Proc. Estonian Acad. Sci. Geol., 2004, **53**, 4, 267–287

Application of OSL and ^{10}Be techniques to the establishment of deglaciation chronology in Estonia

Anto Raukas

Institute of Geology at Tallinn University of Technology, Estonia pst. 7, 10143 Tallinn, Estonia; raukas@gi.ee

Received 3 September 2004, in revised form 23 September 2004

Abstract. The deglaciation history of Estonia has been under research for about a century. Despite the great number of publications devoted to this subject and marked improvements in study methods, many problems of topical interest have not been solved yet, especially due to the lack of good direct dating methods. In this paper the suitability of OSL and ^{10}Be dating techniques for establishing accurate deglaciation chronology for Estonia is assessed. Turbidity and water depth, velocity of outwash streams and transport length, possible fast sedimentation at night hours or below the ice, incorporation of older, unbleached particles, and other factors affected the extent of the bleaching of the TL signal in different ways, causing great variability of dates. Surface inclination, height of the surface over ground, snow and vegetation cover, and evolution of water bodies influenced the calculation of reliable exposure ages of objects dated using the ^{10}Be method. It means that age determinations of both glaciofluvial deposits with the OSL method and erratic boulders with the ^{10}Be method are highly problematic, especially for glaciofluvial intertill sediments where the exact genesis of deposits is unknown and for boulders, which have been in the forest, under the waters of proglacial lakes and/or the Baltic Sea, or under snow cover for a long time.

Key words: ice-marginal formations, glaciofluvial deposits, OSL dating, deglaciation chronology, erratic boulders, cosmogenic ^{10}Be.

INTRODUCTION

Deglaciation history in Estonia has been studied for about a century using different methods. Important conclusions have been made by H. Hausen, W. Ramsay, A. Tammekann, K. Orviku, and many other well-known scholars. Most remarkable ideas were advanced by G. de Geer at the beginning of the last century. In the lecture, presented on the occasion of the XI International Geological

Congress in Stockholm in 1910 (de Geer 1912), he proposed a new precise geochronological method, varvochronology, and divided the deglaciation history in Scandinavia into three major stages: Daniglacial (20 000–13 000), Gotiglacial (13 000–10 000), and Finiglacial (10 000–8000 years ago), which had different palaeoglaciological conditions. He mentioned that the deglaciation process was fast. According to de Geer, the Gotiglacial and Finiglacial together covered only about 5000 years, according to Kalm (2004), deglaciation of Estonian territory (average 130 m/yr) lasted 1650 ^{14}C or 1725 varve years. This hampers the usage of physical methods for elaborating the Late-glacial chronology.

The most promising is the radiocarbon method but it has also limited application due to lack of good interstadial sections for dating. Often interstadial or interphasial layers are contaminated by redeposited ancient carbon and the dates are inconsistent with each other. On the other hand, in several cases anomalously high ages even in Holocene sections have been obtained due to the “hard-water” effect.

During the last years, much attention has been paid in Estonia to the varve chronology, but as proglacial lakes were isolated from each other, too many gaps exist between Estonia and the neighbouring countries. Therefore, the accuracy of the estimated rate for the ice recession in the areas where glaciolacustrine sediments are absent is extremely disputable. The lack of absolute and even semi-absolute dates beyond the radiocarbon dating range has been hampering the development of the Pleistocene stratigraphic charts and the correlation of ice-marginal formations.

In 1974, Dr. Galina Hütt founded a radiometrical dating laboratory at the Institute of Geology at Tallinn University of Technology (former Institute of the Estonian Academy of Sciences), which soon became internationally well known. Together with the author of this paper she collected and analysed a great amount of samples of glaciofluvial sediments from different parts of Estonia. Unfortunately, the untimely death of Galina Hütt did not allow us to realize this project to the planned extent.

In 1999 a collaborative research – Developing an improved chronology of the southern margin of the Scandinavian ice sheet (principal investigator P. U. Clark, U.S.A., co-principal investigators A. Bitinas, Lithuania; E. J. Brook, U.S.A.; L. Marks, Poland; I. Pavlovskaya, Belarus; J. Piotrowski, Germany; G. Raisbeck and F. Yiou, France; A. Raukas, Estonia; and V. Zelčs, Latvia) – was undertaken to date deposits and landforms of the Scandinavian ice sheet in Belarus, Poland, Lithuania, Latvia, and Estonia, mainly by dating key organic-bearing units by AMS radiocarbon and erratic boulders on moraine surfaces using cosmogenic nuclides (^{10}Be and ^{26}Al) in quartz. Common work was organized by P. U. Clark and V. R. Rinterknecht (U.S.A.). Part of the results has already been published (Rinterknecht et al. 2003). Nine samples from the North Lithuanian (Haanja) zone have a weighted mean age of 13.0 ± 0.8 ^{10}Be ka, close to radiocarbon and varvochronological measurements. Most of the standard deviations are larger than the analytical uncertainties, indicating a geological source of the latter in addition to analytical ones.

In the present paper the Estonian sites dated by the OSL and ^{10}Be methods are described and possible errors analysed.

DATING PROCEDURES

OSL dating

In the Tallinn laboratory, both quartz and alkali feldspars have been used in the OSL dating. In our studies mainly the infrared optically stimulated luminescence (IR OSL) dating technique bases on alkali feldspars was applied due to the simple technical solution. Physical bases of the method were proposed by Hütt et al. (1988) and Hütt & Jaek (1996a,b). Alkali feldspars (100–160 μm) were extracted from the sediments following the techniques described by Mejdahl (1983) and Hütt & Smirnov (1983).

The light source used for stimulation was a semiconductor laser with emission in the wavelength region of 810 ± 1 nm. The light beam intensity on the sample was 6 mW/cm^2, which corresponds to ordinary sunny day conditions. The laser was operated in the pulse mode with a pulse length of 3 s. For detection of emitted light, an OSL/TL reader constructed in Tallinn jointly by the researchers of the Institute of Geology and the Ingrid Company was used.

The optical response for the samples studied was determined and the wavelength region used for stimulation was chosen in order to reach electrons in stable traps. The emitted light was detected in the UV-band around 380 nm. After gamma irradiation from a ^{60}Co source (dose rate 1 Gy/min) the samples were stored at room temperature for three weeks before measurements.

The accumulated dose was reconstructed using the additive dose method. The dose-rate was calculated from the U, thermoluminescence, and K concentrations, determined by gamma-spectroscopy from the bulk sample with natural water content, and the internal potassium content in the feldspar grains was measured by flame-photometry.

The analytical error of the determined accumulated dose was calculated using the “jack-knifing method”, following Grün & MacDonald (1989). The residual signal was reconstructed in the laboratory after natural sun bleaching during 20 h, which corresponds to the age less than 300 years in the case of IR OSL, and about 1000 years for TL. In age calculations, residual signals were taken into account. Different aliquots were dated, and for the control quartz was used parallel to alkali feldspars. As a rule, the alkali feldspar measurements give somewhat higher ages than OSL from quartz, which can be explained by slower bleaching of the feldspar in the sunlight exposure. In June 2004 Prof. W. Stankowski from Poznan University took a series of samples from surficial glaciofluvial sediments of eastern Estonia, which, using quartz, were analysed by Prof. Andrzej Bluszcz in

Gliwice Laboratory in Poland. The preliminary results also demonstrated a great variability of dates, insufficient bleaching of mineral grains, and higher ages than those obtained by other dating methods.

