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15th Meeting of the Association of European Geological Societies

Georesources and public policy:
research, management, environment

16-20 September 2007, Tallinn, Estonia

Excursion Guidebook

Edited by Anne Põldvere & Heikki Bauert

Association of European Geological Societies

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INTRODUCTION TO THE GEOLOGY OF ESTONIA

Ivar Puura

Estonia lies on the northwestern margin of the East European Plain. The boundary between the sedimentary rocks of the East European Plain and the Precambrian rocks of the Fennoscandian Shield runs along the seabed of the Baltic Sea. The geological structures of mainland Estonia continue along the seabed, reaching the opposite seashores in Finland and Sweden. This brief introduction is based on a thorough overview of Estonian geology and mineral resources edited by Raukas and Teedumäe (1997).

The geological structure of Estonia has been revealed by studies of outcrops and numerous drill cores. The upper surface of the Proterozoic crystalline basement has been reached at a depth of about 100 m in northern Estonia and about 800 m in southern Estonia. The thickness of sedimentary cover grows from north to south (Figs 1 and 2). The basement is overlain by sedimentary cover consisting of Ediacaran (Vendian) and Paleozoic (Cambrian–Devonian) sedimentary rocks and Quaternary cover.

Fig 1

Crystalline basement

The Proterozoic crystalline basement is composed of Paleoproterozoic rocks, mainly of 1.8–1.9 Ga old gneisses and migmatites of the Svecofennian orogenic complex intersected by 1.54–1.67 Ga old rapakivi intrusions.

From northern Estonia toward Finland, the basement lies closer to the surface. It is exposed in the central part of the Gulf of Finland, about 100 m below water level. Estonia is situated in the central part of a block of the Earth's crust 50 to 65 km thick and as large as 1 million square kilometers. The structures of this block formed during an orogeny about 2.0–1.8 Ga ago and during rapakivi magmatism about 1.65–1.50 Ga ago.

Ediacaran and Paleozoic sedimentary rocks

The Ediacaran (630 to 540 Ma) and Paleozoic (540 to 360 Ma) sedimentary rocks of Estonia formed in a shallow sea basin. The Ediacaran rocks of

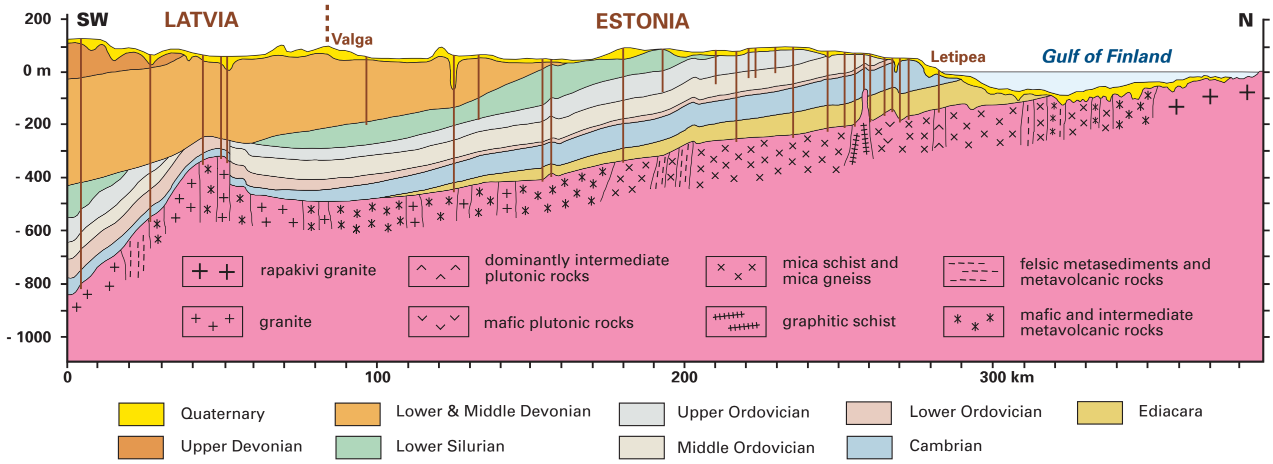

Fig 2. Generalized cross-section showing Precambrian crystalline basement and Paleozoic sedimentary cover from southern Finland to Latvia along the Letipea – Valga line (Puura, V. and Vaher, R., 1997, modified after Fig. 115)

Estonia are usually referred to as the Vendian complex. The sea basin has been traveling with an ancient Baltica plate that has been drifting since Ediacaran times from the high southern paleolatitudes to its present position in the northern hemisphere. It crossed the equator during the Silurian and Devonian (Fig. 3).

The smooth surface of the crystalline basement is covered by the Upper Vendian sedimentary rocks, represented by sandstones and clays, exposed at the bottom of the Gulf of Finland. The Paleozoic sedimentary rocks usually overlie the Vendian rocks. Only in northwestern Estonia, where the Vendian rocks thin out, do the Paleozoic rocks overlie the weathered surface of the crystalline basement. Because of a slight dip to the south, about 0.1 to 0.3 degrees (2 to 5 m per kilometer), the Paleozoic rocks are exposed as sublatitudinal belts, successively younger in the southward direction (Figs 1 and 2).

Cambrian sandstones and clays are exposed in the coastal plain of northern Estonia. Ordovician limestones are exposed in northern Estonia as a wide belt from the Narva River in the east to Hiiumaa Island in the west. Silurian limestones are exposed as a belt in central and western Estonia and on Saaremaa Island. Devonian terrigenous rocks, mostly sandstones, are exposed south of the Pärnu Mustvee line, extending from southeastern and southern Estonia to Kihnu and Ruhnu islands in the west. Upper Devonian limestones occur near Narva and in southeastern Estonia.

The sediments between the Devonian and the Quaternary have been eroded. This means that rocks corresponding to about 300 million years of geological history are missing in Estonia. At the same time, the accessibility and extraordinary preservation of the Cambrian to Devonian rocks makes Estonia a unique field museum for Paleozoic geology.

The Quaternary cover of Estonia consists mostly of glacial, glaciolacustrine, and glaciofluvial deposits of the Pleistocene age. Holocene sediments are thin and have patchy distribution. Quaternary sediments are usually less than 5 m thick in northern Estonia and more than 10 m thick in southern Estonia. They exceed dozens of meters and often 100 meters in the Haanja and Otepää heights and in the buried valleys (207 m in the buried valley of Abja). Five till beds corresponding to different glaciations have been distinguished. The sediments overlying the till began to accumulate in southern Estonia in the Late Pleistocene. During the Late Glacial and Holocene, Estonia

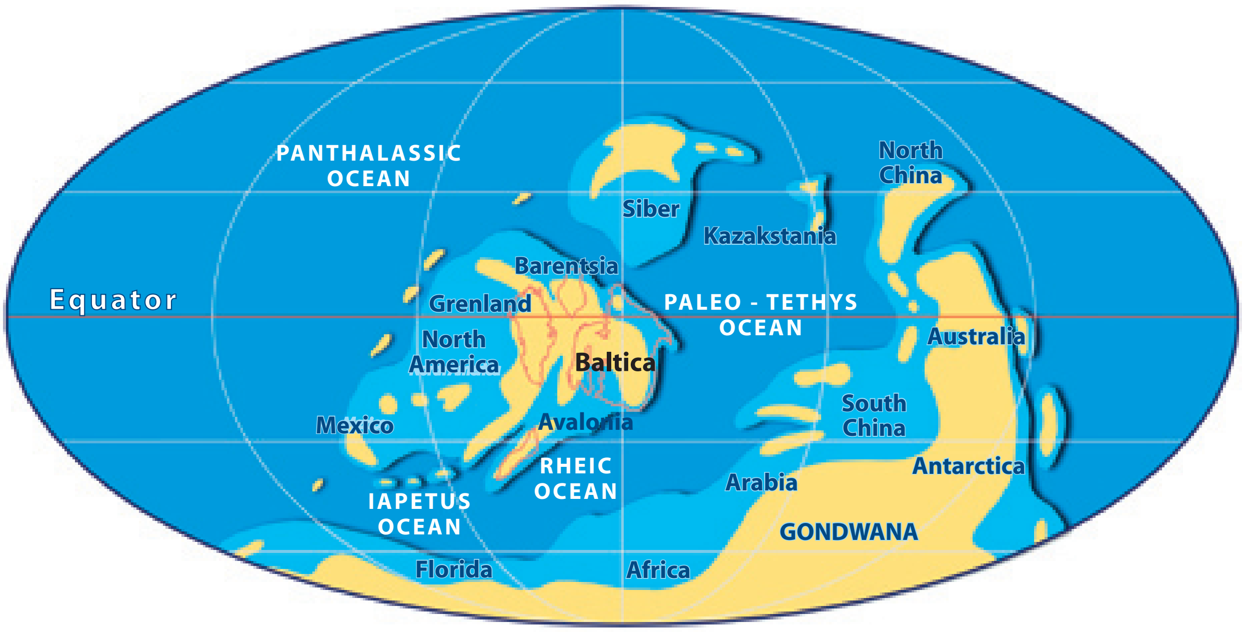

Fig 3. Position of continents in the mid-Silurian, ca. 425 Ma (modified after C.R. Scotese, “Plate tectonic maps and continental drift animations”, PALEOMAP Project, www.scotese.com).

was influenced by glacioisostatic rebound (neotectonic uplift), most intensively in northwestern Estonia. Because of the uplift, the width of Estonia's coastal region exceeds 130 km and ancient coastal formations occur at various elevations.

