SSI Report 2005:16
SGU Dnr. 08-466/2002

RADON RISK MAP OF ESTONIA

Explanatory text to the Radon Map set of Estonia at scale of 1:500 000

Tallinn – Stockholm
2005

Valter Petersell, Gustav Åkerblom, Britt-Marie Ek,
Margit Enel, Voldemar Mõttus, Krista Täht

RADON RISK MAP OF ESTONIA

Explanatory text to the Radon Risk Map Set of Estonia at scale of 1:500 000

SSI Report 2005:16
SGU Dnr. 08-466/2002

EESTI GEOLOOGIAKESKUS
Geological Survey of Estonia

Tallinn – Stockholm 2005

RADON RISK MAP OF ESTONIA
Explanatory text to the Radon Risk Map Set of Estonia at scale of 1:500 000

Authors: Valter Petersell, Gustav Åkerblom, Britt-Marie Ek, Margit Enel, Voldemar Mõttus, Krista Täht

Editorial office: Kadaka tee 82, 12618 Tallinn
Tel. (372) 672 0094
Fax (372) 672 0091
E-mail egk@egk.ee

Editors:
Jaan Kivisilla, Research director, Geological Survey of Estonia
Gustav Åkerblom, Senior geologist, Swedish Radiation Protection Authority

English text revision: Robert Szava-Kovats

Layout: Mare Kukk

Front cover: North-Estonian Klint. Photo by Tõnis Saadre

ISBN 9985-815-55-6

ABSTRACT

Radon Risk Map of Estonia has been produced to provide an overview of the concentration of the radioactive inert gas radon-222 in soil air and of the concentrations of uranium, thorium and potassium in the soil. The aim of the map is to serve as a tool in the effort to reduce the health risk posed by radon in dwellings and workplaces. The Radon Risk Map gives general information on areas where the risk for indoor radon merits attention at planning of new buildings for dwellings and workplaces. The map can also be used to aid in the search for existing buildings, in which the indoor radon concentrations may exceed the permissible limit. The map presented is preliminary; as research proceeds, the new results need to be incorporated. In this way the current areas of radon risk will be more precisely delineated.

The Radon Risk Map is based on existing geologic knowledge as well as results from field surveys conducted in 2002 and 2003. During the surveys, measurements of the radon concentration in soil air and gamma-ray spectrometric measurements were performed at 566 sites. These sites were chosen so to achieve a representative sampling throughout Estonia.

Geologic information was gathered from earlier geochemical surveys and from bedrock and Quaternary maps, including maps of airborne gamma-ray spectrometric surveys, which display the activity concentrations of radium-226 (^{226}Ra), thorium-232 (^{232}Th) and potassium-40 (^{40}K) on the ground surface. Results from measurement of indoor radon concentrations in Estonian homes carried out by The Estonian Radiation Protection Centre (EKK) have also been included.

Radon was measured at least once with a Gammadata MARKUS-10 emanometer at each of the 566 sites. Soil air was sucked through a steel pipe from a depth of 0.8 m into the emanometer and analysed. At the same spot or within a few meters, a 0.8–1 m deep hole was dug for gamma spectrometric determination of the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K. The maximum ^{222}Rn activity concentration in the soil was calculated from the concentration of ^{226}Ra.

The results of the radon risk surveys are reflected in a set of maps comprised of nine maps on 1:500 000 scale. Eight maps show the concentration of radon in soil air, the concentrations of uranium (^{226}Ra), thorium and potassium in soil, as well as their major distribution. In accordance with Estonian standards, the **Radon-222 Risk Map of Estonian Soil** distinguishes areas classified as *low radon ground* (<10 kBq/m³), *normal radon ground* (10–50 kBq/m³), *high radon ground* (50–250 kBq/m³) and *very high radon ground* (>250 kBq/m³). The concentration of radon in soil air in the high and very high radon areas exceeds the limit established for unrestricted construction of new dwellings (50 kBq/m³), above which special measures have to be taken against indoor radon. The **Preliminary Map of Radon Risk Areas in Estonia** shows areas with different risks for radon. The classification of these areas is based mainly on the radon levels in soil air, but also considers soil permeability. This map distinguishes four risk classes: l*ow radon risk* (≤10 kBq/m³), *normal radon risk* (10–50 kBq/m³), areas with *local occurrences of high radon ground* (> 50 kBq/m³), and *high radon risk* (> 50 kBq/m³).

In the north Estonian Klint zone, the activity concentration of ^{226}Ra in the soil exceeds the Guidance safety value in some localities (Order No. 12 of 2 April, 2004). Also the outdoor gamma radiation is often elevated in these localities.

CONTENTS

MAPS:
Radon Risk Map Set of Estonia consists of the following nine Map Sheets:

1. RADON-222 RISK MAP OF ESTONIAN SOIL, SCALE 1:500 000
    1.1. Maximum Radon Concentration in Soil Air (on this map are shown contoured areas of different radon concentration)
    1.2. Radon (Rn) Concentration in Soil Air by Direct Measurement (in depth 1 m)
    1.3. Radon Concentration in Soil Air calculated after eU (^{226}Ra)
    1.4. Uranium (^{226}Ra) Concentration in Soil
    1.5. Map of Factual Material [Location of Observation Points**,** On the Map of Quaternary Sediments (Kajak, 1999)]
    1.6. Thorium (^{232}Th) Concentration in Soil
    1.7 Potassium (^{40}K) Concentration in Soil
    1.8. Natural Radiation of Soil
2. PRELIMINARY MAP OF RADON RISK AREAS IN ESTONIA, SCALE 1:500 000

INTRODUCTION

Radon-222 (^{222}Rn) is formed by the decay of radium-226 (^{226}Ra). Radium-226 is formed in the decay series originating with uranium-238 (^{238}U). Radon is a highly radioactive and carcinogenic inert gas that can cause cell mutations in organisms if inhaled or ingested. Next to smoking radon is the most significant cause of lung cancer in humans.

Estonia is located on the eastern coast of the Baltic Sea (Figure 1) and its territory covers 45.2 thousand km². Uranium-rich Lower Ordovician sedimentary rocks outcrop along the Klint[1] in the northern part of Estonia. Fragments of these rocks occur in the soils throughout Estonia.

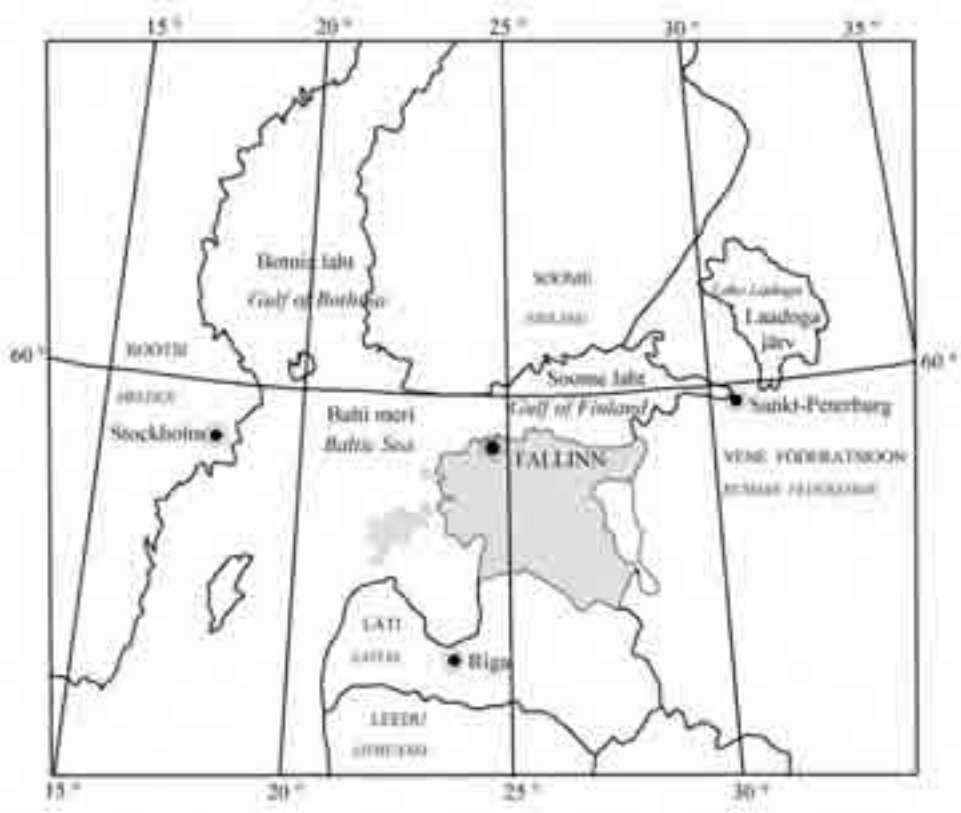


Figure 1. Location of the mapped area.

Bedrock units in Estonia with unusually high concentrations of uranium and radium are Dictyonema shale, phosphorite and Obolus sandstone (Figure 2). These rocks outcrop in the sandstone and limestone escarpment known as the North-Estonian Klint. Ordovician to upper Devonian sedimentary rocks overlie these older rock units. The concentration of uranium in these older rocks is near to the average concentration in the Earth's crust (2.5 ppm U).

Geochemical mapping of Estonian soils reveals that the concentration of uranium exceeds 4–6 ppm in many areas. Research in Sweden indicates that in soils containing more than 4–6 ppm U, the concentration of radon in the soil air often exceeds 50 kBq/m^3, the value above which requires safety measures against radon in new residential buildings or workplaces.

The map sheets of the Radon Risk Map of Estonian Soils provide an overview of the concentration of radon-222 in soil air and of the concentrations of uranium, radium (^{226}Ra), thorium (^{232}Th) and potassium (^{40}K) in the soil. The Radon Risk Map of Estonian soils is based on existing geological, geophysical and geochemical data as well as surveys undertaken for this project. Information on geology was obtained from existing bedrock, Quaternary and geochemical maps. Additional information was gleaned from maps of gamma ray spectrometric airborne surveys carried out in 1990–1993 (Rešetov et al., 1993). These maps show the concentrations of ^{226}Ra, ^{232}Th and ^{40}K at ground level. In addition, results from measurements of

[1] Klint is the Scandinavian name of the sharp cliff along the northern coast of Estonia. The sequence of sediments exposed in the Klint from bottom to top: Cambrian clays and sandstones, Lower Ordovician Obolus sandstone, Dictyonema shale and Ordovician limestone. Of these the Obolus sandstone contains layers of phosphorite, which contain uranium (10–30 ppm). The Dictyonema shale is a uranium-rich black shale (20–300 ppm U).

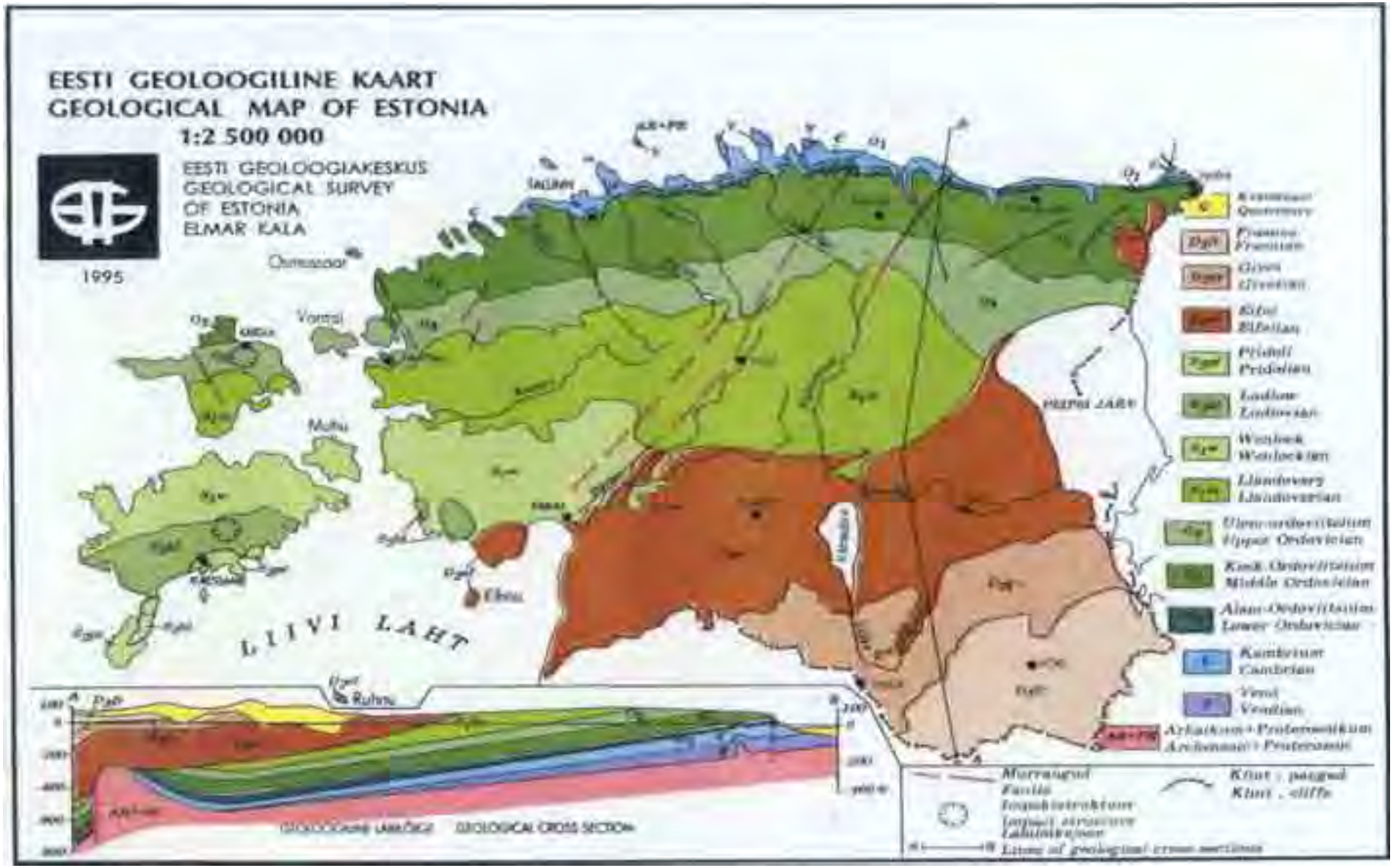


Figure 2. Geological map of Estonian bedrock (Eesti Geoloogiakeskus, Tallinn, 1999).

Figure 3. Margit Enel performing a gamma spectrometer measurement. The detector unit is located in the plastic bag in the hole.

indoor radon concentrations in Estonian homes performed by Eesti Kiirguskeskus (Estonian Radiation Protection Centre, EKK) have been used to identify areas of different radon risks (low, normal, high or very high).

Field surveys were carried out during 2002 and 2003 in order to gain information on the radon concentration in the soil air. At these surveys measurements of radon and in situ gamma spectrometric measurements at 566 observation points were carried out. These points were chosen to reflect a representative sampling of Estonia's land territory**.** The concentration of uranium (^{226}Ra), thorium (^{232}Th) and potassium (^{40}K) in soil was determined by gamma ray spectrometry in 80-cm-deep holes (Figure 3) and the concentration of ^{222}Rn in soil air was sampled and analysed in the field with a Gammadata MARKUS-10 emanometer (Figure 4). The recorded concentrations of ^{226}Ra obtained by gamma spectrometry were used to calculate the maximum ^{222}Rn concentration in soil air at the observation points.

After processing and systematisation, these measurements have been used to distinguish and identify soil types and regions with different radon concentrations in soil air. In addition, the rationale for the different radon concentrations in the soil air has been studied.

Two types of Radon Risk Maps have been produced. One map made at EGK, which is based on typical geochemical mapping principles in Estonia, and the other made at SGU, which is based on principles and methods developed in Sweden to map radon risk. The differences in methodology are described in the report. However, both maps agree in general on their delineation of areas of radon risk.

Figure 4. Measurement of radon in soil air with MARKUS-10.

The EGK map, in accordance with Estonian standards, depicts four levels of radon activity: low radon ground (<10 kBq/m^3), normal radon ground (10–50 kBq/m^3), high radon ground (50–250 kBq/m^3), and very high radon ground (>250 kBq/m^3). The SGU map features the following classification: low radon risk (<10 kBq/m^3), normal radon risk (10–50 kBq/m^3), high radon risk (>50 kBq/m^3), areas with local occurrences of high radon ground and areas with karst.

The Radon Risk Map of Estonian Soil is supplemented with additional maps depicting the concentration of uranium (^{226}Ra), thorium (^{232}Th) and potassium (^{40}K) in soil. Interpretation of these maps enables estimation of the variation of natural radioactivity of the soil throughout Estonia.

The explanatory text to the maps describes the concentration of ^{222}Rn and U (^{226}Ra), Th (^{232}Th) and K (^{40}K) of the main soil types. In addition, the reasons for high and very high concentration of radon in soil air are discussed and recommendations given on minimising the risk of radon exposure. The natural radioactivity of soil and related problems are described as well.

The Radon Risk Map is the result of a joint project between the Geological Survey of Estonia, the Swedish Radiation Protection Authority and the Geological Survey of Sweden. The Environmental Investment Centre financed the work done by the Estonian partner, while the Swedish International Development Cooperation Agency provided funding for the activities of the Swedish partners.

Field investigations were carried out in 2002 and 2003 using equipment belonging to Swedish partners (Portable gamma ray spectrometer – 2 sets, and MARKUS-10 – 2 sets) and Estonian Radiation Protection Centre (Portable gamma ray spectrometer – 1 set and MARKUS-10 – 1 set). The normal course of work was hindered by early frosts and snow in the autumn of 2002 and a very moist summer in 2003.

Prior to fieldwork the Estonian partners visited Sweden for training in the use of the equipment and to learn the methodology used to map radon risk. The Swedish partners travelled to Estonia to participate in the fieldwork and to produce maps and reports.

The observation points were chosen to preferentially represent areas expected to have high radon concentrations in the soil air. These areas included the fore-Klint lowland and limestone plateau on top of the klint, ancient buried valleys, eskers, drumlins and tectonic fault zones, as well as other geological features with potential radon risk, e.g. buried karst, coastal ridges, and wastes of abandoned phosphorite quarries along the Klint zone at Maardu east of Tallinn.

The sampling density was very low, averaging 1 point per 70–80 km². Nevertheless, the surveys indicate that in Estonia there exist significant and distinct radon risk potential areas in Estonia. Areas with high radon concentration in the soil air are common in the North-Estonian Klint zone, but also occur in south-eastern and southern Estonia, and in other areas. Consequently, the nature of the research and sampling density led to a map at scale of 1:500 000. These maps together with this accompanying report are intended to serve as a preliminary review of the concentration of radon in the soil air and the distribution of natural radioactive elements – uranium, thorium and potassium in Estonian soils.

Despite the low sampling density, the results provide a preliminary demarcation of regions of different radon concentrations and identification of areas that require more in depth research.

The chemical analyses for this study were carried out at the Laboratory of the Geological Survey of Estonia and at Becquerel Laboratories Inc., Canada.

The fieldwork, data processing and map production was carried out by the authors listed on the title page. Office Technician Olga Rudõka also participated in the work.

The project leaders were Valter Petersell, Leader Geologist of the Geological Survey of Estonia, Gustav Åkerblom, Senior Geologist at the Swedish Radiation Protection Institute and Britt-Marie Ek, Geologist at the Geological Survey of Sweden.

2. RADON (Rn)

2.1. Basic information

Radon (Rn) is a decay product formed by the decay of radium (Ra) in the decay series of the radioactive elements, uranium and thorium (Table 1 and 2). Three isotopes of radon exist: radon-222 (^{222}Rn) formed by the decay of radium-226 (^{226}Ra) in the decay series of uranium-238 (^{238}U), radon-220 (^{220}Rn) also called thoron, formed by the decay of radium-224 (^{224}Ra) in the decay series of thorium-232 (^{232}Th), and radon-219 (^{219}Rn) called actinon formed by the decay of radium-223 (^{223}Ra) in the decay series of uranium-235 (^{235}U). The half-life of ^{238}U is 4.468 10^9 years, of ^{226}Ra – 1620 years and of ^{222}Rn – 3.82 days.

Natural uranium (U) consists of three isotopes – ^{238}U constituting 99.27% of all U, ^{235}U, forming 0.72% and ^{234}U forming 0.005%. Most thorium (Th) exists as ^{232}Th, but thorium isotopes are also formed in the decay series of ^{238}U (^{234}Th and ^{230}Th) and ^{235}U (^{231}Th and ^{227}Th).

The radon isotope that presents the greatest health hazard is ^{222}Rn (Table 1). As the half-life of thoron (^{220}Rn) is only 55.6 seconds (Table 2), thoron constitutes only a small part of the natural radon in the above ground atmosphere. The portion of actinon (^{219}Rn) is very small for two reasons. Firstly, the concentration of ^{235}U is low, and secondly, the half-life of ^{219}Rn is very short (3.92 seconds). Thus, the radioactivity resultant from ^{222}Rn is the major contributor to the radiation dose received by exposure to radon gas in dwellings, workplaces and underground premises (UNSCEAR, 1993). References to radon in this text refer to ^{222}Rn.

The average concentration of radium and radon in the Earth's crust is $n \cdot 10^{-6}$ ppm Ra and $n \cdot 10^{-10}$ ppm Rn respectively (Ivanov, 1996). Under natural conditions the uranium/radium/radon ratio in Palaeozoic rocks is normally constant[1] . Therefore, transition coefficients can be applied to determine the concentration of an element on the basis of the concentration of another element. When young sediments such as Quaternary deposits are formed and rocks are weathered, the different chemical properties of uranium and its radioactive decay elements (daughters) provide for different means of migration. Under different pH level, electric conductivity and aeration conditions these elements also dissipate or concentrate in different ways. At the same time, due to the short half-life of radon, the Ra/Rn ratio in soils is generally stable and balanced as long as the radon gas concentration is not reduced by ventilation nor by radon escaping by diffusion.

Radon is an inert gas with a density of 9.73 kg/m^3 (7.7 times heavier than air). Upon the decay of the radium atom in a mineral grain, the resultant radon atom is expelled from the mineral lattice by the recoil effect from the emitted alpha particle (Figure 5). The distance of transport by the recoil effect in minerals of normal density is 0.02–0.07 μm and 64 μm in water. If a radium atom is situated near the surface of a mineral grain or a micro-crack in a grain, the newborn radon atom may reach a pore space. This transport of radon atoms from grains to pore spaces is known as emanation. The partition of radon atoms that emanates to the pore space in a soil depends to a large degree on grain size, but also on the distribution of radon atoms in different grains and on the moisture in the soil. Thus, the emanation factor is low when the water content of the soil is low (less than 5%) and increases as the water content increases. Under normal conditions, the emanation factor for gravel is 15–40%, for sand 15–30% and for clay 30–70%. (For more detailed information on emanation, see Åkerblom and Mellander, 1997.).

Subsequent transport in soil of radon atoms from pore spaces occurs by diffusion or by active transport by moving air or water. In a soil layer with a homogenous radium concentration, the concentration of radon in soil air is greatest at a depth of 2 m and below. At this depth the emitted and decaying radon atoms are in equilibrium. The radon concentration at depths <2 m is reduced by diffusion of radon to the atmosphere above the ground surface or by ventilation effects due to wind. The nearer to the ground surface, the better the soil air is aerated, enhancing radon migration into the atmosphere. The radon flux from the ground surface is known as exhalation.

However, if the pore spaces in soil air are filled with water (i.e. below the groundwater level) radon gas can escape from only the 6 upper centimetres of the water (the maximum diffusion distance for radon in water before it decays totally). Thus the radon concentration in ground water in a soil is constant and depends on the radium concentration in the soil and the emanation factor of the soil.

[1] At radioactive equilibrium within the 238U decay series, the rate of 238U decay is the same as for each subsequent nuclide. Thus the activity concentration, for example expressed as Bq/kg, is the same for each nuclide at equilibrium.

Table 1

Decay series of uranium-238 (^{238}U)

Isotope	Radioactive half-life	Radiation Type	Notes
Uranium -238 (U)	$4.5x10^9$ years	α	Solid
Thorium -234 (Th)	24.1 days	β	Solid
Protactinium-234 (Pa)	1.17 minutes	β	Solid
Uranium-234 (U)	$2.24x10^5$ years	α	Solid
Thorium-230 (Th)	$8.0x10^4$ years	α	Solid
Radium-226 (Ra)	1620 years	α	Solid
Radon-222 (Rn)	**3.823 days**	**α**	**Gas**
Polonium-218 (Po)	3.05 minutes	α	Solid
Lead-214 (Pb)	26.8 minutes	β, γ	Solid
Bismuth-214 (Bi)	19.7 minutes	β, γ	Solid
Polonium-214 (Po)	$1.6x10^{-4}$ seconds	α	Solid
Lead-210 (Pb)	21.3 years	β	Solid
Bismuth -210 (Bi)	5.01 days	β	Solid
Polonium-210 (Po)	138.4 days	α	Solid
Lead-206 (Pb)	-	-	Solid

Table 2

Decay series of thorium-232 (^{232}Th)

Isotope	Radioactive half-life	Radiation type	Notes
Thorium-232 (Th)	$1.41x10^{10}$ years	α	Solid
Radium-228 (Ra)	5.76 years	β	Solid
Actinon-228 (Ac)	6.13 hours	β, γ	Solid
Thorium-228 (Th)	1.913 years	α, γ	Solid
Radium-224 (Ra)	3.66 days	α, γ	Solid
Radon-220 (Rn)	**55.6 seconds**	**α**	**Gas, also known as thoron**
Polonium-216 (Po)	0.15 seconds	α	Solid
Lead-212 (Pb)	10.64 hours	β, γ	Solid
Bismuth-212 (Bi)	60.6 minutes	α, β, γ	Solid
Polonium-212 (Po)	$3.4x10^{-7}$ seconds	α	Solid
Thallium-208 (Tl)	3.05 minutes	β, γ	Solid
Lead-208 (Pb)			Solid

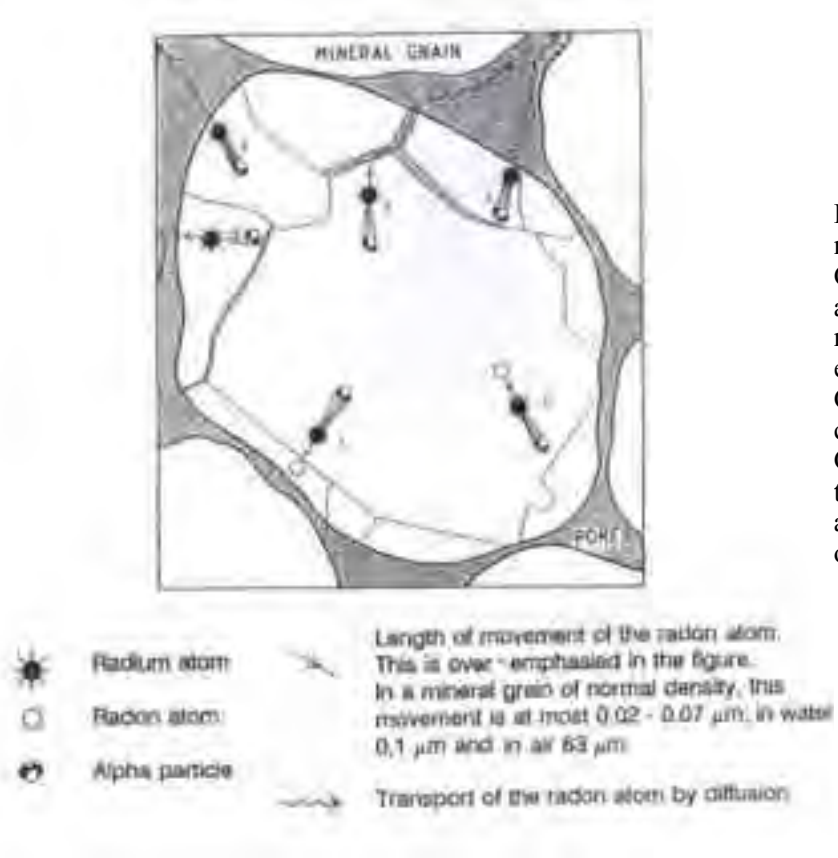


Figure 5. Principles of radon emanation from mineral grains (Åkerblom et al., 1988).
Case 1.When radium decays, a radon atom and an alpha particle are formed. The radon atom migrates into an adjacent crystal by a recoil effect from the ejected alpha particle.
Case 2.The radon atom migrates through the crystal.
Cases 3 and 4.The radon atom migrates from the crystal to a micro-fissure or the gas in an adjacent pore. Further transport is assumed to occur by diffusion.

2.2. Radon in indoor air

Almost all buildings are affected by radon that leaks in and mixes with the indoor air from under lying ground. Radon is either transported together with soil air, in which case the soil air is actively drawn into the building through cracks, joints and holes in the foundation by the stack effect caused by the pressure difference between indoor and outdoor atmosphere, or by diffusion through the upper soil layer and the floor/concrete slab laying on the ground or above the crawl space. The leakage of radon into most buildings results in low indoor radon concentrations (<50 Bq/m^3) only, but if the volume of incoming soil air is greater than 1–5 m^3/h or if the radon concentration in the soil air is high (>50,000 Bq/m^3), indoor radon concentrations greater than 200 Bq/m^3 often result. (The maximum annual indoor radon concentrations so far measured in Estonia is 12,000 Bq/m^3.)

2.3. Inhaled radon and radon daughters constitute a health risk

As mentioned before, radon is highly radioactive and carcinogenic, and second to smoking the main cause of lung cancer. Radon decays into a number of radioactive elements (daughters) until the formation of stable ^{206}Pb (Table 1). Of these daughters ^{218}Po and ^{214}Po decay by alpha radiation. When inhaled these daughters adhere to the epithelium in the lungs. The emitted alpha radiation can damage the epithelium cells and their chromosomes. This cell damage can result in cancer, the risk being related to the duration of exposure and the concentration of radon. Smokers exposed to radon run a multiplicative risk for lung cancer (Figure. 6) (Mjönes and Falk, 2002; Darby et al., 2004).

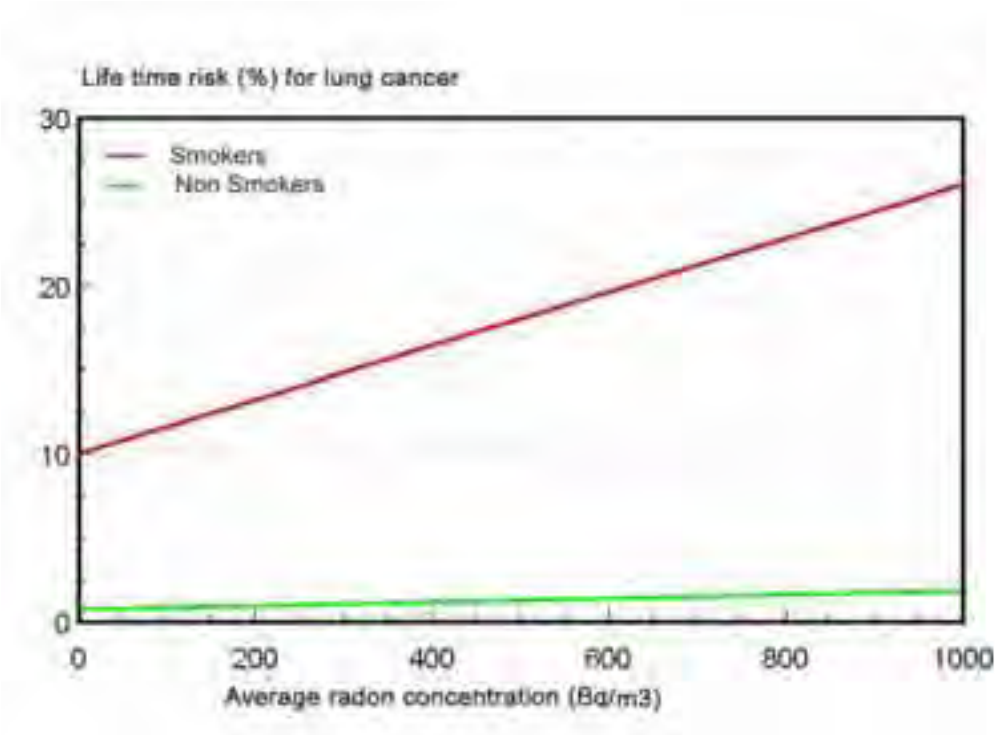


Figure 6. Lifetime risk of lung cancer as a result of exposure to radon gas. Calculated from a relative increased risk of 16% per 100 Bq/m^3 (Mjönes and Falk, 2002).

3. REGULATIONS AND GUIDELINES FOR RADON AND NATURAL RADIATION

3.1. EU guidelines and recommendations

Due to the hazardous effect on human health caused by radon and especially by its daughters it became inevitable to establish limits or guidelines for maximum permissible radon gas concentrations of indoor air in residential buildings and workplaces. In most European countries the limits or highest recommended radon concentration is 200 Bq/m^3 for new residential buildings and 200–400 Bq/m^3 for existing buildings (Åkerblom, 1999).

The European Commission published in 1990 a specific recommendation for exposure to radon in dwellings (EC, 1990). Although the dose conversion from annual average radon concentration to effective dose is based on earlier recommendations from the International Commission on Radiological Protection (ICRP) (Publications 50, 1987; 60, 1990 and 65, 1965) the recommended action level for existing buildings (400 Bq/m^3) and the planning level for future constructions (200 Bq/m^3) are still regarded as applicable by the Commission.

