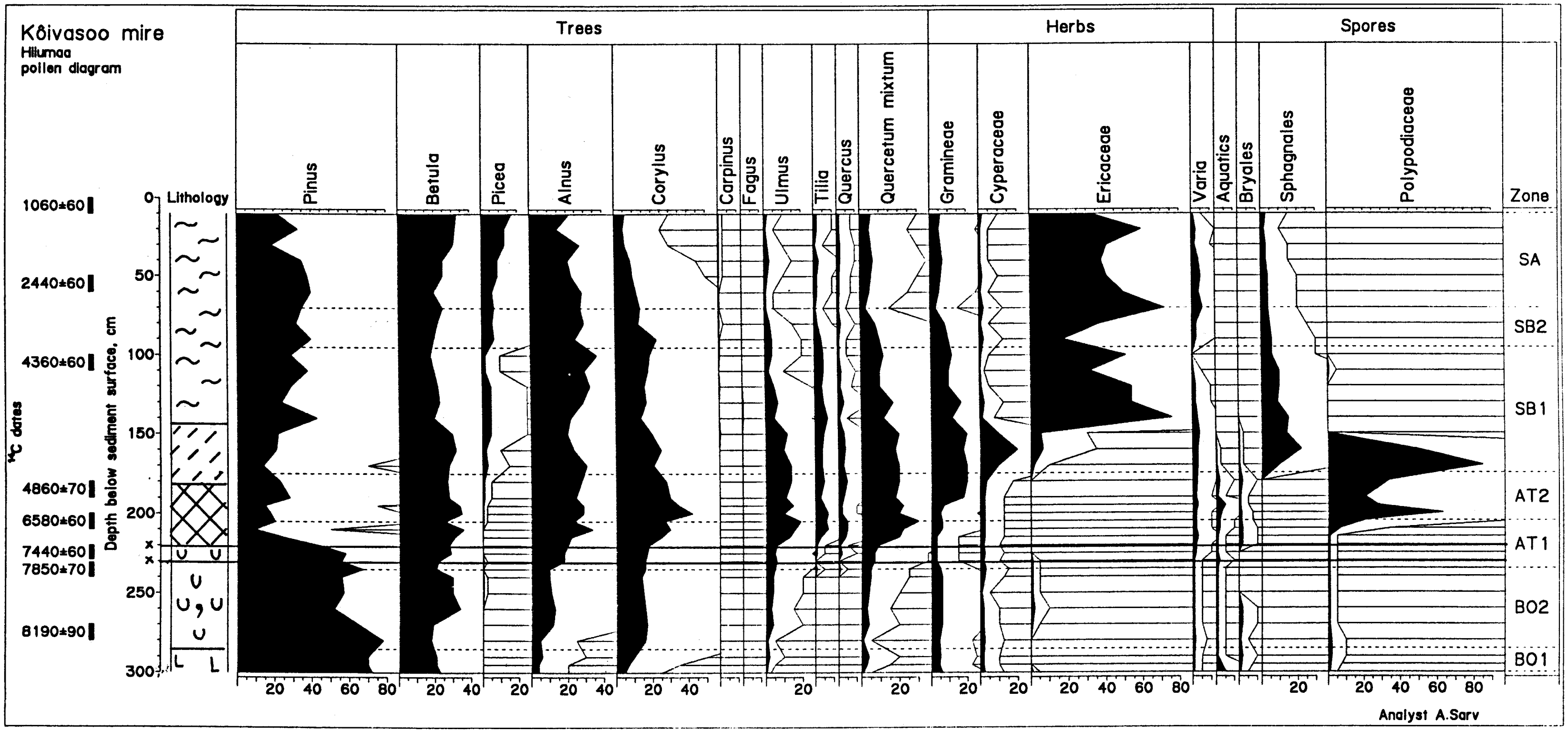
The Kaali meteorite belongs to IA group of coarse octahedrites and is very similar to the well-known Odessa iron meteorite from the USA. According to chemical analyses, in fragments of Kaali meteorite Fe and Ni make up 91.5 and 8.35%, respectively. It contains also up to 0.41% Co and different rare elements (Czegka & Tiirmaa 1998). The composition of Ilumetsa meteorite is unknown.