Estonia is a flat land whose uplands and plateau-like areas alternate with lowlands, depressions, and valleys. These landforms, along with the coastal cliffs in northern and western Estonia, are larger features of Estonian topography. The bases of the uplands of Estonia are usually 75 to 100 m above the sea level. The highest point in Estonia and the Baltic states, the Suur Munamägi Hill (318 m), is in the middle part of the Haanja Heights.

The erosional uplands are mostly flat, with relatively thin Quaternary cover. The relief is dominated by moraine plains: the Pandivere Upland (Emumägi Hill, 166 m) and the Sakala Upland (Rutu Hill, 146 m). The accumulative uplands have a relief dominated by hills and valleys built up from Quaternary sediments: the Haanja Upland (Suur Munamägi Hill, 318 m), the Otepää Upland (Kuutse Hill, 217 m), and the Karula Upland (Rebasejärve Tornimägi Hill, 137 m). Other elevations include the Saadjärv Drumlin Field, reaching 144 m, the West Saaremaa elevation, at 54 m, and the Ahtme or the Jõhvi elevation, at 81 m above sea level.

Among the higher areas are the plateaus. The Harju and Viru plateaus are in northern Estonia and are bordered on the north by the steep escarpment of the Baltic Klint. Both plateaus are about 30 to 70 m above sea level. The flat surface of the plateaus is occasionally cut by river valleys and karst features. The erosion of the Harju Plateau has left some separate flat plateau-like hills: Toompea Hill and the Viimsi Lubjamägi Hill in Tallinn, and the Pakri islands. The relief of the Viru plateau is formed by artificial features (oil shale pits and hills of waste rock and ash). The Ugandi Plateau (elev. 40 to 100 m) in southern Estonia is a sandstone plateau cut by ancient valleys and bordered by high escarpments: Tamme outcrop near Lake Võrtsjärv in the west and the Kallaste outcrop on the beach of Lake Peipsi. Other relatively high areas are the Central Estonian Plain (elev. 60 to 80 m) and Kõrvemaa (elev. 50 to 90 m).

Lowlands are plains reaching less than 50 m above sea level that have been flooded by the Baltic Sea, the ancient Lake Peipsi, and the ancient Lake Võrtsjärv. Lowlands cover nearly half of Estonia. The most extensive are in western Estonia.

Geological features and sights of interest

The North Estonian Klint is part of a limestone cliff about 1,200 km long that begins on the western coast of Öland island in Sweden, extends under the sea to the western coast of Estonia, and then runs through Estonia to northwestern Russia, ending at the southern shore of Lake Ladoga. The rocks exposed in the klint wall (Cambrian and Lower Ordovician sandstones, siltstones and shales, overlain by Lower and Middle Ordovician limestones) are about 470 to 540 million years old. At Valaste, near the village of Ontika, the klint rises 54 m above sea level and can be observed from a platform. The highest part of the klint (elev. 68 m) is near Sagadi. The western part of the klint can be observed at Türisalu cliff near Tallinn. The klint is dissected by river valleys and klint bays, and its present form is the result of abrasion by the Baltic Sea. South of the klint, several Ordovician limestone outcrops have been formed in North Estonian river valleys, cut through the limestone plateau during the neotectonic uplift. Some of the outcrops are hidden behind waterfalls, as at Jägala-Joa. **The West Estonian Klint** runs from the mainland through the island of Muhu and the northern coast of Saaremaa Island. It is part of the Silurian (Gotland–Saaremaa) Klint, 500 km long, that continues westward on the sea floor and appears from the sea on the northern and western coasts of Gotland Island. The klint does not form a continuous escarpment but consists of isolated small hills and cliffs. The Silurian limestones and dolostones exposed in the klint outcrops are about 420 million years old. Picturesque sites are Panga cliff on Saaremaa Island and a large Silurian bioherm, Üügu cliff on Muhu Island.

The Kaali meteorite craters in Saaremaa are the best-known Estonian meteorite craters. They have been recognized since the early nineteenth century. Among the nine craters located in

1 square km, the largest is the main crater, 110 m in diameter and at least 22 m deep. Estimates of the age of the craters vary from about 2,400 to 7,500 years before present (BP). The crater site is a well-known tourist attraction. **The Ilumetsa craters** are near the Ilumetsa railway station 30 km east of Põlva. Of five depressions registered at Ilumetsa, a meteoritic origin has been proved for two. Larger and more accessible is Põrguhaud, 80 m in diameter and 12.5 m deep. The crater site includes a trail to the crater and a small exposition on the origins of meteorite craters. Another crater, Sügavhaud, 50 m in diameter and 4.5 m deep, lies about 900 m south of Põrguhaud. The age of the craters is about 6,500 years BP. **The Kärdla crater** in Hiiumaa is from the Middle Ordovician age (455 Ma), buried under sediments; it is 540 m deep and 4 km in diameter. The crater's features are vaguely reflected in surface topography. As a result of the impact, Ordovician limestone layers dip at about 20 degrees in the abandoned Paluküla limestone quarry. It is the second-largest meteorite crater in Estonia. **The Neugrund crater** is located in the shallow sea at the mouth of the Gulf of Finland, northeast of Osmussaar. The diameter of its outer rim is 20 km. As the crater infill includes Lower Ordovician and Cambrian sediments, it is assumed that the crater formed in the Lower Cambrian.

Estonia has been completely free of continental ice only for some 11,000 years. Before that, Estonia was shaped by ice, which invaded and retreated several times. Common landforms in Estonia accumulated by the continental ice are drumlins, eskers, and kames. **A drumlin** is an oval or elongated hill, usually 1 to 2 km long, 400 to 600 m wide, and up to 60 m high. It is believed that drumlins are formed by the streamlined movement of glacial ice sheets across rock debris, or till. The long axes of drumlins are usually roughly parallel to the path of glacial flow. In broad lowland regions, drumlins can form drumlin fields. The Saadjärve Drumlin Field, also known as Vooremaa (literally, "land of drumlins"), is the largest in Estonia, with the drumlins usually longer than 2 km. Here we find the Laiuse drumlin, 13 km long and 60 m high. It is the largest in Estonia. Smaller drumlin fields occur near Türi and Kolga-Jaani.

An esker is a long, narrow, winding ridge. Eskers may range from 5 to 50 m in height, from 50 to 700 m in width, and from 100 m to dozens of kilometers in length. They are composed of stratified sand and gravel deposited by a meltwater stream. Eskers are considered to be channel deposits (left by streams that flowed through tunnels in and below the ice) that were let down onto the ground surface as the glacier retreated. The Uljaste esker in Ida-Virumaa County and the Pähnimäe esker near Rakvere are protected. The large Iisaku esker is also well-known.

A kame is a hillock deposited a near the terminus of a glacier in dead ice. A kame may be formed through the accumulation of sandy deposits in the depressions on the ice surface or between the ice blocks in front of the ice margin. A group of closely associated kames is called a kame field. The Kurtna and Viitna kame fields are the best-known in Estonia.

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A BRIEF OVERVIEW OF THE HISTORY AND GEOLOGY OF TALLINN

Jaak Nõlvak

Tallinn has two main parts differing in location, size, relief, and history. The heart of its medieval centre, the present Old Tallinn, comprises the fortress of Toompea and the lower town. Toompea (Dome Hill), the oldest part of the town on a high limestone elevation, rises like an island dozens of meters above the surrounding quarters. Even today, it dominates the new tall buildings.

According to an Estonian epic, the Kalevipoeg (Son of Kalev), Toompea is the tomb of Kalev, the ruler of the Old Estonians, of stones heaped up by his widow Linda.

History

The ancient Estonians built their stronghold (probably wooden) named Lyndanise, and later known in Danish as Castrum Danorum and in German as Ordensburg, on the top of the elevation, which offered natural protection. It is not known whether the stronghold was inhabited year-round or only during the navigation period and in wartime. It also served as a guarantee for the development of a port at its site. The port was supposedly in the estuary of the Härjapea River, which today is enclosed in underground pipes. From the river sailors could easily get freshwater from Lake Ülemiste. In time the port was shifted seawards because of the constant withdrawal of the sea. The area is currently rising at a rate of 2 to 2.5 mm per year.

Throughout the Middle Ages, the lower town (*suburbium*, *Unterstadt*), known (from 1280) as the Hanseatic town Reval, was a trade centre, populated by craftsmen, merchants and the lower-class people depending on them.

According to the data available, the first written record of Tallinn dates from 1154, when al-Idrisi, an Arabian geographer, included it in his world map. With its position at the crossroads of the land and sea routes, the stronghold of Toompea turned into a major centre of northern Estonia at the turn of the tenth century.