In 1996, the European Council adopted a revised European Basic Safety Standards Directive (EU BSS, Directive 96/29/Euratom laying down basic safety standards for the protection of the health of workers and the general public against the dangers from ionising radiation) (EC, 1996). The EU BSS directive is based on the general recommendations in ICRP Publication 60 regarding practices and intervention. The EU BSS states: "shall not apply to exposure to radon in dwellings or to the natural level of radiation, i.e. to radionuclides contained in the human body, to cosmic radiation prevailing at ground level or to aboveground exposure to radionuclides present in the undisturbed earth's crust". The EU BSS Directive gives the Member States a high degree of flexibility in implementing the articles on natural radiation sources into national legislation.

On request by the European Commission the Group of Experts established under the terms of Article 31 of the Euratom Treaty has given guidance for radon and natural radiation at workplaces (EC, 1997). In parts these guidance also apply to the exposure of the public. The Commission recommend the National Authorities of the Member States to "undertake surveys to determine the scale and nature of radon exposures" and to perform "control of domestic as well as occupational exposures". It also stresses the "use of defining radon prone areas".

A review of the situation in Scandinavia has been published in Naturally Occurring Radioactivity in the Nordic Countries – Recommendations (Naturally…, 2000).

Since 2002 the Swedish compulsory limits are 200 Bq/m^3 for indoor radon in existing and new dwellings, schools, day-care homes and other public access buildings and 400 Bq/m^3 in workplaces. If the limit is exceeded the owner of the building or the employer can be forced to remediate the situation to reduce radon concentrations to below the limit.

In Russia the limit for the radon daughter activity concentration is 100 Bq/m^3 in new buildings and 200 Bq/m^3 in existing dwellings (Assuming an F-factor of 0.5, 100 Bq/m^3 corresponds to a radon concentration of 200 Bq/m^3 and 200 Bq/m^3 to 400 Bq/m^3) (Gigieničeskie …, 2003). A recommended action limit of 150 Bq/m^3 has been established for both new and existing dwellings and schools in USA (EPA, 1992).

Recommendations for building materials

Building materials made of soil or rock emit gamma radiation and radon. Both gamma radiation from building materials and radon exhaled from building material will contribute to the dose received by those living or working in the buildings.

The Group of Experts established under the terms of Article 31 of the Euratom Treaty has also provided guidelines on natural radioactivity in building materials (EC, 1999). These guidelines give the following basic recommendations:

(17) The amount of radium in building materials should be restricted at least to a level where it is unlikely that it could be a major cause for exceeding the design level for indoor radon introduced in the Commissions Recommendation (200 Bq/m^3).

(18) Within the European Union, gamma doses due to building materials exceeding 1 mSv a^{-1} are very exceptional and can hardly be disregarded from the radiation protection point of view. When gamma doses

are limited to levels below 1 mSv a^{-1}, the ^{226}Ra concentrations in the materials are limited, in practice, to levels, which are unlikely to cause indoor radon concentrations exceeding the design level of the Commission Recommendation (200 Bq m^{-3}).

(19) Controls on the radioactivity of building materials can be based on the following radiological criteria and principles:

a) Dose criterion for controls

Controls should be based on a dose criterion, which is established considering overall national circumstances. Within the European Union, doses exceeding 1mSv a^{-1} should be taken into account from the radiation protection point of view. Higher doses should be accepted only in some very exceptional cases were materials are used locally (see Paragraph 30). Controls can be based on a lower dose criterion if it is judged that this is desirable and will not lead to impractical controls. It is therefore recommended that controls should be based on a dose in the range 0.3 – 1 mSv a^{-1}. This is the excess gamma dose to that received outdoors.

b) Exemption level

Building materials should be exempted from all restrictions concerning their radioactivity if the excess gamma radiation originating from them increases the annual effective dose of a member of the public by 0.3 $mSva^{-1}$ at the most. This is the excess gamma dose to that received outdoors.

(20) Separate limitations for radon or thoron exhaling from building materials should be considered where previous evaluations show that building materials may be a significant source of indoor radon or thoron and restrictions put on this source is found to be an efficient and a cost effective way to limit exposures to indoor radon or thoron.

(21) Investigation levels can be derived for practical monitoring purposes. Because more than one radionuclide contribute to the dose, it is practical to present investigation levels in the form of an activity concentration index. The activity concentration index should also take into account typical ways and amounts in which the material is used in a building. The following activity concentration index (*I*) is derived for identifying whether a dose criterion is met:

$$I = C_{Ra}/ 300 + C_{Th}/200 + C_K/3000$$

where C_{Ra}, C_{Th}, C_K are the radium, thorium and potassium activity concentrations (Bq kg^{-1}) in the building material. The activity concentration index shall not exceed the following values depending on the dose criterion and the way and the amount the material is used in a building:

Dose criterion	**0.3 $mSva^{-1}$**	**1 $mSva^{-1}$**
Materials used in bulk amounts, e.g. concrete	$I \leq 0.5$	$I \leq 1$
Superficial and other materials with restricted use: tiles, boards, etc	$I \leq 2$	$I \leq 6$

(22) The activity concentration index should be used only as a screening tool for identifying materials, which might be of concern. Any actual decision on restricting the use of a material should be based on a separate dose assessment. Such assessment should be based on scenarios where the material is used in a typical way for the type of material in question. Scenarios resulting in theoretical, most unlikely maximum doses should be avoided.

The Scandinavian Radiation Protections Authorities recommend that the use of building materials should be restricted if the concentration of ^{226}Ra in the produced building material exceeds 100 Bq/kg. (Naturally..., 2000). Therefore, soil (sand, gravel, clay, etc.) or rock materials should be restricted if their use results in a concentration of ^{226}Ra in the building material in excess of 100 Bq/kg.

3.2. Estonian regulations and guidelines

The Estonian limit for new buildings is 200 Bq/m^3 (Radooniohutu..., 2003); no limit has yet been emplaced for existing buildings.

In accordance with Estonian standards, sites for construction of new buildings for dwellings and workplaces are classified as *low radon ground* (<10 kBq/m³), *normal radon ground* (10–50 kBq/m³), *high radon ground* (50–250 kBq/m³) and *very high radon ground* (>250 kBq/m³) (Radoooniohutu…, 2003).

According to the Estonian regulations, the limit of radon in the soil air at 1 meters depth is 50 kBq/m^3 (Radooniohutu..., 2003). Construction of residential buildings and workplaces in areas where the radon level exceeds 50 kBq/m^3 require remedial action against radon in-leakage.

According to Estonian Building regulation no. 55 of the Minister of the Environment, 24 August 1998 (Looduskiirgusest…, 1998), the maximum permissible index value **C** for natural radioactive elements in soils or rocks used for building materials in Estonia shall not exceed 1. The requirements for materials in playgrounds are less strict (2.5 times on average), consequently **C** for the building materials (soils) of playgrounds must not exceed 2.5. Paragraph 5 of the regulation states: "Licensee or other entrepreneur shall perform the monitoring and assessment of public dose and inform the ERPC when the specific activity index **C** of the used material exceeds the established value". For different use of material different values of **C** are used, e.g. for building material $\mathbf{C} \leq 1$.

The **C** index may be used by residents to assess the natural radiation level where they live. The index also indicates the natural radioactivity of e.g. sand, clay and gravel and other rock materials that may be unsuitable for use as building material for dwellings and workplaces.

The **C** index for building materials used for dwellings and occupational buildings is calculated by the following formula (activity concentration of elements in Bq/kg):

$$\mathbf{C} = {}^{226}\mathrm{Ra}/300 + {}^{232}\mathrm{Th}/200 + {}^{40}\mathrm{K}/3000 \leq 1,$$

where

C – the maximum permissible index for natural radioactive elements in building materials and the activity concentrations of the elements is in Bq/kg.

The **C** index for materials or ground used for playgrounds is:

$$\mathbf{C} = {}^{226}\mathrm{Ra}/700 + {}^{232}\mathrm{Th}/500 + {}^{40}\mathrm{K}/8000 + 137\mathrm{Cs}/2000 \leq 1$$

Note

1 mg U /kg is equivalent to12.3 Bq ^{226}Ra/kg (when in the uranium-238 series there is radiation equilibrium between ^{238}U and ^{226}Ra); 1 mg Th /kg to 4.0 Bq ^{232}Th/kg; 1% K = 313 Bq ^{40}K/kg. It is noteworthy that if ^{226}Ra and uranium are naturally balanced the concentration of uranium in the building materials for houses can exceed 20 ppm U and in the building materials for playgrounds – 50 ppm U, which exceeds the recommended and maximum permissible concentration established for the residential areas (Pinnases…, 2004).

4. BRIEF REVIEW OF NATURAL AND ECONOMIC CONDITIONS IN ESTONIA

Estonia is located on the eastern coast of the Baltic Sea and can be divided into mainland Estonia and the West-Estonian Archipelago. Estonia borders the Gulf of Finland to the north, the Baltic Sea and Gulf of Livonia to the west, and from the east the Narva River, the depression of Peipsi and Pihkva lakes and the Russian Republic to the east. The southern border of Estonia with the Republic of Latvia features no notable geographic features. Estonia occupies 45.2 thousand km², of which mainland Estonia covers 41.1 thousand km².

Post-glacial tectonic movement causes north-western Estonia to rise up to 3–3.5 mm per year and south-eastern Estonia to drop up to 1 mm per year. The approximate axis between these regions runs northeast to southwest and coincides roughly with a Pärnu–Narva transect (Garetsky et al., 1995).

Estonia is generally low-lying, mostly 30–80 m above sea level. Northern Estonia consists of an extensive undulating or hummocky limestone plateau. The northern edge of this plateau forms an abrupt escarpment known as the Klint. The Klint achieves its maximum altitude (56 m above sea level) in north-eastern Estonia. A fore-Klint lowland of variable width exists between the Klint and sea, but in a number of localities to the east of Aseri (north-eastern Estonia) and to the west of Tallinn the fore-Klint lowland is absent and the sea borders the foot of the Klint. The highest part of the limestone plateau is the Pandivere Upland, characterised by undulating or hummocky areas that rise 80–120 m (maximum 166 m) above sea level. South and west of the upland is the Central Estonian plain, which falls towards the west and gradually merges into the West-Estonian and Pärnu coastal plains. Both open and buried karst is common on the Pandivere upland, North-Estonian (Harju) limestone plateau, as well as in other parts of the North-Estonian Plateau. Karst occurs also on Saaremaa and Hiiumaa islands. To the east of the Pärnu Lowland, in southern Estonia, the Sakala, Otepää and Haanja uplands are separated by depressions. The ground surface is undulating or irregular, often hummocky with steep slopes and depressions. The highest hills in these uplands are Rutu (146 m), Kuutse (217 m) and Suur Munamägi (318 m), respectively. Towards the eastern boundary of Estonia the hummocky relief gradually merges into the Peipsi Lowland.

River water is the main agent transporting humus and mineral grains, as well as elements and their compounds, including uranium, thorium, their daughter isotopes and potassium. Data on uranium and thorium concentration in the water of Estonian rivers are incomplete or missing. ICP-MS analyses incorporated in the Geochemical Atlas of Europe (2005) show that the concentration in river water (total two streams with catchments areas 30–90 km²) of U and Th are 0.55–4.58 µg/l and 0.07–0.026 µg/l respectively.

Estonia contains a total of 7378 rivers, brooks and large ditches. These water bodies total 31,153 km in length. The large ditches all intersect the humus horizon and underlying soils to a depth of at least 2 m. The rivers within the Lake Peipsi and Gulf of Livonia–Väinameri catchments originate on the slopes of Pandivere uplands, meander through their middle and lower course and their river valleys are paludified. In these areas the soil is often saturated. The previously mentioned tectonic uplift enhances paludification. The rivers within the Gulf of Finland catchment originate on the North-Estonian limestone plateau, often from springs. Upon crossing the klint escarpment, these rivers commonly cut into the bedrock and form V-shaped valleys, rapids and low waterfalls.

Estonia contains about 1200 natural and artificial lakes with an area of 1 hectare or more. These lakes and large bog pools cover approximately 2130 km². These lakes serve as sedimentary basins into which the rivers, brooks and ditches transport both solid and dissolved material.

Forests constitute approximately one third of Estonia's land area and mires cover about ten thousand square kilometres (22.3% of land area)**.** The 48 largest mires have an area greater than 30 km², of which 11 mires cover more than 100 km². Puhatu mire, the largest in Estonia, has an area of 570.8 km² (Orru, 1995). Mires are found mostly in the Alutaguse region (north-eastern Estonia), southern part of the Central-Estonian Limestone Plateau, Pärnu Lowland and northern part of the Lake Võrtsjärv depression. These mires have received considerable amounts of uranium and other heavy materials from flowing waters or springs (Orru and Orru, 2003).

Estonia is located in the temperate climatic zone and the Atlantic-continental sub-zone. The Baltic Sea casts considerable influence on the climate. The average annual temperature is +3.7 to +6 °C and the average annual precipitation is 550–800 mm. The annual precipitation is at least twice the annual average evaporation. Sandy soil can freeze down to a depth of about 1 m.

Mining of Estonia's major minerals occurs in north-eastern Estonia: the areas where oil shale and limestone (raw material for cement production) are excavated constitute almost 4600 km² and as a result, the natural mineral and chemical composition of the soils has been altered considerably. Tailings of materials from oil shale mining and processing currently cover almost 191 km² and this area is expanding (Kattai et al, 2000). The uppermost 5–6 m (in places even more) of natural soils or rocks has been excavated and mixed with materials from underlying beds in quarries from which raw material for producing building materials, glass, and other products is extracted.

At the Sillamäe town there are huge waste dams containing waste from uranium production from the Dictyonema shale and uranium ores brought to Estonia for refining during the Soviet era. Refining of rare earth elements, niobium and tantalum from imported ores continues in Sillamäe. Attention should be paid in the future to the depository of the waste from this enterprise as the waste contains radioactive material.

5. PREVIOUS INVESTIGATIONS

The radon issue is relatively recent; it first received attention in the 1950–1960s when high concentrations of radon gas was identified as a cause of lung cancer in miners working in uranium mines in USA.

In recent decades various aspects of the hazardous affects of radon gas on human health have been investigated thoroughly in Sweden (Mjönes, 1991; Pershagen, Åkerblom et al., 1993), and other Nordic countries (Naturally..., 2000), USA (Gundersen, 1991), Czech Republic (Mikšova and Barnet, 2002) etc. Research in the Czech Republic has indicated that a rise in radon gas concentration of 100 Bq/m^3 above the permissible concentration (200 Bq/m^3) increases the risk of lung cancer 9–15% and more (Mikšova and Barnet, 2002). Radon is especially hazardous to smokers (Figure 6).

The main source of indoor radon is radon transported from the ground by soil air. Therefore, understanding of the concentration of radioactive elements – above all uranium – in rocks and soils is the principle means by which to identify radon prone regions, areas and sites. Investigations to determine the concentration of uranium and thorium in the bedrock of Estonia began immediately after World War II with studies of the Dictyonema shale (Pakerort Stage, Lower Ordovician) and phosphorite (to lesser extent). As a result of these investigations, the Sillamäe region was deemed a suitable area to refine uranium (in this area the average concentration of uranium in Dictyonema shale is 300 ppm). However, the results of these investigations are missing from the Depository of Manuscript Reports of the Geological Survey of Estonia.

Extensive, but often indirect, investigations of radon in soils and bedrock began in 1958 in association with geological mapping at scale of 1:200 000. These studies included measurements of the natural gamma-radiation levels in soils and bedrock (in boreholes). Rock samples were collected, which were analysed for uranium and thorium, in areas with enhanced radiation levels. Estonian uranium deposits were deemed nonviable in the 1960s, but investigations continued irregularly until the beginning of the 1970s.

Analyses of the bedrock concentration of uranium and thorium became obligatory in the 1970s and continued until 1990. The level of natural radiation in almost all boreholes was measured by gamma-ray logging, and the concentration of uranium and thorium was determined in samples collected from the sections with enhanced natural radiation levels. This analysis led to the identification of elevated uranium concentrations in some dark-coloured clay-rich varieties of Devonian sedimentary rocks in southern Estonia.

In conjunction with prospecting for phosphorite deposits, determination of uranium and thorium concentrations in the Dictyonema shale and phosphorite was ubiquitous during 1972–1986.

Investigations specifically aimed to determine the concentration of uranium, thorium and potassium in Estonian soils began in 1985 in conjunction with systematic geochemical mapping of the topsoil and subsoil. The concentration of uranium, thorium and potassium was determined in 860 samples collected during 1985–1986. These samples were extracted from the sides of 1–1.2 m deep excavations; samples were collected from the A-horizon (the upper humus rich 10-30 cm thick soil layer) and the C-horizon (below a depth of 60 cm) (Petersell et al., 1997; 2000). This survey revealed that the concentration of uranium exceeded 4–5 mg/kg in 20–30% of the samples. The Swedish Radiation Protection Authority suggests an increased potential for enhanced radon concentrations in the soil air at such uranium levels (Åkerblom, 1994).

Indoor radon was first measured in 1985–1990 in the basements or on the ground floor of dwellings (Naumov, 1993). In 1995 the Estonian Radiation Protection Centre started systematic investigations in cooperation with the Swedish Radiation Protection Authority. To date, almost 1475 measurements of indoor radon have been made in single-family and multi-family residences. The results have revealed very variable indoor radon concentrations (Pahapill, 2000; Pahapill et al, 2003). The radon concentration is often elevated in ground-floor homes and apartments, and in some counties and municipalities, radon levels exceeded the maximum permissible concentration (200 Bq/m^3) in 35–72% of the analyses. In several homes the radon concentrations measured 800 to more than 1000 Bq/m^3 with a maximum concentration of 12,000 Bq/m^3. These measurements – taken in randomly selected dwellings – place Estonia third among European countries for the highest radon levels (following Finland and Sweden).

These indoor radon measurements underline the necessity for determination of radon concentration in Estonian soils to be a criterion for environmental assessment.

The first measurements of radon in soil air in Estonia were carried out by EKK with the equipment of and in co-operation with the Swedish Radiation Protection Authority. The highest radon concentration

measured at the time was 2.5 million Bq/m^3 in a soil consisting of Dictyonema shale fragments in Sillamäe (Pahapill, 2000).

The first map depicting radon risk areas was based on the confines of Dictyonema shale and phosphorite outcrop areas (Raudsep and Samuel, 1999).

6. PRINCIPAL GEOLOGIC FEATURES

Estonia is located in the north-western part of the East-European platform in an area bordering the Fennoscandian (Baltic) Shield, where the Earth's crust consists of three complexes of variable composition: Proterozoic crystalline basement, which is overlain by Vendian and Palaeozoic sedimentary bedrock and unconsolidated Quaternary deposits. The latter comprises the crushed, ground and weathered fragments of both sedimentary and crystalline rocks.

6.1. Crystalline basement and sedimentary bedrock (Figure 2)

The crystalline rocks influencing the mineral and chemical composition of Estonian soils lie directly under the Quaternary cover in the central and northern Gulf of Finland, in southern and central Finland, on the bottom of the Baltic Sea and elsewhere on the Fennoscandian Shield. These rocks consist of shales, gneisses and intrusive rocks of variable mineral and chemical composition, from acid to ultrabasic and including alkaline rocks. Granitoids rich in uranium, thorium and potassium often underlie the Quaternary deposits in southern Finland and southern Karelia (The Geochemical..., 1992). Among these granitoids, Rapakivi granites have the greatest influence on the concentration of radon in Estonian soils.

In the southern part of the Gulf of Finland and throughout Estonia the crystalline basement is overlain by Vendian and Palaeozoic sedimentary rocks (Figure 7). These formations are sub-parallel beds that dip slightly southward (ca 3 m per km) with west–east orientated belts, whereby the oldest rocks occur in the north and increasingly younger rocks gradually follow towards the south. The thickness of the sedimentary cover increases southwards reaching approximately 600 m in southern Estonia. This fairly uniform bedding is displaced by low-amplitude tectonic faults, such as the Viivikonna, Aseri and Tapa faults, residual uplift of the crystalline basement near Uljaste and Assamalla, the Mõniste and Lokno tectonic uplifts, and impact craters, such as Kärdla (ca 4 km in diameter) and the much smaller Kaali and Ilumetsa impact craters (Geology..., 1997).

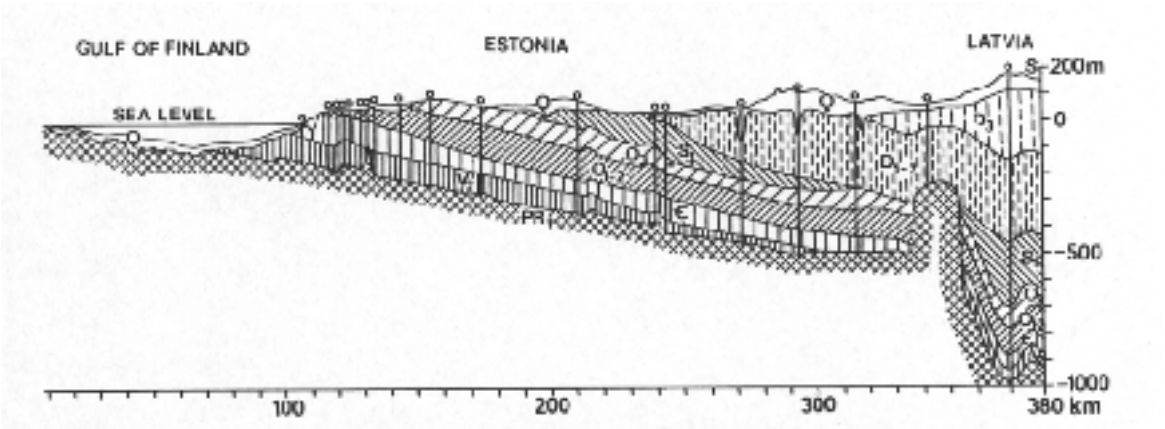


Figure 7. N-S cross-section from the Gulf of Finland through Estonia to north Latvia along a profile of deep boreholes. PR_1, Paleoproterozoic crystalline basement; V_3, Upper Vendian; Ɍ, Cambrian; O_{1-2}, Lower and Middle Ordovician; O_3, Upper Ordovician; S_1, Silurian; D_{1-2}, Lower and Middle Devonian; D_3, Upper Devonian; Q, Quaternary [5].[a]

Vendian and Cambrian clays, siltstones and sandstones lie directly on the crystalline basement. The thickness of these formations in the North-Estonian outcrop area decreases from 160–180 m in the east to 110–130 m in the west. These deposits were deposited in shallow seas and consist mainly of quartz, feldspars, mica and clay minerals – kaolinite, illite and some chlorite and montmorillonite. Carbonates, if present, are uncommon (Viiding et al., 1983). Minerals rich in uranium and thorium occur irregularly, mainly as varieties resistant to weathering (zircon, monazite, xenotime and apatite).

Lower-Ordovician rocks (Obolus sandstone, phosphorite, Dictyonema shale, clay and glauconite sandstone lie discordantly on the Cambrian sedimentary rocks. These form the Lower-Ordovician terrigenous complex and outcrop in the Klint escarpment (Figure 8) and in valleys cutting the limestone plateau. Their outcrops occur along the entire Klint from Paldiski to Narva and on the sea floor west of the Pakri Islands. Some formations of the Lower-Ordovician complex – Dictyonema shale and Obolus sandstone (phosphorite) – are typically rich in uranium, potassium and a number of other trace elements (Loog and Petersell, 1994; Petersell, 1991). Ordovician and Silurian carbonate rocks (limestones, dolomites, marlstones and domerites) either underlie the Quaternary cover or lie directly on the ground surface south of the Lower-Ordovician outcrop area from Navesti to Mustvee. The oil shale (kukersite) beds, which form the Estonia and Tapa deposits, are parts of the Middle-Ordovician Uhaku and Kukruse stages. All these formations are shallow sea deposits.

Figure 8. The Klint escarpment at the Valaste waterfall. From top to bottom: Ordovician limestone, Dictyonema shale (black), Obolus sandstone with phosphorite.

Devonian sandstones and siltstones, with occasional clays, underlie the Quaternary cover or outcrop in a few localities south of Navesti–Mustvee line in southern Estonia. Marlstones of the Narva stage outcrop irregularly on the western bank of the Narva River and as a narrow belt in central Estonia, and dolomite, domerite and dolomitised sandstone is distributed in south-eastern Estonia. The Devonian sedimentary rocks consist primarily of quartz, feldspars, micas, illite, and less commonly kaolinite and chlorite. The sandstones poor in clay minerals are often enriched with zircon and orthite, monazite, apatite and Fe-minerals.

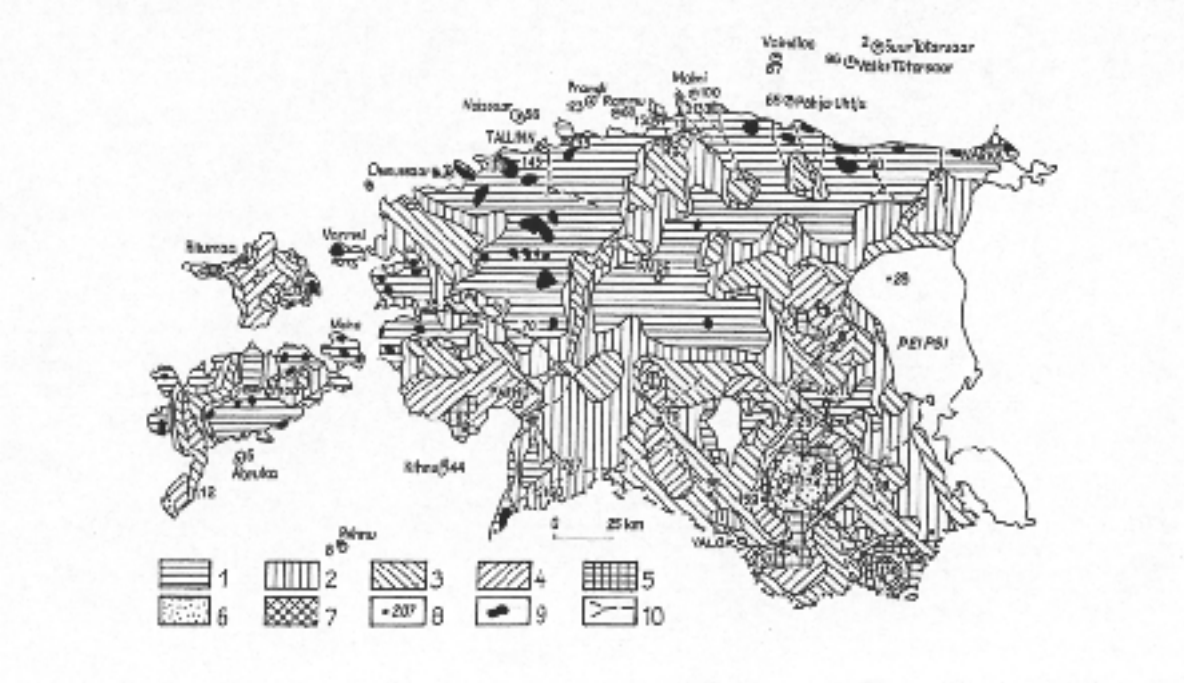
The Devonian marls were deposited primarily in shallow coastal waters or in lagoons, and the carbonates in shallow seas. Sandstones, siltstones and clays are usually red, laminated and cross-bedded (Rõõmusoks, 1983). The colour formed during sedimentation when colloidal ferric hydroxides precipitated from the percolating water (Viiding, 1961). These rocks are typical of riverbeds, deltas, lakes and shallow near shore seas. They were transported to the depositional area from the Caledonides in northern Scandinavia and from the Fennoscandian Shield.

The average concentrations of major and trace elements in the rocks of the Fennoscandian Shield approximate the average concentrations in the Earth's crust. Except for the Lower-Ordovician Tremadocian complex, the major and trace element content in Estonian bedrock has been inadequately studied. However, given its mineral composition and the results of mineral exploration, the average elemental abundance likely approximates those calculated globally for clays, sandstones or carbonate rocks, respectively (Turekian and Wedepohl, 1961).

The Devonian was followed by a long and likely uninterrupted continental period of 400 million years. During this period the present-day Estonian territory and the Fennoscandian Shield migrated through tropical and subtropical climatic zones to arrive finally the temperate zone. The deep (200 m and more) preserved valleys reveal that the territory rose and was intensely eroded at the end of the Devonian. The weathered surface formed under the different climatic conditions was subject to denudation and accumulation. A weathered crust of variable mineral composition and degree of weathering had been formed at the onset of the continental glaciations.

6.2. Quaternary deposits (Map Sheet 1.5)

The Quaternary cover in Estonia consists of Pleistocene deposits formed by several continental glaciers and their melt waters, and Holocene marine, aeolian and lacustrine sediments. In the north and northwest, these deposits are usually less than 5 meters thick (Raukas, 1993), because the soil was largely removed by glacial erosion and wave-action during uplift. On the limestone and dolomite plains (alvars) almost all soil was removed. The deepest soils, 50 to 200 m, are located in the buried valleys, the Saadjärv drumlin field and in the Haanja and Otepää heights in southern Estonia (Geology …,1997). Deep soils also occur near Viljandi and on the outwash plains in western Estonia (Figure 9**).** Deep soils are often associated with deposits from more than one glaciation. The principal direction of ice movement was southward, but deviated both eastward and westward.



Joon.1. Kvaternaarisete paisused. 1 - < 5 m, 2 - 5-10 m, 3 - 10-20 m, 4 - 20-40 m, 5 - 40-60 m, 6 - 60-80 m, 7 - > 80 m, 8 - puurauk ja kvaternaarisete paisus, 9 - lood (alvarid), 10 - maetunud orud (koostanud K. Kajak).
Fig.1. Thickness of the Quaternary deposits. 1 - below 5 m, 2 - 5-10 m, 3 - 10-20 m, 4 - 20-40 m, 5 - 40-60 m, 6 - 60-80 m, 7 - over 80 m, 8 - boreholes with the thickness of the Quaternary deposits, 9 - alvars, 10 - buried valleys (compiled by K. Kajak).

Figure 9. Thickness of Quaternary deposits in Estonia.

The continental glaciers carried to Estonia large amounts of crushed material from the crystalline Precambrian rocks on the bottom of the Baltic Sea (chiefly the Gulf of Finland), Finland and northern Scandinavia. The Pleistocene soils are dominated by tills deposited by the different glaciers; as many as five till units have been discerned in Estonia (Geology …., 1997). In places these tills contain, or are separated by, sorted sediments such as sands, silts and clays from interglacials and interstadials. Organic material in these sediments can be dated by C^{14} (Liivrand, 1992, Raukas, 1992). The stages of the Pleistocene are presented in Table 3. Each glacial stage is disassociated by shorter ice-free interstadials. At least two ice-free periods occurred during the Weichsel, the latest glaciation. During glacial advances the ice mass eroded, deformed or displaced both tills and sorted sediments. Ice margin features were formed during pauses in glacial advance or retreat.

Table 3

Pleistocene stratigraphy of Estonia (Geology..., 1997)

Units						
Division	**Sub-division**	**Main formations**		**Subformations**	**Facies**	**Litostratigraphy/vegetation**
		Estonia	*North Europe*			
Holocene						Continental and marine deposits
Pleistocene	Upper Pleistocene	Järva	Weichsel	Võrtsjärve	Stadial	Grey till in North Estonia, reddish-brown till in South Estonia
				Savala	Interstadial	Dry periglacial vegetation
				Valgjärve	Stadial	Grey till in North Estonia, purplish-grey till in South Estonia
				Keinase	Interstadial	Tundra vegetation
		Prangli	Eem		Interglacial	Forest vegetation, marine and continental deposits
	Middle Pleistocene	Ugandi	Saale	Upper Ugandi	Stadial	Brown till in North Estonia, grey till in South Estonia
				Middle Ugandi	Interstadial	Periglacial vegetation
				Lower Ugandi	Stadial	Brown till in North and South Estonia
		Karuküla	Holstein		Interglacial	Forest vegetation
		Sangaste	Elster	Sangaste	Stadial	Shaly brownish till in Central and South Estonia

The most prominent *ice marginal* zone, the Palivere zone, features end moraines (Saaremaa and Haapsalu), marginal eskers (NW Estonia) and glaciofluvial deltas (between Tallinn and Kunda and on Hiiumaa) (Raukas, 1992). Further south the older Pandivere zone stretches from Narva in the east over the Pandivere Upland to Pärnu on the western coast. The Pandivere Upland was a part of the ice-shed zones between the Baltic and the Finnish ice streams. During late glacial time, the ice cover formed numerous ice lobes with individual dynamics (Salonen, 1992; Karukäpp, 2003). The Pandivere Upland features eskers and esker systems in addition to kame fields, hummocky moraines and glaciolacustrine deposits.

Drumlins occur in clusters in Estonia. The best known drumlin field is the Saadjärv drumlin field. The composition of drumlins varies; many drumlins contain sorted sediments as well as older tills (Rõuk & Raukas, 1989).

Glaciofluvial sediments, which are overlain by relatively thin (<2 m) till layers deposited during the latest glacial stage are fairly common. These sediments have often been encountered in drillcores and in open pit excavation, e.g. in the Rapla area.