Surface exposure dating using cosmogenic ^{10}Be

This method was developed in the 1990s and has since then been significantly improved. It is now used as a standard procedure for determining exposure ages of erratic boulders and the respective moraines, glacially polished bedrock surfaces, terraces, and landslides (Zech et al. 2004). Boulder exposure ages by V. Rinterknecht were calculated from the ^{10}Be/^{9}Be ratios measured by accelerator mass spectrometry at the tandetron facility, Gif-sur-Yvette, France. The moraine-age uncertainty he presented as the error associated with analytical plus systematic uncertainties. He followed standard practices of documenting sample locations, altitudes, and orientations with GPS and measured cosmic ray shielding by surrounding topography. Only big and stable boulders, preferably with flat top surfaces (Fig. 1), were sampled. The chemical preparation was performed at Oregon State University, Washington State University, and at the Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, Orsay Campus, France.

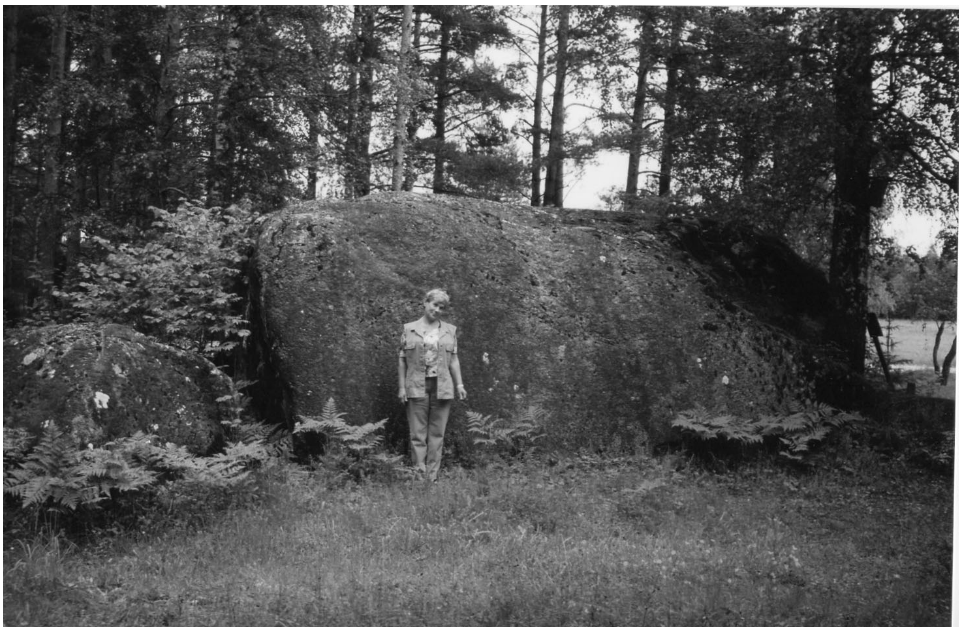

Fig. 1. In determining exposure ages using cosmogenic ^{10}Be only big and stable boulders, preferably with flat top surfaces, were sampled. Eedukivi boulder at Nõva (EST-4). Photo by A. Raukas.

ICE-MARGINAL FORMATIONS

In 1938 A. Tammekann compiled a map of glacial landforms and presented five zones of ice-marginal formations (Tammekann 1938), which were renamed and modified later by A. Raukas with co-authors (Raukas 1963; Raukas & Rähni 1966; Raukas et al. 1971). These formations, named Haanja, Otepää, Sakala, Pandivere, and Palivere by A. Raukas, are closely located (Fig. 2) and used up to now (Raukas et al. 2004). The first attempt to date the ice-marginal formations with modern methods was made already in 1969 (Raukas et al. 1969). It was concluded that the territory of Estonia was freed from the continental ice in Gotiglacial time during a time span lasting approximately 2000 years. The ice cover began to retreat from the southeastern part of Estonia some 13 000 years ago, from the Otepää belt about 12 600 years ago, and from the Pandivere belt about 12 500 years ago. According to Pirrus & Raukas (1969), the territory of Estonia was finally cleared of ice in the Allerød. This was proceeded by a new temporary advance of glacier approximately 11 200 years ago, which led to the formation of the Palivere marginal zone, described in detail in Raukas (1992a). The first attempt to correlate the ice-marginal formations with the neighbouring countries was undertaken by Serebryannyi & Raukas (1966, 1967).

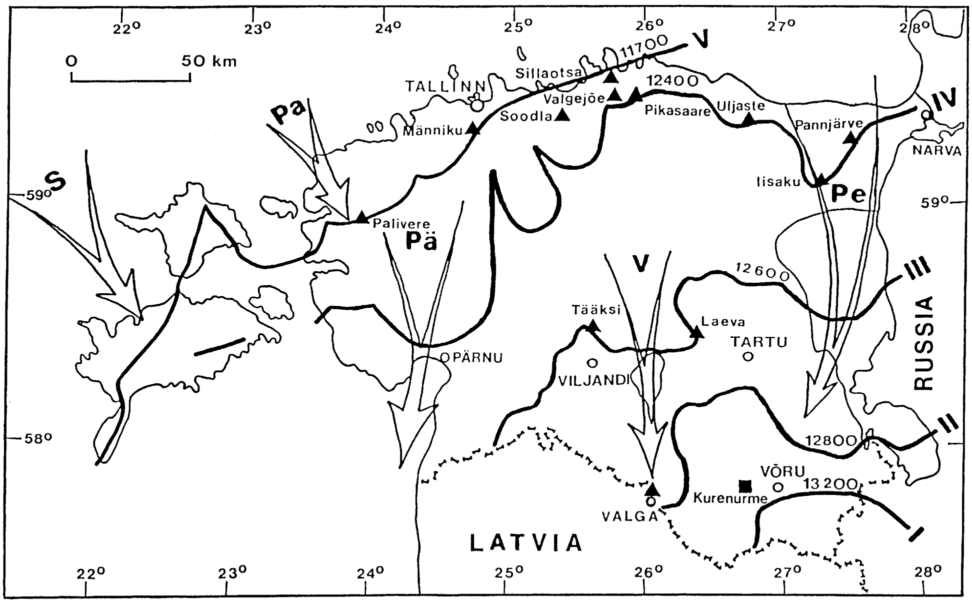

Fig. 2. Location of OSL dated sites (black triangles) and ice-marginal zones: I, Haanja; II, Otepää; III, Sakala; IV, Pandivere; V, Palivere. Ice streams: S, Saaremaa; Pa, Palivere; Pä, Pärnu; V, Võrtsjärv; Pe, Peipsi. The black quadrangle shows the location of the Kurenurme interstadial site.

Traditionally, the beginning of the Late-glacial interval in Estonia is placed at the time span, when the deposits of the Raunis Interstadial below Haanja till started to accumulate in Central Latvia (dated by different laboratories as 13 390 ± 500, Mo-196; 13 250 ± 160, TA-177; 13 320 ± 250, Ri-39 conventional ^{14}C ages). From the Raunis section together with the Kurenurme (Fig. 2) section (piece of wood dated 12 650 ± 520, TA-57 and organic detritus 12 420 ± 100, Tln-35) we could establish also the age of the Haanja and Otepää zones. However, new datings (9302 ± 83, Tln-2319 and 9227 ± 70, Tln-2322) allow us to conclude that in the Raunis section organic deposits accumulated in the Early Holocene and are covered with pseudotill (slope deposits). The majority of the ^{14}C dates obtained from sub- and intertill sequences with organic remains in Estonia (Petruse, Viitka, etc.) are younger than one would expect on the basis of the conventional radiocarbon method (Raukas 1986). Therefore, the real geological age of main ice-marginal zones is rather questionable. Up to now the main conclusion is that Estonia became ice-free at about 13 500–11 000 ^{14}C yr BP (Raukas 1986; Pirrus & Raukas 1996; Raukas & Kajak 1997). In the light of pollen analytical interpretations, the retreat of the ice margin from the Haanja zone (the oldest in Estonia) began in the Bølling, whereas Estonia was finally free of ice in the second half of the Allerød chron (Pirrus & Raukas 1969, 1996).