In June 1219, in the course of the crusade to Christianize and subordinate Estonia, the stronghold was conquered by the Danes, who pulled it down and built one of their own. The first stone stronghold was completed in 1229 by the German Order of the Brothers of the Sward, who had subjugated the Danes. The material for the construction was taken from the place that is now under Toompea Cathedral (Dome Church, the Cathedral of Saint Mary the Virgin). It was probably the first Ordovician limestone quarry in the region. However, this quarry seems to have existed only for a short time, because according to some data, the construction of the cathedral was under way at the same place as early as 1233.

The fortress of Toompea was thoroughly rebuilt in the thirteenth century, and the cathedral has maintained its Late Gothic countenance. At the same time, the development of the lower town was also active. The population consisted mainly of Germans and Estonians, with Swedes and Finns and a smaller number of Russians and others. Important were the privileges granted by the Lubeck Law, which became the main legal act adopted in the Codex Revaliensis between 1238 and 1248, and which shows clearly that the region belongs to Europe. In 1265 the order to secure the city with a wall (Revaler Stadtmauer) was given by the Danish Dowager Queen Margrethe, who ruled northern Estonia from 1266 to 1282. The most noteworthy buildings of that period are the monasteries (St. Catherine, started in 1246 by Dominicans, also Cistercians, etc.), City Hall (finished in 1404), the city wall with more than 45 defensive and gate towers (of which 26 have been preserved), guild houses, basilicas (Oleviste or St. Olaf's Church, first mentioned in 1267; Niguliste or St. Nicolas Church in 1308), numerous dwelling houses with a specific layout, and other stone buildings. The town got several privileges, building activities intensified, and large quantities of building materials (limestone, clay, sand, etc.) were needed, especially after lime mortar was taken into use.

"Tall Hermann" is the corner tower of Toompea castle

Later the main structure of the old town was preserved but adapted to new tasks. All buildings were reconstructed, especially during the Late Gothic period (the fifteenth and beginning of the sixteenth century). The advancing war technique impelled improvement of the Toompea stronghold and modernization of the town wall, which was repeatedly reinforced and made higher, up to 14 m. For all these works building material was needed. And a magnificent material – a unique light grey limestone for blocks, plates and lime – was (and still is) available.

Geology

In the Tallinn area and throughout northern Estonia, the Proterozoic crystalline basement is covered with Upper Proterozoic and Lower Paleozoic sedimentary rocks, up to the lowest Upper Ordovician (some 456 million years ago) near the North Estonian Klint. The klint forms about a quarter of the huge Baltic Klint, a limestone escarpment stretching 1,200 km from Lake Ladoga in Russia to Öland Island in Sweden. The upper boundary of the basement is at a depth of 130 to 150 m below sea level. The layer of sedimentary rock forming the upper surface of the basement has a gentle southward inclination, on average 3 to 4 m per kilometer. On the basis of the lithology of the sedimentary rocks, the Lower Paleozoic in Tallinn can be divided into two main parts: (1) the uppermost Neoproterozoic (Ediacaran, earlier Vendian), Lower and Upper Cambrian (Furongian) and the Lower Ordovician (Tremadocian), composed mostly of terrigenous rocks; and (2) the upper part of the Lower Ordovician to the lower part of Upper Ordovician (Arenig to lowest Caradoc), formed mainly by carbonate and fine-terrigenous rocks.

Lower Cambrian sandstones and clays crop out at Rocca-al-Mare (where the Estonian Open Air Museum is located) and in the valley of the Pirita River. The clays of the Lontova and Lükati Formations are of economic value. These so-called *blue clays* crop out on the Kopli Peninsula and have served for centuries as raw material in the manufacture of rough ceramic products (roof tiles, bricks, etc.) and cement. The clay quarries are now closed.

A hiatus corresponds to the Middle Cambrian. Yellow sandstones typical of the Furongian (Upper Cambrian) range into the lowest Ordovician as well. The section continues with dark brown kerogenous argillites, which also can be observed in the lowest parts of the Toompea sections (e.g. near Nunne Street). These argillites pose a serious threat to the environment because they tend to self-ignite when disposed in waste dumps. They also contain some radioactive elements that cause heavy pollution. This happened in the Maardu area (east of Tallinn) before the open-cast pits for phosphorite mining were closed in 1991. In the limits of the town, the layer with phosphorite-bearing valves of fossils (lingulate brachiopods) and fragments rich in P_2O_5 (up to 35%) is absent (e.g., at Toompea) or is represented by some about 10 cm thick lenses (e.g., at Mäekalda). The layer is thickest (0.7 m) in the Iru section. Oil shale (kukersite), one of the main mineral resources in northeastern Estonia, occurs in Tallinn sections only as layers a few centimeters thick in the limestones of the Kukruse Stage near Sõjamägi. It does not occur in the klint sections.

Within the town, the topography of the bedrock is characterized by several relatively small positive – Toompea, Sõjamägi – and no longer visible negative features – three valleys up to 140 m deep filled with Quaternary sediments (Figs 1, 2). The topography of the bedrock is of complicated genesis because of the contribution of different relief-forming forces. The most important factor is the heterogeneous lithological composition (i.e., unequal resistance of the rocks to denudational processes).

A steep escarpment, the North Estonian Klint, is the most notable bedrock relief form. The development of the klint started, in all likelihood, during the Cenozoic. It was formed by denudation during a prolonged continental period. Later on, it was transformed by glacial erosion and marine abrasion according to the hardness of the rocks (Figs 1, 2). The klint emerged from the waters of the Baltic Sea during the Yoldia

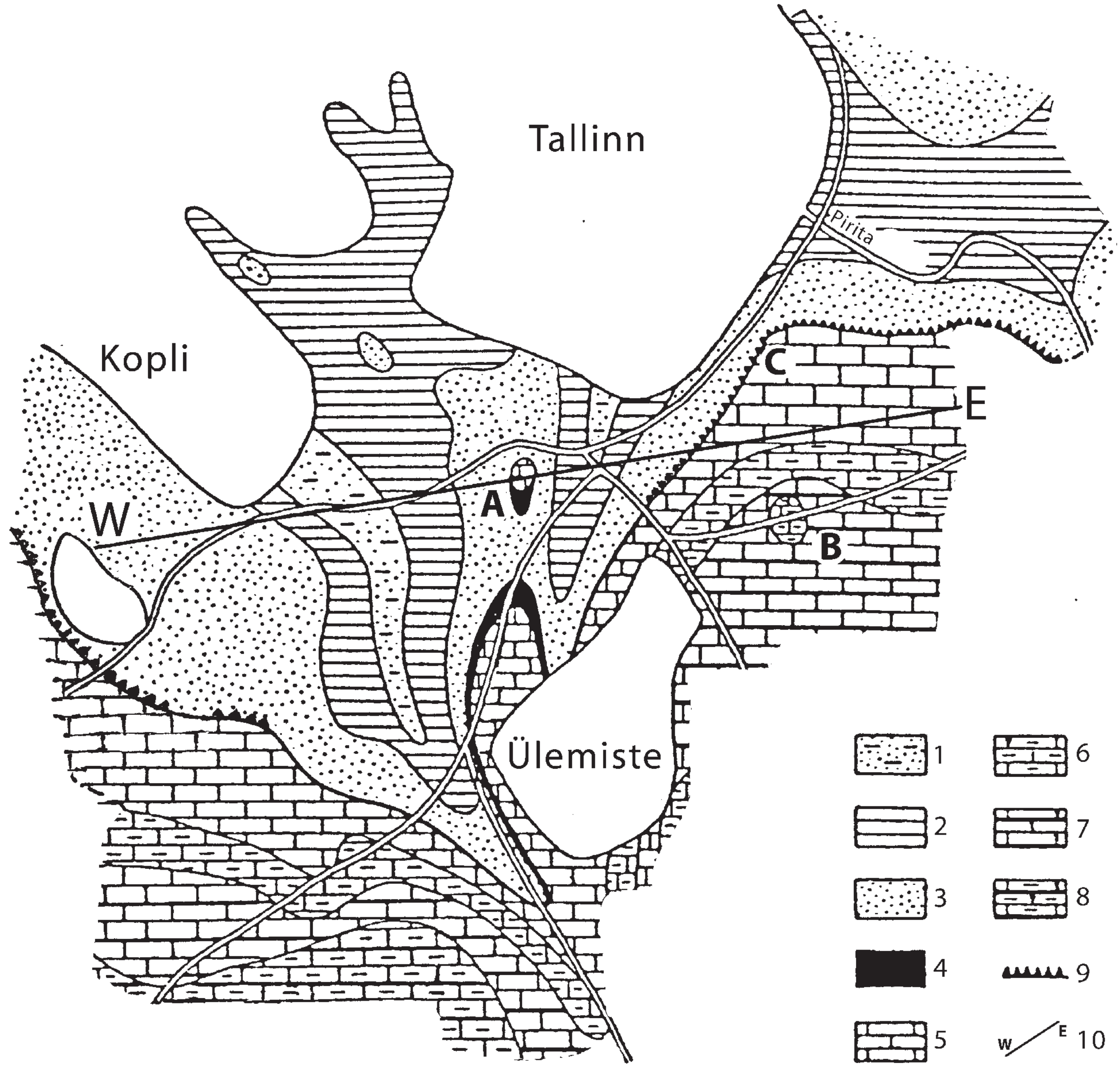


Fig. 1. Geological map of Tallinn (modified from Müürisepp 1976). 1 – Lower Cambrian sandstones, 2 – Lower Cambrian clays, 3 – Upper Cambrian–Lower Ordovician sandstones, 4 – Lower Ordovician argillites, 5 – Lower–Middle Ordovician limestones, 6 – Middle Ordovician limestones, 7 – Middle–Upper Ordovician limestones with kukersite, 8 – Upper Ordovician argillaceous limestones with marls, 9 – North Estonian (Baltic) Klint, 10 – profile (Fig. 2). A – erosional island (outlier) Toompea, B – Sõjamägi, C – Suhkrumägi