Carbonate-rich silty and sandy tills are common in north-west Estonia (Kadastik & Ploom, 2000). Three till units dating from late Weichsel have been distinguished on the west Estonian Islands: two basal tills and a clayey, cacao-brown melt-out till. The youngest basal till, the Palivere till, was deposited during the latest glacial advance. This till is rich in Rapakivi granite and granites originating from Åland and southwest Finland. The Palivere till overlies the older basal Pandivere till, except in the eastern part of Saaremaa, which was beyond the last glacial advance (Kadastik & Kalm, 1998, Kalm & Kadastik, 2001).

Hilly moraine topography is characteristic of south and south-eastern Estonia, where the Devonian sandstone is overlain by as many as five till layers and by glaciofluvial and glaciolacustrine deposits. These deposits are thickest in the Haanja and Otepää heights and in the buried valleys. The tills can be distinguished by colour, granulometric composition and stratigraphic position. The uppermost layer consists of a silty reddish-brown till, which is underlain by a clayey purplish-grey till in many areas. Some tills are rich in carbonaceous clasts, whereas others are abundant in crystalline clasts. The composition of the uppermost till layer (Late Valdian) was influenced by the underlying bedrock (Raukas, 1978). Quartz, garnet and zircons in the light fine sand fraction are more common in the south than in the north, whereas carbonates are more common in the north (Raukas, 1969). The local variations are frequently overshadowed by regional differences or differences in age of bedrock strata (Raukas, 1974). Zircon may attribute to greater uranium content in the sediments. The granulometric composition of the tills varies from very compact clayey tills to coarse-grained sandy tills with high permeability.

Figure 10. Sand rich in fragments of Dictyonema shale in a gully south of the Klint at Voka.

The main cause for high radon and uranium contents in soils is the Dictyonema shale and phosphorites that outcrop in the lower part of the Klint and in valley walls south of the Klint. Various glaciers have eroded and crushed material from the Klint zone and transported it southwards with some eastward and westward movement, depending on the particular ice flow. However, the amount of uranium-rich material that the glaciers could remove from the Klint zone was limited. The glacially dispersed uranium-rich material was deposited throughout Estonia and can even be found in small amounts in southern Estonia. During the last glaciation nappes of the Klint were displaced 4–5 kilometres southwards to form e.g. Vaivara Blue Hills (Raukas, 1993). These hills feature both vertical and folded Lower Ordovician beds containing Dictyonema shale with till either overlying or in-bedded in the bedrock layers. In other places along the northern Klint zone, abundant shale fragments occur in the sediments above the Klint or along the south-oriented valleys (Figure 10)**.** In the Klint zone near Kunda, ridge like forms are found associated with the Klint. These ridges were formed initially by glaciers and have been subsequently reworked by coastal processes. The ridges ge-

nerally contain coarse gravel and pebbles, but till is also found together with fine-grained sediments (Geology…, 1997; Karukäpp, 2003).

Despite southward dispersal of uranium-rich material, little uranium-rich material was detected in upper soils south of the Klint zone in our surveys. Our gamma-ray spectrometry measurements show that Dictyonema shale and phosphorites occur in all soil types in the Klint zone. The Devonian bedrock in southern Estonia has influenced till composition, which may have enhanced their radon- and uranium-concentrations.

Marine and lake sediments, such as sand, silt and clays have been deposited during interglacials and interstadials as well as the present postglacial period. The silty and clayey sediments on the outwash plains north and north-east of Pärnu are in buried valleys often more than 50 m thick. In late glacial times northern Estonia and other areas were covered periodically by large ice lakes. Glaciolacustrine sediments in the form of varved clays, silt and sand are found on the Võru and Valga plains, Peipsi Lowland and Pärnu River basin and in the hilly areas south-east of Tartu. Younger sediments covered these late glacial sediments during different stages of the Baltic Sea: the Yoldia Sea, Ancylus Lake, Litorina Sea and the Limnea Sea. The Holocene marine deposits consist of pebbles, gravel, sand and silt and are dominated by carbonaceous material. Alluvial deposits are found in the river valleys and dune sands can be found both along the present shorelines in northern and western Estonia as well as along old coastlines (Häädemeeste and northern coast of Lake Peipsi).

The sediments in the fore-Klint zone have considerable thickness in some areas, up to 143 m in the ancient Harku valley but are generally thinner (Geology…, 1997). Several till layers with inter-morainic sediments have been identified. The tills on the outcrops of Vendian and Cambrian clays are bluish-grey and the pebble-cobbles consist entirely of crystalline rocks from the Gulf of Finland or Finland (Raukas 1992). These tills are almost entirely covered by Holocene marine sediments consisting of gravel, sand and silt. Erosion of the Klint area has resulted in uranium-rich material being transported and redeposited in the fore-Klint zone. Gamma spectrometry reveals enhanced uranium concentrations in the soils in many localities north of the klint. This indicates the presence of Dictyonema shale and phosphorites fragments.

Permafrost phenomena are common among Younger Dryas sediments in Estonia (Geology…, 1997). These phenomena disturb the generally horizontal bedding of the sediments through cryoturbation and ice wedges, which can provide means for transport of radon containing soil air.

7. METHODS

The Radon Risk Map of Estonian Soil is based on the available geologic information, earlier measurements and chemical analyses of natural radioactive elements and nuclides in bedrock and soil, surveys made by airborne gamma-ray spectrometers and measurements of radon in existing Estonian homes and workplaces, as well as on the surveys undertaken especially for this project. These surveys included measurements of radon concentrations in the soil air, gamma-ray spectrometric in situ analyses of the concentrations of radium-226, thorium-232 and potassium-40 in soils and chemical analyses of uranium, thorium and potassium in soils samples.

7.1. Site location

Site selection of locations was based on the following criteria:

- The concentration of U, Th and K in soils in the Geochemical Atlas of the Parent Rocks of Estonian Soils (Petersell et al., 2000),
- Bedrock geological maps and maps of Quaternary deposits (Geological Survey of Estonia),
- Arial gamma-spectrometric maps (Rešetov et al., 1993),
- Radon measurements in existing buildings and workplaces (Estonian Radiation Protection Centre, 2004),

  Other geological reports (see References).

Field surveys were conducted during the summer and autumn of 2002 and 2003. Radon in soil air was measured and gamma spectrometric determinations of radium-226, thorium-232 and potassium-40 were performed at 254 locations in 2002 and at 312 locations in 2003. These locations were located throughout Estonia, but the sampling density was greater near the North-Estonian Klint (between Muraste and Narva). The local geology was noted at all locations. Holes were dug at each site to record soil profiles to a depth of 1 m and to measure natural nuclides by gamma spectrometry. Soil samples were collected from the bottom of some of the holes.

Fieldwork as well as the number of measurements, samples and analyses had to comply with financial constraints.

The sites were selected on the grounds of the above listed information. It was deemed that the sites must characterise possible radon risk regions, and that more observations should be made in the most densely populated areas than in rural areas. Taking into account the existing geological information and the Swedish experience, areas of potential radon hazards were northern Estonia where Dictyonema argillite and phosphorite form the outcropping bedrock and where fragments of these rock units occur in soils. Other areas of special interest were those with elevated and high concentration of uranium identified by geochemical mapping and aerial gamma-ray spectrometry, as well as ancient valleys, eskers, drumlins, kames and tectonic fault zones. The preliminary site locations were selected at 1:50 000 scale topographic maps. The final locations were established during the fieldwork and determination of their coordinates made by Garmin GPS 76. The error of geodetic marking was +10 m.

7.2. Field measurements

Instruments belonging to the Swedish Radiation Protection Authority, the Geological Survey of Sweden and the Estonian Radiation Protection Centre were used for the fieldwork. All instruments were checked and calibrated at the Swedish Radiation Protection Authority and at the Geological Survey of Sweden in April and May 2002 and 2003 prior to the fieldwork.

Before the exact location of an observation point was determined, the site was checked by gamma measurements to ensure that the point chosen was representative of the geology of the location. This entailed assurance that the gamma radiation level would be characteristic of the area with no visible evidence of technogenic pollution.

The radon-222 concentration in the soil air was established by direct measurement of radon in the soil air and by calculating the ^{222}Rn concentration based on the measured concentration of ^{226}Ra in the soil.

Radon in the soil air, measured in kBq/m^3, was determined with a Gammadata MARKUS-10 emanometer calibrated by the manufacturer (Gammadata, 2005). Under optimal conditions, instrument precision is ±10% at a radon concentration of 200 kBq/m^3 and ± 20% at 20 kBq/m^3, given that the instrument is used in an atmosphere of the temperature of +20^o C, 80% relative air moisture and free movement of air. However, in practice, temperature changes, high soil moisture, and the hindering of soil air migration by water in the pores (which can restrict the volume of air sucked into the instrument) often results in a reduced accuracy. The measured value may in some cases considerably differ from the true radon concentration in the soil air at the measured point.

Figure 11. Krista Täht hammering the steel pipe to sample soil air.

At each site the soil air was sucked from a depth of 80 cm via a steel pipe into the emanometer (Figure 4 and 11). The radon concentration of the sampled air was then analysed by the instrument by measuring the decay of the radon daughter polonium-218 for 15 minutes. At sites where the soil contained abundant stones the measurement was made at the depth of 60 cm.

The 2003 field season was very moist, especially in southern Estonia, which hampered the radon measurements. The soil pores were often filled with water in moist glaciolacustrine clays and the clayey tills in southern Estonia. In such cases the device was unable to collect soil air. This difficulty curtailed direct measurement of radon in soil air at 59 (10.5%) observation points in 2003. These problems were not encountered in 2002.

Figure 12. Valter Petersell digging a hole to measure with the gamma spectrometer.

At each site where radon was measured, one or two 0.8–1 m deep holes were dug (Figure 12), from which the genetic type and lithologic composition of the soil was determined. The gamma radiation at the bottom of the holes was measured with a handheld scintillometer. In addition, the concentrations of ^{226}Ra (equivalent uranium, eU), ^{232}Th (Th) and ^{40}K (K) in the soil at the bottom of the holes were determined with a portable gamma ray spectrometer (Exploranium GR-256, 1989) (Figure 3). The gamma spectrometers were calibrated in Sweden on SGU's calibration pads at the Dala airport, Borlänge, before the fieldwork. The measurement error in the field was approximately ±10% with a measuring time of 400 seconds.

The detector unit was placed at the bottom of the hole for measurement. As the spectrometers are adjusted for a 2 π configuration (an infinite flat surface) the recorded values required conversion from 4 π to 2 π configuration with a factor of 0.65. The spectrometer also recorded the number of radioactive impulses (decays) per a certain time unit. This allowed a continuous check of the gamma spectrometer's reliability and on the accuracy of the elemental composition. Soil samples were taken from the bottom of the holes for laboratory analyses of uranium, thorium and potassium if needed.

The field measurements were checked by repeated analysis at the same point or hole with different instruments. The U (^{226}Ra), ^{232}Th and ^{40}K concentration in the soil was measured at the bottom of the same hole, but also in a nearby duplicate hole. In addition, repeated measurements of the concentration of radon in the soil air were made at the same point or at another point ca 2–3 metres away. These control measurements are shown in Table 4 and they show that the results are reliable.

Table 4

Results of control measurements with two different gamma-ray spectrometers and two emanometers

Observation point	eU, ppm[1]		Th, ppm		K, %		Rn, kBq/m^3	
	SGU[2]	SSI[3]	SGU[2]	SSI[3]	SGU[2]	SSI[3]	SGU[2]	EKK[4]
Rn02-001	2.1	1.9	3.8	4.0	2.2	2.3	7	9
Rn02-001a	1.7	1.5	12.2	7.5	1.4	1.4	11	9
Rn02-003	4.0	4.5	2.9	3.3	0.7	0.8	6	8
Rn02-005	1.1	1.1	5.2	4.4	1.5	1.4	6	7
Rn02-009	17.6	14.8	9.9	6.2	1.7	1.1	259	195
Rn02-013	2.7	2.7	11.4	11.3	3.4	3.4	94	61
Rn02-023a	5.1	4.6	11.1	11.5	2.5	2.2	No meas.	98
Rn02-104	37.1		15.5		3.1			411
Repeated measurements	37.7		14.2		3.3			422
Repeated measurements	37.2		14.5		3.2			390
Rn03-300	8.1	8.8	6.1	5.5	1.2	1.3	80	84
Rn03-301	24.6	25.4	11.2	10.6	5.2	5.6	191	194
Rn03-302	25.5	27.0	13.6	13.3	5.6	5.7	340	348
Rn03-303	7.9	8.1	7.4	6.8	1.2	1.2	148	124
Rn03-304	34.5	35.4	13.3	12.4	3.6	4.0	172	142
Rn03-305	6.2	6.5	12.7	11.6	2.9	2.9	58	47
Rn03-512	2.0	2.1	9.5	9.5	2.6	2.6	61	70
Rn03-513	1.4	1.5	6.6	6.5	2.1	2.2	20	22
Rn03-551	0.5	0.8	4.9	4.3	1.7	2.0	7	5
Rn03-571	2.7	2.7	18.4	18.5	3.8	3.9	Too moist	
Rn03-787							45	39
Rn03-778							50	53
Rn03-797							222	247
Rn03-799							10	10
Rn03-600A[5]	2.1		8.8		3.6		46	
+30 m - B	1.9		9.6		3.6		55	
+30 m - C	2.1		11.7		3.6		55	

[1] eU, equivalent uranium concentration as calculated from analyses of ^{226}Ra, assuming equilibrium within the uranium-232 series
[2] SGU – gamma spectrometer and MARKUS-10 belonging to the Geological Survey of Sweden
[3] SSI – gamma spectrometer belonging to the Swedish Radiation Protection Authority
[4] EKK – MARKUS-10 belonging to the Estonian Radiation Protection Centre
[5] In the observation points Rn02-104 and Rn03-600A the stability of the instrument and the repeatability of the method was tested

7.3. Data processing

In addition to the concentration of eU (^{226}Ra) determined by gamma spectrometer, the uranium concentration in the <2 mm fraction of soil samples taken at the bottom of 28 holes was determined by X-ray fluorescence. The analyses were made at the Laboratory of the Geological Survey of Estonia. The results show a positive correlation between uranium and ^{226}Ra in the deposits. However, the concentrations of uranium calculated from ^{226}Ra in some samples were up to twice those obtained from chemical analyses (Figure 13). This relation was also confirmed by analyses carried out at the Becquerel Laboratory, where the samples were analysed by neutron-activation (Table 5).

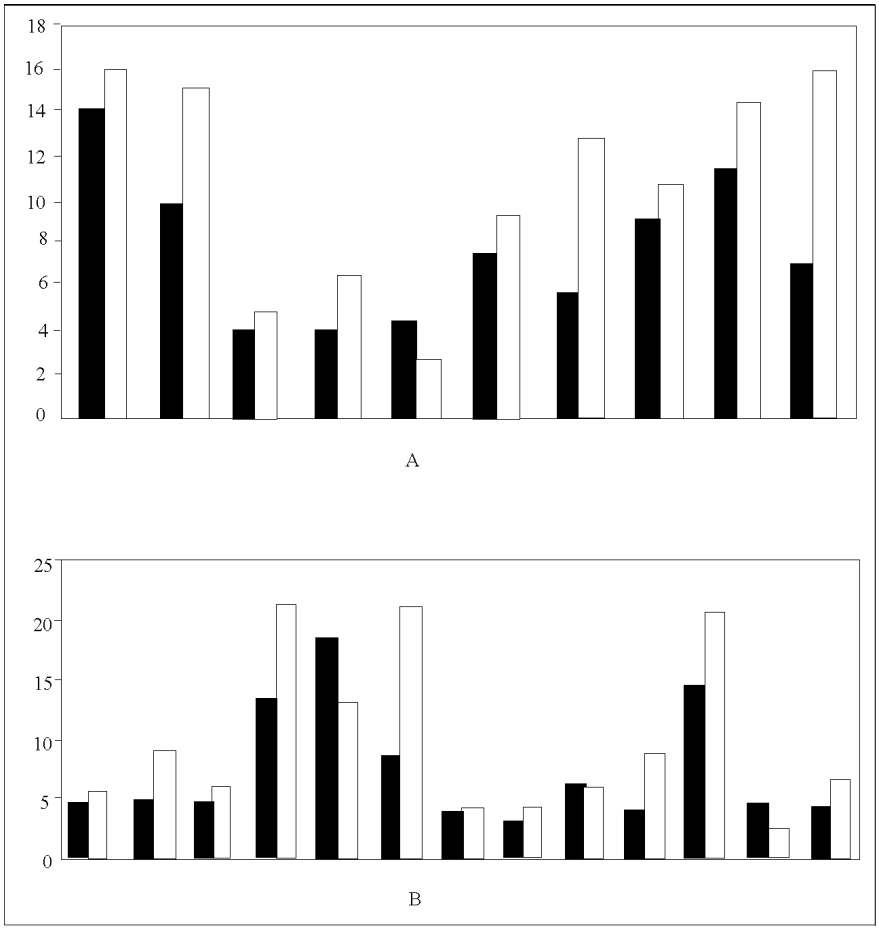


Figure 13. Comparation of U concentrations in soil samples determined by X-ray method (dark) and eU calculated from gamma spectrometry in the same hole as the soil sample was collected from. A – sands and silts. B – North Estonian tills.

Table 5

Uranium determined at Becquerel Laboratory (Canada) by BQ-NAA-1 method and concentration of eU (^{226}Ra) measured by gamma spectrometer in the field

Observation point	**Soil type**	**Concentration of U (ppm) by BQ-NAA-1 method**	**Concentration of eU[1] (ppm) (by gamma spectrometer)**
02Rn-009	Klint sediment	10.0	17.6
02Rn-026	Klint sediment	5.3	5.1
02Rn-053	Uranium enhanced north Estonian till	5.9	5.7
02Rn-059	Klint sediment	5.1	6.6
02Rn-070	Uranium enhanced north Estonian Till	5.0	5.9
02Rn-083	Silt	2.4	2.8
02Rn-085	South Estonian till	1.9	2.5
02Rn-092	Clay	2.6	3.4
02Rn-096	North Estonian till	2.1	2.1
02Rn-137	North Estonian till	2.4	2.1
02Rn-141	North Estonian till	1.7	1.8
02Rn-162	Clay	3.0	3.1
02Rn-215	South Estonian till	2.1	2.5

[1]eU, equivalent uranium concentration as calculated from analyses of ^{226}Ra, assuming equilibrium within the uranium-238 series.

The results presented in Table 5 show a fairly good agreement between the uranium concentrations obtained by chemical analyses of soil samples and those from gamma spectrometry. Differences occur because the gamma spectrometer measures the activity concentration of ^{226}Ra and the radioactive equilibrium between ^{238}U and ^{226}Ra in the soil out of equilibrium due to different chemical properties of uranium and radium, which lead to different abilities for leaching and precipitation. Moreover, the uranium content of soil fragments varies and the rather small sample may not be fully representative of the soil, whereas the gamma spectrometric determination of the radium activity represents approximately 500 kg of the soil surrounding the detector. Therefore, analyses of subsoil are unsuitable to determine the radon risk (Petersell et al., 2000).

The equilibrium between ^{238}U and ^{226}Ra in Estonian soils has been disturbed in favour of ^{226}Ra by weathering in soil development. Calculating the ^{222}Rn concentration in soil air from the uranium concentration can yield results as low as half of the actual concentrations. A similar phenomenon has been observed in Swedish soils. For example, specific investigations of gravel and sand from eskers show that the uranium concentration calculated from ^{226}Ra is 1.2 to 3.2 times higher than the total uranium concentration obtained by laboratory analyses of soil samples with larger differences noted for finer fractions (Ek and Ek, 1996).

Limits on the radon concentration in soil air have been established traditionally at a depth of 1 m. Therefore, it was necessary to extrapolate the concentrations of ^{222}Rn obtained at a depth of 0.8 m to 1 m. This extrapolation was done with a graph depicting the relationship between measurement depth, soil type and radon diffusion (Figure 14) (Clavensjö and Åkerblom, 1994).

Based on the activity concentration of ^{226}Ra determined in soil by in-situ gamma-spectrometry, the maximum activity concentration of ^{222}Rn in the soil air balanced with ^{226}Ra (the balance between the ^{222}Rn formed by decay of ^{226}Ra and emanating into soil air, and ^{222}Rn decaying in soil air), was calculated as follows:

$$C_{max} = A \cdot e \cdot ¡ \cdot (1 - p)\, p^{-1}$$ (Åkerblom, 1994),

Where:
C_{max} – maximum activity concentration of Rn (kBq/m^3)
A – activity concentration of ^{226}Ra (Bq/kg)
e – ^{222}Rn emanation factor
¡ – compact volume weight, for soils (kg/m^3)
p – porosity, (ratio pore volume/total volume)

The parameters used for porosity, compact volume weight and the emanation factor for different soil types are shown in Table 6. Determination of the emanation factor for the different soil types was based on the average ^{222}Rn by MARKUS-10 and ^{226}Ra activity concentrations by gamma spectrometer at each site.

The ^{222}Rn emanation factor has been calculated in two ways. The *Radon Risk Map of Estonian Soil* (Map Sheet 1.1) produced by EGK incorporated 68% (1 ¡) of the radon values obtained from combined measurements by MARKUS-10 and gamma spectrometry (outliers omitted). The *Preliminary Map of Radon Risk Areas in Estonia* produced at SGU incorporated all the combined measurements (Map Sheet 2). The results of these two calculations are shown in Table 6. For most soil types the difference is insignificant, <25%, but the emanation factor for tills in south Estonia in Map Sheet 2 is 50% higher. However, this does not affect significantly risk classification because the radon concentration measured by MARKUS-10 is higher than the calculated radon concentration at most sites in this area.

In addition, two methods were used to categorise the sampled soils. For the *Radon Risk Map of Estonian Soil* (Map Sheet 1.1) produced by EGK the soils were classified by soil properties (Tables 7 A and B, Chapter 9). The *Preliminary Map of Radon Risk Areas in Estonia* (Map Sheet 2) produced at SGU encompasses all combined measurements. In addition to classification according to soil types the soils were also classified with respect to uranium content and U/Th ratio (Tables 8 A and 8B, Chapter 9). Soils with an elevated uranium concentration are those with a U concentration greater than 4 ppm. All such soil was found in or near the Klint zone.

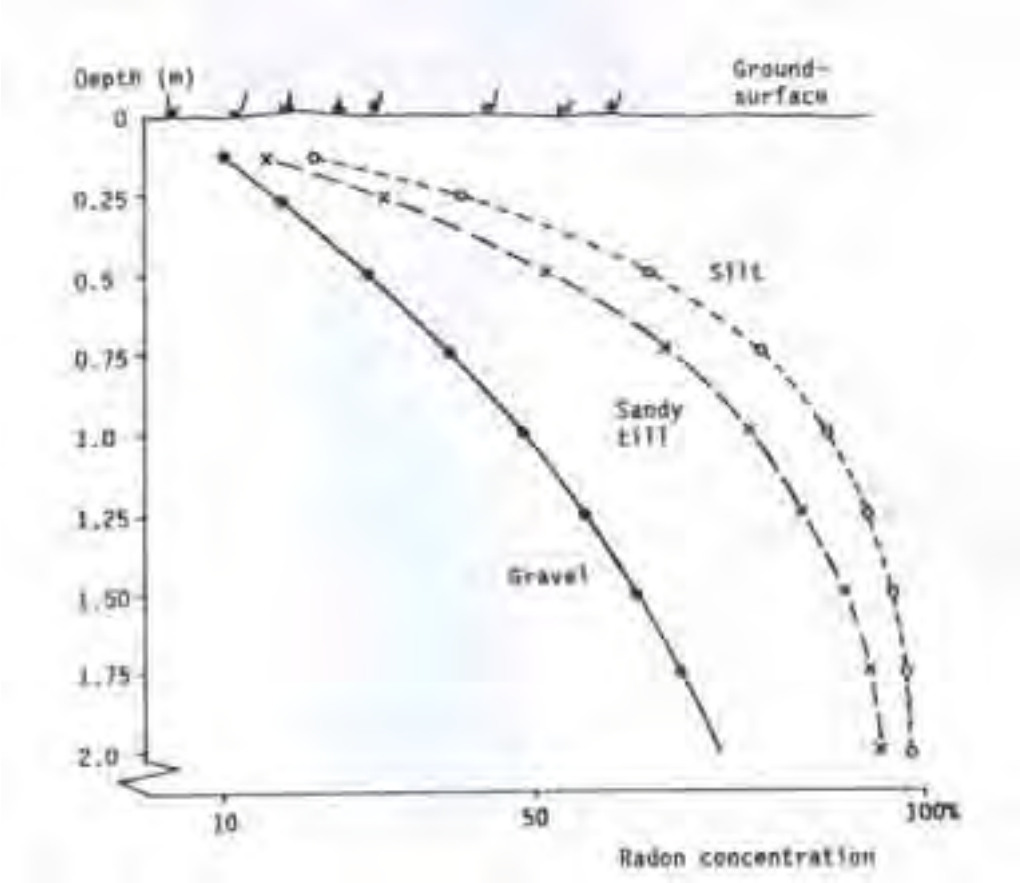


Figure 14. Theoretical effect of diffusion on radon concentration in soil air with depth and soil texture (Åkerblom et al., 1990).

Table 6

Porosity, compact volume weight and emanation factor for different soil types

Soil type	**Porosity, %**	**Compact volume weight, g/cm^3**	**Emanation factor**	
			For map sheets 1.1 and 1.3	**For map sheet 2**
N-Estonian till (mp)	32	2.70	0.20	0.24
S-Estonian till (ml)	38	2.65	0.30	0.46
Glacioaqueous deposits:				
Sand (fine gravel) (lgl)	35	2.66	0.25	0.20
Silt (lga)	40	2.63	0.34	0.29
Clay (lgs)	45	2.60	0.44	0.39
Glaciofluvial deposits (fgl)	30	2.70	0.19	0.23
Baltic Sea sand and silts (b)	35	2.60	0.25	0.22
Deposits of fore-Klint lowland and colluvium (kla)	40	2.66	0.30	0.28
Waste from Maardu phosphorite deposits (t)	30	2.70	0.20	0.20

8. RADON RISK MAP SET OF ESTONIA

8.1. Description of Radon Risk Map Set of Estonia, scale 1:500,000;

1. Radon Risk Map Set of Estonian Soil *consists of nine Map Sheets. It was compiled in accordance with Estonian standard EVS 840:2003 (Radooniohutu..., 2003) and based on the following map sheets:*

1.1. Maximum Radon Concentration in Soil Air *(on this map are shown contoured areas of different radon concentration);*

1.2. *Radon (Rn) Concentration in Soil Air by Direct Measurement* (in depth 1 m);

1.3. *Radon Concentration in Soil Air calculated after eU (^{226}Ra)*;

1.4. *Uranium (^{226}Ra) Concentration in Soil*;

1.5. *Map of Factual Material* [Location of Observation Points, On the Map of Quaternary Sediments (Kajak, 1999)];

1.6. *Thorium (^{232}Th) Concentration in Soil*;

1.7 *Potassium (^{40}K) Concentration in Soil*;

1.8. *Natural Radiation of Soil*.

2. The *Preliminary Map of Radon Risk Areas in Estonia,* scale 1:500 000. This single-sheet map is an interpretation and compilation of the field measurements, geological observations and existing information. The Swedish method to compile radon risk maps was used for its production.

8.2. Map Sheets 1.1–1.8

Map Sheet 1.1. *Maximum Radon Concentration in Soil Air* displays the maximum radon concentrations in the soil air for different soil types as either obtained by measurements or calculated from the ^{226}Ra activity concentration (the maximum value from either method was used) in the observation points. These values have been computerized and by use of a kriging method borders between areas characterised by different radon in soil air concentrations have been drawn. On the map are shown areas of the following different radon classes: *Low radon ground* (<10 kBq/m^3), *normal radon ground* (10–50 kBq/m^3), *high radon ground* (50–150 kBq/m^3), *high radon ground* (150–250) and *very high radon ground* (>250 kBq/m^3). The extension of these areas is based on a combination of kriging and interpretation of occurrence of soil types.

Map Sheet 1.2. *Radon (Rn) Concentration in Soil Air by Direct Measurement* shows the radon concentrations obtained at measurements of soil air by MARKUS-10.

Map Sheet 1.3. *Radon Concentration in Soil Air Calculated after eU (^{226}Ra)* shows the calculated radon concentrations based on gamma spectrometry.

Map Sheet 1.4. *Uranium (^{226}Ra) Concentration in Soil* shows the uranium (^{226}Ra) concentrations in the sampled observation points.

Map Sheet 1.6. *Thorium (^{232}Th) Concentration in Soil* shows the thorium (^{232}Th) concentrations.

Map Sheet 1.7. *Potassium (^{40}K) Concentration in Soil* shows the potassium (^{40}K) concentrations.

Map Sheet 1.5. *Map of Factual Material* shows the location of Observation Points, on the Map of Quaternary Sediments (Kajak, 1999)].

Map Sheet 1.8. *Natural Radiation of Soil* shows for each observation point the calculated Estonian index value for radioactivity of building materials **C** for the soil at the point as calculated from the activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K.

On the Map Sheets 1.1, 1.2, 1.3, 1.4, 1.6 and 1.7 are the following genetic-lithologic types distinguished: South Estonian till (ml), North Estonian till (mp), glacioaqueous clay (lgs), silt (lga) and sand (lgl), glacio-fluvial gravel (fgl), Baltic Sea (Holocene) marine deposits (b) and technogenic (waste from the Maardu phosphorite quarry) (t). In addition, the fore-Klint marine deposits are often mixed with colluvium from the Klint (kla). The colour of the circle on the map identifies the soil type at each site and its diameter depicts the elemental concentration. On Map Sheets 1.2, 1.3, 1.4, 1.6 and 1.7 the dispersion of radon, uranium, thorium and potassium in the soils is characterised by frequency plots.

The activity concentration of radon in soil air in a soil layer is controlled by five main factors:

- activity concentration of ^{226}Ra in the soil, the degree of soil weathering, and the amount of ^{222}Rn emanating into soil air;
- soil porosity;
- soil permeability, diffusion and aeration (Chapters 2, 7 and 9);
- water content;
- dry density;
- and rarely, the activity concentration of ^{226}Ra in deeper beds and the amount of ^{222}Rn transported to the upper soil layers.

On the map exhibiting the *Maximum radon concentration in soil air* (Map Sheet 1.1) are displayed the maximum ^{222}Rn activity concentrations, either obtained by direct measurements of ^{222}Rn concentration in soil air or calculated from activity concentration of ^{226}Ra measured in each observation point. Direct measurement values were used when they exceeded the calculated values.

In accordance with Estonian standards, Map Sheet 1.1 distinguishes four levels of radon risk: low, normal, high, and very high radon risk ground (Radooniohutu**…,** 2003**).** The classification of these areas is based on the activity concentration of ^{222}Rn in the soil air.

The radon concentration in soil air for *Low radon ground* does not exceed 10 kBq/m³. Research suggests that it is improbable that soil radon will result in indoor radon concentrations greater than 200 Bq/m³ in such conditions.

Areas where the radon concentration in soil air is 10–50 kBq/m³ are considered *normal radon ground.* Radon originating from the soil sometimes may result in high indoor radon in these areas.

Areas where the concentration of radon in soil air exceeds 50 kBq/m³ are considered *high radon ground.* The concentration of indoor radon frequently exceeds the permissible limit if special radon protection measures are not applied during construction of buildings. Areas of *very high radon ground*, with radon concentrations exceeding 250 kBq/m³, can occur within high radon areas. Radon protection measures need to be taken against indoor radon where the concentration of radon in soil air exceeds the limit established for unrestricted construction (50 kBq/m³).

Elevated uranium concentration (>20 ppm) is also very common in areas classified as *very high radon ground.* 20 ppm U is the recommended upper concentration of uranium in the soil or bedrock for residential sites in Estonia (Pinnases..., 2004). However, this recommendation came into force before our survey. In our view this recommended value is too stringent considering that the uranium concentration in parts of Estonia is greater than 20 ppm and no exposure risk of any sort has been demonstrated – neither as a result of soil ingestion nor through ingestion of plants and vegetables grown in the soil.

Different methods were combined to contour areas of radon risk on the map *of Radon Concentration in Estonian Soil* (Scale 1:500 000) (Map Sheet 1.1.). The colour and size of the circle in each site depict the radon concentration, and differently coloured areas the approximate range of radon concentration. The contours were produced by Surfer and MapInfo, the boundaries of the fields between sites have been drawn by interpolating the concentrations. Because of the sparse sampling density and high variation in radon concentration, the boundaries of contoured area are preliminary.

Compared with Sweden, little is known of the radon concentration in Estonian soils. Research in Sweden (Åkerblom, 1994) shows that emanation of radon into air is hampered in soils with low permeability, e.g. soils rich in clay. Such soils are normally considered *low or normal radon ground*, although the radon concentration in soil air may range from 50–100 kBq/m³. However, if the soil contains fragments of uranium-rich Alum shale (similar to Dictyonema shale), the ground is classified as *high radon ground*.

Glaciofluvial deposits in Sweden consist to large extent of granitoidal material often enriched in uranium and radon. The favourable aeration properties of these deposits create enhanced possibilities for pressure driven transport of soil air, e.g. the sucking of soil air from the ground into a building caused by the lower air pressure indoors than in the soil layer. Our survey suggests that glaciofluvial deposits in Estonia are generally normal radon areas, as these deposits consist mostly of carbonate material and the measured radon contents are generally low to normal.