During the thinning of the ice sheet, the movement of its individual lobes was controlled by the subglacial topography (Tavast & Raukas 1982). Ice-marginal positions are represented in the modern topography mainly by discontinuous chains of end moraines and glaciofluvial formations (Raukas & Kajak 1997) and the correlation of such chains is rather disputable (e.g. Raukas & Karukäpp 1979, 1999). They were formed either as a result of standstills of the ice margin or in some cases as a result of readvances. At some sites where till-covered interstadial-type sediments occur, lithostratigraphical observations provide evidence for events of ice front oscillations (Raukas & Rähni 1966; Karukäpp & Miidel 1972; Kajak et al. 1976; Raukas 1986; Pirrus & Raukas 1996). The Haanja, Otepää, Sakala, and Palivere stadials are characterized by a dominant southeasterly ice movement direction. During the Pandivere Stadial ice movement was in a southerly or even southwesterly direction (Raukas & Karukäpp 1979; Raukas 1978, 1992a).

As for the Pleistocene intertill beds very different and contradictionary TL dates were obtained (e.g. Kajak et al. 1981; Liivrand 1991), we decided to check the reliability of the OSL method on the basis of surficial glaciofluvial sediments, the age of which is more or less controlled with other dating methods.

We should take into consideration that part of the sites dated by us are located in the frontal part on the ice-marginal zone and some sites between different-aged zones, which hampers the estimation of their real age. In dead ice conditions the melting out of sediments could happen hundreds or even thousands of years later than in the ice-marginal zone.

DISTRIBUTION OF GLACIOFLUVIAL SEDIMENTS IN ESTONIA AND OSL DATING STRATEGY

Surficial glaciofluvial deposits cover 3.1% of Estonia's territory (Vares & Raukas 1981) and are divided into englacial and periglacial genetical types with frequent transitions between them (Raukas 1978). According to Gudelis (1963), marginal glacial formations are divided into frontal, intramarginal, and extra-marginal ones. Deposits of radial eskers and fluviokames are conventionally regarded as englacial glaciofluvial deposits, and those of glaciofluvial deltas, sandurs (outwash deltas), and marginal eskers as periglacial ones. Glaciofluvial deposits form also kame terraces and often fill ancient valleys. In general, glaciofluvial deposits show great variations in grain size and structure, but also in the petrological and mineral composition, being everywhere closely connected with the composition of adjacent till and bedrock. Therefore, one of our tasks was to sample all genetical varieties of glaciofluvial deposits in Estonia. Another task was to sample different-aged surficial glaciofluvial deposits needed for the establishment of reliable deglaciation history. Main attention was paid to the so-called ice-marginal formations where glacial and aqueoglacial landforms are concentrated in more or less clearly outlined belts of various ages, which can be correlated with analogical formations in neighbouring areas.

Based on the palynological and varvometrical data available, as well as ^{14}C datings from both the study area and its neighbourhood, we rounded the age of the Haanja belt to some 13 200 yr BP, Otepää belt – ca 12 800, Sakala belt – ca 12 600, Pandivere belt – ca 12 400, and Palivere belt – ca 11 700 yr BP (Fig. 2); however, there can also be some different interpretations (Raukas et al. 2004). Most of the samples were collected from the ice-marginal zones of the Palivere and Pandivere stadials to establish the time when Estonian territory was finally freed from the ice cover.

Theoretically, the most promising study objects in the former glaciated areas seem to be glaciofluvial and outwash deltas; however, even in deltas fast accumulation of sediments at night-time is not excluded. The area of deltas in Estonia fluctuates from a few square kilometres to some hundreds of square kilometres (Raukas 1978). The extent and shape of the deltas as well as the thickness of the deposits occurring within their boundaries depend essentially on the subglacial topography. The grain size of the delta sediments decreases in a distal direction where deltas often pass over into glaciolacustrine plains. We tried to sample middle parts of deltas where sandy fractions prevail (Fig. 3). Sometimes, the deposits of proglacial lakes occur under delta deposits (e.g. at Männiku, Vaivara, and Valgejõe), which evidently points to a temporary advance of the glacier. In delta deposits the gravel material rich in crystalline rocks and coarse sand predominates. Only seldom carbonaceous rocks dominate among gravel and pebbles.

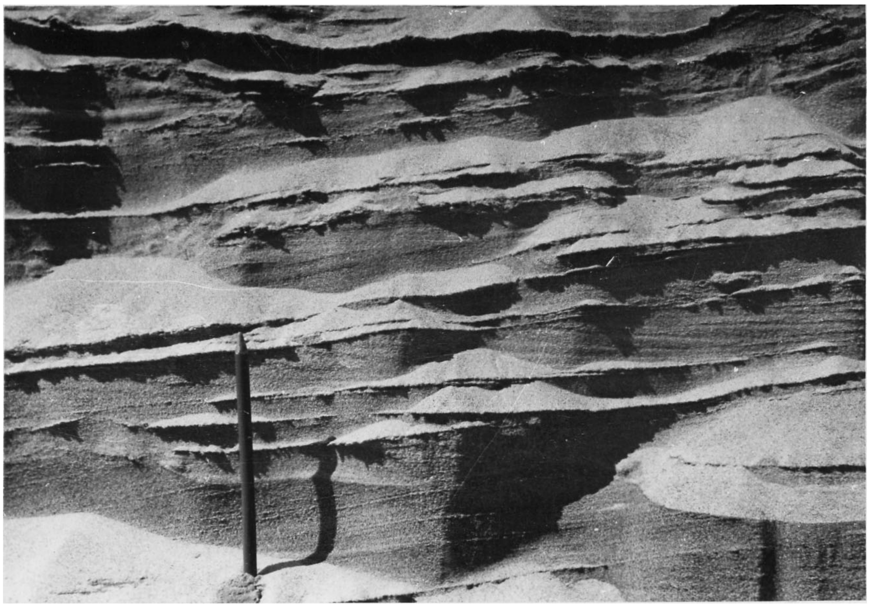

Fig. 3. For OSL dating of glaciofluvial and outwash deltas we tried to sample central parts of deltas where sandy fractions prevail. Männiku delta. Photo by A. Raukas.

In the mineral composition of sand fraction quartz (80–90%) prevails, followed by feldspars. The proportion of micas and carbonates is insignificant (Raukas 1978).

Dated deltas

Different-aged deltas (Männiku, Sillaotsa, Valgejõe, Soodla, Laeva, and Valga) were sampled (Fig. 2) and dated. We took samples also from the classical marginal esker near Palivere settlement in northwestern Estonia, which is a specific type of glaciofluvial deltas. Marginal eskers are narrower than deltas, have more or less ridge-like morphology and asymmetric transverse profile. The proximal slope of the Palivere marginal esker (usually 7–15°) is steeper than the distal slope (5–10°). The proximal part consists of coarser material (cobbles, pebbles, gravel) than the distal one (gravel, sand, silt). The bedding of the deposits is mostly at an angle of 5–15° in a distal direction where, evidently, the flow did not have any obstacle. According to de Geer's classical theory (1897), marginal eskers of this kind were formed near the edge of the glacier as it descended into the basin.

Palivere zone

Site 1. Palivere (58°58′12.6″N; 23°55′43.2″E)

Gravel pits and their surroundings near the Palivere settlement in NW Estonia (Fig. 2) are areal stratotype for the corresponding stratigraphic unit (Palivere

Stade), where classical glaciofluvial deltas, marginal eskers, and typical grey till with a specific content of indicator boulders from SW Finland are present (Raukas 1992a). In the central part of the westernmost gravel pit near the former silicalcite factory a ca 5 m high non-excavated “island” is located. It consists mainly of pebbles and coarse gravel with sand interlayers. From the sand layers we took two samples at a depth of 4.6 m from the ground surface (the horizontal distance between the samples was 2 m), which were dated at 9800 ± 1300 (R-29) and 10 900 ± 1300 (R-30) OSL years.