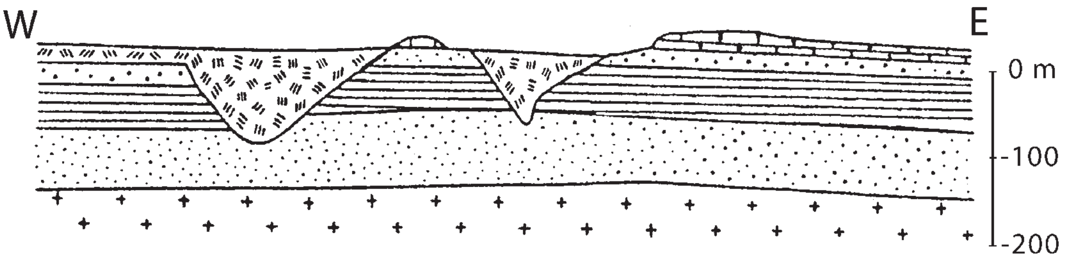
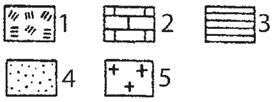


Fig. 2. Geological section of the Tallinn area (Fig. 1, W–E)
1 – Quaternary sediments, 2 – limestones, 3 – clays,
4 – sandstones, 5 – crystalline basement



regression, some 10,300 to 9,500 years BP. The lower areas of the present-day town became dry land later, according to the withdrawal of the sea. The klint consists of rocks with unequal resistance. The section at Suhkrumägi displays pure hard limestones and dolostones in the topmost 6.5 m. The limestones and dolostones are underlain by soft Furongian–Lower Ordovician terrigenous rocks, mainly sandstones.

Higher in the section, among much harder Middle Ordovician carbonate rocks, there are limestones some 462 million years old, known as the *Building Limestone*. Of the numerous quarries used at different times in the limits of the town, the most important ones were in the Lasnamägi area. When the handwork of craftsmen was prevailing, 58 limestone layers had specific names, reflecting the quality of the rock and its suitability for certain purposes (e.g., for walls, stairs, floor plates, facing panels or lime burning). There were also "bad" layers – more argillaceous intercalations, which were unfit for building but could be used as road metal.

The topmost layers on Toompea Hill (480 by 220 m; elev. 47.5 m) belong to the lowest Uhaku Stage (see Fig. 1, point A). This stratigraphic level is a little higher than the topmost limestone beds at Suhkrumägi (Fig. 1, point C), where the klint is at its highest in the limits of the town, rising up to 47 m above sea level. In the outlier Toompea, the denudational relic of Toompea Hill (probably of pre-Quaternary age), the Lower and Middle Ordovician layers have a slight southward dip (0°15′) typical of all the Lower Paleozoic rocks of Estonia. However, in a small outcrop 20 to 50 m north of the tower "Tall Hermann," some of the uppermost limestone layers are deformed, having a dip of 5 to 10 degrees. At the same place seven small dislocations crop out with an amplitude of 15 to 60 cm, in all 2.2 m. The dislocations are easy to see, as they follow the layers of the Aseri oolitic limestone (demonstrated by Heinsalu 1976). Fissures up to 25 cm wide are filled with Pleistocene sediments (till), which gives an idea about their glaciotectonic nature.

In many places at the foot of the klint, there are terraces of different stages of postglacial seas. For this reason the klint is partly covered and does not always occur as an abrupt escarpment. South of the klint, the bedrock relief continues as a limestone plain with a very thin Quaternary cover, or without it (alvar), reworked also by Quaternary glaciers and waters of the Baltic Sea and glacial lakes, and with more or less filled ancient valleys. This is characteristic of the northern Estonian landscape. Lake Ülemiste, on the outskirts of Tallinn, became isolated from the sea during the Ancylus transgression, about 9,500 years BP. The lake provides the town with drinking water.

According to the Estonian epic Kalevipoeg, the lake was formed from the bitter tears of Linda, crying over old Kalev's death.

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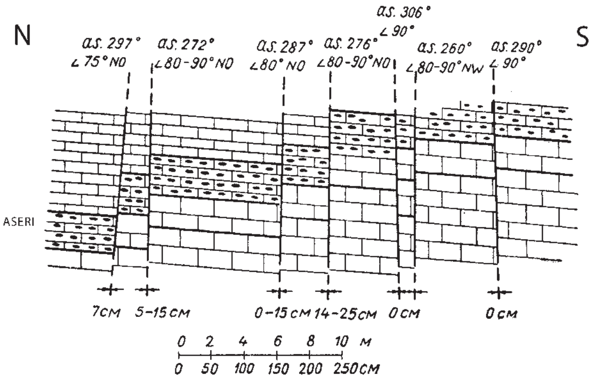


Fig. 3. Dislocations (normal faults) at the Toompea outcrop (modified from Heinsalu, 1976). Upper scale = horizontal scale, lower scale = vertical scale, both in meters

THE MINERAL RESOURCES OF ESTONIA: CARBONATE ROCKS

Aada Teedumäe

Carbonate rocks of commercial interest are widespread in Estonia. A continuous outcrop belt of Ordovician and Silurian carbonate rocks embraces the territory northward of the Pärnu–Lake Peipsi line. Owing to the rather thin Quaternary cover, these rocks have been accessible for use since 5,000 to 4,000 BC. Devonian carbonate rocks, occurring on some levels only and cropping out in southeastern Estonia where Quaternary sediments are rather thick, are available for use in restricted areas.

Estonia is well-endowed with limestone resources. Workable deposits occur at many levels. However, because of the thinness of the overburden, the high quality and consistency of the material, and the convenient location of the outcrops, Ordovician limestones (Lasnamägi, Oandu and Keila stages) make up more than 75% of the quarried rock. Limestones of the Lower Silurian Juuru Stage and dolostones of the Raikküla and Jaagarahu stages are also of industrial importance.

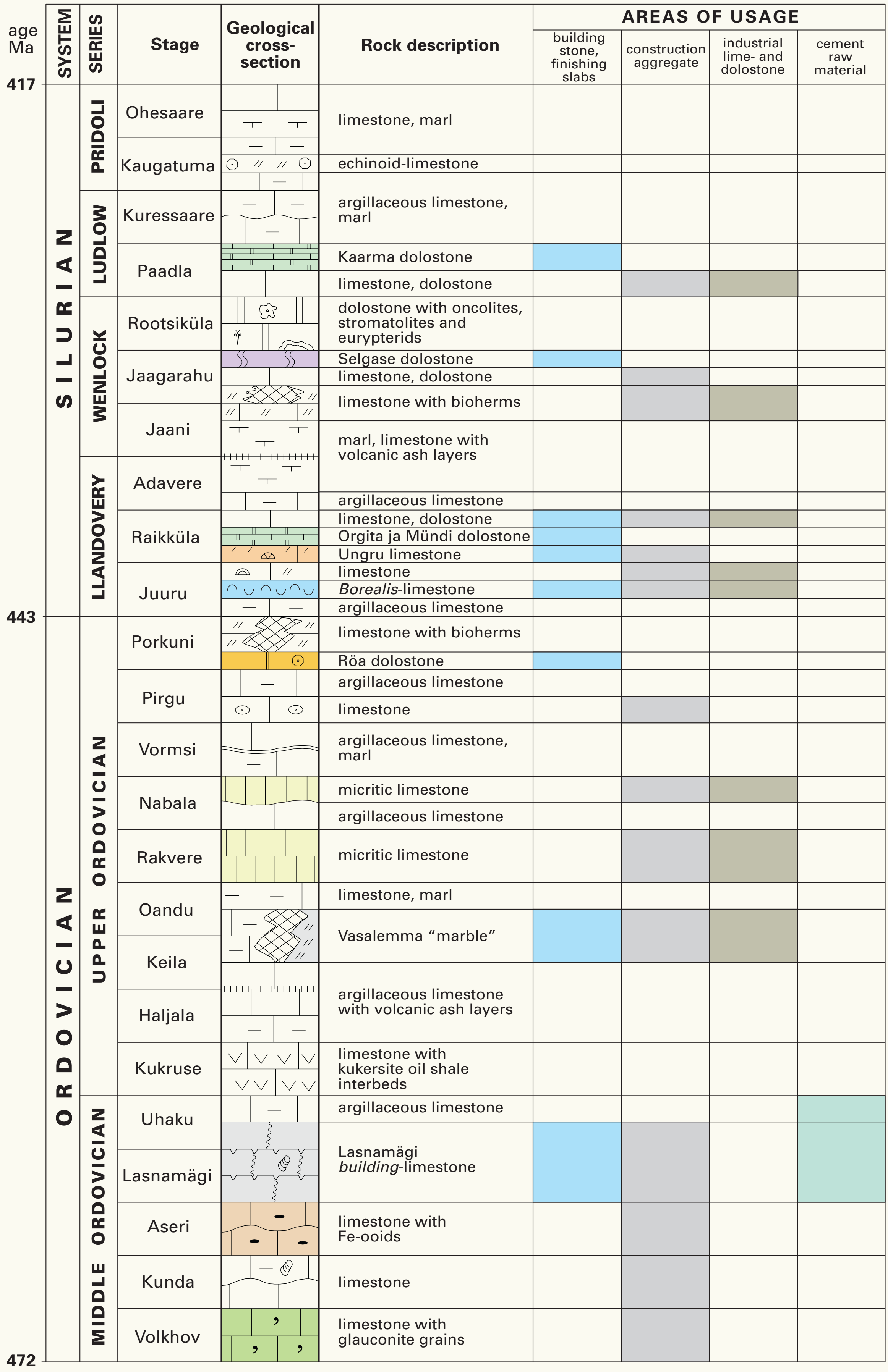
In contrast to the rest of the territory, limestone and dolostone resources are few in southeastern Estonia. They are found only on some levels of the Devonian, mainly terrigenous rocks.