Map Sheets 1.2, 1.3, 1.4, 1.6 and 1.7 show the distribution of radon, uranium, thorium and potassium in different soil types. Results from gamma spectrometry in observation holes are also shown in Tables 9 A, B and C. Elements show concentrations of ^{222}Rn, eU (^{226}Ra), ^{232}Th that approach a log-normal distribution.

Potassium shows a normal (arithmetic) distribution (Table 9C). Distribution diagrams of these elements have been shown on the map sheets.

Natural Radiation of Soil (Map Sheet 1.8.) was compiled according to the requirements established by regulation no. 55 of the Minister of the Environment, 24 August 1998 (Looduskiirgusest…, 1998 and (Pinnases…, 2004). The principal unit on the map is the maximum permissible index value **C** of natural radioactive elements in soils or rocks used for construction materials in Estonia (Chapter 3.2).

8.3. Map Sheet 2: The Preliminary Map of Radon Risk Areas in Estonia

The *Preliminary Map of Radon Risk Areas in Estonia* (Map Sheet 2) is a prognostic map to show areas were the radon concentration in the soil air is or may be expected to exceed 50 kBq/m^3 or be less than 10 kBq/m^3. Constructions where the radon concentration in the soil air exceeds 50 kBq/m^3 requires preventive measures against radon. Constructions where the radon concentration is less than 10 kBq/m^3 usually requires no remedial action.

The *Preliminary Map of Radon Risk Areas in Estonia* may also be used to predict where excessive indoor radon (e.g. >200 Bq/m^3) may exist in existing dwellings and workplaces and where such problems do not exist or are uncommon.

Regions on the map are classified as follows:

- *high radon risk areas*, where conditions prevail for the soil air radon concentration to be >50 kBq/m^3,
- *areas with local occurences of high radon ground*, where the concentration in soil air is often >50 kBq/m^3,
- *normal radon risk areas*, where the radon concentration in soil air is normally 10–50 kBq/m^3. There may be isolated areas where the radon concentration in the soil air is higher than 50 kBq/m^3 or lower than 10 kBq/m^3.
- *low radon risk areas*, where the radon concentration is <10 kBq/m^3. There may be isolated occurrences where the radon concentration exceeds 10 kBq/m^3.

The map also distinguishes *karst areas* and *areas with clay*.

The map is based on existing knowledge of the bedrock and Quaternary geology, radon concentrations in the soil air or gamma spectrometric measurements of radium-226, field observations during this survey, and airborne gamma ray spectrometric surveys. In addition, the map incorporates interpretation of the results from indoor radon measurements conducted by the Estonian Radiation Protection Centre in northern Estonia. These provide information on the distribution of radon in existing dwellings and point out areas where radon problems occur and areas with few or no problems.

It should be noted that the extent and position of the boundaries on this map is based on limited measurements of radon in soil air. Therefore, the map should be considered preliminary and will require revision as more information becomes available.

Radon risk maps are used globally to assess the risk of indoor radon. Most of these maps have been produced according to methods by Åkerblom (Åkerblom 1980, 1981, 1986 and 1998). The *Preliminary Map of Radon Risk Areas* in Estonia has also been compiled and produced according to this system.

The main factors on this map to classify the radon risk are the radon concentration measured in soil air and the transport potential for soil air based on soil permeability.

Karst regions are also shown on the *Preliminary Map of Radon Risk Areas*. Karst areas are potential radon risk areas throughout the world. Buildings constructed on karst formations often have elevated indoor radon. Air from karst cavities, fractures and caves is pushed into buildings through fractures in the rock. The driving force for the air transport is the pressure differential at low-pressure weather when expanding air migrates out of the cavities (during high-pressure weather the air is forced into the cavities). The radon concentration in the cavities normally is not greater than 1000–10,000 Bq/m^3, but this adequate to elevate indoor radon concentrations given sufficient volume. A house with an indoor air volume of 500 m^3 and a ventilation rate of 0.3 air changes per hour would exhibit a radon concentration of 200 Bq/m^3 if 3 m^3 per hour of air with radon activity concentration of 10, 000 Bq/m^3 leak into the house from the cavities.

8.3.1. Methods for compiling Map Sheet 2, the Preliminary Map of Radon Risk Areas in Estonia

The *Preliminary Map of Radon Risk Areas in Estonia* has been compiled at the Geological Survey of Sweden using MapInfo program 7.0. A map of Estonian Quaternary deposits (1:400 000 scale) was transferred from MicroStation to MapInfo for this project. The map was produced for printing at 1:400 000 scale.

Results of field measurements of radon in soil air, and concentrations of uranium, thorium and potassium in soils were transferred to MapInfo. ERPC supplied the values of radon measurements in buildings, which also were included into the MapInfo project. Other material used to compile the map was the soil information gathered during fieldwork and soil and bedrock data from available geological maps and reports.

Radon risks areas could be classified with the combined data. The areas were then digitized in MapInfo.

8.3.2. Classification of areas used for Map Sheet 2

The following classification was used to distinguish risk for the *Preliminary Map of Radon Risk Areas in Estonia* (Map Sheet 2):

Low radon risk area. Mainly sandy and silty soils with low radioactivity. High radon levels in houses are rare. These areas consist largely of postglacial marine sediments. The radon concentration in the soil is generally <10 kBq/m^3.

Normal radon risk area. Soils with normal radioactivity. Small areas with low and high radon ground can occur. The radon concentrations in the soils are generally between 10 and 50 kBq/m^3. All soil types are represented in this risk class.

Areas with local occurrences of high radon ground. Areas dominated by till and / or glaciofluvial and glaciolacustrine sediments with locally elevated radioactivity. Areas where some building may have high radon levels. Most of these areas are *normal radon risk areas* but results from measurements show that high radon ground (>50 kBq/m^3) occurs within the areas. Further investigations are needed to delimit and identify areas with high radon ground.

High radon risk area. Areas where uranium-rich Dictyonema shale, Obolus sandstone and phosphorite occur in soils and outcrops. High radon levels in buildings are common. The radon concentration in soil is often >50 kBq/m^3. This area is restricted to a rather narrow zone along the Klint area from Muraste to Narva, generally less than 10 km wide, but the zone stretches >20 km south of Kunda. High radon concentrations occur in all soil types in these areas. Indoor radon levels also indicated areas with high radon risks.

Karst. Karst areas are known as potential radon prone areas. If a building is situated on a karst cavity and / or a fracture radon gas may migrate into the building by a pressure driven airflow when the atmospheric pressure is low. Karst can also be found beyond marked areas. Information on karst areas has been collected from many reports and maps but some karstic areas are still unidentified. See also 6.2.

Bedrock, mainly limestone, with little or no soil layer. Often alvar land. Normally low radon risk area. Karst may occur within the area. Most of these areas are found in north-western Estonia and south of the Klint.

Clay. Areas with clayey sediments are generally classified as normal radon ground despite that their radon concentration is frequently greater than 50 kBq/m^3. The low permeability of clay inhibits radon migration into buildings. The classification is only valid as long as the clay is water saturated. Direct measurements of radon in clay are seldom possible. Therefore, determinations of the radon concentrations in many cases are based on gamma spectrometry. The geometric mean of 22 gamma spectrometric measurements is 48 kBq/m^3 (standard deviation 10 kBq/m^3), indicating that the uranium content is only moderately elevated in clays (Figure18).

Peat lands. Peat lands rarely serve as construction sites. The areas were identified from the Quarternary map of Estonian soils.

Escarpment in bedrock and *outcrop of Dictyonema shale.* Identified from the Quarternary map of Estonian soils. These areas also include outcrops and subcrops of Dictyonema shale, Obolus sandstone and phosphorites and soils derived from these rocks.

Soil types on the Quaternary map were identified based on several factors and parameters, e.g. granulometric composition, age, lithology and underlying bedrock. From the perspective of radon potential and risk classification, this distribution is crude. Eight natural soil types were distinguished in this project. This entails an additional limit to distinguishing risk areas. The granulometric composition of the postglacial marine sediments varies between silts and gravel and the age embraces the entire postglacial period. The

Quaternary map was used to distinguish different classes of radon risks of the marine sediments. Most marine sediments are classified as low radon risk but in many places sediments from the Ancylus Lake are classified as normal radon risk areas because their radon concentration exceeded 10 kBq/m^3.

The tills are categorised as north Estonian till and south Estonian till. These categories are based principally on the underlying bedrock, i.e. Palaeozoic rocks for north Estonian till and Devonian bedrock for south Estonian till. No granulometric or other lithologic differentiation was incorporated, although field observations were made. Both categories show large granulometric and lithologic variation. Future research needs to address these variations, as they are important factors for radon risk. Some clayey tills in southern Estonia have relatively high radon and radium concentration but their compactness limits the transport of soil air and exhalation of radon from the ground surface. These tills are therefore designated as *normal radon risk areas*. Areas with gravelly tills or moraines with both till and sorted sediments, such as in several of the marginal zones, with similar radon and uranium content are classified *high radon risk areas*.

Areas classified as *local occurrences of high radon ground* are mostly located in areas with south Estonian till. Many of the tills, e.g. in the Viljandi area, show radon levels >50 kBq/m^3. Recent indoor radon measurements in Viljandi area have confirmed this area as a high radon risk area (in 18 houses from 42 the indoor radon exceeds 200 Bq/m^3.

On the islands of Saaremaa and Hiiumaa the three distinguished tills are classified as *normal radon risk areas*. One of the tills, a clayey water-lain till, has a radon concentration 50–60 kBq/m^3 at three sites on Saaremaa. Because the clay content of the till is very high (mean of 32%), the till is classified as part of the normal risk area.

Drumlins and related features are widely distributed in Estonia numbering ca 1000. The most well-known drumlin field is the Saadjärv drumlin field in the Pandivere upland. Many drumlins contain older deposits, e.g. melt water sand and gravel, varved clays and different aged till beds. So-called stratified drumlins with a thin till layer covering melt water deposits are common. Drumlins in north Estonia consist of a compact massive grey till. South Estonian drumlins feature tills with fissile structures and thin dark intercalations, boulder pavements, stratification and involutions into underlying layers (Rõuk, 1989). These structures may act as pathways for radon diffusion and exhalation. Fissile structures may be responsible for the difference between measured and calculated radon in south Estonian tills.

The soil cover in south Estonia tends to be very thick; Devonian bedrock is exposed only along river valleys. The soils often consist of several older layers. Hilly moraines in e.g. Otepää Heights and Haanja Heights contain both tills of different ages and glaciofluvial and glaciolacustrine sediments. The radium and radon concentration in the different soil types and layers can be expected to depend on structure and the other soil parameters. Several areas in south Estonia have been classified as *areas with local occurrences of high radon ground* on the basis of results of measurements and local geology.

8.3.3. Comparison between Map Sheet 1, Radon-222 Risk Map of Estonian Soil and Map Sheet 2, Preliminary Map of Radon Risk Areas

In the map *Maximum Radon Concentration in Soil Air*, Map Sheet 1.1, five classes of radon risks are distinguished and areas are contoured with a kriging method. The classification is based on measured or calculated radon in the soil. In the *Preliminary Map of Radon Risk Areas*, Map Sheet 2, areas have been distinguished on a geologic basis and other available information has also been incorporated.

Both maps are dominated by normal radon risk areas/normal radon ground. Low radon risk areas are more frequent on the *Preliminary Map of Radon Risk Areas*, Map Sheet 2, than on the map *Maximum Radon Concentration in Soil Air*, Map Sheet 1.1. High radon risk areas/high radon ground are designated over large areas mostly in the southern Estonia on both maps but the total high radon risk area is larger in Map 1.1. The areas classified as high radon risk areas/high radon ground are not always the same on both Map Sheets. High risk areas/high radon ground areas are designated along the Klint on both maps. In the Klint area three radon classes are marked in Map 1.1, whereas the whole Klint zone from Muraste to Narva is classified as a high radon risk area on Map 2. On Map 1.1, two areas have been deemed high radon ground (150–250 kBq/m^3) each one based on one single observation point in the south of the country.

Clay areas on Map 2 are marked specially and classified as normal radon risk area*s* even though the measured or calculated radon concentration is above 50 kBq/m^3 at some sites (see 6.3.2. and Figure 19). On Map 1.1 the clays are classified as high radon ground at all but one site. Areas with karst or exposed bedrock are not marked on Map 1.1.

9. RADON IN SOIL

9.1. Distribution of radon in soil air

The activity concentrations of radon in soil air of different soil types in Estonia vary greatly. Tables 7A and B and 8A and B summarise the radon activity concentrations measured by MARKUS-10 and those calculated from ^{226}Ra concentrations obtained from gamma spectrometric measurements. A full account of the field measurements is given in Appendix. Tables 7A and B show the results and partition in different soil types used by EGK for Map Sheets 1.1. Maximum Radon Concentration in Soil; 1.2. Radon Concentrations in Soil Air determined by direct measurements (at a depth of 1 m) and 1.3. Radon Concentration in Soil Air calculated from the ^{226}Ra concentration, whereas Tables 8A and B show the results and partition used by SGU/SSI for Map Sheet 2 Preliminary Map of Radon Risk Areas in Estonia. Tables 7A and B and 8A and B differ in that soils are distinguished according to type in 7A and B. The classification in 8A and B also considers whether U/Th is >1/3 and the uranium concentration is enhanced, indicating the presence of fragments of Dictyonema shale or phosphorites. Soils that fill this criterion are shown separately. In addition, the emanation factor used by EGK was used to calculate the radon activity concentration in Table 7B, whereas the emanation factor used by SGU/SSI was used in Table 8B.

Table 7A

Radon in soil air. Activity Concentration of ^{222}Rn. Results obtained by MARKUS-10.
Major soil types of Quaternary deposits in Estonia. Results by EGK.

Soil type	No of obs	Min kBq/m^3	Max kBq/m^3	Mean$_a$ kBq/m^3	Std dev$_a$ kBq/m^3	Mean$_g$ kBq/m^3	Std dev$_g$ kBq/m^3	Regu-larity
Baltic Sea sand, silt, gravel (b)	48	1	50	13.2	11.5	8.9	2.65	L
Glacioaqueous deposits:								
Sand, gravel (lgl)	67	2	108	19.5	18.8	13.3	2.45	L
Silt (lga)	40	2	520	50.3	82.2	26.7	2.88	L
Clay (lgs)	11	13	220	64.0	59.8	47.1	2.23	N
Glaciofluvial deposits (fgl)	51	2	99	24.6	21.0	17.4	2.41	L
Till:								
North-Estonian till (mp)	130	1	452	47.5	60.4	31.2	2.46	L
South-Estonian till (ml)	113	6	200	53.0	38.5	41.0	2.13	L
Deposits of fore-Klint lowland and colluvium (kla)*	42	14	2112	157	319	89.0	2.60	L
Tailings of Maardu phosphorite (t)	5	25	34	29.6	4.2	29.4	1.15	N
Total	**507**	**1**	**2112**	**49.0**	**197**	**27.0**	**2.92**	**L**

Mean$_a$ – arithmetical mean concentration
Std dev$_a$ – arithmetical standard deviation
Mean$_g$ – geometrical mean concentration
Std dev$_g$ – geometrical standard deviation
N and L – normal and lognormal distribution
* Glaciolacustrine, partly Ancylus Lake deposits and deposits of the Klint slopes (gravel, sand, silt; colluvium).

Table 7B

Radon in soil air. Activity concentration of ^{222}Rn calculated from ^{226}Ra measured by gamma spectrometer. Major soil types of Quaternary deposits in Estonia. Results by EGK.

Soil type	No of obs	Min kBq/m^3	Max kBq/m^3	Mean$_a$ kBq/m^3	Std dev$_a$ kBq/m^3	Mean$_g$ kBq/m^3	Std dev$_g$ kBq/m^3	Regu-larity
Baltic Sea sand, silt, gravel (b)	55	1	138	19.3	21.7	13.0	2.50	L
Glacioaqueous deposits:								
Sand, gravel (lgl)	71	1	219	27.9	30.4	21.2	2.08	L
Silt (lga)	47	9.6	235	44.6	40.3	36.1	1.81	L
Clay (lgs)	23	29	1802	130	365	61.7	2.15	L
Glaciofluvial deposits (fgl)	52	3.2	104	20.9	17.4	18.4	1.98	L
Till:								
North-Estonian till (mp)	145	1	524	44.0	61.9	29.5	2.26	L
South-Estonian till (ml)	125	17	69	35.9	10.6	34.5	1.34	L
Deposits of fore-Klint lowland and colluvium (kla)*	42	51	825	177	132	149	1.73	L
Tailings of Maardu phosphorite (t)	5	134	382	223	109	204	1.59	N
Total	**566**	**1**	**1802**	**50.6**	**99.2**	**30.8**	**2.47**	**L**

Mean$_a$ – arithmetical mean concentration
Std dev$_a$ – arithmetical standard deviation
Mean$_g$ – geometrical mean concentration
Std dev$_g$ – geometrical standard deviation
N and L – normal and lognormal distribution
* Glaciolacustrine, partly Ancylus Lake deposits and deposits of the Klint slopes (gravel, sand, silt; colluvium).

The arithmetical mean radon concentration obtained by direct measurement of radon in soil air is 49 kBq/m^3 (geometric mean 27 kBq/m^3), and 51 kBq/m^3 (EGK) and 54 kBq/m^3 (SGU/SSI) (geometric means 31 kBq/m^3 and 34 kBq/m^3, respectively) based on gamma spectrometry. Figure 15 depicts all radon measurements, measured by MARKUS-10 respectively calculated from gamma spectrometry of radium-226.

Samples collected in areas where the soil is clearly enriched with uranium averaged 127 kBq/m^3 in direct measurements and 160 kBq/m^3 based on gamma spectrometry (Figure 16). The arithmetic mean radon concentration in soil air collected from soils without enhanced uranium concentration was 32 kBq/m^3 and 33 kBq/m^3 respectively. Figure 17 depicts radon measurements of North Estonian tills.

Table 8A

Radon in soil air. Activity Concentration of ^{222}Rn. Results obtained by MARKUS-10.
Major soil types of Quaternary deposits in Estonia. Results by SGU/SSI.

Soil type	No of obs	Min kBq/m^3	Median kBq/m^3	Max kBq/m^3	>50 kBq/m^3 %	Mean$_a$ kBq/m^3	Std dev$_a$ kBq/m^3	Mean$_g$ kBq/m^3	Std dev$_g$ kBq/m^3
Baltic sea sediments (b)	43	1.1	10.0	50.0	2.3	11.3	9.9	7.7	2.6
Baltic sea sediments, enhanced U	5	10.1	29.0	48.0	0.0	27.7	14.9	24.1	1.8
Sand, gravel (lgl)	61	2.2	12.0	81.0	1.6	16.9	13.8	12.3	2.3
Sand, gravel, enhanced U	6	5.0	38.7	108	33.3	45.5	39.0	29.2	3.2
Silt (lga)	35	2.5	22.4	80.0	11.4	27.8	19.5	21.1	2.3
Silt, enhanced U	5	30.8	113	520	80.0	107	189	138	2.9
Clay (lgs)	10	13.0	48.2	125	50.0	48.4	31.5	40.3	1.9
Clay, enhanced U	1			220					
Glaciofluvial deposits (fgl)	47	20	17.4	78.0	4.3	21.2	16.5	15.7	2.3
Glaciofluvial deposits, enhanced U	4	36.0	60.5	99.0	50.0	63.9	29.9	58.6	1.6
North Estonian till (mp)	117	1.1	88.1	157	16.2	31.4	22.2	25.0	2.1
North Estonian till, enhanced U	22	34.1	28.0	452	86.4	125	110	94.7	2.1
South Estonian till (ml)	104	6.0	47.0	200	45.2	55.2	39.3	42.7	2.2
Deposits of fore-Klint low-land and colluvium (kla), all with enhanced U	42	15.0	99.0	2112	78.6	157	319	89.1	2.6
Tailings of Maardu phos-phorite, all with enhanced U	5	29.0	32.5	39.4	0.0	34.3	4.8	34.1	1.1
Total	**507**	**1.1**	**29.0**	**2112**	**27.0**	**49.0**	**107**	**27.0**	**2.9**

Mean$_a$ – arithmetical mean
Std dev$_a$ – standard deviation of arithmetical mean
>50 kBq/m^3 % – percentage above 50 kBq/m^3
Mean$_g$ – geometrical mean
Std dev$_g$ – standard deviation of geometrical mean
enhanced U – with enhanced uranium concentration

Table 8B

Radon in soil air. Activity concentration of ^{222}Rn calculated from ^{226}Ra measured by gamma spectrometer. Major soil types of Quaternary deposits in Estonia. Results by SGU/SSI.

Soil type	No of obs	Min kBq/m^3	Median kBq/m^3	Max kBq/m^3	>50 kBq/m^3 %	Mean$_a$ kBq/m^3	Std dev$_a$ kBq/m^3	Mean$_g$ kBq/m^3	Std dev$_g$ kBq/m^3
Baltic sea sediments (b)	48	0.8	10.2	28.0	0.0	11.4	6.8	9.0	2.2
Baltic sea sediments, enhanced U	7	28.0	55.2	121	57.1	54.2	33.1	47.3	1.7
Sand, gravel (lgl)	65	0.8	16.6	52.9	1.5	17.3	8.4	15.0	1.8
Sand, gravel, enhanced U	6	34.8	47.8	175	50.0	77.9	57.9	63.6	2
Silt (lga)	40	8.2	26.5	45.7	0.0	27.7	9.4	26.0	1.5
Silt, enhanced U	7	47.6	71.3	202	85.7	100	59.1	87.3	1.7
Clay (lgs)	22	26.7	49.5	66.3	50.0	48.5	9.8	47.5	1.2
Clay, enhanced U	1			1608					
Glaciofluvial deposits (fgl)	48	3.5	18.5	55.5	2.1	21.0	11.4	18.1	1.8
Glaciofluvial deposits, enhanced U	4	57.8	74.6	127	100	83.6	30.5	79.9	1.4
North Estonian till (mp)	124	1.1	28.6	90.3	12.1	31.4	15.2	27.6	1.8
North Estonian till, enhanced U	22	57.2	111.2	631	100	172	138	138	1.9
South Estonian till (ml)	125	25.4	52.5	106	54.4	55.2	16.3	53.0	1.3
Deposits of fore-Klint low-land and colluvium (kla), all with enhanced U	42	45.6	120.1	741	97.6	159	118	134	1.7
Tailings of Maardu phos-phorite, all with enhanced U	5	133	154.9	382	100.0	223	109	204	1.6
Total	**566**	**0.8**	**35.2**	**1608**	**32.2**	**54.3**	**92.4**	**33.8**	**2.6**

Mean$_a$ – arithmetical mean
Std dev$_a$ – standard deviation of arithmetical mean
>50 kBq/m^3 % – percentage above 50 kBq/m^3
Mean$_g$ – geometrical mean
Std dev$_g$ – standard deviation of geometrical mean
enhanced U – with enhanced uranium concentration

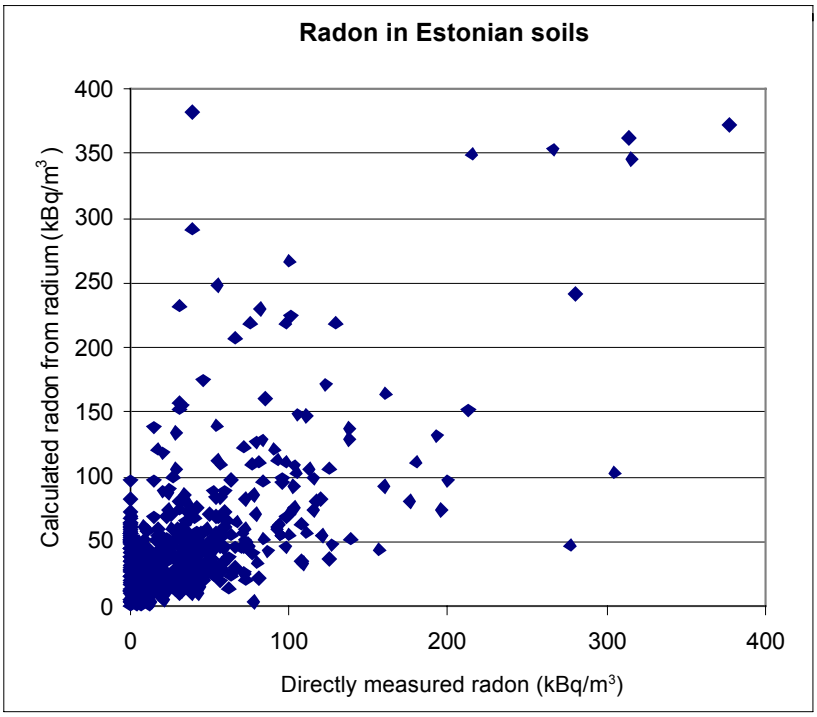


Figure 15. Radon concentrations in Estonian soil air from both MARKUS-10 and those calculated from gamma spectrometric measurements of ^{226}Ra. Results from all measurements.

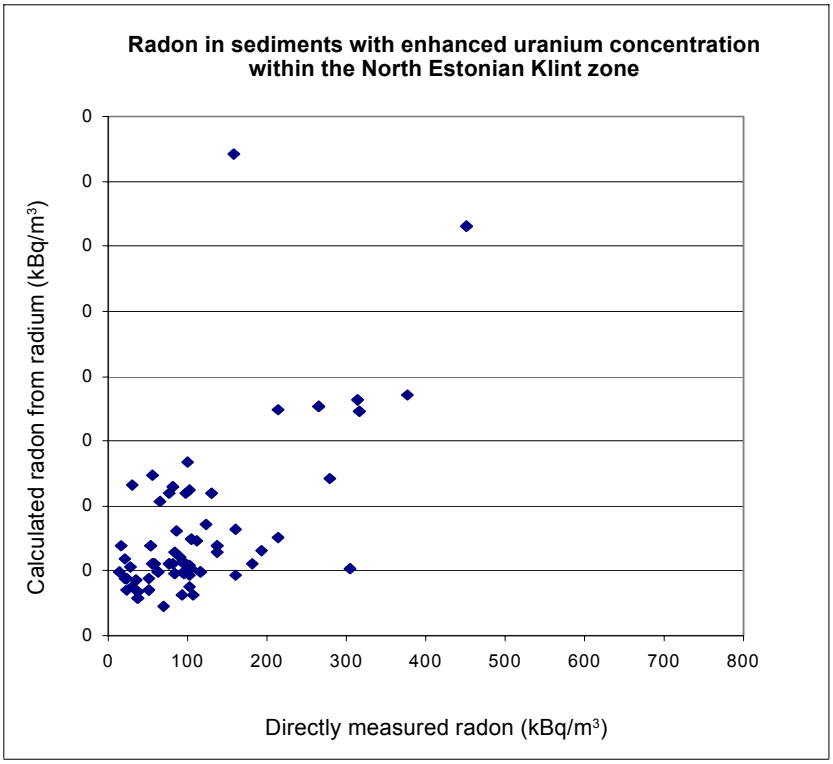


Figure 16. Soil air radon concentrations within the Klint zone for soils with enhanced uranium. Results from radon measurements and calculated from gamma spectrometry of radium-226.

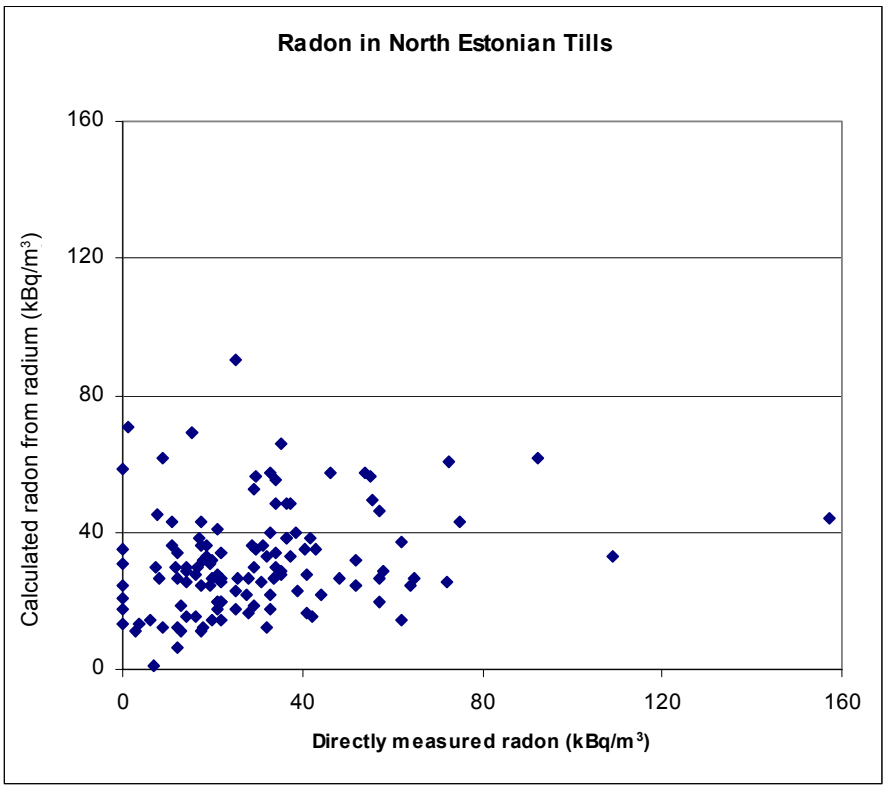


Figure 17. Soil air radon in North Estonian tills. Direct radon measurements and calculated from gamma spectrometry of ^{226}Ra (excluding tills with enhanced uranium concentration).

Radon concentrations as high as 2112 kBq/m^3 have been measured in this investigation. A concentration of 2500 kBq/m^3 was measured in a till rich in Dictyonema shale fragments in Sillamäe in 1996 (Pahapill, 2000).

Comparisons of measured or calculated radon concentrations to the permissible level for non-limited construction activity (<50 kBq/m^3) show that the level is exceeded by up to three times in 25.8% of the sites, by 3–5 times in 3.7% of the sites, and by more than 5 times in 3.4% of the sites.

Excluding soils with the highest radon concentrations in soil air, Klint sediments (kla) and sediments with enhanced uranium (Tables 8A and 8B and Figure 18), the radon level in soil air exceeds 50 kBq/m^3 in about 20% of the sites.

Of the soils with enhanced uranium and the Klint sediments, 92% have radon concentrations exceeding 50 kBq/m^3 and none less than 10 kBq/m^3 (Figure 18). None of the marine sediments and only two samples of sand, four samples of silt and three glaciofluvial sediments have a radon concentration exceeding 50 kBq/m^3, when the soils with enhanced uranium are excluded (Tables 8A and 8B and Appendix). Of clays 8 out of 21 samples have concentrations that are lower than 50 kBq/m^3 and 10 samples concentrations between 50 and 60 kBq/m^3 (Figure 19).

Till is the most common soil type of the Quaternary deposits in both northern and southern Estonia. Therefore, it is very important to determine the radon concentration of the soil air in tills, either by direct measurement or calculated from ^{226}Ra concentration. The largest number of measurements, 271 of 566, was made in till (Tables 7A, 7B, 8A and 8B).

The results of radon measurement with MARKUS-10 in soil air in northern Estonian tills are close to those calculated from ^{226}Ra. High radon concentrations were measured in the fore Klint lowland on the Klint, and south of the Klint edge. High concentrations were also detected in limestone fissures and in ancient buried valley areas a few kilometres south of the Klint.

Direct measurement of radon in soil air in southern Estonia approaches the values calculated from ^{226}Ra. However, the measured radon concentration was up to 1.5 times higher than the calculated values at many sites.

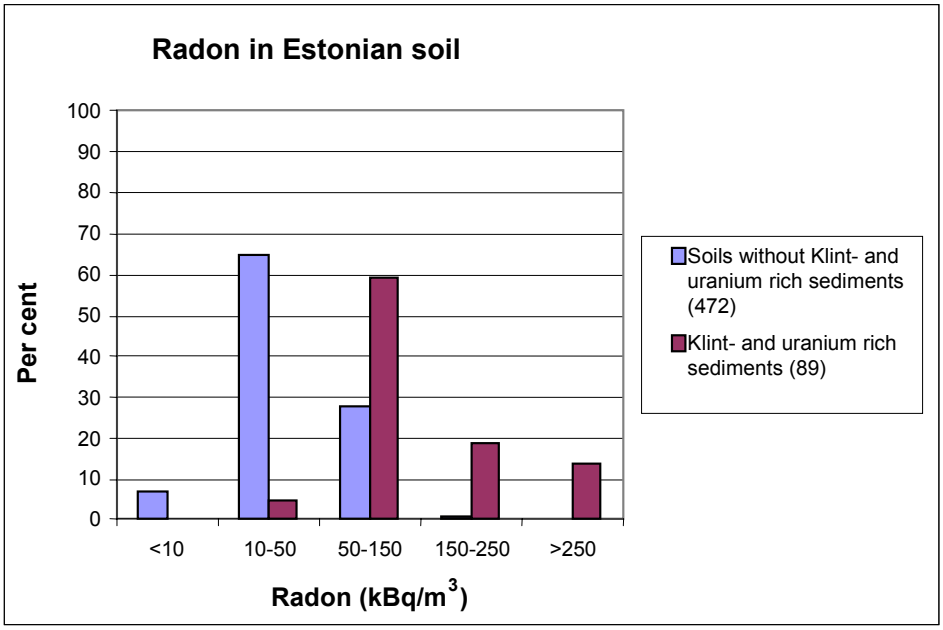


Figure 18. Soil air radon concentrations within the Klint zone and in soils without enhanced uranium grouped in radon risk classes. Observations from the Maardu tailings are excluded. (Note: measurements were concentrated in areas where high radon levels were expected.)