Site 2. Männiku (59°21′43″N; 24°43′08″E)

Männiku glaciofluvial delta is part of the ice-marginal formations of the Palivere Stadial. The up to 20 m thick delta deposits overlie up to 7 m thick clayey deposits of proglacial lake, probably indicative of a temporary advance of the glacier (Raukas & Rähni 1966). For several decades Männiku delta served as the main mining area providing Tallinn with sand and gravel. Grain size decreases in a distal direction (Fig. 3), and wave-like textures appear where the delta turns into a glaciolacustrine plain. The gravel in delta deposits is rich in crystalline rocks, coarse (0.5–1.0 mm) and medium (0.25–0.5 mm) sand predominates. In the main mining area the content of silt is less than 1%, gravel (more than 1mm) ranges from 15 to 25%. Three samples, from the depths of 2.0 m (R-31), 4.0 m (R-32), and 6.0 m (R-33), were taken from the outcrop near the border of Tallinn at the Tallinn–Saku highway, which gave the OSL ages of 10 200 ± 1200, 21 000 ± 2500, and 12 300 ± 1700 years, respectively.

Site 3. Sillaotsa (59°32′00.2″N; 25°46′37.1″E)

One single fine sand sample was taken and dated (R-34) at a depth of 4.7 m in the eastern slope of Sillaotsa gravel pit about 1 km east of the Nõmmeveski waterfall in the Valgejõgi River. The age of 11 300 ± 1300 OSL years was obtained.

Pandivere zone

Site 1. Soodla (59°23′39″N; 25°23′00″E)

Two samples were taken from the southern side of the northernmost Soodla gravel pit in the middle part of the delta south of the Tallinn–Narva highway (Karukäpp & Mikalauskas 1972). The samples (R-44 and R-45) were taken from the medium-grained sand at a depth of 3.5 m from the surface, with the horizontal distance between the sampling points being 4 m. Fully unreliable OSL ages of 81 000 ± 5000 and 94 000 ± 6000 years were obtained.

Site 2. Valgejõe (59°27′46″N; 25°45′28″E)

Two fine sand samples (R-35, R-36) were taken at a depth of 4.4 m (with the sampling points located 4 m apart) and one sample (N-3) was collected at a depth of 7 m from the surface from the Valgejõe glaciofluvial delta at the Tallinn–Narva highway some 800 m west of the Valgejõgi River. The results obtained were 12 400 ± 1200, 12 200 ± 1200, and 59 000 ± 5000 OSL years, respectively.

Sakala zone

Site 1. Laeva (58°28′16.5″N; 26°21′36.6″E)

A single sample (R-47) from the northeast–southwest oriented Laeva glaciofluvial delta 35 km northwest of Tartu near the Tallinn–Tartu highway gave the age of 13 800 ± 1500 OSL years. The delta consists of poorly sorted pebbly gravel in its proximal side and coarse sand to silt in the distal side. Deformation structures caused probably by melting out of buried ice are common in the gravel pit, located in the southwestern part of the delta. The sample was taken from the medium sand layer at a depth of 7.8 m from the ground surface.

Otepää zone

Site 1. Valga (57°49′28″N; 26°03′12″E)

A big outwash plain at the Latvian–Estonian border has a key position in solving the problems related to the evolution of proglacial lakes in northern Latvia and southern Estonia. The area of the outwash plain is about 300 km^2 and average thickness of deposits, mainly gravel, coarse and medium sand, is about 5 m. Three samples (R-50, R-51, and R-54) were taken from the fine sand at a depth of 2 m in the roadcut of the Valga–Tõrva highway, near Taimeaia bus stop 4 km of Valga. The distance between the first two sampling points was 4 m, and between the second and the third one, 20 m. The dates received were 7500 ± 1100, 13 200 ± 1400, and 70 000 ± 12 000 OSL years, respectively.

Dated eskers and kames

We were not very optimistic in sampling radial eskers and kames (crevasse fillings). It is well known that eskers have formed in different ways – in dead ice as well as in active and passive glaciers. There are eskers, which were probably built according to the delta theory proposed by de Geer (1897), but also those conforming to the river-bed theory is open channels (e.g. at Aravete). At the same time, some eskers (at Neeruti, Kuusalu) were probably formed in subglacial tunnels (Raukas et al. 1971). Since we do not know how the study object was exactly formed, we tried to avoid sampling radial eskers. We dated only two eskers in NE Estonia – Uljaste near the town of Kiviõli and Iisaku (Fig. 2) –, which probably were formed in open crevasses.

Morphologically, the kames of Estonia are represented by hills, cupolas, ridges, terraces, and plateaus, which within the limits of the kame field alternate with various negative forms, mainly of glaciokarst origin. Some kame fields (e.g. at Viitna) are mostly composed of hills and cupolas and accompanying glaciokarstic forms, while in some kame fields (e.g. Kaiu, Selguse) the prevalent positive forms are ridge-like formations. The area of kame fields is generally inconsiderable, only seldom exceeding 10–20 km^2.

The kames of northern Estonia have been distributed under different topographical conditions. They are located mainly in depressions of bedrock topography, sometimes within the limits of adjacent valleys. Less frequently, they occur on the slopes of elevated bedrock or on the top of an elevation (Tavast & Raukas 1982). Kames are often associated with eskers or represent transitional forms to the hilly topography.

As kames have been formed in dead ice and had limited possibilities of bleaching, we investigated and dated only one, Pikasaare kame field close to the Pandivere zone (Fig. 2). Being dead-ice formations, kames can have a much lower real age than the ice-marginal belt marking the maximal distribution of the ice during one or another stadial.

Site 1. Uljaste (59°21′00″N; 26°48′19″E)

The Uljaste radial esker is 9 km long and consists of gravelly (30–40%) sand (40–55%) with some content of pebbles and cobbles (10–20%) and silt (less than 5%). In the mineral content quartz (70%), feldspars (up to 20%), and carbonates (about 10%) prevail. The height of the esker is 18–22 m. The bedding is highly variable, showing prevalence of different types of cross-lamination. The absence of till on the slopes and top of the esker suggests that this body was formed in the open crack of dead ice near the maximal border of the Pandivere zone (Fig. 2). The sampled outcrop lies in the roadcut on the Kiviõli–Sämi highway. One single dating (R-40) at a depth of 2.2 m from the ground surface gave the age of 96 000 ± 12 000 OSL years.

Site 2. Iisaku (59°07′25″N; 27°19′3″E)

The Iisaku esker has been formed between two ice lobes during the Pandivere Stadial (Fig. 2). Two samples from the fine sand interlayers in gravel and pebble deposits at depths of 3.0 (R-46) and 5.0 m (N-5) from the distal part of the esker in the Tärivere gravel pit (Fig. 4) near the Jõhvi–Tartu highway gave the OSL ages of 11 600 ± 1100 and 114 000 ± 8000 years, respectively.

Site 3. Pikasaare (59°26′16.8″N; 25°51′22.1″E)

The Pikasaare kame field is a north-northwestern chain of the 20 km long Pikasaare–Tapa esker and kame system (Karukäpp 2003). Up to 20 m high kames are of elongated form and alternate with steep-sloped deep hollows. Medium-grained, in some places coarse and fine sand with gravel admixture is prevailing in the kame deposits. The sand consists mainly of quartz and feldspars. The most dissected part of the kame field was completely excavated in the late 1980s for building the Tallinn–St. Petersburg highway. In the Kalajärve sand pit (37 ha) three samples were taken at depths of 3.2 (R-37), 6.4 (R-38), and 8.2 m (R-39). The ages obtained were 13 700 ± 1300, 23 000 ± 6000, and 16 200 ± 4200 OSL years, respectively.