In 2004 the reserves of carbonate rocks in 95 explored deposits were 560 million m^3 of limestone and 230 million m^3 of dolostone. These values are almost as high as the preliminarily estimated reserves. About 80% of the reserves were explored for use in construction, 10% for the cement industry, and 10% for various technological purposes (lime production, environmental and metallurgical purposes, etc.). The Soviet years brought about the concentration, low specialization, and extensive growth of the industry. The number of the exploited deposits varied between 10 and 15, with a total annual output of about 4 million to 5 million m^3 (10 million tons). At the same time, technological progress came to a halt, and in 1991 most of the industry was operating at the technological level of the 1970s. During the past decade, considerable reorientation has taken place because of the demands of the market economy, foreign investments, and legislative regulations. In 2006 the annual total output of carbonate rocks was about 3.2 million m^3 (8.4 million tons). In addition to large industrial quarries, small hand-mined quarries have started to develop in the recent years. Building stone, crushed aggregate, and decorative stone (facing slabs) are produced to meet local needs. The first renovated cement plant at Kunda exports cement through its port to destinations all over the world. Technological dolostone and limestone are also exported to European countries. Only a small amount is used for lime burning.

Actually, the problems of the availability and exploitation of deposits, related to competing demands of land use and other factors, need to be assessed in light of present conditions in every particular case. The process has already started, and the first results have shattered the illusion of unlimited resources of carbonate rocks. The resources available for mining are limited for many reasons. The most favorable of them tend to be located near towns, harbors, and roads. In particular, this concerns industrially developed northern Estonia, where the largest resources are and where consumption of construction materials is highest. The problem is acute and awaits a reasonable solution.

Carbonate rocks in the Ordovician-Silurian succession, Estonia (Figure from Perens, H. and Kala, E., 2007. Paekivi - Eesti rahvuskivi)

CARBONATE ROCKS AND USAGE IN ESTONIA



age Ma	SYSTEM	SERIES	Stage	Geological cross-section	Rock description	AREAS OF USAGE			
						building stone, finishing slabs	construction aggregate	industrial lime- and dolostone	cement raw material
417	SILURIAN	PRIDOLI	Ohesaare		limestone, marl				
			Kaugatuma		echinoid-limestone				
		LUDLOW	Kuressaare		argillaceous limestone, marl				
			Paadla		Kaarma dolostone	■			
					limestone, dolostone		■	■	
		WENLOCK	Rootsiküla		dolostone with oncolites, stromatolites and eurypterids				
			Jaagarahu		Selgase dolostone	■			
					limestone, dolostone		■		
					limestone with bioherms		■	■	
			Jaani		marl, limestone with volcanic ash layers				
		LLANDOVERY	Adavere		argillaceous limestone				
			Raikküla		limestone, dolostone	■	■	■	
					Orgita ja Mündi dolostone	■			
					Ungru limestone	■	■		
			Juuru		limestone		■	■	
					Borealis-limestone	■	■	■	
					argillaceous limestone				
443	ORDOVICIAN	UPPER ORDOVICIAN	Porkuni		limestone with bioherms				
					Röa dolostone	■			
			Pirgu		argillaceous limestone				
					limestone		■		
			Vormsi		argillaceous limestone, marl				
			Nabala		micritic limestone		■	■	
					argillaceous limestone				
			Rakvere		micritic limestone		■	■	
			Oandu		limestone, marl				
			Keila		Vasalemma “marble”	■	■	■	
			Haljala		argillaceous limestone with volcanic ash layers				
			Kukruse		limestone with kukersite oil shale interbeds				
		MIDDLE ORDOVICIAN	Uhaku		argillaceous limestone				■
			Lasnamägi		Lasnamägi *building*-limestone	■	■		■
			Aseri		limestone with Fe-ooids		■		
			Kunda		limestone		■		
			Volkhov		limestone with glauconite grains		■		
472									

THE MINERAL RESOURCES OF ESTONIA: KUKERSITE OIL SHALE

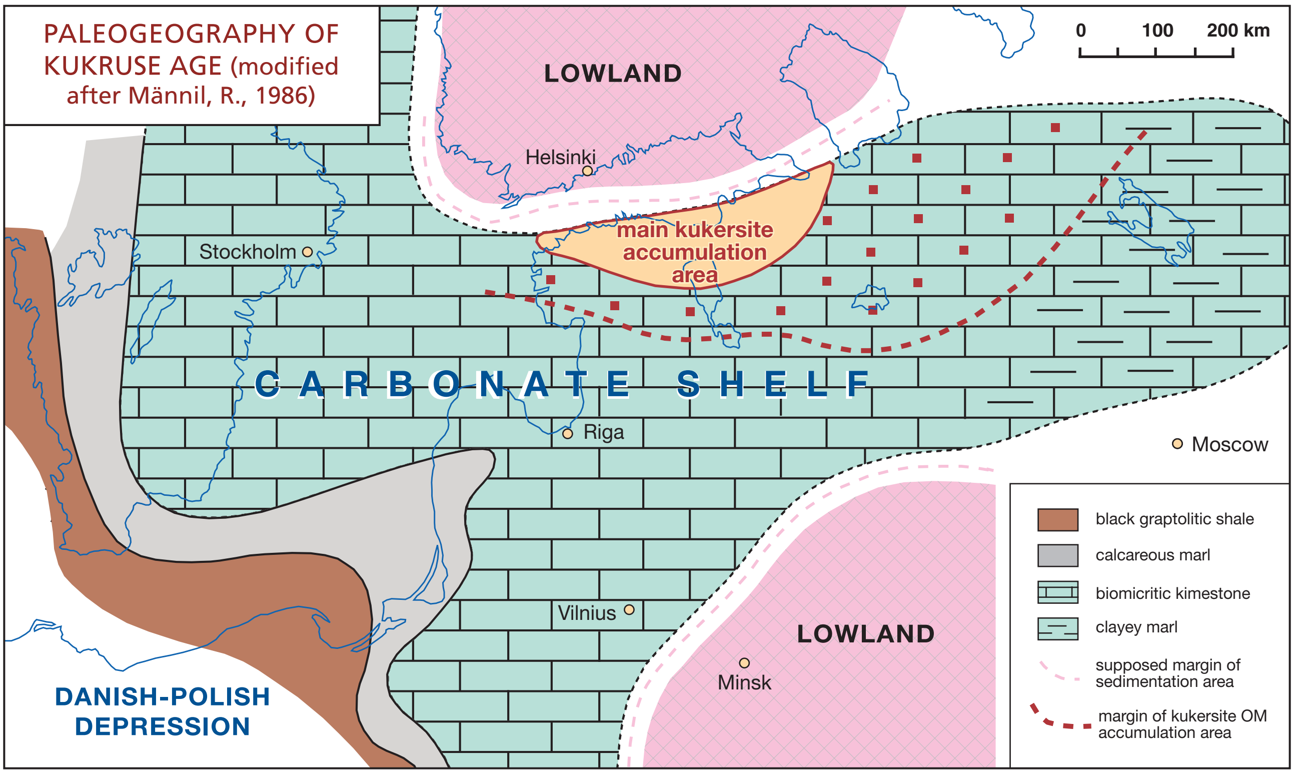
Vello Kattai and Heikki Bauert

The Baltic Oil Shale Basin is located near the northwestern boundary of the East European Platform. The Estonia deposit lies in the western part of the basin. In its eastern part, which is on Russian territory (east of the Narva River), the Leningrad, Veimarn and Tshudovo–Babinskoye deposits are distinguished. In Estonia, the basin partly embraces three regional landforms: the Pandivere Upland, the Northeast Estonian Limestone Plateau, and the Alutaguse Lowland. The topography of the basin area is mainly flat or undulating. The northern boundary of the basin is erosional. Throughout the Estonia deposit, the oil shale beds are cut by numerous ancient buried valleys.