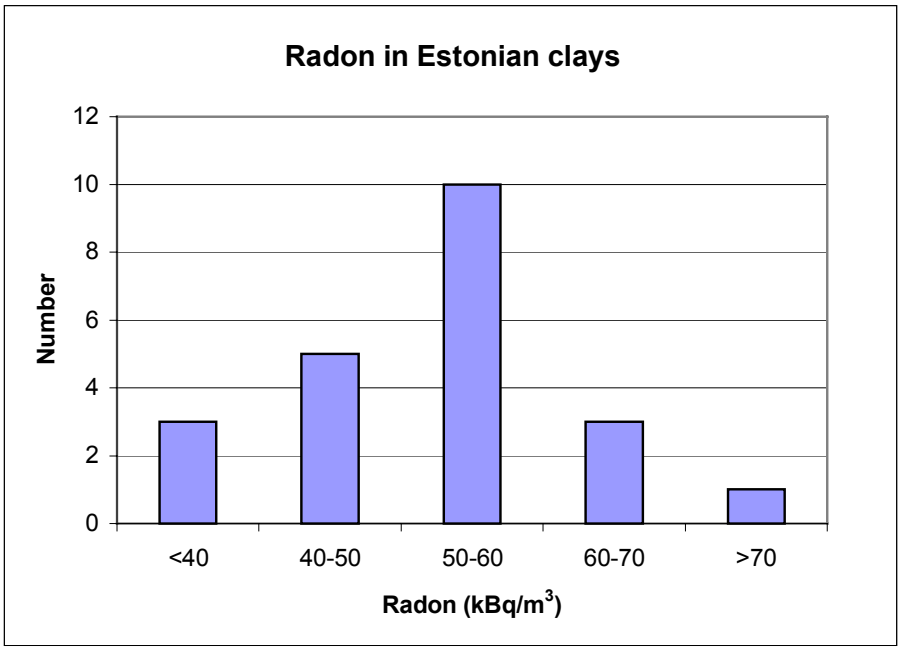


Figure 19. Soil air radon concentrations in clays grouped according to radon concentration. Results from 4 direct radon measurements and 18 calculated from gamma spectrometric measurements of radium-226.

The areas in the fore-Klint lowland and the Klint area, especially those where the soils contain visible fragments of Dictyonema shale and Obolus phosphorite are classified as *high radon ground* / *high radon risk areas.* The radon concentration in soil air exceeded 50 kBq/m^3 in all measured observation points in areas with these types of soils.

Sand and gravel deposits display a pattern similar to that of the North-Estonian tills. Clays, mainly varved clays, are distinguished by higher average concentrations of ^{222}Rn as calculated from ^{226}Ra. (However, direct measurement of radon is seldom possible in clays due to their low permeability and high water content). The activity radon concentration in clays was generally 40–60 kBq/m^3, and the calculated concentration exceeded 50 kBq/m^3 in 14 out of 22 observation points (Figure 19).

Swedish research suggests that the low permeability of clayey soils hinders the migration of soil air and areas with clays are generally not considered a high radon risk (compare Map Sheet 1.1 and Map Sheet 2) (Clavensjö and Åkerblom, 1994). The radon risk in clayey areas in Estonia requires further study.

High concentrations of radon in soil air occur in glaciofluvial deposits consisting primarily of granitoid material (e.g. observation point no. 172), and in soils with an admixture of Dictyonema shale and phosphorite (sites in the Klint zone).

Internationally areas with karst and tectonic fault zones are often classified as areas of high radon risk (Åkerblom, 1994). However, radon measured in such areas exceeded 50 kBq/m^3 in only a few cases, where the measurements were made in limestone fractures (see also Chapter 9.2). Deeper fissures are known to be pathways for radon migration if the fractures are dry and open. No radon migration can occur if these fractures are filled with water, unless transported by geogas.

The highest radon concentrations were identified in the north Estonian Klint zone. These high concentrations are located directly at outcrops of Dictyonema shale and phosphorite, between escarpments, in areas in front of the escarpments with a slight incline towards the sea, and also in a number of places on the limestone plateau. With few exceptions, measurements were not made on the steep slope of Klint escarpment (>10–30^o) where talus occurs. The plains between the Klint escarpments, where high or extremely high concentrations of radon occur, are up to 150–200 m wide (e.g. in Tiskre, North-Estonia), and the width of fore-Klint lowland may exceed 3–4 km (e.g. Merivälja–Lepiku area in north Estonia, Aseri in north-east Estonia, etc.). High radon concentrations are found also on the limestone plateau (on the top of the Klint) where the thin soil cover consists of till and sand and silt deposits. These areas extend several kilometres south of the Klint (Kahala, Palmse, Kunda, Lüganuse, etc). Elevated radon has been detected in homes south of Kunda up to 20 km south of the Klint indicating a widespread southward distribution of sediments enriched with Dictyonema shale and phosphorites or transport of radon through fractures in the limestone or karst.

In addition to the Klint zone, high radon occurrences have been measured in both eastern and southern Estonia, but are more common in southern Estonia where Devonian rocks underlie Pleistocene sediments. (Map Sheet 1.1 and 2). Outcrops of these Devonian rocks occur along some river valleys. Special attention should be paid to Luunja, Põlva, Tsooru, Taagepera, Viljandi, and some other regions in southern Estonia, where the radon concentration in soil air (as calculated from ^{226}Ra) can be twice the limit of 50 kBq/m^3, while direct measurements are up to four times higher (Figure 20 and Map Sheets 1.2, 1.3 and 2). The dominant soil type in these areas is a reddish-brown till, although grey and purplish-grey tills are also found. The thickness of these tills is variable (often greater than 10 m) and sorted sediments such as sand and gravel can be found between individual till layers. The granulometric composition of the tills varies. Although their clay content varies considerably, most tills are clay-rich. Such tills generally feature elevated ^{226}Ra concentrations. The very sandy tills or tills rich in clay and silt material can contain less than 10% coarse material, represented mainly by crystalline rocks. Carbonates in the coarse fraction exceed 60–70% in some tills. The granulometric variation of tills in southern Estonia might account for the differences between the measured radon concentration and the radon concentration calculated from ^{226}Ra at many sites.

Western Estonia and the West-Estonian Archipelago generally feature normal radon risk areas. These regions are characterised by tills rich in carbonates, sand and gravel. However, the radon concentration in soil air was greater than 50 kBq/m^3 in some observation points, e.g. near Rapla and on southern Saaremaa Island. The silty-clayey till on Saaremaa has an elevated uranium concentration. High radon concentrations are associated with areas of till, silt and clay. High radon concentrations also occur in the silts and the clay-rich tills within the Kärdla impact structure, where an especially high concentration of 277 kBq/m^3 was measured in soil air (observation point 797), while the value calculated from ^{226}Ra was only 48 kBq/m^3.

Areas are considered low radon ground / low radon risk areas when the radon concentration in soil air is less than 10 kBq/m^3 (Radooniohutu..., 2003). Such areas accounted for only 8.0% (total 45) of the sites. However, our measurements were directed to areas in which higher radon concentration could be expected. The sites with low concentrations were located typically in areas where gravel, sand and silt were deposited during the Limnea Sea or in soils consisting mainly of carbonates and quartz. Regions with low or close to low (<20 kBq/m^3) radon occur mainly in the coastal region of the West-Estonian Archipelago, Pärnu–Ikla region in south-western Estonia, and Jägala–Eisma in northern Estonia.

The measured radon concentration in soil air in the tailings of the Maardu phosphorite deposit was low, ranging from 29 to 39 kBq/m^3. The radon concentration calculated from ^{226}Ra was 134–382 kBq/m^3, almost 5–10 times higher. The results indicate that the tailings are very well aerated. However, if buildings are constructed on the tailings, sealing of the top layer of the soil would cause radon concentration in the ground below the buildings to reach 300 kBq/m^3. Therefore, the tailings are classified as *very high radon areas*. More investigations are recommended before this land is used for construction.

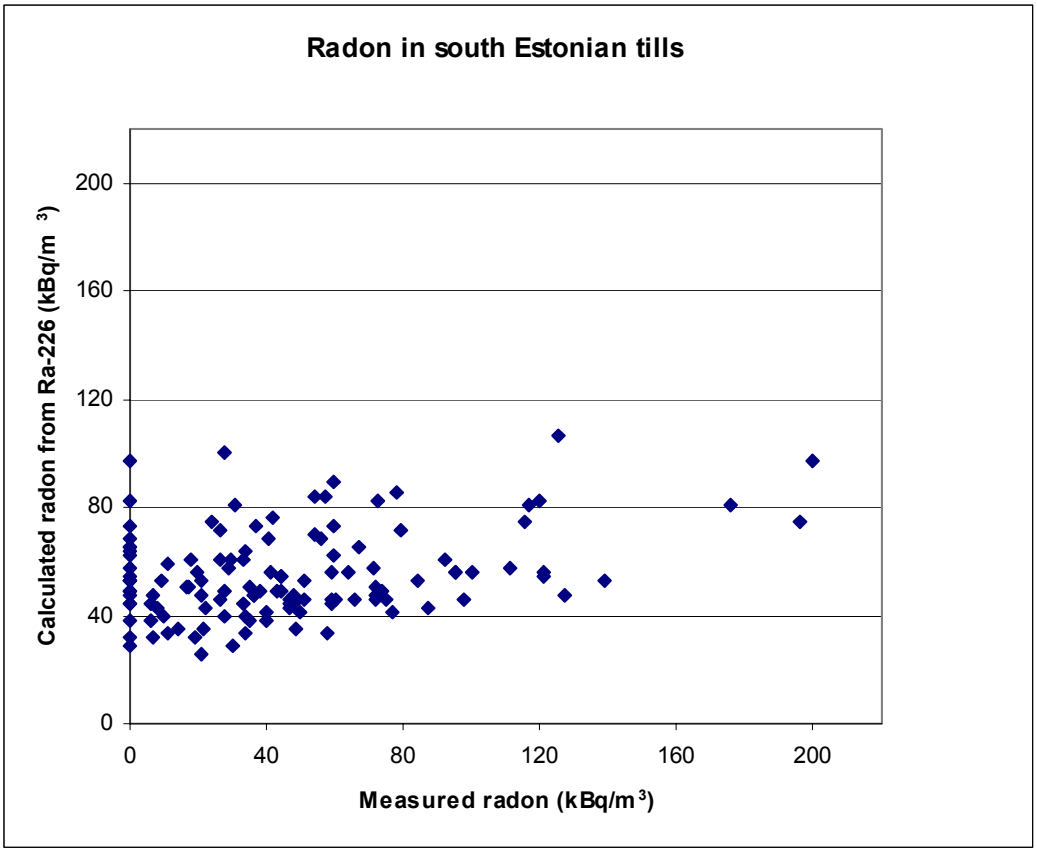


Figure 20. South Estonian tills. Results from radon measurements and calculated from gamma spectrometric measurements of radium-226. (In many observation points it was not possible to perform measurements with MARKUS-10.)

9.2. Radon concentration in soil air obtained by direct measurements and calculated from the ^{226}Ra concentration

The radon activity concentrations in soil air are shown on Map Sheet 1.2 and those calculated from the ^{226}Ra concentration are shown in Map Sheet 1.3. Map Sheet 1.1 depicts the maximum radon concentration obtained by these methods as a base to classify and demarcate areas of different radon ground. These Map Sheets are supplemented with diagrams characterising the frequency of radon concentrations. These diagrams, Figures 15, 16, 17, 18, 19, 20 and 22 and the data presented in Table 7A and 7B and 8A and 8B show a frequent discrepancy between the radon concentrations obtained by direct measurement and those calculated from the radium-226. Depending on the soil type, south of the Klint zone the radon concentration in soil air under normal soil aeration conditions is 79–87% of that with respect to the ^{226}Ra concentration in the soil (gravel and sand about 82%, NE-till 87%, SE-till 81%, silt 79% and clay 85%). The difference is much greater in soils rich in uranium and phosphorites, from 46% in sand to 127% in silt (the results from the measurement in Kärdla greatly affects the silt value, observation point 797). The reason for the lower radon concentrations obtained by direct measurement with MARKUS-10 is caused by diffusion of radon to the atmosphere above the surface and wind aeration. The magnitude of the deficiency depends on the moisture and the grain size of the soil – the coarser the soil, the greater the radon loss (Åkerblom, 1994).

Radon concentration in soil air in marine silt, sands and gravel deposits are on average lower than the values calculated from ^{226}Ra in the same sites. The radon measurements in the tailings of the abandoned Maardu phosphorite quarry are 5–10 times lower than those calculated from ^{226}Ra (Table 7A and B).

The radon concentration in soil air can vary considerably over time. The better the soil is aerated, the faster radon exhales from the ground surface, which is reflected by a reduced concentration. Figure 21 shows the variability of radon based on Swedish radon monitoring (Lindmark and Rosén, 1985). The ground was frozen in 1982 and the soil pores were filled with ice, which inhibited aeration and elevated radon concentrations. During the snowmelt, the radon concentration decreased abruptly to as low as a quarter of the probable maximum concentration (Åkerblom and Mellander, 1997). Similar processes likely affected our measurements.

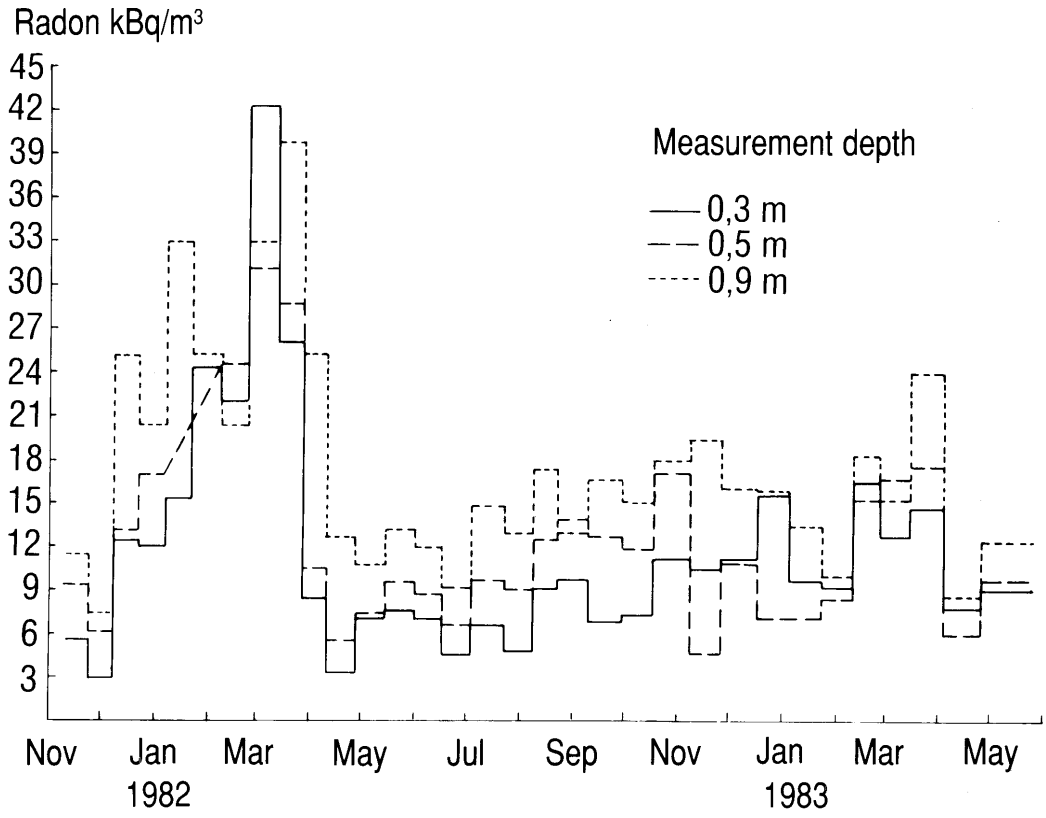


Figure 21. Soil air radon concentrations at different depths and seasons in coarse silt. Measurements using LR 115 alpha track film performed by the Swedish Geotechnical Institute (Lindmark and Rosén, 1985). During December – April 1981/1982 the ground was frozen and the pores filled with water which hindered transport of radon, this contrary to December – April 1982/1983 when the ground was frozen but the pores were open, which permitted transport of radon to the atmosphere above ground level. Outside these seasons the variation is due to effects of rain that lowers the radon exhalation, wind that ventilates the soil and of water that partly fills the pores causing the radon concentration to rise (Åkerblom and Mellander, 1997).

The 2002 field season was very dry. The normally moist clayey horizon above the underlying soils dried and allowed fissures to form, which enabled radon from deeper layers to migrate to the sampling points. In contrast, direct measurements made in 2003 only occasionally exceeded concentrations from^{226}Ra. (Map Sheet 1.2 and 1.3). Figure 22 shows the median radon concentration in south Estonian tills in 2002 and 2003 from direct radon measurements and calculated from radium-226.

The 2003 field season was very rainy. The topsoil layer was very wet, but the soil beneath was usually dry. The wet topsoil layer acted as an airtight cover, which hindered the exhalation of radon. This might account for the large discrepancy between direct and calculated measurements in the area of Tartu, Põlva, Tsooru, Taagepera, Viljandi, and other places in southern Estonia (Map Sheet 1.2 and 1.3 and Figure 20 and 22). We are unable to say whether the radon measurements reflect the maximum radon concentrations in the soil air at a depth of 80 cm or if additional transport of radon occurs from deeper soil layers.

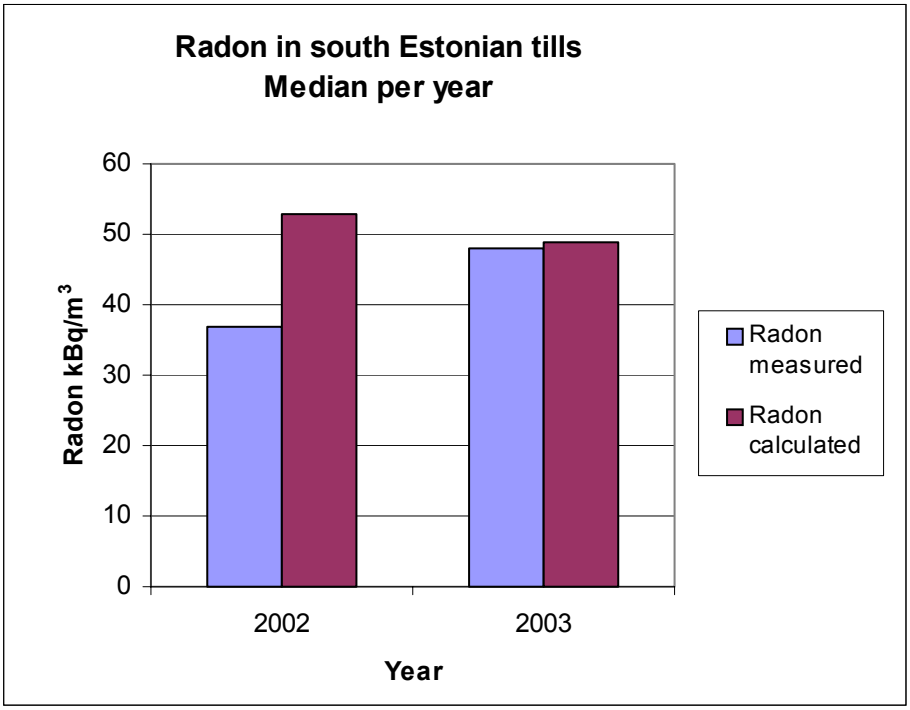


Figure 22. Radon concentration in South Estonian tills, median values per year. Results from radon measurements and calculated from gamma spectrometry of ^{226}Ra.

Also a a number of sites within till, silt, sand and gravel deposits in northern Estonia, measured radon concentrations were greater than those calculated from ^{226}Ra. The greatest difference was recorded on the fore-Klint lowland between Narva and Sillamäe, where the radon concentration in the soil air reached 2112 kBq/m^3 (observation point 059), whereas the calculated radon concentration was only 91 kBq/m^3 (Figure 17). Migration of radon occurs through fissures in carbonate rocks on alvars in some localities in the south of the Klint. For example, on an alvar to the north-east of Lake Kahala (observation point 254) the concentration of ^{222}Rn was 96 kBq/m^3 in a fissure in Lower-Ordovician limestone.

It should be mentioned that the buried valleys, eskers and drumlins we investigated normally constitute normal radon ground on the basis of directly measured concentrations or those calculated from ^{226}Ra. These low concentrations are results of the high content of carbonate rocks in these deposits. However, the radon concentration in these soil types exceeded 50 kBq/m^3 in some parts of Estonia (Map Sheet 1.1, 1.2, 1.3 and 2). These areas are designated as *Local occurrences of high radon ground* on the *Preliminary Map of Radon Risk Areas in Estonia* (Map Sheet 2).

10. NATURAL RADIONUCLIDES IN ESTONIAN SOILS, ACTIVITY CONCENTRATIONS

In this report natural radiation is defined as the radioactivity of all nuclides of natural origin in rocks, soils and water. This definition excludes radiation of cosmic origin (Realo and Viik, 1997). Natural radiation is caused by natural radioactive elements present in the Earth's crust. The most important elements are uranium (U), thorium (Th), their radioactive decay products and potassium (K).

In nature uranium occurs as ^{238}U (99.28%), ^{235}U (0.72%) and also ^{234}U (0.0054%) as decay product in the uranium-238 series, thorium as ^{232}Th (>99.9%) and as decay products in the uranium and thorium series (Chapter 2, Tables 1 and 2). The radioactive isotope ^{40}K constitutes 0.012% of all potassium. By decay in the series of uranium and thorium alpha, beta and gamma radiation is emitted (Table 1 and 2) and by decay of ^{40}K beta and gamma radiation.

The most intensive source of natural radiation in bedrock and soil is the alpha, beta and gamma radiation emitted by radium-226 and radium-228 and the daughter elements of these radium isotopes. The beta and gamma radiation emitted by the decay of ^{40}K is the second most important source. The concentrations of uranium (equivalent uranium, eU) calculated from the measured concentrations of ^{226}Ra, the concentration of thorium (Th) calculated from ^{232}Th and the concentration of potassium (K) calculated from ^{40}K for genetic soil types are presented in Table 9A, 9B and 9C. Measured activity concentrations are given in Bq/kg and the chemical concentrations in ppm (eU and Th) and percent (K). The distribution of these elements is shown in Map Sheets 1.4, 1.6 and 1.7.

10.1. Concentration of uranium as calculated from ^{226}Ra

The most important source of natural radiation in Estonia is uranium and its decay products. The uranium concentration in Estonian soils, as calculated from the gamma spectrometric measurements performed in this project, ranged from 0.1 to 106 ppm (the latter value was recorded in a dark clay, possibly a re-deposited weathered Dictyonema shale) (Map Sheet 1.4). For all soil types there exists a sample in which the uranium concentration exceeds 4–5 ppm (Tables 9A, 9B and 9C). However, higher uranium concentrations greater than 5 ppm were encountered only in soils at or near the Klint zone.

If a soil has a nearly, equal or higher uranium concentration (in ppm) than the thorium concentration, this is a clear indication that the soil contains fragments of Dictyonema shale or phosphorite. In contrast, thorium concentrations which are at least three times greater than the uranium concentration suggests that the soil is mainly made up of granite or other Precambrian rock fragments.

Thus, if those samples that clearly show an enrichment of ^{226}Ra and an abnormal proportion of ppm eU and ppm Th (normally 1/3) are excluded, no marine sediments (of totally 48 samples), no glaciofluvial sediments (of totally 48 samples), no silts (of totally 39 samples), no sand sediments (of totally 65 samples), and only two SE-tills, one clay and three NE-tills contained eU concentrations above 4 ppm. This indicates that the uranium concentration in Estonian soils is typically moderate or low. Elevated uranium concentration was restricted in general to the northern areas along the Klint zone. High radon or radium concentrations at isolated sites are indicative of locally enhanced radioactivity due to fragments and particles of Dictyonema shale, phosphorites or zircon minerals and perhaps weathered uranium-rich granites. These sites require additional research.

Tables 9 A, B and C. Concentrations of eU (ppm), Th (ppm) and K (%) in major soil types. Results obtained by gamma spectrometry. All sediments with enhanced uranium concentration originate from the Klint area.

Table 9A

Concentration of uranium (eU, ppm)

Soil type	No of obs	Min ppm	Median ppm	Max ppm	$Mean_a$ ppm	$Std\ dev_a$ ppm	$Mean_g$ ppm	$Std\ dev_g$ ppm
Baltic sea sediments (b)	48	0.1	0.8	2.1	0.9	0.5	0.7	2.2
Baltic sea sediments, enhanced U	7	2.1	4.2	9.3	4.2	2.5	3.6	1.7
Sand, gravel (lgl)	65	0.1	1.4	4.4	1.4	0.7	1.2	1.8
Sand, gravel, enhanced U	6	2.9	3.9	14.4	6.4	4.8	5.2	2
Silt (lga)	40	0.6	1.9	3.3	2.0	0.7	1.8	1.5
Silt, enhanced U	7	3.4	5.1	14.4	7.1	1.8	4.8	1.7
Clay (lgs)	22	1.8	3.3	4.4	3.2	0.6	3.1	1.2
Clay, enhanced U	1			106				
Glaciofluvial deposits (fgl)	48	0.2	1.0	3.1	1.2	0.6	1.0	1.8
Glaciofluvial deposits, enhanced U	4	3.3	4.2	7.2	4.7	1.7	4.5	1.4
North Estonian till (mp)	124	0.1	1.7	5.3	1.9	0.9	1.6	1.8
North Estonian till, enhanced U	22	3.4	6.6	37.3	10.2	8.2	8.2	1.9
South Estonian till (ml)	125	1.0	2.1	4.4	2.3	0.7	2.2	1.3
Deposits of fore-Klint low-land and colluvium (kla)	42	3.3	8.7	54	11.6	8.6	9.8	1.7
Spoils of Maardu deposits (t)	5	8.6	10.0	24.7	14.4	7.0	13.2	1.6
Total	**566**	**0.1**	**2.0**	**106**	**3.1**	**6.2**	**2.0**	**2.5**

$Mean_a$ = arithmetic mean, $Std\ dev_a$ – standard deviation of arithmetic mean, $Mean_g$ – geometric mean, $Std\ dev_g$ – standard deviation geometrical mean.

The geometric mean of uranium in Estonian soils is 2.0 ppm. The uranium concentration calculated from our in-situ determinations of ^{226}Ra at 1 m depth is almost 10% greater than the value obtained from earlier geochemical soil mapping (Petersell et al., 1997; 2000). The results suggest a lack of radioactive equilibrium between ^{238}U and ^{226}Ra due to uranium leaching from the soil while thorium-230 and radium-226 (nuclides in the uranium-238 decay series) remain longer in the upper part of the soil profile. Leaching of ^{238}U is reflected in the accumulation of ^{238}U in mires; the uranium concentration of uranium in peat ash often exceeds 8–10 ppm (Orru and Orru, 2003), whereas the gamma radiation level is less than 0.03 mSv/h. For example, the uranium concentration (x-ray fluorescence analysis) in peat ash from the flood plain of the Mustjõgi River is more than 50 ppm, whereas the γ-radiation level is 0.01–0.03 mSv/h and the eU concentration is 3 ppm (gamma spectrometry). The same phenomenon has been observed in the peat of Raudna and other bogs and the same uranium enrichment has been observed and studied in several peat bogs in Sweden (Armands, 1967).

Table 9B

Concentration of thorium (Th, ppm)

Soil type	No of obs	Min ppm	Median ppm	Max ppm	$Mean_a$ ppm	$Std\ dev_a$ ppm	$Mean_g$ ppm	$Std\ dev_g$ ppm
Baltic sea sediments (b)	48	0.8	4.4	10.5	4.3	2.0	3.8	1.7
Baltic sea sediments, enhanced U	7	1.7	3.4	6.1	3.9	1.8	3.6	1.6
Sand, gravel (lgl)	65	1.9	6.6	17.4	6.9	3.0	6.2	1.6
Sand, gravel, enhanced U	6	4.5	9.1	10.2	9.7	3.9	9.0	1.5
Silt (lga)	40	2.7	8.5	18.5	9.3	3.4	8.6	1.5
Silt, enhanced U	7	4.7	8.9	19.2	10.4	5.3	10.8	1.6
Clay (lgs)	22	10.1	15.6	20.3	15.6	3.0	15.3	1.2
Clay, enhanced U	1			12.0				
Glaciofluvial deposits (fgl)	48	1.0	5.4	15.9	5.6	3.0	4.9	1.7
Glaciofluvial deposits, enhanced U	4	6.5	9.6	14.4	10.0	3.7	9.5	1.5
North Estonian till (mp)	124	0.3	7.7	17.1	8.0	3.6	7.1	1.7
North Estonian till, enhanced U	22	4.7	9.6	16.1	9.7	2.8	9.3	1.3
South Estonian till (ml)	125	5.1	10.5	18.9	10.6	2.5	10.3	1.3
Deposits of fore-Klint low-land and colluvium (kla)	42	2.9	6.9	13.8	7.9	3.2	7.2	1.5
Spoils of Maardu deposits (t)	5	4.7	6.3	9.2	6.5	1.7	6.4	1.3
Total	**566**	**0.3**	**8.1**	**20.3**	**8.4**	**3.9**	**7.4**	**1.7**

Areas with high uranium concentrations in soil tend to coincide with high radon areas. The north Estonian Klint zone between Paldiski and Narva is discernible because the uranium-enriched sand, silt, colluvium and till have uranium concentrations often exceeding 8–9 ppm and reaching 20–37 ppm at four sites (Table 9A). The uranium concentration near the Klint zone is uniformly high (3–5 ppm U) also in the till (Map Sheet 1.4) and clay-rich silt.

In tills with no direct influence of Dictyonema shale, the average uranium concentration is greater in southern Estonia than in northern Estonia with little variation in either northern or southern till. Maximum uranium concentrations are 4–5 ppm, which were measured in the same areas where measured radon concentration exceeds that expected on the basis of the ^{226}Ra concentration in soil.

Table 9C

Concentration of potassium (K, %)

Soil type	No of obs	Min %	Median %	Max %	$Mean_a$ %	$Std\ dev_a$ %	$Mean_g$ %	$Std\ dev_g$ %
Baltic sea sediments (b)	48	0.1	1.7	3.2	1.7	0.8	1.4	2.1
Baltic sea sediments, enhanced U	7	0.2	0.9	2.3	1.1	0.8	0.9	2.3
Sand, gravel (lgl)	65	0.3	2.2	3.4	2.2	0.6	2.0	1.5
Sand, gravel, enhanced U	6	0.5	1.5	2.5	1.6	0.8	1.4	1.8
Silt (lga)	40	1.1	2.7	4.0	2.7	0.5	2.6	2.0
Silt, enhanced U	7	1.1	1.8	3.3	2.0	0.9	1.9	1.5
Clay (lgs)	22	2.7	3.5	4.2	3.4	0.4	3.4	1.1
Clay, enhanced U	1			4.2				
Glaciofluvial deposits (fgl)	48	0.5	1.8	3.4	1.8	0.8	1.6	1.6
Glaciofluvial deposits, enhanced U	4	0.9	2.0	2.9	2.0	0.9	1.8	1.7
North Estonian till (mp)	124	0.1	2.0	3.8	2.1	0.7	1.9	1.5
North Estonian till, enhanced U	22	1.0	1.8	3.5	1.9	0.7	1.8	1.5
South Estonian till (ml)	125	1.7	3.1	4.4	3.1	0.5	3.0	1.2
Deposits of fore-Klint low-land and colluvium (kla)	42	0.1	1.5	5.7	1.7	1.3	1.2	2.6
Spoils of Maardu deposits (t)	5	0.6	1.3	5.1	2.1	1.9	1.6	2.4
Total	**566**	**0.1**	**2.4**	**5.7**	**2.3**	**0.9**	**2.0**	**1.8**

10.2. Concentration of Th as calculated from ^{232}Th

More than 99.9% of the natural thorium in the Earth's crust consists of ^{232}Th. Consequently, the Th concentration calculated from ^{232}Th concentration obtained from gamma spectrometry comprises virtually all thorium present in the soil.

Thorium is an important source of the natural radiation from Quaternary deposits in Estonia with a median value of 8.1 ppm and a range of 0.3 to 20.3 ppm (Table 9B and Map Sheet 1.6). Although the average thorium concentration in the major types of soil differs up to four times, the concentration is normal distributed**.**

The lowest thorium concentration occurs in sands of the different Baltic Sea stages, and the highest in clays (Table 9B). The Th concentration is ca 10% lower than in Quaternary sediments in southern Finland (The Geochemical…, 1992). The external radiation emitted by Th (concentration Th >16–17 ppm) may exceed one third of the Estonian index value $\mathbf{C \leq 1}$ for natural radioactivity of building materials (Chapter 3.2).

10.3. Concentration of K as calculated from ^{40}K

Gamma spectrometric analysis reveals a median K concentration in Estonian soils of 2.4%. This is ca 10% less than the average concentration in the upper crust (Wedepohl, 1995). The variation is moderate or low and the concentrations range from 0.1 to 5.7%. These concentrations are similar to those in soils in southern Finland where the concentration is 2.5–3.1% K (The Geochemical…, 1992). However, the concentration in some soil types is 20–70% higher than concentrations previously determined in Estonian soils (Table 9C, Map Sheet 1.7).