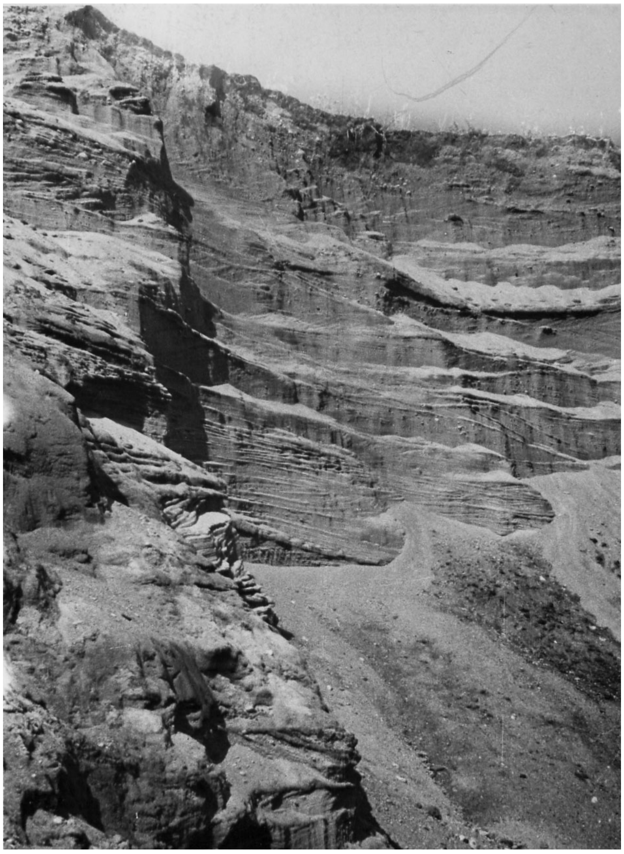

Fig. 4. The sediments in Iisaku esker have probably accumulated in an open crevasse. Tärivere pit. Photo by A. Raukas.

Dated ancient valley fillings

The bedrock surface in Estonia is strongly dissected by deep ancient valleys (Tavast & Raukas 1982), which, according to their geological structure, can be subdivided into valleys filled mainly with glaciofluvial deposits of the last glaciation, valleys filled mainly with glaciolacustrine deposits of the last glaciation, valleys with one till bed with underlying or covering glaciofluvial and glaciolacustrine deposits, valleys of a complicated structure with more than one till bed and accompanying glaciofluvial and glaciolacustrine deposits. We took samples only from the first type of valleys at Pannjärve in the Kurtna kame field near the maximum distribution of the Pandivere zone and Tääksi near the maximum distribution of the Sakala zone (Fig. 2).

Site 1. Pannjärve (59°16′40″N; 27°34′00″E)

Pannjärve is the largest sand deposit in Estonia, with the active proved reserves of 71.1 million m^3. The content of quartz exceeds 90%. Glaciofluvial deposits infill an ancient buried valley and form a kame topography. In the Vasavere ancient valley (Tavast & Raukas 1982) within the Kurtna kame field, sand and gravel layers are up to 80 m thick. Five samples collected from the medium and coarse sand sediments in the eastern wall of the gravel pit were dated. Two samples at a depth of 5 m (N-9 and N-10), with sampling-points located 10 m apart, yielded the ages of 72 000 ± 11 000 and 75 000 ± 9000 OSL years. Two samples (R-41 and R-42) at a depth of 8 m from the ground surface, spaced 20 m apart, yielded the ages of 9800 ± 1100 and 11 500 ± 1200 OSL years and one sample (R-43) from a depth of 15 m gave the age of 13 400 ± 1200 OSL years.

Site 2. Tääksi (58°31′08.8″N; 25°38′31.6″E)

The exposures in the Tääksi gravel pit illustrate the complicated history of subglacially formed valley-like depressions in the Devonian sandstones of the Sakala Upland. The valley floor is covered with loamy reddish-brown basal till of the last glaciation. The stratified glaciofluvial and glaciolacustrine sediments have two genetically clearly different parts. The lower, 4–5 m thick coarse-grained complex was probably deposited from intensive subglacial stream flowing from upland to the north. The well-rounded gravel-and-pebble material with sand and cobbles and rather large (up to 2 m in diameter) boulders prevail. The pebble and gravel material is rich in carbonates (60–70%) washed out of carbonaceous till. As a result of the short local readvance of the glacier, meltwaters in the valley were dammed up and the overlying sandy-silty complex, about 6–8 m thick (Fig. 5),

Fig. 5. The upper sandy complex in the Tääksi pit where fully unreliable dates (54 000 ± 5000 and 62 000 ± 7000 OSL years) were obtained. Photo by A. Raukas.

accumulated in the proglacial lake (Raukas 1993). Two samples (R-48 and R-49) were taken from the fine sand of the upper complex, at a depth of 6.2 m from the ground surface. Horizontal spacing of the sampling points was 10 m. The dates obtained were 54 000 ± 5000 and 62 000 ± 7000 OSL years, respectively.

OBTAINED OSL RESULTS AND DISCUSSION

The recently developed OSL methods enable the dating of sediments that were only exposed to a limited amount of light prior to deposition. Thus, OSL dating provides the opportunity to date the active period of a glaciofluvial system. The ages, obtained by OSL dating of potassium feldspars from Holocene channel deposits in the Rhine-Meuse delta, were consistent with ^{14}C ages. Even coarse grains that were sampled from the base of the channel deposits appeared to have received enough light to bleach their signal prior to deposition (Wallinga et al. 1998). As is known, glaciofluvial deposits have accumulated in extremely different sedimentological conditions: in front of the ice margin, on the top, below or inside the ice cover. As they exhibit a wide range of sedimentary characteristics, the assumption that the TL signal is completely zeroed prior to final deposition is not only arguable but in many cases impossible. The degree of bleaching during glaciofluvial transport remains the topic that deserves attention. In glacial outwash the transport distances are short and water is muddy. It will be difficult to establish the cycles of erosion and new deposition of mineral grains before final deposition.

It is clear that most of the bleaching will occur when the sediment grains in the moving medium are close to the water surface where the light intensity is greater and light spectrum wider. An important factor is also the muddiness of water, which in the silty material is undoubtedly higher. This means that the results depend not only on the transport distance, but also on many other factors whose role is difficult to establish. Based on the results obtained, it may be concluded that less than half the dates are more or less reliable, and quite a high percentage of dates are fully unreliable. This may be explained partly with a high admixture of unbleached mineral grains from till and bedrock, especially in the Devonian sandstone area (e.g. at Tääksi).

In applying OSL dating, it is important to assess whether the light-sensitive trapped charge of every grain was zeroed prior to final deposition. If such is the case, the age of the deposit can be obtained using OSL dating of any number of grains. If not, special care has to be taken to use only the OSL signal from those grains that had their charge zeroed, or alternatively, the age obtained should be interpreted as a maximum age of the deposits (Wallinga 2002).

Often the stratigraphers state that the OSL ages of glaciofluvial sediments are in correct stratigraphical order. In our studies it was frequently not so and even theoretically it will be impossible, because in most cases we do not know the formation peculiarities of dated sediments and the time expancy of the light. Mineral grains in and below the ice were not exposed to the light at all. And even in case of good bleaching in glaciofluvial streams the dated samples can be contaminated with poorly bleached grains from older Quaternary sediments and Palaeozoic rocks during recurrent deposition of the material.