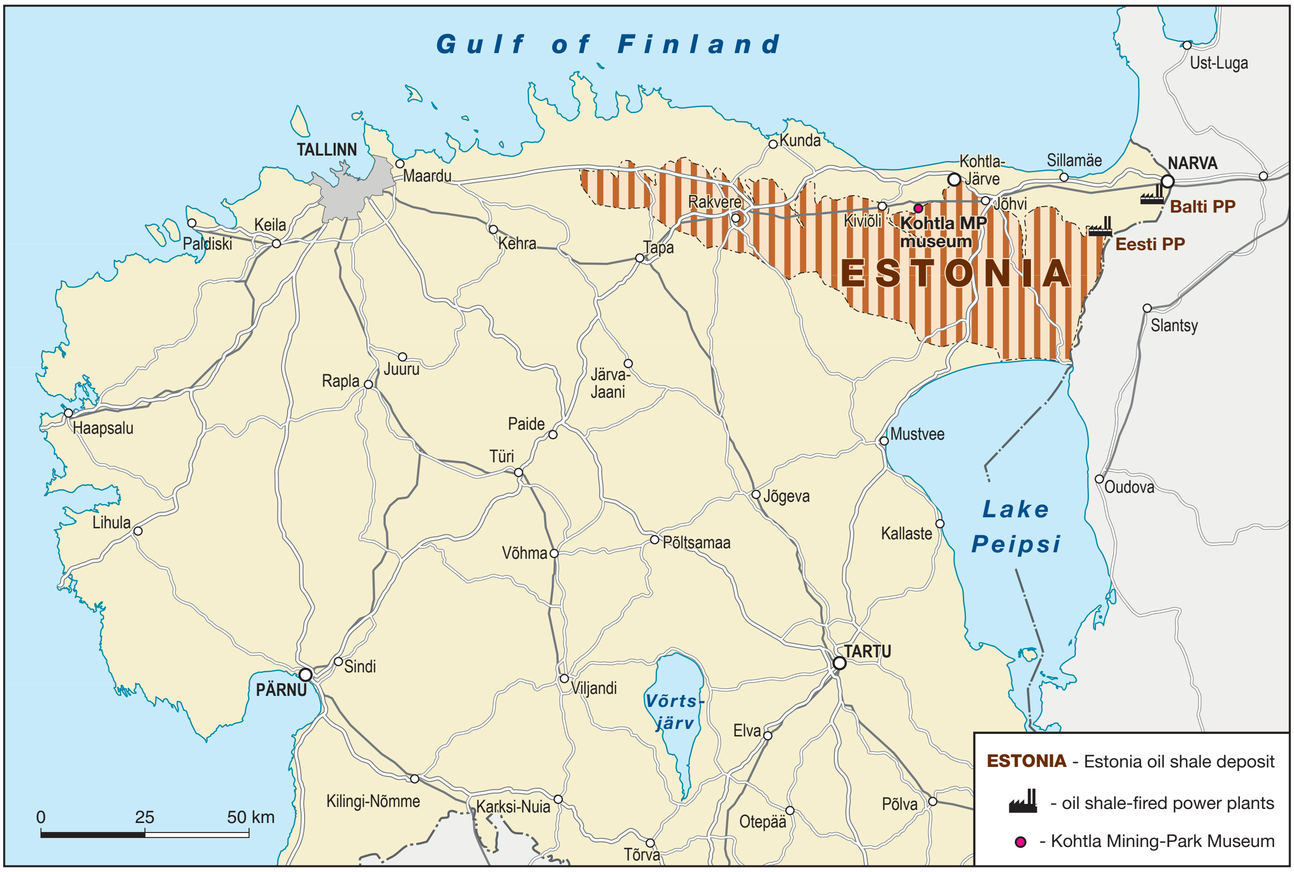
Kukersite-type organic matter is widely distributed in the sediments of the Ordovician Baltic Paleobasin. The kukersite formation embraces the upper part of the Uhaku Regional Stage and the entire Kukruse Regional Stage. The lower portion of the Kiviõli member of the Kukruse Stage, whose seven indexed kukersite seams (A–F_1) form the productive or commercial bed of the Estonia deposit, is the richest in kukersite. The commercial seam of the Leningrad and Veimarn deposits in the eastern part of the Baltic Basin is related to the same complex. The share of kukersite seams increases in the Peetri member (upper part of the Kukruse Stage), and the kukersite bed III (the thickest bed) forms the potential minable seam of the Tapa region.

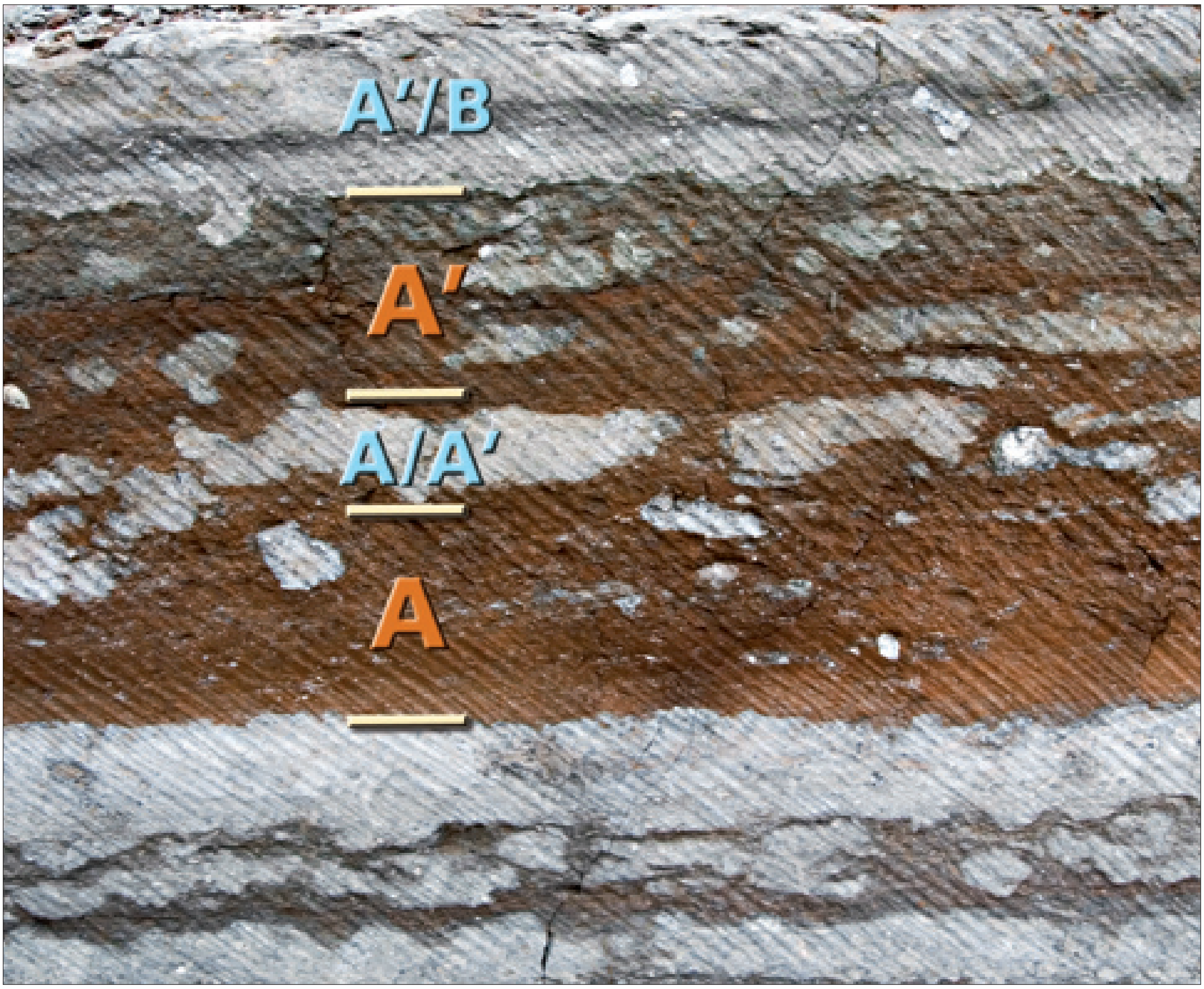
The Estonia deposit is the largest deposit in the Baltic Oil Shale Basin, and it contains shale of the highest quality. Its northern boundary is erosional; its southern and northwestern boundaries are arbitrarily drawn by the thickness of 1.4 m of the minable bed. In the east the deposit borders the Narva River. The area of the deposit within the boundaries described is about 3,000 km^2. The deposit is divided into 26 fields; those currently developed are called mine fields and the ones geologically explored but not currently developed are called exploration fields. The mined areas cover 426 km^2. The oil shale on 850 km^2 is not taken into account in the Environmental Register of Estonia. The total area of blocks with proved and probable reserves is 1,695 km^2.