The lowest potassium concentrations were found in sands of the different Baltic Sea stages, and sands and silts of the fore-Klint lowland, while the highest concentrations occur in clays. In addition, elevated concentrations of potassium are observed in tills in south-eastern Estonia.

Potassium contributes substantially to the natural radiation in soil. In regions where the K concentration exceeds 3.3%, the natural radiation emitted from ^{40}K may exceed one third of the Estonian index value $\mathbf{C \leq 1}$ for natural radioactivity of building materials.

10.4. Natural radiation

The **C** index for natural radioactivity in building materials is the sum of the radioactivity of ^{226}Ra, ^{232}Th and ^{40}K expressed in Bq/kg. The maximum permissible level of the concentrations of natural radioactive elements in building materials has been stated in the current Estonian regulation for building materials. In accordance with this regulation, issued by the Minister of the Environment No. 55, 24 August 1998 (Looduskiirgusest…, 1998), the maximum permissible **C** index in building materials is 1 (Chapter 3.2).

The **C** index may also be used by residents to establish the natural radiation level where they live. The index also helps to determine the natural radioactivity of sand, clay, gravel and other materials, which may be unsuitable for building materials of dwellings and workplaces.

A few sites where the **C** index is 1.5–3.0 and one case 5 times higher than the permissible level are located in the Klint area (Map Sheet 1.8). The main reason for these high natural radiation levels is elevated concentration of ^{226}Ra in soil. Because radium is the source for radon, areas with elevated natural radiation coincide with high radon concentrations coincide.

Areas with elevated natural radiation levels occur frequently in the north Estonian Klint zone, between Paldiski in north-west and Narva in north-east. At a couple of sites in this region, **C** exceeds the maximum index values established for playgrounds, $\mathbf{C \leq 2.5}$, two and a half times higher than that for building materials. These areas are marked as *very high radon ground* on the map *Maximum Radon Concentrations in Soil Air* (Map Sheet 1.1) Areas where **C** exceeds 1 are not recommended for permanent residence (Looduskiirgusest…, 1998) without remedial action to reduce radon risk and to shield off the gamma radiation exposure from the ground. **C** exceeds 1 when the uranium concentration is greater than 20 ppm even if the concentrations of ^{232}Th and ^{40}K are normal. Investigation of the radon risk in these areas is an environmental task of high priority.

11. MAJOR SOURCES OF RADON AND NATURAL RADIATION

Until now, all possible sources of radon and natural radiation have not been unambiguously identified. However, the major sources are:

- granitoidal material rich in U, Th and K originating from outcrops of crystalline rocks;
- Dictyonema shale and phosphorite outcropping in the Klint escarpment;
- certain varieties of Devonian rocks;
- possible uranium mineralisations.

Granite stones and fragments of the Rapakivi formation are the most significant source in Estonia of uranium-rich Precambrian basement rocks. These granites, which outcrop on the bottom of the Gulf of Finland and in southern Finland and Karelia, have been deposited throughout Estonia by glacial ice. Rapakivi granites contain 3–10 ppm U, 10–50 ppm Th and 2.2–3.5% K (The Geochemical..., 1992). The amount of Precambrian material varies in the till in front of and south of the Klint, as well as in the deposits between the Klint escarpment and in the fore-Klint lowland.

The Lower-Ordovician complex comprises the Obolus sandstone and phosphorite, Dictyonema shale and glauconitic sandstone (clay). These rock units are exposed in the Klint escarpment and in the valleys intersecting the limestone plateau. Among these, the Dictyonema shale and Obolus sandstone (phosphorite) are typically rich in uranium, potassium and a number of other trace elements (Loog and Petersell, 1994; Petersell, 1991) (Table 10).

Sandstones in south Estonia contain interbeds or lenses of clay and siltstone, which are up to 3 m thick and dark in colour. The concentrations of Mo, U and Pb (and occasionally of other elements) in the siltstones are frequently elevated. For example, in the Joosu clay deposit the U concentration in the clay interbeds (less than 1 m thick) reaches 30 ppm (according to logging results). In the Pskov Region near the eastern border of Estonia, mineralization of Mo, Cu and other elements has been detected in similar clays and siltstones. These mineralised rocks contain up to 300–740 ppm U (Sammet et al., 1974).

Table 10

Concentrations of radioactive elements in Dictyonema shale and phosphorite (Lower Ordovician) in the Maardu, Toolse, Sillamäe and Narva regions of Estonia

Element	**Area**			
	Maardu	**Toolse**	**Sillamäe**	**Narva**
Dictyonema shale				
Uranium (average), ppm	36	162	300	
Uranium (min, max), ppm	13–70	40–447	80–810	
Thorium, ppm	7.4	14.5	14	
Potassium, %	7.47	5.73	5.71	
Phosphorite				
Uranium*, ppm	17	28		47
Thorium, ppm	< 10	< 10		<10
Potassium, %	< 0.1	< 0.1		
P_2O_5, %	10.07	9.98		8.21

*The uranium concentration in phosphorite is correlated directly to the P_2O_5 concentration.

Devonian sandstones poor in clay minerals often are enriched with zircon (up to 3–5 kg/m^3). These sandstones also contain orthite, monazite (up to 0.2–0.5 kg/m^3), apatite, xenotime and other minerals that often have elevated concentrations of rare earth elements, uranium and thorium (Taalmann, 1969). Regions of high radon in the Czech Republic are usually related to the presence of such minerals in rocks and soils (Mikšova and Barnet, 2002). Occasionally in K-feldspars the uranium concentration may be enhanced (Srednie..., 1973).

Mineralization of uranium has been discovered in drillcores of Ordovician limestones and kukersite (oil shale) in north-eastern Estonia, the concentration of which is 200–300 ppm (Barankin, 1962).

The location of the northern boundary of Dictyonema shale and Obolus sandstone (phosphorite) prior to continental glaciation is unknown, but palaeogeographical maps (Männil, 1966) suggest a location several or even tens of kilometres north of the current outcrop in the Klint escarpment. The thickness of these sedimentary rocks increases towards the north. Consequently, several billions of tons of crushed uranium-rich rocks were transported southward by the land ice that once covered all Estonia. This resulted in uranium-rich material being mixed with other material in tills, glaciofluvial and lacustrine sediments. Since the last continental glacier melted, sediments have been reworked and redeposited by the Baltic Sea, rivers and lakes.

The low sampling density of this survey is insufficient to identify high radon and natural radiation areas more precisely than the preliminary borders outlined on these small-scale maps. To produce maps at scale of 1:50 000 or larger requires further information, which can only be gained through more detailed radiometric measurements and geological observations. It should be acknowledged that the areas with high radon levels are of variable size and shape, which can embody several or even tens of square kilometres.

Few investigations have considered the radon concentration in the near-surface (up to 3 m) outdoor air layer in the *high radon ground* areas in Estonia. The radon concentration in outdoor air under normal circumstances is 2–15 Bq/m^3 and in enclosed areas up to 100 Bq/m^3 (Naturally..., 2000). However, the influence of outdoor radon on enclosed areas in Estonia remains undetermined. It is possible that radon levels in outdoor air increase on calm days with inversion, especially where the radon concentration in the soil air ten times or more exceeds the normal background concentration (5–30 kBq/m^3). For example, radon concentrations of up to 90 Bq/m^3 have in Sillamäe been recorded in outdoor air (Ehdwall et al, 1994). However, as soon as the wind blows the outdoor radon concentration returns to background levels.

SUMMARY

Radon (Rn) is a highly radioactive and carcinogenic inert gas. It is the second most common cause of lung cancer after smoking. The deleterious effects of radon have been thoroughly investigated during the last decades. These studies have led many countries to establish compulsory or recommended limits for radon concentrations in the indoor air of residential and non-residential buildings, and for air for unrestricted construction (Chapter 3.1). Estonian regulations dictate that the maximum permissible radon concentrations in indoor air of new buildings must be less than 200 Bq/m^3 (Chapter 3.2). Radon protective building construction is required for new residential dwellings and workplaces if the radon concentration in the soil air at a depth of 1 m below ground surface is higher than 50 kBq/m^3.

The *Radon Risk Map of Estonia* was produced in cooperation with the Geological Survey of Estonia, the Swedish Radiation Protection Authority and the Geological Survey of Sweden.

This project employed the experience and methodology of the Swedish partners. Field measurements of radon in soil air and additional measurements of the ^{226}Ra, ^{232}Th and ^{40}K concentrations in soils at a depth of 80 cm were carried out at 566 sites in 2002 and 2003. The location of these investigation points was determined with a precision of ±10 m using Garmin GPS 76.

Analysis of the results was a continuous process. The activity concentration of ^{222}Rn obtained by direct measurements mainly at the depth of 0.8 m was recalculated to a standard depth of 1 m with a graph of the relationship between depth, soil type and radon diffusion. Maximum concentrations of ^{222}Rn in the soil air were calculated from the ^{226}Ra activity concentration obtained by gamma spectrometry.

As a result of the survey land areas of the following radon classes were distinguished: low radon areas (<10 kBq/m^3), normal radon areas (10–50 kBq/m^3), high radon areas (50–250 kBq/m^3), and very high radon areas (>250 kBq/m^3).

The *Radon Risk Map Set of Estonia* includes the following 9 Map Sheets, all at scale of 1:500 000.

1. *Radon-222 Risk Map of Estonian Soil*,
   - 1.1. *Maximum Radon Concentration in Soil Air*,
   - *1.2. Radon Concentration in Soil Air determined by direct measurements* (at a depth of 1 m),
   - *1.3. Radon Concentration in Soil Air calculated after eU (^{226}Ra)*,
   - *1.4. Uranium (^{226}Ra) Concentration in Soil*,
   - *1.5. Map of Factual Material* [Location of Observation Points on the map of Quaternary sediments (Kajak, 1999)],
   - *1.6. Thorium (^{232}Th) Concentration in Soil*,
   - *1.7. Potassium (^{40}K) Concentration in Soil*,
   - *1.8. Natural Radiation of Soil*.
2. *Preliminary Map of Radon Risk Areas in Estonia*.

The survey shows that the radon concentration in soil air is frequently elevated, especially in northern Estonia. The radon concentration exceeds the maximum concentration for unrestricted building activity by 3 times in 25.8% of the observation points, by 3–5 times in 3.7% of the observation points, and by more than 5 times in 3.4% of the observation points (total 32.9%).

Areas with high and very high radon concentration in soil air occur in the Estonian Klint zone: directly on the outcrops and subcrops of Dictyonema shale and phosphorite, between the escarpments and on plains slightly inclined towards the front of the escarpments, and within a 5–15 km wide zone on the limestone plateaus south of the Klint.

Several towns (Tallinn, Maardu, Kunda, Sillamäe, Narva) and settlements (Ülgase, Püssi, Varja, Toila, etc) as well as numerous farmsteads are located in the Estonian Klint zone. In this zone the radon concentration in soil air at the depth of 1 m exceeded 50 kBq/m^3 in 50% of the studied sites. At many sites the radon concentration is much (up to 8 times) higher, at one site 42 times higher.

High concentration of radon in soil air occurs also in eastern and southern Estonia, usually in association with Devonian rocks, e.g. in Luunja, Põlva, Tsooru, Taagepera, Viljandi, etc. In these parts of Estonia the measured radon concentration was often greater than that calculated from the activity of radium-226, which indicates migration of radon into upper portion of soil from deeper situated soil layers. This radon migration requires further study to be confirmed.

Normal radon concentration dominates in western Estonia and in the West-Estonian Archipelago. The radon concentration in soil air in these regions exceeded 50 kBq/m^3 only at a few sites, such as the circular impact structure at Kärdla on Hiiumaa, and also on Saaremaa and in the Rapla area where clayey tills, silts or clays occur.

The ^{238}U/^{226}Ra ratio in Estonian soils shows a slight deficiency in ^{238}U. Elevated uranium (^{226}Ra) level causes the total natural radiation level (caused by ^{226}Ra, ^{232}Th and ^{40}K) to exceed the Estonian index value, **C ≤ 1** for building materials in 3.2% of the observation points. At two sites, **C** exceeded the value established for playgrounds, **C ≤ 2.5** (for more information on the index, see page 16).

Areas that at first hand merit more detailed investigations are the north Estonian Klint zone and those areas in southern Estonia where the radon concentration in soil air is more than three times greater than 50 kBq/m^3, with particular emphasis on determining the radon origin and variation during the year.

The regions with very high radon in soil air vary in shape and size, some covering several square kilometres. The natural radiation level in these areas is also often high and the uranium concentration in soil often exceeds 20–25 ppm U. Before building of dwellings or summer homes, schools, nursery schools etc. in these regions additional testing of radon in soil air and uranium in soil is required, and if found necessary, radon preventive actions have to be taken in order to prevent inflow of radon from the ground into the buildings.

To prevent unnecessary exposure to radon gas and gamma radiation, it is important to carry out large-scale investigations to delimit the high radon risk areas. This will enable planning authorities and the construction industry to determine where detailed radon investigations should be carried out before construction of new buildings, or alternatively, where buildings require special construction methods (Radooniohutu..., 2003). Post-construction alterations or renovation of buildings could prove to be very expensive.

The *high radon risk areas* are also areas where existing dwellings and other buildings often are affected by indoor radon. In these areas it is important to carry out measures against indoor radon to prevent unnecessary radon exposure. In 1996 the Estonian Radiation Protection Centre initiated radon measurements in dwellings throughout Estonia. These measurements show that the radon concentration in buildings can exceed 10 times the recommended limit of 200 Bq/m³ (in some buildings even higher radon concentrations have been measured) (Pahapill, 2000; Pahapill et al, 2003).

The influence of radon on human health in Estonia remains undetermined, although research is ongoing. Large parts of Estonia are classified as *high radon areas*, mainly due to the occurrence of Dictyonema shale and phosphorite in the north Estonian Klint, widespread distribution of these rocks in glacial deposits overlying the bedrock, and distribution of uranium-rich minerals in the tills made up of Devonian sandstones.

Health care institutions have a role to play in the prevention of radon exposure. The means to mitigate the influence of radon on human health in Estonia are favourable. These investigations would serve as a basis to establish regulations concerning the permissible radon concentrations and amending existing legislation if needed.

Recommendations for reducing radon risk:

- Areas where the radon concentration in soil exceeds 50 kBq/m³ require detailed surveys prior to construction. At constructions of buildings in sites designated as high radon ground it is required that these buildings are provided with appropriate radon protection measures (Radooniohutu…, 2003) to abate excessive indoor radon in new buildings and to ensure that the radon concentration will be below the maximum permissible limit, 200 Bq/m³.
- A specialist in the field of radon studies should be included in the commission inspecting new buildings. This specialist would check the concentration of indoor radon in the building and order remedial action if necessary.
- The radon concentration in soil air and the level of natural radiation should be monitored during the planning of future dwellings and workplaces in *high radon risk areas*.
- People residing in or intending to move into apartments should be informed if the building is located in a high radon or natural radiation area and of previous measurements of indoor radon as well as of the risk for elevated levels of radon in soil air and outdoor gamma radiation.

ACKNOWLEDGEMENTS

We wish to thank the Estonian Environmental Investment Centre and the Swedish International Development Cooperation Agency for financing the project.

We are grateful to Raivo Rajamäe, Head of the department, and Lia Pahapill, Senior Engineer at the Estonian Radiation Protection Centre for their cooperation, valuable advice as well as for technical and methodical assistance. We also thank Robert Szava-Kovats for his excellent help with the translation.

REFERENCES

Åkerblom, G., 1986. Investigation and mapping of radon risk areas. Paper presented at the International Symposium on Geological Mapping in the Service of Environmental Planning: Commission for the Geological Map of the World, Trondheim, Norway, 6–9 May, 1986. In: Geology for Environmental planning. Edited by Wolff, F. C. Geological Survey of Norway. Special Papers, 2. 15 p.

Åkerblom, G., 1994. Ground radon – monitoring procedures in Sweden. Geoscientist, v. 4., Nr 4, p. 21–27.

Åkerblom, G., 1999. Radon Legislation and National Guidelines. Swedish Radiation Protection Institute, Report 99:18, 40 p.

Åkerblom, G. and Mellander, H., 1997. Geology and Radon. In: Radon Measurements by Etched Track Detectors. World Scientific Publishing, Singapore New Jersey London Hong Kong, pp. 29–49.

Åkerblom, G., Petterson, B. and Rosén, B., 1988. Markradon (Ground Radon). In the series: Radon in Dwellings (In Swedish). The Swedish Building Council. Report R85. Second revised edition, 1990, 159 p. ISBN 91-540-4937-7.

Åkerblom, G. and Wilson, C., 1980. Radon gas – a radiation hazard from radioactive bedrock and building materials. Bulletin of the International Association of Engineering Geology, 23, Krefeld 1981, pp. 55–61.

Åkerblom, G. and Wilson, C., 1981. Radon – geological aspects of an environmental problem. Papers presented at the International Meeting on Radon – Radon Progeny Measurements. Montgomery, Alabama, August 27–28 1981. Geological Survey of Sweden. Reports and communications, no. 30, Uppsala 1982, 47 p. ISBN 91-7158-271-1.

Armands, G., 1967. Geochemical prospecting of a uraniferous bog deposit at Masugnsbyn, northern Sweden. In: Geochemical Prospecting in Fennoscandia, Interscience Publishers, New York London Sydney, pp. 127–154.

Barankin, V. S, 1962. Otčet o rezul'tatah rabot po ustanovleniju perspektivnosti Kontsoskoj radioaktivnoj anomalii. Tallinn, EGF.

Clavensjö, B., Åkerblom, G., 1994. The Radon book. Measures against radon. Stockholm, 129 p.

Darby, S., Hill, D., Auvinen, A. et al., 2004. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. British Journal of Medicine. Doi:10.1136/bmj.38308.477650.63.

EC, 1990: "Commission Recommendation of 21 February 1990 on the protection of the public against indoor exposure to radon". European Communities. 90/143/Euratom. 1990.

EC, 1996: "Council Directive 96/29/EURATOM of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation. Legislation". Official Journal of the European Communities. L159, Vol.39. 1996.

EC, 1997: "Recommendations for the implementation of Title VII of the European Basic Safety Standards Directive (BSS) concerning significant increase in exposure due to natural radiation sources. Radiation Protection 88. Directorate-General Environment, Nuclear Safety and Civil Protection. Office for Official Publications of the European Commission. Radiation Protection Series. European Commission. 1997.

EC, 1998: "Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption". Official Journal of European Communities. L 330/32-54. 5.12.98.

EC, 1999: "Radiological protection principles concerning the natural radioactivity of building materials". Radiation Protection 112. Directorate-General Environment, Nuclear Safety and Civil Protection. Office for Official Publications of the European Commission. Radiation Protection Series. European Commission. 1999.

Ehdwall, H., Sundblad, B., Nosov, V., Putnik, H., Mustonen, R., Salonen, L., Qvale, H., 1994. The content and environmental impact from the waste depository in Sillamäe. SSI-rapport 94-08, Stockholm, 41 p.

Ek, J., Ek, B.-M., 1996. Radium and Uranium Concentrations in Two Eskers with Enhanced Radon Emission. Geological Survey of Sweden, Uppsala, Sweden, 11 p.

Ek, B.-M., 1996. Effects of Freezing and Thawing on Radon in Soils. Radon Investigations in the Czech Republic VI and the Third Int. Workshop on the Geological Aspects of Radon Risk Mapping.

Exploranium G.S. Ltd., 1989. Portable Gamma Ray Spectrometer, model GR-256 with model GPS-21 detector. Manual. Exploranium G.S. Ltd. Toronto, Canada.

Gammadata, 2005. MARKUS 10 manual.

Garetsky, P. G., Ludwing, A.O., Schwab, G., Stackebrandt, W., 1995. Neogeodynamics of the Baltic Sea depression and adjacent areas. Germany, Teltow.

Geochemical Atlas of Europe. 2005. Geological Survey of Finland, 525 p. ISBN 951-690-291-3.

Geology and mineral resources of Estonia. Tallinn, 1997, 436 p.

Gigieničeskie trebovanija po ograničeniju oblučenija naselenija za sčet prirodnyh istočnikov ionizirujuščego izlučenija, 2003. Sanitarno-gigieničeskie pravila SP 2.6.1.1292–03, Moskva, ss 24–26.

Gundersen, L., 1991. Preliminary radon potential map of the United States. Proceedings of the EPA International symposium on radon and radon reduction technology, v. 5, paper IX-4.

ICRP 60: "1990 Recommendations of the International Commission on Radiological Protection". ICRP Publication 60. Annals of the ICRP 21(13). 1991.

ICRP 65: "Protection against Radon-222 at Home and at Work. A Report of the International Commission on Radiological Protection". ICRP Publication 65. Pergamon Press. 1993. 45 p.

Ivanov,V.V, 1994. Čkologičeskaja geohimija člementov. Spravočnik, kniga 1, s - člementy, Moskva,Čkologija, 305 p.

Ivanov, V.V., 1996. Čkologičeskaja geohimija elementov. Spravočnik, kniga 4, glavnye d-člementy, Moskva, Čkologija, 409 p.

Kadastik, E., 1995. Texture and mineralogical characteristics of Weichselian till on Saaremaa Island. Bull. of the Geological Survey of Estonia, 5/1, pp. 4–11.

Kadastik, E., Kalm, V., 1998. Lithostratigraphy of late Weichselian tills on the west Estonian islands. Bull. of the Geol. Soc. of Finland 70, Parts 1–2, pp. 5–17.

Kadastik, E., Ploom, K., 2000. Pleistocene deposits and deglaciation of the Nõva–Padise area (NW Estonia). Bull. of the Geological Survey of Estonia, 9/1, pp. 4–10.

Kalm, V., Kadastik, E., 2001. Waterlain glacial diamicton along the Palivere ice-marginal zone on the West-Estonian Archipelago, eastern Baltic Sea. Proc. Estonian Acad. Sci. Geol., 50, 2, pp. 114-127.

Karukäpp, R., 2003. Deglaciation of Northern Estonia. Int. Symp. On Human Impact and Geological Heritage. Excursion Guide and Abstracts. Inst. of Geol. Tallinn Technical University.

Kattai, V., 2000. Eesti põlevkivi: geoloogia, ressurss, kaevandamistingimused. Tallinn, Eesti Geoloogiakeskus, 248 lk.

Liivrand, E., 1992. Problems of reconstructing Pleistocene stratigraphy in Estonia. Sveriges geologiska undersökning, Ser.a 81, pp. 171–176.

Lindmark, A. and Rosén, B., 1985. Radon in soil gas – Exhalation tests and in situ measurements. In: The Science of the Total Environment **45**, pp. 397–404.

Looduskiirgusest, kiirgustegevusest, kiirgusallikatest ja avariidest elanikkonnale põhjustatud kiirgusdooside seire ja hindamise korra kinnitamine. Keskkonnaministri 24. augusti 1998. a määrus nr 55.

Loog, A., Petersell, V., 1994. The distribution of microelements in Tremadoc graptolitic argillite of Estonia. Tartu Ülikooli Toim., 972, Töid geol. alalt XIV. Tartu, pp. 57–76.

Mikšova, J., Barnet, I., 2002. Geological support to the National Radon Programme (Czech Republic). Bulletin of the Czech Geological Survey, v. 77, No 1, pp. 13–22.

Mjönes, L., 1991. The Swedish view on radon control. Proceedings from: Messung von Radon und Radonfolgeprodukten, Berlin, May 6–7 1991. Publication Series: Progress in radiation protection. Verlag TUV Rheinland, Köln.

Mjönes, L. and Falk, R., 2002. Cancer risks from radon in indoor air and drinking water in Sweden. Paper presented at the VII International Symposium Natural Radiation Environment (NRE-VII) 20–24 May 2002, Rhodos, Greece.

Männil, R., 1966. Istorija razvitija Baltijskogo bassejna v ordovike. Valgus, Tallinn, 200 p.

Naturally Occurring Radioactivity in the Nordic Countries – Recommendations. 2000. The Radiation Protection Authorities in Denmark, Finland, Iceland, Norway and Sweden, 2000, 73 p. ISBN 91-89230-00.

Naumov, B., Puura, V., Karise, V. i dr., 1993. Radonovyj faktor radiacionnogo fona v naselennyh punktah Severnoj Čstonii (Čkologičeskij aspekt) – Eesti TA Toim., Geoloogia, 42, pp. 82–93.

Nõukogude Eesti, 1978. Tallinn, Valgus, 382 p.

Orru, M., 1995. Eesti turbasood. Teatmik. Tallinn, Eesti Geoloogiakeskus, 240 p.

Orru, M., Orru, H., 2003. Kahjulikud elemendid Eesti turbas. Eesti Geoloogiakeskus, Tallinn, 144 p.

Osnovnye sanitarnye pravila obespečenija radiacionnoj bezopasnosti, 2000. (OSPORB-99). CP 2.6.1.799-99. Izdanie oficial'noe. Moskva, ss. 68–70.

Pahapill, L., 2000. Siseõhu radoonist Eestis. Keskkonnatehnika, 3, lk 2–7**.**

Pahapill, L., Rulkov, A., Rajamäe, R.**,** Åkerblom, G., 2003. Radon in Estonian Dwellings. Results from a National Radon Survey. SSI Report: 2003:16, october 2003, 20 p. ISSN 0282-4434.

Pershagen, G. et. al., 1993. Radon in dwellings and lung cancer. A country-wide epidemiological study (in Swedish). Institute for Environmental Medicine, IMM Report 2/93, Stockholm. ISSN-1101-2803.

Pershagen, G., Åkerblom, G., Axelsson, O., Clavensjö, B., Damber, L., Desai, G., Enflo, A., Lagarde, F., Mellander, H., Svartengren, M., Swedjemark, G.A., 1994. Residential radon exposure and lung cancer in Sweden. New England Journal of Medicine, 330, pp. 159–164.

Petersell, V., 1991. Geochemistry of F, Sr, REE and U in phosphorites of the East Baltic phosphorite basin. Exploration Geochemistry 1990, Prague, pp. 278–290.

Petersell, V., Kivisilla, J., Niin, M., Pukkonen, E., Põldvere, A., Täht, K., 1991. Otčet ob ocenke rudoprojavlenij i toček mineralizacii v osadočnom čehle i kristalličeskom fundamente Estonii. Tallinn, EGF.

Petersell, V., Mõttus, V., Enel, M., Täht, K., Võsu, M., 2000. Eesti mulla lähtekivimite geokeemiline atlas (käsikiri). Tallinn, EGF.

Petersell, V., Ressar, H., Carlsson, M., Mõttus, V., Enel, M., Mardla, A., Täht, K.,1997. Eesti mulla huumushorisondi geokeemiline atlas, Tallinn–Uppsala, Seletuskiri, 75 lk, kaart 37 lehte.

Pinnases ja põhjavees ohtlike ainete piirnormid. Keskkonnaministri 2. aprilli 2004.a määrus nr 12.

Plink, P., Kask, J., Eltermann, G., 1992. Formation of Quaternary sediments on Kassari Island. Bull. of the Geol. Survey of Estonia 2/1, pp. 32–37.

Quaternary Deposits of Estonia. 1999. Explanatory note. Geol. Survey of Estonia.

Radoon. Looduslik risk sinu tervisele! 2003. Teabematerjal. Eesti Kiirguskeskus.

Radooniohutu hoone projekteerimine**,** 2003. Eesti standard EVS 840:2003. Eesti Standardikeskus. Ametlik väljaanne, 16 lk.

Raukas, A., 1969. Composition and genesis of Estonian tills. Z. N. U. A. M. Poznan. Geografia 8.

Raukas, A., 1974. The peculiarities of the mineralogical composition of the Würmian till of Estonia. Z. N. U. A. M. Poznan. Geografia 10.

Raukas, A., 1978. Pleistocene deposits of the Estonian SSR. Valgus, 310 p. (In Russian with English and Estonian summaries).

Raukas, A., 1992. Ice marginal formations of the Palivere zone in eastern Baltic. Sveriges geologiska undersökning, Ser Ca 81, pp. 177–284.

Raukas, A., Gaigalas, A., 1993. Pleistocene glacial deposits along the eastern periphery of the Scandinavian ice sheets – an overview. Boreas, v. 22, pp. 214–222.

Raudsep, R., Samuel, G., 1999. Radooniohu piiritlemine. Eesti projekteerimisnormid EPN 12.2., ET Eesti Ehitusteave.

Realo, E., Viik, T., 1997. Kiirguskaitse sõnastik, Tallinn, EKK, 96 lk.

Rešetov, V.V, Puminov, J.A., Kapinos, V. M. i dr., 1993. Otčet po rezul'tatam ačrogammaspektrometričeskih rabot na territorii Čstonskoj Respubliki (Dogovor 33/6 ot 21.10.93). GGP "Nevskgeologija", Eesti Kiirguskeskus.

Rõuk, A.-M., Raukas, A., 1989. Drumlins of Estonia. Sedimentary Geology 62, pp. 371–384.

Rõõmusoks, A., 1983. Eesti aluspõhja geoloogia. Tallinn, Valgus, 224 p.

Salonen,V.-P., Glückert, G., 1992. Late-Weichselian glacial activity and sediments in south-western Finland. Sveriges geologiska undersökning, Ser Ca 81, pp. 313–318.

Sammet, E.J., Nasonova, L.D., Kiseljov, V. I., 1974. Otčet o rezul'tatah proverki redkometal'nogo orudenenija v verhnedevonskih otloženijah Pskovskoj oblasti v 1973–1974. gg. Leningrad, EGF.

Schovsbo, N.H., 2002. Uranium enrichment shorewards in black shales: A case study from the Scandinavian Alum Shale. GFF v. 124, pp. 107–115.

Srednie soderžanija élementov-primesej v mineralah, 1973. Moskva, 208 p.

Taalmann, V., 1969. Otčet po teme "Izučenie tjaželoj frakcii devonskih otloženij Čstonskoj SSR", Tallinn, EGF.

The Geochemical Atlas of Finland. Part 2. Till. 1992, 218 p.

The Map of the Estonian Quaternary Deposits. 1995. Compiled by K.Kajak. Ed: A. Raukas. Geol. Survey of Estonia.

Titov, V.K., Laškov, B.P.,Cernik, D.A., 1992. Čkspressnye opredelenija radona v počvah i zdanijah, Sankt-Peterburg, 39 p.

Turekian, K. and Wedepohl, K., 1961. Distribution of the elements in some major units of the Earth's crust. - Bull., Geol. Soc. of Amer., v. 72, N 2.

UNSCEAR, 1993. United Nations Scientific Committee on the effects of Atomic Radiation. Report to the General Assembly, with scientific annexes. United Nations 54. ISBN 92-1-1-142200-0.

Viiding, H., 1961. Võrdlevaid andmeid erivärviliste devoni liivakivide mineraloogiast ja litoloogiast. Geoloogilised märkmed N 2. Tallinn, lk 34–39.

Viiding, H., 1984. Eesti mineraalid ja kivimid. Tallinn, Valgus, 247 lk.

Viiding, H., Kleesment, A., Konsa, M., Heinsalu, I., Jürgenson, E., 1983. Čvoljucija mineral'nogo sostava terrigennogo komponenta osadočnogo čehla na južnom sklone Baltijskogo □čita.- V kn.: Terrigennye mineraly osadočnyh porod Pribaltiki. Tallinn, pp. 7–22.

Wedepohl, K.H., 1995. The composition of the continental crust. Geochimica et Cosmochimika Acta. v. 59, No 7, pp. 1217–1232.