The age of Kaali and Ilumetsa craters

Before World War II, the Kaali craters were the only geologically established meteoritic craters in Europe. Various methods have been used to determine the age of the craters.

Reinwald (1933) concluded that the Kaali craters on the Island of Saaremaa formed 4000–5000 years ago. In his first paper A. Aaloe (1958) expressed the same opinion, but a few years later he maintained that the craters could not be older than 3000–4000 years. On the basis of the radiocarbon dates obtained on charcoal from the bottom of twin craters 2/8 (2530±130 BP, TA-19 and 2660±250 BP, TA-22) and from the bottom of crater No. 4 (2920±240 BP, TA-769), he reached the conclusion that the Kaali craters are about 2800±100 years old (Aaloe *et al.* 1963), or at least they could not have formed later than 2800 BP (Aaloe 1981). Archaeologists believe that the Kaali meteorite fell before the turn of the 7th-8th centuries BC, some 2600 years ago, and that the striking impression this catastrophic event produced preserved long in the minds of islanders of that time (Lõugas 1995). However, this opinion is not scientifically grounded. The palynological analyses by Kessel (1981) showed that the bottom sediments in the Kaali main crater (Fig. 2) date from the Sub-Boreal and are at least 3500 years old. On the basis of simultaneous ^{14}C and palynological research of the lake sediments in the Kaali main crater, Saarse *et al.* (1992) established the ^{14}C age of bottom sediments of the crater – 3390±35 BP (Tln-1353). They believe that the meteorite fell onto the Earth about 4000 BP. As it was not clear, whether this was the bottommost part of the sediments or not, before the spherule studies the real age of the craters was still open.

In 1994, we detected a high concentration of microimpactites in the Early Atlantic peat of the Piila Mire, about 10-km northwest of the Kaali craters (Fig. 1). A clear concentration of silicate spherules was established at a depth of 3.00–3.10 in the layer dated at 7586±67 yr BP by ^{14}C method (Raukas *et al.* 1995). In 1995, spherules with a similar age we discovered also in the Early Atlantic peat of the Pelisoo Bog about 18 km northwest of the Kaali craters at a depth of 4.00–4.25 m and in the Kôivasoo Mire on the Island of Hiiumaa at a depth of 2.20–2.30 m (Fig. 5). In 1996, spherules were found in the Pitkasoo in the central part of Saaremaa (Fig. 1) at a depth of 1.80–1.90 m.



Kõivasoo mire
Hiiumaa
pollen diagram
Trees
Herbs
Spores
Pinus
Betula
Picea
Alnus
Corylus
Carpinus
Fagus
Ulmus
Tilia
Quercus
Quercetum mixtum
Gramineae
Cyperaceae
Ericaceae
Varia
Aquatics
Bryales
Sphagnales
Polypodiaceae
Zone
SA
SB2
SB1
AT2
AT1
BO2
BO1
Lithology
Depth below sediment surface, cm
^{14}C dates
1060±60
2440±60
4360±60
4860±70
6580±60
7440±60
7850±70
8190±90
Analyst A.Sarv

The results from the four mires studied in Saaremaa and Hiiumaa, suggest that the layer with microimpactites, which spreads over a vast area, was formed in the Early Atlantic about 7500 BP.

The Ilumetsa impact craters in SE Estonia (Fig. 1), all in all 5, were discovered in 1938 in the course of geological mapping. Pôrguhaud, the crater which has been studied in particular detail, has a diameter of 75... 80 m. The bottom of the crater is covered with a thin layer of gyttja and a 2-m-thick layer of peat (Fig. 2). The radiocarbon dates obtained on the bottommost organic layer are 6030±100 (TA-130) and 5970±100 (TA-725) years BP, which together with palynological evidence suggested some 6000 years for the age of the crater (Liiva *et al.* 1979). In the summer of 1996, we found glassy spherules of impact origin at a depth of 5.70 m in the Meenikunno Bog, 6-km SW of the Ilumetsa craters. The layer was dated by means of the ^{14}C method. The dates obtained were as follows: 6542±50 (Tln-2214) for the depth interval 5.6–5.7 m, and 6697±50 (Tln-2316) for the depth interval 5.7–5.8 m. Based on these ages, it may be said that the Ilumetsa craters were formed about 6600 years ago.