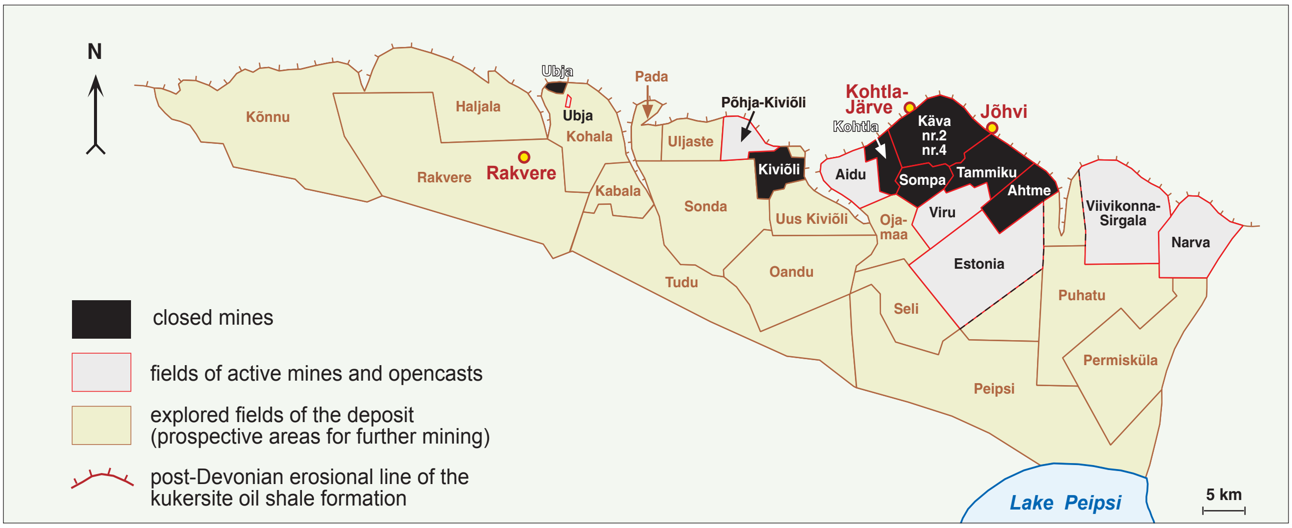
Close-up of kukersite oil shale bed A in the Põhja-Kiviõli open-cast mine (right)



PALEOGEOGRAPHY OF KUKRUSE AGE (modified after Männil, R., 1986)

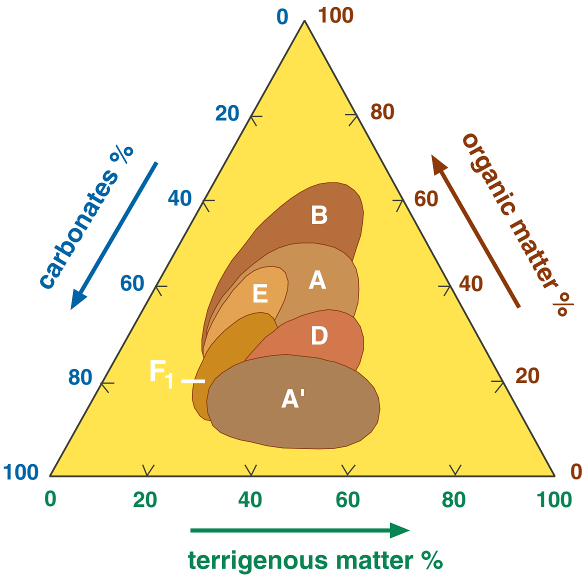

Gulf of Finland
Ust-Luga
TALLINN
Maardu
Kunda
Kohtla-Järve
Sillamäe
NARVA
Balti PP
Eesti PP
Rakvere
Kiviõli
Jõhvi
Kohtla MP museum
ESTONIA
Keila
Paldiski
Kehra
Tapa
Slantsy
Juuru
Rapla
Järva-Jaani
Haapsalu
Paide
Türi
Mustvee
Lake Peipsi
Oudova
Jõgeva
Lihula
Kallaste
Võhma
Põltsamaa
TARTU
Sindi
PÄRNU
Viljandi
Võrtsjärv
Elva
Kilingi-Nõmme
Karksi-Nuia
Otepää
Põlva
Tõrva
0
25
50 km
ESTONIA - Estonia oil shale deposit
- oil shale-fired power plants
- Kohtla Mining-Park Museum


A'/B
A'
A/A'
A



Mining fields of the Estonia oil shale deposit (Bauert, H. and Kattai, V. 1997, modified after Fig. 208)

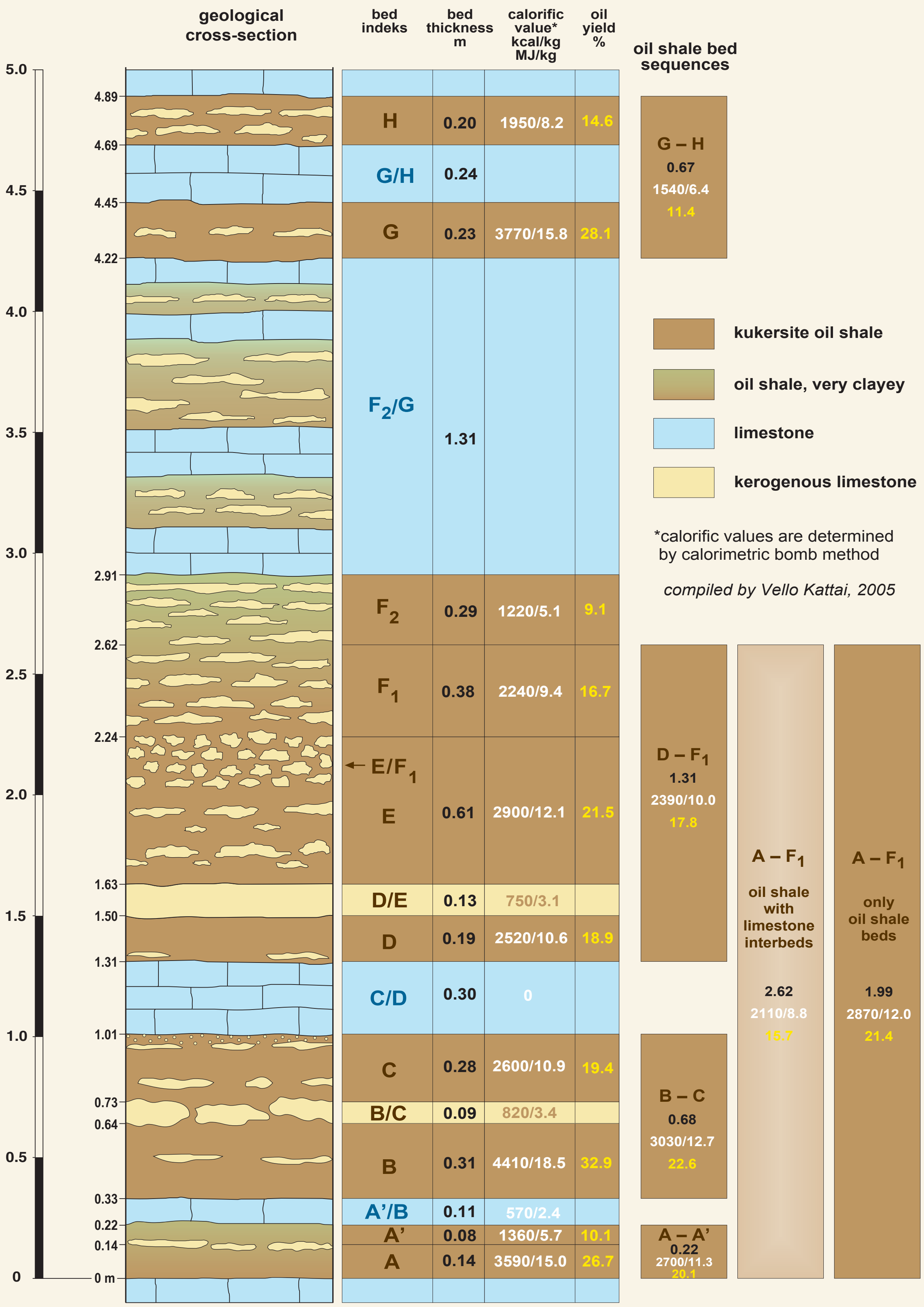
The commercial bed consists of seven indexed kukersite seams (from the bottom): A, A′, B, C, D, E, and F_1, alternating with five host limestone interbeds (A′/B, B/C, C/D, D/E, and E/F_1). Most of the kukersite seams also contain lens-like nodules of kerogenous limestone. The commercial bed A–F_1 is at its thickest (2.7–2.9 m) in the northern part of the central and eastern areas of the Estonia deposit. Its thickness decreases gradually southward to 2.1 m and westward to 1.6 m. The total thickness of the kukersite seams changes in a similar way. In terms of practical approach, three kukersite seam complexes can be distinguished in the commercial bed: lower A–A′, middle B–C and upper D–F_1. These complexes are separated from each other by laterally continuous host limestone interbeds A′/B and C/D.