APPENDIX:

RESULTS OF MEASUREMENTS AND CALCULATIONS

The used abbreviations

[1] Calculated with emanation factor for map 2, table 6
[2] Calculated with emanation factor for map 1, table 6

mp	North-Estonian till
ml	South-Estonian till
fgl	Glaciofluvial deposits

Glacioaqueous deposits:

lgs	Clay
lga	Silt
lgl	Sand

b	Holocene, marine deposits (silt, sand, gravel)
kla	Sediments in fore-klint area
t	The spoil of Maardu phosphorite opencast

Observation point	Estonian soil abb.	Soil type	Radon measured (kBq/m^3)	K (%)	eU (ppm)	Radium (Bq/kg)	Th (ppm)	Radon calculated from ^{226}Ra[1] (kBq/m^3)	Radon calculated from ^{226}Ra[2] (kBq/m^3)	C
Rn02-001	b	Marine	12,3	2,3	1,9	23,2	4,0	24,6	27,9	0,39
Rn02-002	mp	NE-till	3,5	1,6	0,8	9,6	3,1	13,2	10,9	0,26
Rn02-003	b	Marine	10,1	0,7	4,5	55,2	3,3	58,6	66,4	0,32
Rn02-004	lgl	Sand	12,3	1,4	1,1	13,6	4,7	13,4	16,8	0,28
Rn02-005	lgl	Sand	7,8	1,4	1,1	13,6	4,4	13,4	16,8	0,28
Rn02-006	t	Tekn	39,4	5,1	24,7	303,8	6,3	382,3	381,6	1,66
Rn02-007	fgl	Fluviogl	39,4	1,2	2,0	24,8	4,6	35,9	29,2	0,30
Rn02-008	fgl	Fluviogl	11,6	1,8	1,0	12,0	7,0	17,4	14,1	0,36
Rn02-009	kla	Klint	280,0	1,6	17,6	216,7	9,9	242,1	269,3	1,08
Rn02-010	lgl	Sand	11,2	2,3	1,3	16,0	5,7	15,8	19,7	0,41
Rn02-011	lgl	Sand	23,5	3,3	4,4	53,6	17,4	52,9	65,9	0,86
Rn02-013	ml	SE-till	67,1	3,4	2,7	32,8	11,4	65,2	42,4	0,69
Rn02-014	mp	NE-till	22,0	1,5	1,5	18,4	4,9	25,3	23,8	0,31
Rn02-015	lga	Silt	2,5	2,0	0,8	10,4	2,7	11,9	13,8	0,29
Rn02-017	t	Tekn	32,5	0,6	10,0	123,1	4,7	154,9	154,6	0,56
Rn02-018	t	Tekn	31,3	1,3	9,9	121,5	6,7	152,9	152,7	0,67
Rn02-019	t	Tekn	29,0	0,8	8,6	106,3	5,7	133,8	133,6	0,56
Rn02-020	kla	Klint	103,4	0,8	7,9	97,5	6,6	109,0	121,3	0,55
Rn02-021	kla	Klint	15,4	0,3	10,1	123,9	5,5	138,4	154,1	0,56
Rn02-022	kla	Klint	75,9	2,3	15,9	195,9	11,3	218,8	243,5	1,11
Rn02-024	lgs	Clay	12,8	3,6	1,8	21,6	10,3	26,7	29,9	0,65
Rn02-025	b	Marine	11,2	3,0	2,1	25,6	8,4	27,2	30,8	0,56
Rn02-026	kla	Klint	23,1	1,2	5,1	62,4	5,3	69,7	77,5	0,44
Rn02-027	b	Marine	3,4	2,3	1,2	14,4	4,9	15,3	17,3	0,38
Rn02-028	fgl	Fluviogl	98,6	2,9	3,9	48,0	14,4	69,4	56,5	0,75
Rn02-029	mp	NE-till	129,2	1,0	12,9	159,1	10,9	219,1	182,0	0,85
Rn02-030	kla	Klint	20,9	0,1	8,6	106,3	6,5	118,8	132,2	0,50
Rn02-031	b	Marine	3,4	2,8	0,7	8,0	5,5	8,5	9,6	0,42
Rn02-032	lgl	Sand	10,1	2,7	2,1	25,6	14,0	25,3	31,5	0,65
Rn02-033	lgl	Sand	24,6	1,9	2,0	24,8	8,3	24,5	30,5	0,44
Rn02-034	mp	NE-till	34,2	1,8	2,0	24,8	4,2	34,1	28,4	0,35
Rn02-035	mp	NE-till	37,4	2,9	4,0	49,6	14,3	68,3	56,7	0,75
Rn02-036	kla	Klint	66,0	0,5	15,1	185,5	4,7	207,2	230,5	0,76
Rn02-037	b	Marine	1,2	3,2	1,3	16,0	6,5	17,0	19,3	0,51
Rn02-038	b	Marine	10,1	2,0	1,2	15,2	5,5	16,1	18,3	0,36
Rn02-039	b	Marine	1,1	0,5	0,5	6,4	1,6	6,8	7,7	0,11
Rn02-040	b	Marine	1,1	1,0	0,6	7,2	4,5	7,6	8,7	0,22
Rn02-041	mp	NE-till	11,8	1,8	1,8	21,6	6,3	29,7	24,7	0,39
Rn02-042	mp	NE-till	14,3	2,0	1,5	18,4	5,6	25,3	21,1	0,37
Rn02-043	lgl	Sand	3,4	1,4	0,6	7,2	4,7	7,1	8,8	0,27
Rn02-044	mp	NE-till	14,3	1,6	1,7	20,8	5,3	28,6	23,8	0,34
Rn02-045	mp	NE-till	22,0	2,1	2,0	24,8	7,7	34,1	28,4	0,46
Rn02-046	mp	NE-till	20,9	1,0	1,2	14,4	4,4	19,8	16,4	0,24
Rn02-047	mp	NE-till	36,5	2,1	2,3	28,0	10,5	38,5	32,0	0,52
Rn02-048	lgl	Sand	3,4	1,4	1,4	17,6	6,7	17,4	21,6	0,34
Rn02-049	fgl	Fluviogl	7,8	3,4	2,5	30,4	11,4	44,0	35,8	0,68
Rn02-050	mp	NE-till	57,2	2,1	6,5	80,0	12,6	110,1	91,4	0,73
Rn02-051	b	Marine	2,2	2,9	1,0	12,0	4,4	12,7	14,4	0,42
Rn02-052	b	Marine	20,2	2,1	1,2	15,2	2,6	16,1	18,3	0,32
Rn02-053	mp	NE-till	95,7	2,7	5,7	69,6	10,7	95,8	79,5	0,73
Rn02-054	mp	NE-till	105,6	2,7	8,8	107,9	9,8	148,6	123,4	0,84

APPENDIX, sheet 2

Observation point	Estonian soil abb.	Soil type	Radon measured (kBq/m^3)	K (%)	eU (ppm)	Radium (Bq/kg)	Th (ppm)	Radon calculated from ^{226}Ra^1 (kBq/m^3)	Radon calculated from ^{226}Ra^2 (kBq/m^3)	C
Rn02-055	mp	NE-till	63,8	2,3	5,8	71,2	9,7	98,0	81,4	0,67
Rn02-056	mp	NE-till	33,0	2,0	2,3	28,8	6,2	39,6	32,9	0,43
Rn02-057	mp	NE-till	46,2	2,7	3,4	41,6	10,5	57,2	47,5	0,63
Rn02-058	lga	Silt	6,4	1,9	1,3	16,0	4,2	18,3	21,2	0,33
Rn02-059	kla	Klint	2112,0	1,5	6,6	81,5	4,7	91,1	101,3	0,52
Rn02-060	mp	NE-till	92,4	1,8	6,7	82,3	7,7	113,4	94,2	0,62
Rn02-061	kla	Klint	94,0	3,5	4,6	56,8	10,3	63,4	70,6	0,76
Rn02-066	fgl	Fluviogl	36,0	1,8	4,5	55,2	7,4	79,8	65,0	0,51
Rn02-068	mp	NE-till	92,4	2,5	3,6	44,8	9,2	61,7	51,2	0,60
Rn02-069	b	Marine	48,2	1,0	4,6	56,0	6,1	59,4	67,3	0,41
Rn02-070	mp	NE-till	115,5	2,4	5,9	72,0	10,3	99,1	82,3	0,69
Rn02-071	mp	NE-till	55,0	1,0	6,6	81,5	4,7	112,3	93,3	0,47
Rn02-072	mp	NE-till	313,5	1,4	21,4	263,0	10,1	362,2	300,9	1,22
Rn02-073	mp	NE-till	266,2	2,0	20,9	256,6	10,9	353,4	293,6	1,27
Rn02-074	lgl	Sand	15,7	2,3	1,2	14,4	5,0	14,2	17,7	0,38
Rn02-075	lga	Silt	18,2	3,4	1,9	23,2	8,3	26,5	30,8	0,59
Rn02-076	lgl	Sand	16,8	2,0	1,2	15,2	4,7	15,0	18,7	0,35
Rn02-077	lga	Silt	38,5	2,6	3,0	36,8	10,4	42,1	48,8	0,60
Rn02-078	lgl	Sand	3,4	2,2	1,4	17,6	6,6	17,4	21,6	0,42
Rn02-079	mp	NE-till	16,5	1,6	1,8	21,6	4,2	29,7	24,7	0,32
Rn02-080	lgl	Sand	29,1	2,7	1,6	19,2	8,8	19,0	23,7	0,52
Rn02-081	mp	NE-till	30,8	1,5	1,5	18,4	4,7	25,3	21,1	0,31
Rn02-082	mp	NE-till	72,6	3,2	3,6	44,0	14,5	60,6	50,3	0,77
Rn02-083	lga	Silt	26,8	3,1	2,8	34,4	10,9	39,3	45,6	0,65
Rn02-084	mp	NE-till	19,8	2,6	1,9	23,2	8,6	31,9	26,5	0,52
Rn02-085	ml	SE-till	59,4	3,2	2,5	31,2	9,6	62,0	40,3	0,62
Rn02-086	lga	Silt	8,6	3,1	1,5	18,4	7,3	21,0	24,4	0,53
Rn02-087	lgl	Sand	5,6	2,1	1,6	19,2	5,5	19,0	23,7	0,39
Rn02-088	lgl	Sand	2,2	1,9	1,0	12,0	2,6	11,8	14,7	0,29
Rn02-089	lga	Silt	9,6	1,8	1,5	18,4	4,6	21,0	24,4	0,34
Rn02-090	mp	NE-till	8,8	3,4	3,6	44,8	16,0	61,7	51,2	0,82
Rn02-091	mp	NE-till	1,1	3,6	4,2	51,2	17,1	70,5	58,6	0,88
Rn02-092	lgs	Clay	54,6	3,0	3,4	42,4	10,1	52,4	58,7	0,65
Rn02-093	mp	NE-till	35,4	3,8	3,9	48,0	17,0	66,1	54,8	0,90
Rn02-094	mp	NE-till	34,1	3,4	3,3	40,0	12,2	55,0	45,8	0,73
Rn02-095	mp	NE-till	27,5	1,4	1,3	16,0	4,2	22,0	18,3	0,28
Rn02-096	mp	NE-till	29,7	2,5	2,1	25,6	8,9	35,2	29,2	0,53
Rn02-097	mp	NE-till	15,4	3,3	4,1	50,4	14,4	69,4	57,6	0,80
Rn02-098	mp	NE-till	29,7	2,7	3,3	40,8	11,6	56,1	46,7	0,65
Rn02-099	mp	NE-till	11,0	1,8	2,1	26,4	6,1	36,3	30,2	0,39
Rn02-100	lgl	Sand	7,8	2,5	2,2	27,2	9,7	26,9	33,5	0,55
Rn02-101	lgl	Sand	14,6	2,7	1,5	18,4	9,7	18,2	22,7	0,54
Rn02-102	ml	SE-till	63,8	3,0	2,3	28,0	13,5	55,7	36,2	0,67
Rn02-103	lgl	Sand	3,4	1,6	0,5	6,4	3,6	6,3	7,9	0,26
Rn02-104	mp	NE-till	452,1	3,2	37,2	458,1	14,5	630,8	524,1	2,15
Rn02-105	lgl	Sand	2,2	3,4	1,6	19,2	5,3	19,0	23,7	0,52
Rn02-106	kla	Klint	83,6	2,0	9,4	115,1	11,1	128,6	143,1	0,81
Rn02-107	mp	NE-till	83,8	3,5	5,7	70,4	16,1	96,9	80,5	0,92
Rn02-108	mp	NE-till	16,0	1,6	1,6	20,0	5,7	27,5	22,8	0,35
Rn02-109	mp	NE-till	63,8	2,0	1,4	17,6	6,6	24,2	20,1	0,39
Rn02-110	b	Marine	6,7	2,9	0,8	9,6	2,3	10,2	11,6	0,38

Observation point	Estonian soil abb.	Soil type	Radon measured (kBq/m^3)	K (%)	eU (ppm)	Radium (Bq/kg)	Th (ppm)	Radon calculated from ^{226}Ra[1] (kBq/m^3)	Radon calculated from ^{226}Ra[2] (kBq/m^3)	C
Rn02-111	mp	NE-till	20,9	2,8	1,6	19,2	8,0	26,4	22,0	0,51
Rn02-112	b	Marine	10,1	2,1	0,8	10,4	4,6	11,0	12,5	0,35
Rn02-113	lgl	Sand	33,0	3,3	2,9	35,2	13,0	34,8	43,3	0,71
Rn02-114	kla	Klint	123,0	2,5	12,5	153,5	11,7	171,5	190,8	1,01
Rn02-115	kla	Klint	111,1	2,3	10,7	131,9	13,1	147,4	163,9	0,94
Rn02-116	mp	NE-till	37,2	1,5	3,4	41,6	7,2	57,2	47,5	0,44
Rn02-117	mp	NE-till	25,5	1,9	1,6	19,2	6,0	26,4	22,0	0,38
Rn02-118	mp	NE-till	20,9	2,1	2,4	29,6	8,6	40,7	33,9	0,49
Rn02-119	mp	NE-till	54,5	1,4	8,3	101,5	8,3	139,8	116,2	0,65
Rn02-120	b	Marine	21,3	2,1	0,9	11,2	4,9	11,9	13,4	0,36
Rn02-121	kla	Klint	103,4	0,5	5,6	68,8	2,9	76,8	85,5	0,34
Rn02-122	mp	NE-till	34,1	1,5	5,1	62,4	8,2	85,9	71,4	0,53
Rn02-123	b	Marine	10,1	2,0	1,1	13,6	5,1	14,4	16,4	0,35
Rn02-124	kla	Klint	180,4	2,3	8,1	99,9	6,8	111,7	124,3	0,71
Rn02-125	mp	NE-till	315,5	2,0	20,4	251,0	9,3	345,7	287,2	1,22
Rn02-126	lgs	Clay	220,2	4,2	105,7	1300,0	12,0	1608,2	1801,8	5,01
Rn02-127	mp	NE-till	17,6	3,3	2,5	31,2	12,7	42,9	35,6	0,70
Rn02-128	lgl	Sand	31,4	2,5	3,2	39,2	9,4	38,7	48,2	0,58
Rn02-129	lgl	Sand	45,9	1,3	14,4	177,5	10,2	175,3	218,5	0,93
Rn02-130	mp	NE-till	77,0	1,0	6,5	80,0	5,7	110,1	91,4	0,49
Rn02-131	kla	Klint	97,9	0,9	15,9	195,9	5,4	218,8	243,5	0,85
Rn02-132	kla	Klint	103,0	2,5	6,8	83,1	13,4	92,9	103,4	0,81
Rn02-133	mp	NE-till	20,9	1,8	1,6	20,0	5,9	27,5	22,8	0,37
Rn02-134	mp	NE-till	16,2	1,4	0,9	11,2	3,9	15,4	12,8	0,26
Rn02-135	mp	NE-till	33,6	1,0	1,6	19,2	4,0	26,4	22,0	0,25
Rn02-136	lga	Silt	32,2	2,8	1,9	23,2	12,6	26,5	30,8	0,62
Rn02-137	mp	NE-till	40,7	2,3	2,1	25,6	10,1	35,2	29,2	0,52
Rn02-138	lga	Silt	26,8	2,9	1,8	22,4	11,0	25,6	29,7	0,59
Rn02-139	mp	NE-till	19,4	1,6	1,4	17,6	6,6	24,2	20,1	0,36
Rn02-140	mp	NE-till	19,4	2,5	1,8	22,4	11,9	30,8	25,6	0,57
Rn02-141	mp	NE-till	34,1	2,1	1,8	21,6	9,2	29,7	24,7	0,48
Rn02-142	lgl	Sand	30,2	2,8	2,3	28,0	11,7	27,6	34,4	0,62
Rn02-143	mp	NE-till	35,2	1,9	1,6	20,0	7,9	27,5	22,8	0,42
Rn02-144	mp	NE-till	20,9	1,8	1,0	12,8	7,0	17,6	14,7	0,36
Rn02-145	mp	NE-till	37,4	2,7	2,0	24,0	10,8	33,0	27,5	0,57
Rn02-146	lga	Silt	20,3	2,4	1,8	22,4	6,5	25,6	29,7	0,45
Rn02-147	lgl	Sand	19,0	2,7	2,5	31,2	10,4	30,8	38,4	0,59
Rn02-148	mp	NE-till	18,7	2,1	2,0	24,0	7,9	33,0	27,5	0,45
Rn02-149	mp	NE-till	18,7	2,0	2,1	26,4	8,2	36,3	30,2	0,46
Rn02-150	mp	NE-till	17,6	1,6	1,4	17,6	5,5	24,2	20,1	0,34
Rn02-151	lgl	Sand	17,9	2,5	2,1	25,6	7,4	25,3	31,5	0,49
Rn02-152	lgl	Sand	17,9	2,6	2,5	31,2	9,7	30,8	38,4	0,57
Rn02-153	lgl	Sand	10,1	2,5	2,0	24,0	6,3	23,7	29,6	0,47
Rn02-154	fgl	Fluviogl	32,5	2,1	2,5	31,2	7,0	45,1	36,7	0,46
Rn02-155	mp	NE-till	55,5	2,8	2,9	36,0	10,5	49,5	41,1	0,62
Rn02-156	mp	NE-till	55,0	2,7	3,3	40,8	11,7	56,1	46,7	0,65
Rn02-157	mp	NE-till	33,0	3,1	3,4	41,6	11,8	57,2	47,5	0,69
Rn02-158	mp	NE-till	8,3	1,6	1,6	19,2	8,3	26,4	22,0	0,40
Rn02-159	mp	NE-till	34,1	3,4	2,9	35,2	12,0	48,4	40,3	0,71
Rn02-160	mp	NE-till	31,9	2,8	2,0	24,0	8,5	33,0	27,5	0,54
Rn02-161	lgl	Sand	28,0	2,4	1,9	23,2	6,3	22,9	28,5	0,45

APPENDIX, sheet 4

Observation point	Estonian soil abb.	Soil type	Radon measured (kBq/m^3)	K (%)	eU (ppm)	Radium (Bq/kg)	Th (ppm)	Radon calculated from ^{226}Ra^1 (kBq/m^3)	Radon calculated from ^{226}Ra^2 (kBq/m^3)	C
Rn02-162	lgs	Clay	21,7	2,9	3,1	38,4	16,3	47,5	53,2	0,76
Rn02-163	lga	Silt	40,7	3,0	3,2	39,2	12,5	44,8	52,0	0,69
Rn02-164	mp	NE-till	53,9	2,7	3,4	41,6	10,8	57,2	47,5	0,63
Rn02-165	mp	NE-till	36,3	2,5	2,3	28,0	11,8	38,5	32,0	0,59
Rn02-166	mp	NE-till	37,4	2,9	2,9	35,2	13,3	48,4	40,3	0,69
Rn02-167	lga	Silt	18,2	2,7	2,9	36,0	11,7	41,2	47,8	0,64
Rn02-168	lga	Silt	36,6	3,1	2,6	32,0	14,3	36,6	42,4	0,72
Rn02-169	mp	NE-till	7,7	2,6	2,7	32,8	10,3	45,1	37,5	0,58
Rn02-170	mp	NE-till	7,1	1,7	1,8	21,6	7,0	29,7	24,7	0,39
Rn02-171	lgs	Clay	38,1	2,7	3,2	39,2	13,4	48,5	54,3	0,67
Rn02-172	fgl	Fluviogl	17,4	2,6	3,1	38,4	15,9	55,5	45,2	0,72
Rn02-173	mp	NE-till	33,0	1,0	1,3	16,0	3,8	22,0	18,3	0,23
Rn02-174	lga	Silt	36,6	2,8	3,3	40,0	11,1	45,7	53,1	0,64
Rn02-175	ml	SE-till	27,5	3,5	4,1	50,4	13,8	100,2	65,1	0,81
Rn02-176	lgs	Clay	61,0	3,8	4,4	53,6	15,3	66,3	74,3	0,88
Rn02-177	lgs	Clay	44,9	4,2	3,7	45,6	13,5	56,4	63,2	0,86
Rn02-178	ml	SE-till	30,8	2,7	3,3	40,8	8,8	81,1	52,7	0,59
Rn02-179	ml	SE-till	53,9	2,7	3,4	42,4	7,3	84,3	54,8	0,56
Rn02-180	lgl	Sand	9,0	1,0	1,4	17,6	5,6	17,4	21,6	0,28
Rn02-181	lgl	Sand	80,9	1,4	1,8	22,4	6,1	22,1	27,5	0,34
Rn02-182	lgl	Sand	4,5	2,3	2,1	26,4	8,0	26,1	32,5	0,48
Rn02-183	ml	SE-till	57,2	3,0	3,4	42,4	12,6	84,3	54,8	0,70
Rn02-184	ml	SE-till	125,4	3,2	4,4	53,6	12,4	106,6	69,3	0,75
Rn02-185	lgl	Sand	34,7	2,5	2,2	27,2	7,9	26,9	33,5	0,50
Rn02-186	ml	SE-till	59,4	2,5	3,0	36,8	10,7	73,2	47,5	0,60
Rn02-187	ml	SE-till	41,8	2,7	3,1	38,4	9,1	76,3	49,7	0,59
Rn02-188	lgl	Sand	14,6	2,3	2,0	24,8	10,9	24,5	30,5	0,54
Rn02-189	ml	SE-till	19,8	2,3	2,3	28,0	7,2	55,7	36,2	0,47
Rn02-190	ml	SE-till	115,5	2,6	3,1	37,6	10,3	74,8	48,6	0,60
Rn02-191	fgl	Fluviogl	12,8	2,1	1,6	20,0	6,8	28,9	13,9	0,42
Rn02-192	lgl	Sand	25,8	2,1	1,8	21,6	6,7	21,3	26,6	0,42
Rn02-193	ml	SE-till	26,4	2,4	2,5	30,4	11,1	60,4	39,3	0,57
Rn02-194	ml	SE-till	26,4	3,0	2,9	36,0	11,8	71,6	46,5	0,66
Rn02-195	ml	SE-till	116,8	2,6	3,3	40,8	11,9	81,1	52,7	0,64
Rn02-196	ml	SE-till	53,9	3,8	2,9	35,2	11,4	70,0	45,5	0,74
Rn02-197	lgl	Sand	9,0	2,5	1,8	22,4	7,0	22,1	27,5	0,47
Rn02-198	ml	SE-till	59,4	2,9	3,6	44,8	12,4	89,1	57,9	0,69
Rn02-199	ml	SE-till	72,6	2,7	3,4	41,6	11,2	82,7	53,8	0,64
Rn02-200	ml	SE-till	16,5	3,4	2,1	25,6	12,9	50,9	33,0	0,69
Rn02-201	mp	NE-till	11,0	2,6	2,5	31,2	10,6	42,9	35,6	0,58
Rn02-202	mp	NE-till	14,3	1,3	0,9	11,2	4,4	15,4	12,8	0,26
Rn02-203	mp	NE-till	19,8	2,9	1,6	19,2	11,4	26,4	22,0	0,59
Rn02-204	mp	NE-till	17,6	1,1	0,7	8,0	4,8	11,0	9,2	0,24
Rn02-205	mp	NE-till	25,3	2,3	1,4	16,8	9,4	23,1	19,2	0,48
Rn02-206	fgl	Fluviogl	19,1	2,1	1,2	14,4	9,6	20,8	16,9	0,45
Rn02-207	mp	NE-till	42,9	1,7	2,1	25,6	5,9	35,2	29,2	0,38
Rn02-208	fgl	Fluviogl	37,1	2,7	1,9	23,2	7,2	33,5	27,3	0,50
Rn02-209	lgs	Clay	52,4	3,4	2,9	35,2	14,2	43,5	48,8	0,76
Rn02-210	lgl	Sand	71,7	0,5	10,1	124,7	4,5	123,2	153,6	0,56
Rn02-211	lga	Silt	30,8	1,6	11,2	138,3	7,5	158,2	183,6	0,77
Rn02-212	fgl	Fluviogl	78,9	0,9	7,2	87,9	6,5	127,3	103,6	0,52

Observation point	Estonian soil abb.	Soil type	Radon measured (kBq/m^3)	K (%)	eU (ppm)	Radium (Bq/kg)	Th (ppm)	Radon calculated from ^{226}Ra^1 (kBq/m^3)	Radon calculated from ^{226}Ra^2 (kBq/m^3)	C
Rn02-213	lgl	Sand	5,6	2,4	0,8	9,6	3,8	9,5	11,8	0,36
Rn02-214	lga	Silt	22,4	3,4	2,7	33,6	12,9	38,4	46,1	0,72
Rn02-215	ml	SE-till	29,7	3,4	2,5	30,4	13,7	60,4	39,3	0,73
Rn02-216	ml	SE-till	36,6	3,6	3,0	36,8	16,0	73,2	47,5	0,81
Rn02-217	mp	NE-till	35,2	2,8	1,7	20,8	12,2	28,6	26,9	0,60
Rn02-218	mp	NE-till	36,3	3,1	2,9	35,2	15,7	48,4	45,5	0,75
Rn02-219	mp	NE-till	17,6	2,9	2,1	26,4	13,4	36,3	34,1	0,66
Rn02-22	t	Tekn	39,4	2,9	18,9	231,9	9,2	291,7	291,3	1,25
Rn02-220	ml	SE-till	21,6	2,4	1,4	17,6	6,6	35,0	22,8	0,44
Rn02-221	lgl	Sand	11,2	2,1	1,2	15,2	10,6	15,0	18,7	0,48
Rn02-222	lgl	Sand	9,0	1,3	0,7	8,0	3,4	7,9	9,9	0,23
Rn02-223	kla	Klint	20,8	1,4	6,5	80,0	8,4	89,3	99,4	0,58
Rn02-224	mp	NE-till	38,6	2,0	2,3	28,8	7,0	39,6	32,9	0,44
Rn02-226	mp	NE-till	28,6	2,9	2,1	26,4	12,5	36,3	34,1	0,64
Rn02-227	mp	NE-till	41,8	2,9	2,3	28,0	11,2	38,5	36,2	0,62
Rn02-228	mp	NE-till	22,0	2,1	1,2	14,4	9,2	19,8	18,6	0,45
Rn02-229	lgl	Sand	32,5	3,0	2,0	24,0	10,2	23,7	29,6	0,59
Rn02-230	lga	Silt	21,4	3,0	2,1	25,6	10,2	29,3	33,9	0,60
Rn02-231	lgl	Sand	15,7	1,8	1,0	12,0	6,1	11,8	14,7	0,34
Rn02-232	lga	Silt	17,1	2,4	1,7	20,8	7,6	23,8	27,6	0,47
Rn02-233	lgl	Sand	3,4	2,6	1,6	19,2	7,6	19,0	23,7	0,48
Rn02-234	lga	Silt	80,3	2,9	2,4	29,6	11,5	33,8	39,3	0,62
Rn02-235	lga	Silt	21,4	3,0	2,7	33,6	14,2	38,4	44,6	0,70
Rn02-236	ml	SE-till	33,0	2,5	2,5	30,4	10,3	60,4	39,3	0,57
Rn02-237	ml	SE-till	27,5	2,9	2,0	24,8	12,0	49,3	32,1	0,63
Rn02-238	lgs	Clay	21,4	3,6	2,6	32,0	15,7	39,6	44,3	0,80
Rn02-239	ml	SE-till	66,0	3,3	1,9	23,2	13,9	46,1	30,0	0,69
Rn02-240	ml	SE-till	40,7	3,2	2,8	34,4	15,2	68,4	44,5	0,75
Rn02-241	ml	SE-till	48,4	2,8	1,4	17,6	12,5	35,0	22,8	0,60
Rn02-242	ml	SE-till	26,4	2,2	1,9	23,2	9,5	46,1	30,0	0,50
Rn02-243	lgl	Sand	21,3	2,0	1,3	16,0	6,8	15,8	19,7	0,39
Rn02-244	ml	SE-till	27,5	3,3	1,6	20,0	11,4	39,8	25,8	0,63
Rn02-245	ml	SE-till	35,2	3,2	1,6	19,2	10,7	38,2	24,8	0,61
Rn02-246	ml	SE-till	6,6	2,9	1,3	16,0	9,2	31,8	20,7	0,54
Rn02-247	lgs	Clay	125,2	4,2	2,4	29,6	17,5	36,6	41,0	0,88
Rn02-248	ml	SE-till	22,0	2,8	1,8	21,6	10,7	42,9	27,9	0,57
Rn02-249	lgl	Sand	21,3	1,6	0,5	5,6	3,8	5,5	6,9	0,26
Rn02-250	ml	SE-till	34,1	3,6	2,6	32,0	15,8	63,6	41,4	0,80
Rn02-251	lgs	Clay	51,4	3,3	2,4	29,6	16,3	36,6	41,0	0,77
Rn02-252	fgl	Fluviogl	5,8	1,9	0,7	8,8	5,8	12,7	10,4	0,34
Rn02-253	lga	Silt	520,0	3,0	14,4	176,7	14,2	202,1	234,5	1,18
Rn02-254	mp	NE-till	95,7	1,6	5,9	72,0	9,5	99,1	82,3	0,60
Rn02-616	kla	Klint	30,8	0,1	16,9	207,9	3,4	232,2	258,4	0,77
Rn02-716	kla	Klint	24,2	0,1	6,4	78,4	3,4	87,5	97,4	0,34
Rn02-823	kla	Klint	101,2	0,5	16,3	200,7	5,7	224,2	249,5	0,83
Rn02-923	kla	Klint	107,8	2,2	4,6	56,8	11,5	63,4	70,6	0,65
Rn03-255	b	Marine	4,0	0,6	0,3	4,0	2,1	4,2	4,8	0,12
Rn03-256	mp	NE-till	12,0	0,8	0,4	4,8	2,7	6,6	5,5	0,15
Rn03-257	fgl	Fluviogl	11,0	1,2	1,1	13,6	3,4	19,7	16,0	0,24
Rn03-258	fgl	Fluviogl	6,0	1,0	0,5	5,6	3,1	8,1	6,6	0,19
Rn03-259	fgl	Fluviogl	7,0	1,3	0,9	11,2	4,2	16,2	13,2	0,25

APPENDIX, sheet 6

Observation point	Estonian soil abb.	Soil type	Radon measured (kBq/m^3)	K (%)	eU (ppm)	Radium (Bq/kg)	Th (ppm)	Radon calculated from $^{226}Ra^1$ (kBq/m^3)	Radon calculated from $^{226}Ra^2$ (kBq/m^3)	C
Rn03-260	fgl	Fluviogl	8,0	1,2	1,0	12,0	4,6	17,4	14,1	0,26
Rn03-261	fgl	Fluviogl	2,0	1,0	0,9	11,2	3,4	16,2	13,2	0,21
Rn03-262	fgl	Fluviogl	12,0	1,8	1,6	20,0	6,2	28,9	23,6	0,37
Rn03-263	fgl	Fluviogl	20,0	0,8	0,4	4,8	2,7	6,9		0,15
Rn03-264	fgl	Fluviogl	19,0	2,6	1,2	14,4	5,9	20,8	16,9	0,43
Rn03-265	fgl	Fluviogl	44,0	2,2	1,0	12,8	5,5	18,5	15,1	0,38
Rn03-266	fgl	Fluviogl	11,0	2,4	1,3	16,0	6,5	23,1	18,8	0,43
Rn03-267	lgl	Sand	12,0	2,3	1,9	23,2	12,3	22,9	28,5	0,56
Rn03-268	lgl	Sand	11,0	2,1	1,8	22,4	10,0	22,1	27,5	0,49
Rn03-269	fgl	Fluviogl	25,0	1,5	1,0	12,8	4,4	18,5	15,1	0,28
Rn03-270	fgl	Fluviogl	7,0	0,8	0,5	6,4	2,7	9,3	7,5	0,16
Rn03-271	fgl	Fluviogl	12,0	0,8	0,7	8,0	2,1	11,6	9,4	0,16
Rn03-272	fgl	Fluviogl	43,0	0,8	0,6	7,2	2,7	10,4	8,5	0,17
Rn03-273	fgl	Fluviogl	7,0	1,7	0,5	5,6	4,5	8,1	6,6	0,28
Rn03-274	lgl	Sand	11,0	1,7	3,7	45,6	16,6	45,0	56,1	0,66
Rn03-275	b	Marine	8,0	1,7	0,7	8,0	4,4	8,5	9,6	0,29
Rn03-276	mp	NE-till	50,0	1,5	4,2	52,0	8,3	71,6	59,5	0,49
Rn03-277	mp	NE-till	82,0	1,8	13,6	167,1	7,3	230,1	191,2	0,88
Rn03-278	b	Marine	6,0	2,6	0,8	9,6	3,5	10,2	11,6	0,37
Rn03-279	b	Marine	10,0	2,1	1,2	15,2	10,5	16,1	18,3	0,47
Rn03-280	fgl	Fluviogl	15,0	3,4	2,1	25,6	13,4	37,0	30,1	0,70
Rn03-300	kla	Klint	91,0	1,3	8,8	108,7	5,5	121,5	135,2	0,61
Rn03-301	kla	Klint	215,0	5,5	25,4	312,6	10,6	349,2	388,6	1,82
Rn03-302	kla	Klint	377,0	5,7	27,0	332,6	13,3	371,6	413,4	1,96
Rn03-303	mp	NE-till	138,0	1,2	8,1	99,9	6,8	137,6	114,3	0,59
Rn03-304	kla	Klint	158,0	4,7	54,0	663,6	12,4	741,4	824,8	2,95
Rn03-305	kla	Klint	52,0	2,9	6,5	80,0	11,6	89,3	99,4	0,80
Rn03-501	ml	SE-till	50,0	3,0	1,7	20,8	12,9	41,4	26,9	0,64
Rn03-502	ml	SE-till	58,0	1,7	1,4	16,8	6,2	33,4	21,7	0,36
Rn03-503	ml	SE-till	0,0	2,0	1,6	19,2	7,8	38,2	24,8	0,42
Rn03-504	lgl	Sand	0,0	3,1	1,6	19,2	8,8	19,0	23,7	0,56
Rn03-505	lgl	Sand	29,0	2,5	1,3	16,0	8,0	15,8	19,7	0,47
Rn03-506	ml	SE-till	0,0	3,1	2,0	24,8	8,2	49,3	32,1	0,56
Rn03-507	ml	SE-till	44,0	3,3	2,0	24,8	10,4	49,3	32,1	0,63
Rn03-508	ml	SE-till	51,0	3,3	1,9	23,2	9,1	46,1	30,0	0,60
Rn03-509	ml	SE-till	19,0	4,0	1,3	16,0	10,1	31,8	20,7	0,67
Rn03-510	ml	SE-till	35,0	3,4	2,1	25,6	10,9	50,9	33,0	0,65
Rn03-511	ml	SE-till	71,0	2,3	2,3	28,8	6,8	57,3	37,2	0,47
Rn03-512	ml	SE-till	78,0	2,6	3,5	43,2	10,3	85,9	55,8	0,62
Rn03-513	lgl	Sand	25,0	2,1	1,4	17,6	6,6	17,4	21,6	0,41
Rn03-514	ml	SE-till	0,0	2,1	1,3	16,0	7,7	31,8	20,7	0,42
Rn03-515	lgl	Sand	44,0	2,3	1,3	16,0	6,0	15,8	19,7	0,41
Rn03-516	fgl	Fluviogl	41,0	1,8	1,3	16,0	7,0	23,1	18,8	0,37
Rn03-517	ml	SE-till	0,0	2,3	1,8	22,4	7,9	44,5	28,9	0,48
Rn03-518	ml	SE-till	38,0	2,6	2,0	24,8	10,5	49,3	32,1	0,56
Rn03-519	lgl	Sand	11,0	1,7	0,7	8,8	2,5	8,7	10,9	0,25
Rn03-520	fgl	Fluviogl	3,0	0,9	0,4	4,8	3,3	6,9	5,7	0,18
Rn03-521	fgl	Fluviogl	35,0	2,7	1,6	20,0	8,7	28,9	23,6	0,52
Rn03-522	ml	SE-till	6,0	3,0	1,8	22,4	9,5	44,5	28,9	0,57
Rn03-523	ml	SE-till	34,0	2,7	1,6	20,0	7,3	39,8	25,8	0,49
Rn03-524	ml	SE-till	48,0	3,4	2,0	24,0	8,9	47,7	31,0	0,61