To our mind, the OSL method will not work effectively in the glaciofluvial environment due to inadequate light exposure, especially in the case of relatively young sediments. The extent of bleaching of the TL signal in the studied environments is variable and difficult to reconstruct in the laboratory, causing variability of dates. This limits the use of the TL and OSL methods in solving the problems related to deglaciation history. Even more it influences the dating of older intertill deposits where the genesis of sediments and most of the limiting factors are unknown. If the mechanism of the formation of deposits is not known, even the most accurate measurements of their TL properties will be meaningless. Each sample exhibits unique TL and dosimetric characteristics and therefore the dating technique cannot be routinely applied. In our opinion the possibilities of the OSL method are clearly overestimated at the present time.

COSMOGENIC ^{10}Be CHRONOLOGY FOR THE DEGLACIATION HISTORY OF ESTONIAN TERRITORY

Estonia is a land of large boulders. Only a few gigantic boulders with a circumference above 30 m (or more than 10 m in length) are known in North Europe, outside the boundaries of Estonia. The number of such boulders in Estonia reaches 62 (Raukas 1995). Of the 2150 large boulders registered at the end of the 1980s, some 1900 had a length more than 3 m (Viiding 1986). This facilitates the use of the cosmogenic ^{10}Be method for establishing boulder exposure ages and end moraine belts where the dated boulders are located. On the other hand, the usage of the method for the investigation of the deglaciation history in the Baltic States has great limitations, because at different times this area was under the waters of proglacial lakes (Raukas 1992b). Even more complicated is the problem for Estonia, where lower territories in the so-called Low Estonia were covered with the waters of the Baltic Sea (Raukas 1997). Vast areas of the Palivere zone were freed from the sea waters only during the last 9000 years (Fig. 6). Therefore, the relatively young weighted mean age of the Palivere zone (10 000 ± 1300 ^{10}Be yr BP) between that of the Pandivere zone immediately to the south (13 000 ± 1100 ^{10}Be yr BP) and Salpausselkä I zone to the north (11 800 ± 900 ^{10}Be yr BP) is readily explained by submergence of the boulders by the Baltic Ice Lake, Ancylus Lake, Litorina Sea, and Limnea Sea, which would have substantially reduced the production rate for that period of time (Rinterknecht et al. 2003).

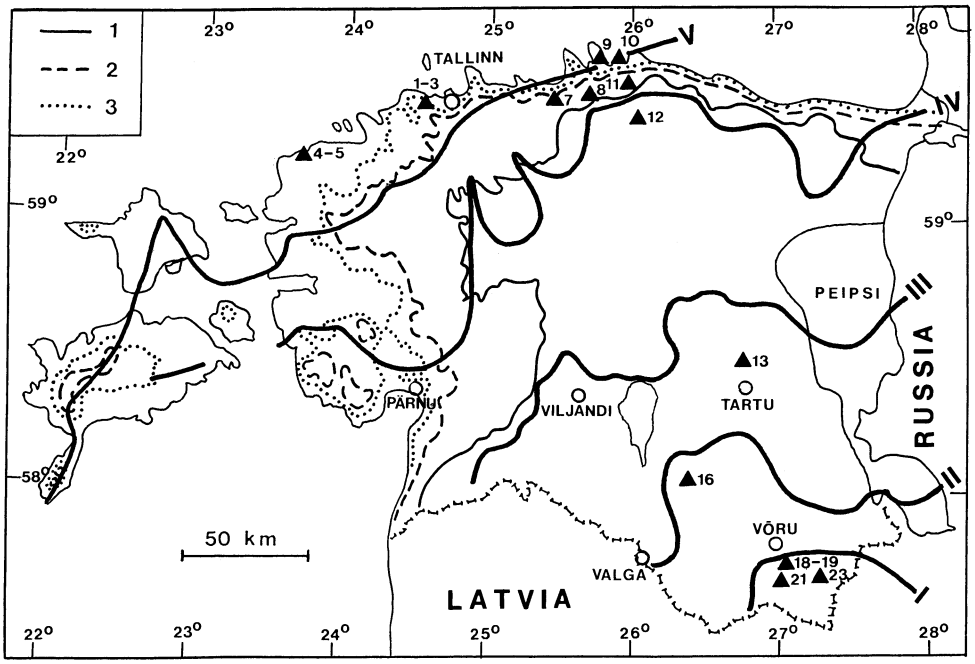

Fig. 6. Location of ^{10}Be dated boulders (black triangles), ice-marginal formations (for explanation see Fig. 2), and transgression lines of: 1, the Baltic Ice Lake (about 10 800 yr BP); 2, Ancylus Lake (about 9000 yr BP), and 3, Litorina Sea (about 7500 yr BP).

In the summer of 2001, P. U. Clark and V. R. Rinterknecht sampled a total of 23 boulders in Estonia (Fig. 7), but final results were not received for all of them. Successfully dated boulders are shown in Fig. 6, where they are marked with the following numbers:

Palivere zone
1 (EST-1) Kallaste boulder at Tabasalu 13 017 ± 1236 ^{10}Be yr BP
2 (EST-2) Noorgeoloogide boulder at Tabasalu 11 938 ± 1053 ^{10}Be yr BP
3 (EST-3) Rahneli boulder at Tabasalu 5464 ± 615 ^{10}Be yr BP
4 (EST-4) Eedukivi boulder at Nõva 12 002 ± 1078 ^{10}Be yr BP (Fig. 1)
5 (EST-5) Nameless boulder at Nõva 15 435 ± 1348 ^{10}Be yr BP
7 (EST-7) Nameless boulder at Kuusalu 11 499 ± 914 ^{10}Be yr BP
8 (EST-8) Urita Suurkivi boulder at Kemba 12 832 ± 940 ^{10}Be yr BP
9 (EST-9) Kasispea Edelakivi boulder 4057 ± 458 ^{10}Be yr BP (Fig. 7)
10 (EST-10) Nameless boulder at Käsmu 14 470 ± 1146 ^{10}Be yr BP
11 (EST-11) Nameless boulder at Palmse 12 872 ± 910 ^{10}Be yr BP

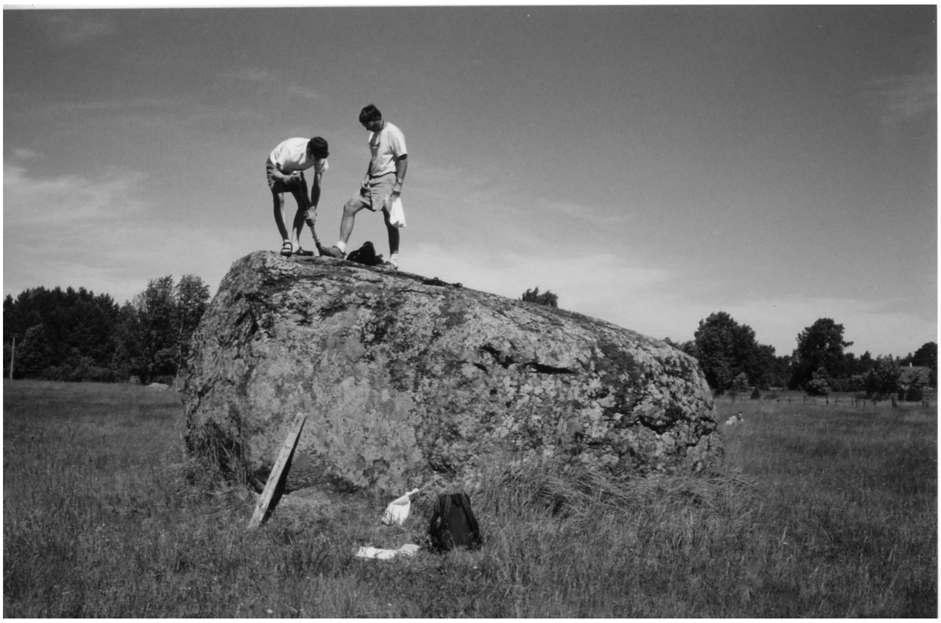

Fig. 7. Peter U. Clark and Vincent R. Rinterknecht sampling Kasispea Edelakivi (EST-9). Photo by A. Raukas.