Conclusions

Since around the both crater fields studied the explosion material occurred only in one stratigraphical level of peat deposits, it provides an excellent stratigraphical marker for the correlation of sedimentary sequences. It also enables one to date the impact event in the most precise way. The correlation method can be recommended for a wider use in different countries. It also allows the unknown genesis of ring structures to be established.

Acknowledgements: First of all, I would like to thank Prof. Wojciech Stankowski who invited me to participate in the conference on "The dating of Quaternary marine and land sediments" (Poznań, June 21–25, 1999) and present this paper. My warmest thanks are due to Mrs. Reet Tiirmaa for the common spherule studies, Dr Enn Kaup for radiocarbon datings, Dr. S. Shymanovich for the microphotos, Dr Rein Vaher for drawings and layout, and Mrs. Helle Kukk for the linguistic improvements and typing of the manuscript. The study was financed by the Estonian Science Foundation (Project No. 1905).

Fig. 5. Palynological diagram of the Kõivasoo Mire (anlysed by A. Sarv) and the layer with microimpactites (marked with lines).

References

AALOE A., 1958: Kaalijärve meteoriidikraatri nr. 5 uurimisest 1955. aastal. *ENSV TA Geoloogia Instituudi Uurimused*, 11: 105–117.

– 1981: Erinevused Kaali kraatrite vanuse määrangutes. *Eesti Loodus*, 4: 236–237.

AALOE A. & TIIRMAA R., 1981: Pulverized and impactite meteoritic matter in the Kaali crater field. *Eesti NSV Teaduste Akadeemia Toimetised. Geoloogia*, 30, 1: 20–27 [in Russian, Estonian and English sum.].

CZEGKA W. & TIIRMAA R., 1998: Das holozäne Meteoritenkraterfeld von Kaali auf Saaremaa (Ösel), Estland. *Aufschluss*, 49: 233–252.

KESSEL H., 1981: Kui vanad on Kaali järviku pôhjasetted? *Eesti Loodus*, 4: 231–235.

LIIVA A., KESSEL H. & AALOE A., 1979: Ilumetsa kraatrite vanus. *Eesti Loodus*, 12: 762–764.

LÕUGAS V., 1995: Must auk Saaremaa ajaloos. *Luup*, 2: 52–56.

RAUKAS A., PIRRUS R., RAJAMÄE R. & TIIRMAA R., 1995: On the age of the meteorite craters at Kaali (Saaremaa Island, Estonia). *Eesti Teaduste Akadeemia Toimetised. Geoloogia*, 44, 3: 177–183.

RAUKAS A. & TIIRMAA R., 1998: Kaali meteorite craters – unique objects for the sphe-rule studies. Papers presented to the 1998 Annual Meeting of I. G. C. P. 384 "Impact and Extraterrestrial Spherules: New Tools for Global Correlation", September 28 – October 2,1998. Geological Institute of Hungary, Budapest: 86–88.

REINWALDT I., 1933: Kaali järv – the Meteorite Craters on the Island of Ösel (Estonia). *Loodusuurijate Seltsi Aruaanded*, 39: 183–202.

SAARSE L., RAJAMÄE R., HEINSALU A. & VASSILJEV J., 1992: The biostratigraphy of sediments deposited in the Lake Kaali meteorite impact structure, Saaremaa Island, Estonia. *Bulletin of the Geological Society of Finland*, 63, 2: 129–139.

SHYMANOVICH S., KOLOSOVA T., RAUKAS A. & TIIRMAA R., 1993: Extraterrestrial spherules in the surroundings of Kaali meteorite craters (Saaremaa Island, Estonia). Proceedings of the Estonian Academy of Sciences. *Geology*, 42, 3: 127–133.

TIIRMAA R., 1994: Kaali meteoriit. *Eesti TA Geoloogia Instituut*, Tallinn, 124 p. (in Estonian, Russian and Finnish sum.).