Observation point	Estonian soil abb.	Soil type	Radon measured (kBq/m^3)	K (%)	eU (ppm)	Radium (Bq/kg)	Th (ppm)	Radon calculated from ^{226}Ra[1] (kBq/m^3)	Radon calculated from ^{226}Ra[2] (kBq/m^3)	C
Rn03-525	fgl	Fluviogl	25,0	1,5	1,2	14,4	6,2	20,8	16,9	0,33
Rn03-526	fgl	Fluviogl	21,0	2,6	1,2	15,2	6,2	22,0	17,9	0,44
Rn03-527	ml	SE-till	0,0	2,3	1,8	22,4	8,4	44,5	28,9	0,48
Rn03-528	fgl	Fluviogl	11,0	2,4	1,0	12,8	6,3	18,5	15,1	0,42
Rn03-529	ml	SE-till	47,0	2,5	1,8	21,6	8,9	42,9	27,9	0,51
Rn03-530	fgl	Fluviogl	3,0	1,6	0,7	8,8	3,8	12,7	10,4	0,27
Rn03-531	fgl	Fluviogl	37,0	1,9	1,4	16,8	6,2	24,3	19,8	0,38
Rn03-532	fgl	Fluviogl	28,0	1,0	0,8	9,6	3,4	13,9	11,3	0,21
Rn03-533	mp	NE-till	31,0	2,4	2,1	26,4	7,8	36,3	34,1	0,49
Rn03-534	fgl	Fluviogl	13,0	2,7	2,1	26,4	8,3	38,2	31,1	0,53
Rn03-535	fgl	Fluviogl	18,0	2,2	2,0	24,0	7,2	34,7	28,3	0,45
Rn03-536	fgl	Fluviogl	42,0	2,4	1,9	23,2	9,4	33,5	27,3	0,51
Rn03-537	lgl	Sand	0,0	1,6	0,8	10,4	5,4	10,3	12,8	0,30
Rn03-538	fgl	Fluviogl	0,0	0,8	0,7	8,0	1,9	11,6	9,4	0,14
Rn03-539	mp	NE-till	7,0	0,1	0,1	0,8	0,3	1,1	0,9	0,02
Rn03-540	fgl	Fluviogl	78,0	0,5	0,2	2,4	1,0	3,5	2,8	0,08
Rn03-542	kla	Klint	160,0	1,4	6,8	83,1	10,6	92,9	103,4	0,63
Rn03-543	kla	Klint	305,0	2,3	7,5	92,7	13,8	103,6	115,3	0,83
Rn03-544	lgl	Sand	5,0	1,1	4,2	51,2	8,8	50,6	63,0	0,46
Rn03-545	mp	NE-till	29,0	2,7	3,1	38,4	12,1	52,8	43,9	0,65
Rn03-546	b	Marine	0,0	1,4	0,3	4,0	2,5	4,2	4,8	0,21
Rn03-547	b	Marine	0,0	2,9	1,0	12,0	5,6	12,7	14,4	0,45
Rn03-548	fgl	Fluviogl	42,0	2,3	3,3	40,0	11,8	57,8	47,1	0,61
Rn03-549	mp	NE-till	52,0	0,9	1,9	23,2	5,1	31,9	26,5	0,27
Rn03-550	lgl	Sand	108,0	2,5	2,9	35,2	8,5	34,8	43,3	0,55
Rn03-551	fgl	Fluviogl	8,0	1,6	0,8	9,6	4,3	13,9	11,3	0,29
Rn03-552	kla	Klint	29,0	1,0	7,7	95,1	5,6	106,3	118,3	0,53
Rn03-553	kla	Klint	15,0	0,8	7,1	87,1	5,9	97,4	108,3	0,49
Rn03-554	kla	Klint	105,0	1,0	7,5	92,7	5,8	103,6	115,3	0,53
Rn03-555	lgl	Sand	7,0	1,6	0,8	9,6	5,0	9,5	11,8	0,29
Rn03-556	kla	Klint	70,0	2,1	3,3	40,8	6,9	45,6	50,7	0,49
Rn03-557	kla	Klint	213,0	0,5	11,1	135,9	4,1	151,8	169,0	0,59
Rn03-558	kla	Klint	193,0	1,9	9,6	118,3	7,7	132,2	147,1	0,74
Rn03-560	b	Marine	2,0	2,0	0,7	8,0	4,5	8,5	9,6	0,32
Rn03-561	kla	Klint	85,0	1,8	11,7	143,9	7,3	160,8	178,8	0,81
Rn03-562	kla	Klint	55,0	0,6	18,1	222,3	9,4	248,3	276,3	0,99
Rn03-563	kla	Klint	100,0	1,6	19,4	239,1	5,8	267,1	297,2	1,07
Rn03-564	lga	Silt	0,0	1,1	4,3	52,8	4,7	60,4	70,1	0,38
Rn03-565	lga	Silt	113,0	1,8	7,5	92,7	7,0	106,1	123,1	0,64
Rn03-566	mp	NE-till	22,0	1,4	1,2	14,4	4,7	19,8	16,4	0,28
Rn03-567	mp	NE-till	0,0	1,9	1,4	17,6	9,2	24,2	20,1	0,44
Rn03-568	mp	NE-till	29,0	1,5	1,1	13,6	4,8	18,7	15,6	0,30
Rn03-569	lga	Silt	27,0	2,7	1,7	20,8	9,0	23,8	27,6	0,53
Rn03-570	mp	NE-till	29,0	2,4	1,8	21,6	8,6	29,7	24,7	0,49
Rn03-571	lga	Silt	0,0	3,2	2,7	32,8	18,5	37,5	43,5	0,81
Rn03-572	ml	SE-till	11,0	2,3	1,4	16,8	7,8	33,4	21,7	0,45
Rn03-573	b	Marine	0,0	1,0	0,4	4,8	2,8	5,1	5,8	0,18
Rn03-574	b	Marine	0,0	1,0	0,3	3,2	3,3	3,4	3,9	0,18
Rn03-575	b	Marine	3,0	0,9	0,4	4,8	2,0	5,1	5,8	0,15
Rn03-576	ml	SE-till	0,0	2,6	1,2	14,4	7,6	28,6	18,6	0,47
Rn03-577	lgl	Sand	11,0	1,7	0,7	8,8	5,5	8,7	10,9	0,31

APPENDIX, sheet 8

Observation point	Estonian soil abb.	Soil type	Radon measured (kBq/m^3)	K (%)	eU (ppm)	Radium (Bq/kg)	Th (ppm)	Radon calculated from ^{226}Ra^1 (kBq/m^3)	Radon calculated from ^{226}Ra^2 (kBq/m^3)	C
Rn03-578	ml	SE-till	10,0	3,4	1,6	20,0	9,8	39,8	25,8	0,62
Rn03-579	ml	SE-till	9,0	3,0	2,1	26,4	10,1	52,5	34,1	0,60
Rn03-580	ml	SE-till	29,0	2,9	2,3	28,8	11,6	57,3	37,2	0,62
Rn03-581	fgl	Fluviogl	6,0	1,4	0,7	8,8	2,7	12,7	10,4	0,22
Rn03-582	lga	Silt	19,0	2,6	2,3	28,8	10,5	32,9	38,2	0,58
Rn03-583	b	Marine	2,0	1,5	0,2	2,4	1,6	2,5	2,9	0,19
Rn03-584	mp	NE-till	13,0	2,2	1,1	13,6	8,3	18,7	17,6	0,44
Rn03-585	lgl	Sand	31,0	2,1	1,0	12,0	8,1	11,8	14,7	0,42
Rn03-586	mp	NE-till	12,0	2,4	1,6	19,2	7,2	26,4	22,0	0,46
Rn03-587	mp	NE-till	33,0	2,1	1,0	12,8	8,1	17,6	14,7	0,43
Rn03-588	lgl	Sand	4,0	1,0	1,3	16,0	9,0	15,8	19,7	0,34
Rn03-589	b	Marine	17,0	0,2	9,3	114,3	4,3	121,4	137,6	0,49
Rn03-600a	ml	SE-till	51,0	3,6	2,1	26,4	8,8	52,5	34,1	0,63
Rn03-600b	ml	SE-till	72,0	3,6	1,9	23,2	9,6	46,1	30,0	0,65
Rn03-600c	ml	SE-till	72,0	3,6	2,1	25,6	11,7	50,9	33,0	0,70
Rn03-601	b	Marine	9,0	2,1	0,7	8,8	4,4	9,3	10,6	0,33
Rn03-602	lgs	Clay	0,0	4,0	3,4	41,6	16,3	51,4	57,6	0,88
Rn03-605	lga	Silt	72,0	1,1	1,9	23,2	7,3	26,5	30,8	0,34
Rn03-606	lga	Silt	100,0	1,8	5,1	62,4	11,2	71,3	82,8	0,61
Rn03-607	b	Marine	25,0	1,9	1,8	22,4	3,8	23,8	27,0	0,35
Rn03-608	b	Marine	14,0	1,9	1,7	20,8	4,4	22,1	25,0	0,35
Rn03-609	b	Marine	8,0	2,0	0,5	6,4	3,7	6,8	7,7	0,30
Rn03-610	lgs	Clay	0,0	3,2	2,3	28,8	20,3	35,6	39,9	0,83
Rn03-611	lga	Silt	29,0	2,5	1,6	20,0	4,0	22,9	26,6	0,40
Rn03-612	mp	NE-till	44,0	1,4	1,3	16,0	5,3	22,0	18,3	0,31
Rn03-613	lga	Silt	47,0	2,4	1,5	18,4	7,8	21,0	24,4	0,47
Rn03-614	lgs	Clay	0,0	3,8	2,7	33,6	14,3	41,5	46,6	0,79
Rn03-615	ml	SE-till	8,0	2,7	1,8	21,6	9,8	42,9	27,9	0,55
Rn03-616	ml	SE-till	0,0	3,1	2,1	26,4	8,9	52,5	34,1	0,59
Rn03-617	ml	SE-till	79,0	3,2	2,9	36,0	11,5	71,6	46,5	0,68
Rn03-618	ml	SE-till	0,0	3,5	2,6	32,0	14,1	63,6	41,4	0,75
Rn03-619	ml	SE-till	0,0	3,4	2,1	26,4	10,7	52,5	34,1	0,66
Rn03-620	ml	SE-till	200,0	4,4	4,0	48,8	18,0	97,0	63,1	0,97
Rn03-621	ml	SE-till	127,0	3,1	2,0	24,0	10,0	47,7	31,0	0,60
Rn03-622	ml	SE-till	43,0	3,4	2,0	24,8	9,9	49,3	32,1	0,63
Rn03-623	lga	Silt	5,0	2,6	1,5	18,4	7,2	21,0	24,4	0,47
Rn03-624	lga	Silt	9,0	2,6	1,6	19,2	7,0	22,0	25,4	0,47
Rn03-625	lga	Silt	7,0	4,0	1,9	23,2	12,4	26,5	30,8	0,74
Rn03-626	ml	SE-till	0,0	3,3	2,7	32,8	8,5	65,2	42,4	0,62
Rn03-627	lga	Silt	0,0	3,1	2,1	25,6	8,6	29,3	33,9	0,57
Rn03-628	ml	SE-till	0,0	3,1	2,0	24,8	10,6	49,3	32,1	0,62
Rn03-629	lgl	Sand	36,0	2,5	1,2	15,2	7,3	15,0	18,7	0,46
Rn03-630	lgl	Sand	39,0	2,6	1,4	16,8	6,7	16,6	20,7	0,46
Rn03-631	lga	Silt	0,0	2,5	1,7	20,8	7,7	23,8	27,6	0,49
Rn03-632	lgl	Sand	0,0	0,3	0,1	0,8	1,9	0,8	1,0	0,07
Rn03-633	ml	SE-till	59,0	2,9	1,9	23,2	10,1	46,1	30,0	0,57
Rn03-634	ml	SE-till	21,0	2,9	2,1	26,4	11,5	52,5	34,1	0,62
Rn03-635	ml	SE-till	139,0	3,3	2,1	26,4	11,4	52,5	34,1	0,66
Rn03-636	ml	SE-till	74,0	2,5	2,0	24,8	8,2	49,3	32,1	0,50
Rn03-637	ml	SE-till	34,0	2,5	1,4	16,8	7,1	33,4	21,7	0,45
Rn03-638	ml	SE-till	0,0	3,6	2,0	24,0	13,7	47,7	31,0	0,72

Observation point	Estonian soil abb.	Soil type	Radon measured (kBq/m^3)	K (%)	eU (ppm)	Radium (Bq/kg)	Th (ppm)	Radon calculated from ^{226}Ra^1 (kBq/m^3)	Radon calculated from ^{226}Ra^2 (kBq/m^3)	C
Rn03-639	ml	SE-till	6,0	2,6	1,6	19,2	7,4	38,2	24,8	0,48
Rn03-640	fgl	Fluviogl	39,0	2,3	1,6	20,0	7,0	28,9	23,6	0,44
Rn03-641	ml	SE-till	14,0	2,9	1,4	17,6	8,6	35,0	22,8	0,53
Rn03-642	ml	SE-till	48,0	3,1	1,8	22,4	9,0	44,5	28,9	0,58
Rn03-643	lga	Silt	73,0	2,5	1,5	18,4	7,2	21,0	24,4	0,47
Rn03-644	ml	SE-till	11,0	3,3	2,4	29,6	9,6	58,8	38,2	0,63
Rn03-645	lgs	Clay	0,0	3,7	3,0	36,8	14,1	45,5	50,9	0,79
Rn03-646	ml	SE-till	40,0	3,1	1,7	20,8	7,3	41,4	26,9	0,53
Rn03-647	ml	SE-till	100,0	3,6	2,3	28,0	10,8	55,7	36,2	0,69
Rn03-648	ml	SE-till	72,0	3,4	2,0	24,0	11,9	47,7	31,0	0,67
Rn03-649	ml	SE-till	36,0	3,1	2,0	24,0	8,4	47,7	31,0	0,57
Rn03-650	ml	SE-till	44,0	3,3	2,2	27,2	11,1	54,1	35,2	0,65
Rn03-651	ml	SE-till	17,0	2,6	2,1	25,6	8,5	50,9	33,0	0,52
Rn03-652	ml	SE-till	21,0	3,3	2,0	24,0	9,7	47,7	31,0	0,62
Rn03-653	ml	SE-till	87,0	3,2	1,8	21,6	10,7	42,9	27,9	0,62
Rn03-654	ml	SE-till	0,0	3,7	2,8	34,4	10,7	68,4	44,5	0,71
Rn03-655	ml	SE-till	84,0	3,3	2,1	26,4	11,2	52,5	34,1	0,65
Rn03-656	ml	SE-till	44,0	2,9	2,2	27,2	8,6	54,1	35,2	0,56
Rn03-657	ml	SE-till	33,0	2,9	1,8	22,4	10,9	44,5	28,9	0,60
Rn03-658	ml	SE-till	0,0	3,8	2,7	32,8	12,4	65,2	42,4	0,75
Rn03-659	ml	SE-till	59,0	2,5	1,8	22,4	8,9	44,5	28,9	0,51
Rn03-660	ml	SE-till	95,0	3,1	2,3	28,0	13,3	55,7	36,2	0,68
Rn03-661	ml	SE-till	0,0	3,4	2,3	28,8	12,5	57,3	37,2	0,70
Rn03-662	ml	SE-till	0,0	4,4	3,4	41,6	17,8	82,7	53,8	0,94
Rn03-663	ml	SE-till	0,0	3,9	3,0	36,8	15,9	73,2	47,5	0,84
Rn03-664	ml	SE-till	120,0	4,2	3,4	41,6	17,2	82,7	53,8	0,92
Rn03-665	ml	SE-till	121,0	2,8	2,2	27,2	9,4	54,1	35,2	0,57
Rn03-666	lgl	Sand	19,0	2,2	0,7	8,0	4,3	7,9	9,9	0,34
Rn03-667	ml	SE-till	56,0	3,1	2,8	34,4	11,2	68,4	44,5	0,66
Rn03-668	ml	SE-till	77,0	2,7	1,7	20,8	8,5	41,4	26,9	0,51
Rn03-669	ml	SE-till	0,0	3,4	2,5	31,2	10,7	62,0	40,3	0,67
Rn03-670	ml	SE-till	196,0	3,6	3,1	37,6	13,3	74,8	48,6	0,76
Rn03-671	ml	SE-till	0,0	3,1	2,1	26,4	8,6	52,5	34,1	0,58
Rn03-672	ml	SE-till	7,0	3,3	2,0	24,0	10,5	47,7	31,0	0,63
Rn03-673	lgl	Sand	3,0	2,1	0,7	8,8	3,6	8,7	10,9	0,32
Rn03-674	ml	SE-till	121,0	3,1	2,3	28,0	11,0	55,7	36,2	0,64
Rn03-675	ml	SE-till	24,0	3,6	3,1	37,6	12,2	74,8	48,6	0,75
Rn03-676	ml	SE-till	18,0	3,3	2,5	30,4	10,0	60,4	39,3	0,64
Rn03-677	ml	SE-till	36,0	3,6	2,0	24,0	9,9	47,7	31,0	0,65
Rn03-678	fgl	Fluviogl	27,0	2,4	0,8	10,4	4,5	15,0	12,2	0,37
Rn03-679	ml	SE-till	59,0	3,4	2,3	28,0	13,2	55,7	36,2	0,71
Rn03-680	ml	SE-till	47,0	3,3	1,8	22,4	10,3	44,5	28,9	0,62
Rn03-681	ml	SE-till	21,0	3,1	1,0	12,8	5,1	25,4	16,5	0,47
Rn03-682	lgl	Sand	39,0	2,3	0,8	10,4	4,9	10,3	12,8	0,38
Rn03-683	ml	SE-till	92,0	2,7	2,5	30,4	10,9	60,4	39,3	0,60
Rn03-684	ml	SE-till	111,0	3,0	2,3	28,8	12,7	57,3	37,2	0,66
Rn03-685	ml	SE-till	60,0	3,0	1,9	23,2	11,6	46,1	30,0	0,62
Rn03-686	lgl	Sand	6,0	3,4	0,9	11,2	5,7	11,1	13,8	0,51
Rn03-687	ml	SE-till	176,0	3,3	3,3	40,8	12,4	81,1	52,7	0,72
Rn03-688	ml	SE-till	75,0	2,5	1,9	23,2	8,4	46,1	30,0	0,50
Rn03-689	ml	SE-till	41,0	2,8	2,3	28,0	11,1	55,7	36,2	0,60

Observation point	Estonian soil abb.	Soil type	Radon measured (kBq/m^3)	K (%)	eU (ppm)	Radium (Bq/kg)	Th (ppm)	Radon calculated from ^{226}Ra^1 (kBq/m^3)	Radon calculated from ^{226}Ra^2 (kBq/m^3)	C
Rn03-690	ml	SE-till	30,0	2,5	1,2	14,4	8,5	28,6	18,6	0,48
Rn03-691	ml	SE-till	95,0	3,0	2,3	28,0	11,3	55,7	36,2	0,63
Rn03-692	lgl	Sand	5,0	2,9	0,8	10,4	4,2	10,3	12,8	0,41
Rn03-693	ml	SE-till	0,0	4,0	2,2	27,2	10,6	54,1	35,2	0,72
Rn03-694	ml	SE-till	98,0	3,0	1,9	23,2	10,3	46,1	30,0	0,59
Rn03-695	ml	SE-till	40,0	3,4	1,6	19,2	6,6	38,2	24,8	0,55
Rn03-696	lgl	Sand	9,0	2,9	1,7	20,8	7,9	20,5	25,6	0,52
Rn03-697	ml	SE-till	47,0	3,8	1,9	23,2	7,5	46,1	30,0	0,62
Rn03-698	fgl	Fluviogl	9,0	2,9	0,8	10,4	5,3	15,0	12,2	0,44
Rn03-699	lga	Silt	30,0	3,0	2,7	32,8	14,2	37,5	43,5	0,70
Rn03-700	lgs	Clay	0,0	3,5	3,3	40,8	16,8	50,4	56,5	0,83
Rn03-701	fgl	Fluviogl	66,0	2,5	1,7	20,8	9,9	30,1	24,5	0,52
Rn03-702	lga	Silt	8,0	3,3	0,6	7,2	3,6	8,2	9,6	0,44
Rn03-703	ml	SE-till	0,0	3,2	4,0	48,8	18,9	97,0	63,1	0,87
Rn03-704	lgs	Clay	0,0	3,5	3,8	46,4	15,6	57,4	64,2	0,83
Rn03-705	mp	NE-till	52,0	2,5	1,4	17,6	9,2	24,2	20,1	0,50
Rn03-706	mp	NE-till	41,0	2,5	1,6	20,0	8,4	27,5	22,8	0,49
Rn03-707	lgs	Clay	0,0	3,3	3,5	43,2	19,4	53,4	59,9	0,87
Rn03-708	lga	Silt	45,0	2,8	2,2	27,2	7,2	31,1	36,0	0,52
Rn03-709	mp	NE-till	0,0	3,1	1,8	22,4	11,7	30,8	25,6	0,62
Rn03-710	lgs	Clay	0,0	3,3	3,5	43,2	12,5	53,4	59,9	0,74
Rn03-711	mp	NE-till	109,0	3,0	2,0	24,0	14,0	33,0	27,5	0,67
Rn03-712	mp	NE-till	157,0	2,6	2,6	32,0	10,5	44,0	36,6	0,59
Rn03-713	mp	NE-till	41,0	1,4	1,0	12,0	5,3	16,5	13,7	0,29
Rn03-714	mp	NE-till	14,0	2,3	1,8	21,6	9,0	29,7	24,7	0,49
Rn03-715	lga	Silt	0,0	2,5	1,6	20,0	7,9	22,9	26,6	0,48
Rn03-716	lga	Silt	0,0	2,6	0,8	10,4	6,0	11,9	13,8	0,42
Rn03-717	lga	Silt	21,0	2,1	1,2	14,4	6,9	16,5	19,1	0,40
Rn03-718	mp	NE-till	21,0	1,7	1,2	14,4	6,0	19,8	16,4	0,34
Rn03-719	lgs	Clay	0,0	2,9	3,0	36,8	12,1	45,5	50,9	0,67
Rn03-720	mp	NE-till	57,0	2,6	2,7	33,6	13,7	46,2	38,4	0,65
Rn03-721	mp	NE-till	28,0	2,4	1,0	12,0	6,6	16,5	13,7	0,42
Rn03-722	lgl	Sand	21,0	1,9	0,8	9,6	5,4	9,5	11,8	0,33
Rn03-723	mp	NE-till	18,0	2,7	1,9	23,2	8,7	31,9	26,5	0,53
Rn03-724	mp	NE-till	22,0	1,4	0,8	10,4	5,3	14,3	11,9	0,28
Rn03-725	lgs	Clay	0,0	2,9	3,7	45,6	18,8	56,4	63,2	0,83
Rn03-726	lgs	Clay	0,0	2,8	4,0	49,6	19,9	61,3	68,7	0,85
Rn03-727	lga	Silt	8,0	2,1	1,1	13,6	7,7	15,5	18,1	0,42
Rn03-728	mp	NE-till	65,0	1,8	1,6	19,2	7,2	26,4	22,0	0,40
Rn03-729	mp	NE-till	9,0	1,1	0,7	8,8	4,1	12,1	10,0	0,23
Rn03-730	mp	NE-till	75,0	2,8	2,5	31,2	13,1	42,9	35,6	0,65
Rn03-731	mp	NE-till	12,0	2,5	2,0	24,8	9,6	34,1	28,4	0,54
Rn03-732	mp	NE-till	32,0	1,2	0,7	8,8	3,7	12,1	10,0	0,22
Rn03-733	mp	NE-till	72,0	1,6	1,5	18,4	6,1	25,3	21,1	0,34
Rn03-734	mp	NE-till	0,0	1,8	0,8	9,6	6,0	13,2	10,9	0,33
Rn03-735	kla	Klint	138,0	1,4	9,4	115,9	7,7	129,5	144,1	0,69
Rn03-737	kla	Klint	161,0	1,5	12,0	147,1	6,0	164,3	182,9	0,76
Rn03-739	kla	Klint	98,0	2,9	8,1	99,9	9,8	111,7	124,3	0,82
Rn03-742	b	Marine	0,0	0,9	2,1	25,6	2,4	27,2	30,8	0,23
Rn03-744	b	Marine	34,0	0,8	2,1	26,4	1,7	28,0	31,8	0,20
Rn03-746	b	Marine	29,0	2,1	2,3	28,0	3,4	29,7	33,7	0,38

Observation point	Estonian soil abb.	Soil type	Radon measured (kBq/m^3)	K (%)	eU (ppm)	Radium (Bq/kg)	Th (ppm)	Radon calculated from ^{226}Ra^1 (kBq/m^3)	Radon calculated from ^{226}Ra^2 (kBq/m^3)	C
Rn03-747	kla	Klint	31,0	1,2	5,5	67,2	3,4	75,0	83,5	0,41
Rn03-750	kla	Klint	81,0	0,7	8,1	99,9	4,9	111,7	124,3	0,51
Rn03-752	b	Marine	0,0	2,3	4,2	52,0	6,4	55,2	62,5	0,54
Rn03-753	fgl	Fluviogl	21,0	0,8	0,5	6,4	2,5	9,3	7,5	0,16
Rn03-754	b	Marine	13,0	1,0	0,3	3,2	2,7	3,4	3,9	0,17
Rn03-755	b	Marine	4,0	0,5	0,3	4,0	4,2	4,2	4,8	0,14
Rn03-756	b	Marine	8,0	0,3	0,7	8,8	1,8	9,3	10,6	0,10
Rn03-757	b	Marine	0,0	1,0	0,4	4,8	1,8	5,1	5,8	0,15
Rn03-758	b	Marine	23,0	1,6	1,2	15,2	4,8	16,1	18,3	0,31
Rn03-759	fgl	Fluviogl	23,0	0,9	0,7	8,0	2,9	11,6	9,4	0,18
Rn03-760	mp	NE-till	28,0	1,3	1,6	19,2	4,2	26,4	22,0	0,28
Rn03-761	b	Marine	15,0	1,3	1,0	12,0	6,5	12,7	14,4	0,30
Rn03-762	mp	NE-till	6,0	1,2	0,8	10,4	4,0	14,3	11,9	0,24
Rn03-763	mp	NE-till	0,0	0,8	1,0	12,8	2,9	17,6	14,7	0,19
Rn03-764	b	Marine	12,0	1,2	0,1	0,8	4,7	0,8	1,0	0,22
Rn03-765	b	Marine	31,0	1,5	0,8	9,6	4,6	10,2	11,6	0,28
Rn03-766	mp	NE-till	18,0	1,1	0,7	8,8	3,4	12,1	10,0	0,21
Rn03-767	b	Marine	18,0	1,2	0,9	11,2	4,7	11,9	13,4	0,25
Rn03-768	mp	NE-till	12,0	1,3	0,7	8,8	3,8	12,1	10,0	0,24
Rn03-769	b	Marine	16,0	1,4	1,1	13,6	5,0	14,4	16,4	0,29
Rn03-770	mp	NE-till	3,0	1,0	0,7	8,0	3,3	11,0	9,2	0,20
Rn03-771	mp	NE-till	25,0	1,5	5,3	65,6	4,8	90,3	75,0	0,47
Rn03-772	mp	NE-till	62,0	1,3	0,8	10,4	3,0	14,3	11,9	0,23
Rn03-773	mp	NE-till	39,0	1,6	1,4	16,8	6,6	23,1	19,2	0,36
Rn03-774	fgl	Fluviogl	12,0	0,8	0,9	11,2	2,0	16,2	13,2	0,16
Rn03-775	lgl	Sand	7,0	1,0	0,3	4,0	2,0	3,9	4,9	0,15
Rn03-776	mp	NE-till	42,0	1,4	0,9	11,2	4,4	15,4	12,8	0,27
Rn03-777	lga	Silt	51,0	2,5	2,0	24,8	12,2	28,4	32,9	0,58
Rn03-778	mp	NE-till	25,0	1,5	1,0	12,8	4,5	17,6	14,7	0,29
Rn03-779	mp	NE-till	13,0	1,1	0,7	8,0	1,7	11,0	9,2	0,17
Rn03-780	mp	NE-till	20,0	1,6	0,8	10,4	4,9	14,3	11,9	0,30
Rn03-781	lga	Silt	37,0	2,2	2,8	34,4	12,8	39,3	45,6	0,60
Rn03-782	mp	NE-till	0,0	2,0	1,2	15,2	6,2	20,9	17,4	0,38
Rn03-783	mp	NE-till	17,0	3,6	2,3	28,0	13,1	38,5	32,0	0,73
Rn03-784	mp	NE-till	58,0	1,0	1,7	20,8	2,9	28,6	23,8	0,24
Rn03-785	b	Marine	16,0	1,1	1,0	12,8	3,7	13,6	15,4	0,23
Rn03-786	mp	NE-till	57,0	2,1	1,2	14,4	6,9	19,8	16,4	0,41
Rn03-787	mp	NE-till	48,0	2,1	1,6	19,2	7,7	26,4	22,0	0,44
Rn03-788	mp	NE-till	62,0	3,3	2,2	27,2	11,2	37,4	31,1	0,65
Rn03-789	b	Marine	24,0	1,7	1,7	20,8	6,3	22,1	25,0	0,37
Rn03-790	b	Marine	30,0	2,7	1,3	16,0	6,3	17,0	19,3	0,46
Rn03-791	mp	NE-till	22,0	1,3	1,6	19,2	4,8	26,4	22,0	0,29
Rn03-792	lgl	Sand	0,0	0,7	1,0	12,0	2,1	11,8	14,7	0,16
Rn03-793	b	Marine	50,0	3,1	2,1	26,4	8,6	28,0	31,8	0,58
Rn03-794	mp	NE-till	0,0	3,1	3,4	42,4	15,3	58,3	48,4	0,76
Rn03-795	mp	NE-till	57,0	1,8	1,6	19,2	5,8	26,4	22,0	0,36
Rn03-796	b	Marine	4,0	0,3	0,2	2,4	0,8	2,5	14,4	0,06
Rn03-797	lga	Silt	277,0	3,3	3,4	41,6	19,2	47,6	50,1	0,86
Rn03-798	lgs	Clay	0,0	3,6	4,0	49,6	20,3	61,3	59,6	0,94
Rn03-799	lgl	Sand	11,0	2,2	1,5	18,4	7,3	18,2	22,1	0,44
Rn03-800	b	Marine	4,0	1,0	0,1	0,8	1,2	0,8	1,0	0,13

Observation point	Estonian soil abb.	Soil type	Radon measured (kBq/m^3)	K (%)	eU (ppm)	Radium (Bq/kg)	Th (ppm)	Radon calculated from $^{226}Ra^1$ (kBq/m^3)	Radon calculated from $^{226}Ra^2$ (kBq/m^3)	C
Rn03-801	b	Marine	4,0	1,9	1,2	14,4	6,4	15,3	17,3	0,37
Rn03-802	b	Marine	7,0	0,1	0,7	8,0	5,9	8,5	9,6	0,15
Rn03-803	b	Marine	11,0	0,7	0,7	8,8	2,7	9,3	10,6	0,15
Rn03-804	mp	NE-till	0,0	2,3	2,1	25,6	10,3	35,2	29,2	0,53
Rn03-805	lga	Silt	0,0	1,4	4,0	48,8	8,9	55,8	64,7	0,48