Pandivere zone
12 (EST-12) Lodikivi (Lindakivi) boulder at Kallukse 13 020 ± 1117 ^{10}Be yr BP

Otepää zone
13 (EST-13) Vedu Nõiakivi boulder 13 448 ± 1037 ^{10}Be yr BP

Haanja zone
16 (EST-16) Äidu Rehekivi boulder 13 031 ± 922 ^{10}Be yr BP

Middle Lithuanian zone (on the top of the Haanja Heights)
18 (EST-18) Jaanimäe Suurkivi boulder 11 574 ± 976 ^{10}Be yr BP
19 (EST-19) Jaanimäe Talukivi boulder 16 251 ± 1121 ^{10}Be yr BP
21 (EST-21) Pikasaare (Viitina-Pikasoo) boulder 11 004 ± 770 ^{10}Be yr BP
23 (EST-23) Pütsepa (Jeremi, Viidrik Mokra) boulder 11 131 ± 863 ^{10}Be yr BP

The boulders sampled for surface exposure dating with the cosmogenic nuclide ^{10}Be from all ice-marginal zones of Estonia show great variations, which can be explained with geological and analytical uncertainties. No corrections for snow cover have been applied (Rinterknecht et al. 2003). Formally the very preliminary results obtained show that the whole of Estonia was freed from ice cover more or less at the same time, but for more reliable results complementary investigations are needed.

CONCLUSIONS

Two modern dating methods (OSL and ^{10}Be) recently used could not help to improve the existing Late-glacial stratigraphical chart of Estonia (Raukas & Kajak 1995) and deglaciation chronology in the northern Baltic area. Even the errors of datings in OSL years are often bigger than the duration of the whole deglaciation of Estonian territory. To our mind the possibilities of the OSL method in dating glaciofluvial sediments are highly overestimated. Especially complicated is the dating of intertill deposits of unknown genesis.

ACKNOWLEDGEMENTS

The author is much obliged to the late Dr. Galina Hütt, a good colleague, who participated in our studies from the very beginning and under whose leadership all the OSL datings presented in this paper were carried out. Dr. P. U. Clark and Dr. V. R. Rinterknecht are thanked for permission to use ^{10}Be dates from Estonia. Thanks are due to Dr. R. Vaher for drawings and to Dr. A. Miidel for fruitful discussions. Special thanks go to referees of the paper Dr. R. Karukäpp and Prof. V. Zelčs for their valuable comments. The research was financed by the Estonian Science Foundation (grant No. 5342) and Estonian State Target Foundation (project No. 0331759s01).

REFERENCES

de Geer, G. 1897. Om rullstensāsarnas bildingssätt. *Geol. Fören. Stockholm Förhandl.*, **19**, 366–388.

de Geer, G. 1912. Geochronologie der letzten 12000 Jahre. In *XI International Geological Congress, Stockholm 1910, Compte Rendu I*, pp. 457–471.

Grün, R. & MacDonald, D. M. P. 1989. Nonlinear fitting of TL/ESR dose response curves. *Appl. Radiat. Isotopes*, **40**, 1077–1080.

Gudelis, V. K. 1963. On the terminology and classification of ice-marginal formations. *Trudy Komissii po izucheniyu chetvertichnogo perioda*, 21, 84–91 (in Russian).

Hütt, G. & Jaek, I. 1996a. Palaeodosimetrical properties of sodium alkali feldspars and problems of luminescence dating of sediments. *Proc. Estonian Acad. Sci. Geol.*, **45**, 102–111.

Hütt, G. & Jaek, I. 1996b. Check of the validity of the common laboratory treatments used for luminescence dating on the basis of alkali feldspars by IR OSL spectra. *Proc. Estonian Acad. Sci. Geol.*, **45**, 165–172.

Hütt, G. & Smirnov, A. 1983. Thermoluminescence dating of sediments by means of the quartz and feldspar inclusion method. *PACT*, 9, 463–473.

Hütt, G., Jaek, I. & Chonka, J. 1988. Optical dating: K-feldspars optical response simulation spectra. *Quat. Sci. Rev.*, **7**, 381–385.

Kajak, K., Kessel, H., Liivrand, E., Pirrus, R., Raukas, A. & Sarv, A. 1976. Local stratigraphical scheme of Quaternary deposits in Estonia. In *Stratigraphy of Quaternary Deposits in the Baltic Countries* (Vaitiekunas, P. P. & Gaigalas, A. J., eds.), pp. 4–52. Pergale, Vilnius (in Russian).

Kajak, K., Raukas, A. & Hütt, G. 1981. Experience of investigation of Estonia's different-aged tills with thermoluminescence method. In *Geologiya Severo-Zapada SSSR* (Yevzerov, V. J., ed.), pp. 3–11. Apatity (in Russian).

Kalm, V. 2004. Pleistocene chronostratigraphy in Estonia. In *International Field Symposium on Quaternary Geology and Modern Terrestrial Processes, Western Latvia, September 12–17, 2004. Abstracts of Papers and Posters* (Zelčs, V. & Seglinš, V., eds.), pp. 21–22. University of Latvia, Riga.

Karukäpp, R. 2003. Pikasaare kames. In *International Symposium on Human Impact and Geological Heritage. Excursion Guide and Abstracts* (Raukas, A. & Kukk, H., eds.), pp. 50–51. Institute of Geology at Tallinn Technical University, Tallinn.

Karukäpp, R. & Miidel, A. 1972. About geological structure and formation of some genetic types of glacial marginal formations. In *Materialy Vsesoyuznogo IV mezhvedomstvennogo soveshchaniya po izucheniyu kraevykh obrazovanii materikovogo oledeneniya* (Aboltinš, O., ed.), pp. 86–103. Latvian State University, Riga (in Russian).

Karukäpp, R. & Mikalauskas, A. 1972. Põhja-Eesti fluvioglatsiaalsetest kruusa-liivaväljadest. In *Eesti Geograafia Seltsi aastaraamat 1970*, pp. 38–49. Tallinn.

Liivrand, E. 1991. *Biostratigraphy of the Pleistocene Deposits in Estonia and Correlations in the Baltic Region*. Department of Quaternary Research, Stockholm University. Report 19, Doctoral Thesis.

Mejdahl, V. 1983. Feldspar inclusion dating of ceramics and burned stones. *PACT*, 9, 351–364.

Pirrus, R. & Raukas, A. 1969. About the character and time of deglaciation of Estonia from the glaciers of last glaciation. In *Voprosy chetvertichnoj geologii, IV* (Danilans, I., ed.), pp. 47–57. Zinatne, Riga (in Russian).

Pirrus, R. & Raukas, A. 1996. Late-Glacial stratigraphy in Estonia. *Proc. Estonian Acad. Sci. Geol.*, **45**, 34–45.

Raukas, A. 1963. The lithology of Soviet-Estonian moraines of a different age. *ENSV Tead. Akad. Geol. Inst. Uurimused*, XII, 3–21 (in Russian).

Raukas, A. 1978. *Pleistocene Deposits of the Estonian SSR*. Valgus, Tallinn (in Russian).

Raukas, A. 1986. Deglaciation of the Gulf of Finland and adjoining areas. *Bull. Geol. Soc. Finland*, **58**, 21–33.

Raukas, A. 1992a. Ice marginal formations of the Palivere zone in the eastern Baltic. *Sver. Geol. Unders.*, Ca 81, 277–284.

Raukas, A. 1992b. Evolution of ice-dammed lakes and deglaciation of the Eastern Peribaltic. In *Jungquartäre Landschaftsräume. Aktuelle Forschungen zwischen Atlantik und Tienschan* (Billwitz, K., Jäger, K.-D. & Janke, W., eds.), pp. 42–47. Springer-Verlag, Berlin.

Raukas, A. 1993. Tääksi gravel pit. In *Pleistocene Stratigraphy, Ice Marginal Formations and Deglaciation of the Baltic States. Excursion Guide* (Raukas, A., ed.), p. 59. Estonian Academy of Sciences, Tallinn.

Raukas, A. 1995. Estonia – a land of big boulders and rafts. *Quaestiones Geographicae, Spec. Issue*, 247–253.

Raukas, A. 1997. Evolution of the Baltic Sea. In *Geology and Mineral Resources of Estonia.* (Raukas, A. & Teedumäe, A., eds.), pp. 268–274. Estonian Academy Publishers, Tallinn.

Raukas, K. & Kajak, K. 1995. Quaternary stratigraphy in Estonia. *Proc. Estonian Acad. Sci. Geol.*, **44**, 149–162.

Raukas, A. & Kajak, K. 1997. Ice ages. In *Geology and Mineral Resources of Estonia* (Raukas, A. & Teedumäe, A., eds.), pp. 256–262. Estonian Academy Publishers, Tallinn.

Raukas, A. & Karukäpp, R. 1979. Eesti liustikutekkeliste akumulatiivsete saarkõrgustike ehitus ja kujunemine. In *Eesti NSV saarkõrgustike ja järvenõgude kujunemine* (Raukas, A., ed.), pp. 9–28. Valgus, Tallinn.

Raukas, A. & Karukäpp, R. 1999. Deglaciation of the lake basin. In *Lake Peipsi. Geology* (Miidel, A. & Raukas, A., eds.), pp. 125–130. Sulemees Publishers, Tallinn.

Raukas, A. & Rähni, E. 1966. On the regression of the last continental ice from the territory of the Estonian S.S.R. In *Eesti Geograafia Seltsi aastaraamat 1964/1965* (Kivila, H., ed.), pp. 5–17. Valgus, Tallinn (in Russian).

Raukas, A., Punning, M. & Rähni, E. 1969. Millal taandus Eestist mandrijää? *Eesti Loodus*, 7, 396–401.

Raukas, A., Rähni, E. & Miidel, A. 1971. *Kraevye lednikovye obrazovaniya Severnoj Estonii*. Valgus, Tallinn (in Russian).

Raukas, A., Kalm, V., Karukäpp, R. & Rattas, M. 2004. Pleistocene glaciations in Estonia. In *Quaternary Glaciations – Extent and Chronology* (Ehlers, J. & Gibbard, P. L., eds.), pp. 83–91. Elsevier B. V.

Rinterknecht, V. R., Raisbeck, G. R., Yiou, F., Clark, P. U., Brook, E. J., Bitinas, A., Lunkka, J., Marks, L., Pavlovskaya, I. & Piotrowski, J. 2003. Late Pleistocene deglaciation chronology of the Scandinavian ice sheet southern margin. In *XVI INQUA Congress. Programs with Abstracts*. Reno, Nevada, USA, 83/10.

Serebryannyi, L. R. & Raukas, A. V. 1966. Transbaltic correlation of Late Pleistocene ice marginal formations. In *Verkhnii Pleistotsen. Stratigrafiya i absolyutnaya geokhronologiya* (Gricuk, V. P., Ivanova, I. K., Kind, N. V. & Ravski, E. I., eds.), pp. 12–28. Nauka, Moscow (in Russian).

Serebryannyi, L. R. & Raukas, A. V. 1967. Correlation of Gothiglacial ice marginal belts in the Baltic Sea depression and the neighbouring countries. *Baltica (Vilnius)*, 3, 235–249.

Tammekann, A. 1938. Die Endmoränen in Estland. In *Comptes Rendus du Congrés International de Géographie Amsterdam*, pp. 51–256. Union Géographique Internationale, Leyden.

Tavast, E. & Raukas, A. 1982. *Rel'ef korennykh porod Éstonii*. Valgus, Tallinn (in Russian).

Vares, K. & Raukas, A. 1981. The Estonian soil-forming rocks. *ENSV TA Toim. Geol.*, **30**, 125–132 (in Russian).

Viiding, H. 1986. Suurte rändrahnude kirjeldamise juhised. *Abiks Loodusvaatlejale*, 85. Loodusuurijate Selts, Tartu.

Wallinga, J. 2002. Optically stimulated luminescence dating of fluvial deposits: a review. *Boreas*, **31**, 303–322.

Wallinga, J., Duller, G. A. T. & Törnqvist, T. E. 1998. Luminescence dating of fluvial deposits. *FLAG News*, 3, 10–11.

Zech, R., Abramowski, U., Glaser, B., Kubik, P. W. & Zech, W. 2004. Surface exposure dating using *in situ* cosmogenic ^{10}Be. *Proc. Estonian Acad. Sci. Geol.*, **53**, 3–12.

Optiliselt stimuleeritud luminestsentsmeetodi (OSL) ja berülliumimeetodi (^{10}Be) kasutamine mandrijää taandumise kronoloogia täpsustamiseks Eestis

Anto Raukas

Mandrijää taandumisaega on Eestis püütud selgitada erinevate meetoditega. Palünoloogiline meetod on rahuldavate tulemuste saamiseks liialt ebatäpne. Oletatakse (Pirrus & Raukas 1996), et mandrijää hakkas Haanja servamoodustiste vööndilt taanduma Bøllingis umbes 13 000 ^{14}C aastat tagasi ja Eesti oli jääst vaba Allerødi teisel poolel ligikaudu 11 200 ^{14}C aastat tagasi. Radiosüsinikumeetodi kasutamist piiravad heade dateerimiseks sobivate läbilõigete vähesus ja dateerimisel tekkivad vead, millest eriti ohtlikud on nooremate puujuurte tungimine varem ladestunud setetesse ja proovi vana süsinikuga saastumine, mis Eesti karbonaatsel aluspõhjal on üsna tõenäoline. Suuri lootusi on viimastel aastatel pandud viirsavide kronoloogiale, kuid selle meetodi kasutamist raskendab hilisglatsiaalsete veekogude omavaheline isoleeritus. Seetõttu osales autor meetodite ringi laiendamisel luminestsents- ja radioaktiivse berülliumi meetodiga. Luminestsentsmeetodil dateeriti Eesti pindmisi erineva tekkeviisiga glatsiofluviaalseid setteid (joonis 2), mis andsid aga väga suure varieeruvuse ja rohkesti ekslikke tulemusi. See on ka loomulik, sest “nullseisu” on praktiliselt võimatu taastada, kuivõrd pole välistatud näiteks setete kuhjumine liustiku all või öistes tingimustes. Me ei oska rahuldavalt modelleerida ka info säilimist, garanteerida aine migratsiooni puudumist ning määratleda sekundaarsete protsesside mõju. Rahuldavaid tulemusi ei andnud ka mandrijää servamoodustiste piires paiknevate suurte rändkivide dateerimine radioaktiivse berülliumi meetodil (joonis 6), sest kivide ekspositsioon päikesekiirte suhtes ja kiiritusaeg on raskesti määratletavad lumikatte erineva kestuse ja paksuse ning taimkatte erinevuste tõttu (kas metsas või lagedal). Pealegi oli suur osa Eestist pikka aega kaetud Läänemere ja kohalike jääjärvede vetega, mis raskendab veelgi ekspositsiooniaja määramist. Seetõttu tuleb endiselt nentida, et mandrijää taandumise kronoloogia on Eestis ebapiisavalt põhjendatud. Varasemate skeemide muutmiseks on uute meetoditega saadud dateeringud liialt vastuolulised ning suures osas koguni eksitavad.