Kukersite is a mixed rock consisting of three main syngenetic components: organic, carbonaceous, and terrigenous matter. It is a mineral resource of low quality and rich in mineral matter, with rest products (ash, low-temperature coke) forming about 50%. The organic matter content ranges from 10 to 65%. According to the mineral composition, kukersite is usually carbonaceous and terrigenous-carbonaceous, less often carbonaceous-terrigenous. The content of carbonaceous matter is 15 to 70%, depending on the seam and part of the deposit. The terrigenous matter is a steadier component than the others. However, its content varies from 15 to 40%, locally even more in seams A′ and D.

Kukersite is composed of calcite or dolomite, illite, quartz, microcline, orthoclase, secondary minerals occurring as an admixture (gypsum, pyrite, plagioclase, chlorite), and accessory minerals. The carbonate mineral is usually represented by calcite, often with some admixture of dolomite. The detrital component of the rock consists of skeletal fragments of various organisms. The orientation of intact fossils and visually observable fragments follows the bedding. The rock matrix consists mainly of silt-size calcite with a terrigenous admixture. In the disturbance and karst zones, calcite is, as a rule, completely replaced by dolomite, both in kukersite and host limestone. The elevated dolomite content (5 to 10%) has also been recorded in the eastern part of the deposit,

PÕHJA - KIVIÕLI OIL SHALE OPEN-CAST MINE



bed indeks	bed thickness m	calorific value* kcal/kg MJ/kg	oil yield %
H	0.20	1950/8.2	14.6
G/H	0.24		
G	0.23	3770/15.8	28.1
F_2/G	1.31		
F_2	0.29	1220/5.1	9.1
F_1	0.38	2240/9.4	16.7
← E/F_1 E	0.61	2900/12.1	21.5
D/E	0.13	750/3.1	
D	0.19	2520/10.6	18.9
C/D	0.30	0	
C	0.28	2600/10.9	19.4
B/C	0.09	820/3.4	
B	0.31	4410/18.5	32.9
A'/B	0.11	570/2.4	
A'	0.08	1360/5.7	10.1
A	0.14	3590/15.0	26.7

oil shale bed sequences

sequence	thickness	calorific value	oil yield
G – H	0.67	1540/6.4	11.4
D – F_1	1.31	2390/10.0	17.8
B – C	0.68	3030/12.7	22.6
A – A'	0.22	2700/11.3	20.1
A – F_1 oil shale with limestone interbeds	2.62	2110/8.8	15.7
A – F_1 only oil shale beds	1.99	2870/12.0	21.4

▨ kukersite oil shale

▨ oil shale, very clayey

▨ limestone

▨ kerogenous limestone

*calorific values are determined by calorimetric bomb method

compiled by Vello Kattai, 2005

Oil shale mining in the Põhja-Kiviõli open-cast mine: mining of D-F_1 oil shale sequence (above). Surface miner Wirtgen 2500 SM allows selective mining of individual oil shale beds as well as limestone interbeds.

where Devonian sedimentary rocks directly overlie Kukruse beds.

Kukersite oil shale is mainly used as a fuel for combustion in power plants and in thermal processing for producing oil and gas. The ash formed by combustion is used in road construction and as a raw material for manufacturing building materials. About 80 to 82% of the annual output of 12 to 13 million tons is used in power plants, 15 to 17% is used for oil retorting; and 2 to 3% is used for producing cement. The composition of the oil obtained as a result of retorting kukersite differs from that of crude oil. Currently, the retorted oil is mainly used as a fuel oil. In the past it was also used for wood impregnation and to produce electrode coke. The shale-oil phenols were used as a feedstock for making resins, synthetic tanning agents, and lacquers. The volatile ash of power plants was used as a lime fertilizer for neutralizing acid soils, for producing ash-Portland cement, sand lime bricks, and construction boards, and in road building.

To estimate the possibilities for the use of kukersite, its calorific value, oil yield and composition, ash content and composition, and water content are determined during the exploration phase. The calorific value, the main indicator of the quality of kukersite seams, may vary from 4 to 20 MJ/kg (measured by a calorimetric bomb), depending on the seam and its location in the deposit. The calorific value of the commercial bed as a whole is highest (9.0 to 10.5 MJ/kg) in the northern part of the central and eastern area of the deposit, that of the kukersite seams (without host limestone interlayers) is 12.5 to 13.5 MJ/kg. Toward the peripheral parts of the deposit, the calorific value of the commercial bed drops to 5.0 to 7.5 MJ/kg. Another important indicator of quality, oil yield, is dependent on the calorific value. The sulfur content of kukersite is relatively stable (1.5% on average). The power plants use finely ground kukersite with an average calorific value of 8.5 to 8.7 MJ/kg. The average calorific value of the beneficiated lump oil shale used for crude-oil retorting is 11.3 to 11.8 MJ/kg.

In 2006 kukersite oil shale was mined in five open-cast mines (Aidu, Narva, Sirgala, Ubja, and Põhja-Kiviõli) and two underground mines (Estonia, Viru). All of these operated at partial capacity because the demand for oil shale has decreased steadily in recent years. Mining in open-casts was carried out at a depth of 2 to 20 m; underground mines reached 30 to 65 m from the surface.

Oil shale mining is directly or indirectly affected by the following factors:

- the thickness, structure, and bedding conditions of the commercial bed, quality of oil shale
- the thickness and structure of the overburden
- geological disturbances in the bedrock (ancient buried valleys, tectonic disturbances, karst)
- the physico-mechanical properties of the rocks

Mining is also considerably influenced by hydrogeological conditions; 10 to 23 m^3 of groundwater is pumped out per ton of mined oil shale. The major source of mine water is the Keila-Kukruse aquifer, providing 80% to 99% (depending on the depth of the mine) of groundwater infiltration.

Northeastern Estonia is the region richest in mineral resources in Estonia, providing raw material for oil shale, peat, and the building-materials industry. Oil shale mining and industrial activity change the natural balance, harm the landscape, lithosphere, hydrosphere, and atmosphere, and damage the health of inhabitants. Ida-Viru County forms 7.5% of Estonia's territory and generates 20% of its industrial output and 90% of its industrial wastes. All branches of the oil shale industry (mining, thermal processing, and combustion) produce much waste.

Ash plateaus near the Estonian and Baltic thermal power plants cover about 20 km^2 and contain more than 230 million tons of ash. Power plants are among the major sources of atmospheric pollution in Estonia. Surface water and the Ordovician and Ordovician-Cambrian aquifer systems are partly polluted in this region. The retorting of oil shale and the upgrading of shale oil into commercial products also contaminate the atmosphere, surface water, and groundwater. The waste products from kukersite processing amount to more than 80 million tons. Waste heaps cover about 2.5 km^2.

According to the current mineral resources classification system, the resources are classified (1) on the basis of the level of geological exploration into proved and possible resources, and (2) on the basis of their potential for utilization as active resources (economic status of resource according to the draft classification of the UN Committee on Natural Resources) and passive (subeconomic status) resources. In determining the active oil shale resources, economic criteria and environmental restrictions are considered. The major criterion for oil shale is the energy rating of the commercial bed A–F_1, which is a sum of the thickness, calorific value, and dry volumetric weight of all beds (including kukersite seams and host limestone interbeds). The resource is considered active when the average energy rating of the block is at least 35 GJ/m^2 and passive when the rating is 25 to 35 GJ/m^2. In the Estonia deposit, the energy rating of the commercial bed of all mine fields and some exploration fields (Ojamaa, Puhatu, Uljaste, and Uus-Kiviõli) meets the requirements for active resources (energy rating 35 to 46 GJ/m^2) without considering the environmental restrictions. In other exploration fields (Haljala, Kabala, Kohala, Oandu, Peipsi, Permisküla, Seli, and Sonda) the oil shale resources are mainly passive; only single blocks meet the requirements of an active resource. In the northwestern and southern exploration fields (Kõnnu, Rakvere, Tudu, part of Peipsi) the commercial bed does not meet the requirements established for a mineral resource; these fields remain outside the deposit boundary. Sixteen landscape and nature protection areas are completely or partly located in the limits of the Estonia oil shale deposit.

In 2006, the total oil shale resources of the Estonia deposit (23 mine and exploration fields) were 4.9 billion tons, including 1.4 billion tons (30%) of minable (active) resources. Considering the present-day level of oil shale consumption, production losses, and written-off resources (about 15 to 17 million tons), the active resources of the mine fields (0.55 billion tons as of 2006) guarantee oil shale production for at least 35 years. In the future the Aidu and Narva open-cast mines will be operating as underground mines because of the increasing thickness of the overburden (25 to 30 m). Supplementary reserves for operating mines can be obtained on account of the other exploration fields. Mining licenses should be obtained for favorable areas in the Aidu and Narva mine fields for which the allotment is currently missing. Old mines (Tammiku, Sompa, Ahtme, and in the future Kohtla) should be closed down after the exhaustion of the active reserves in the places already prepared, since mining the latter through other mines is hardly possible. New open-cast mines were opened in the Põhja-Kiviõli exploration field (mining began in 2003) and in Ubja (2005); the Uus-Kiviõli, Sonda, and Puhatu exploration fields are fit for underground mining. Oil shale mining is expected to range between 12 and 15 million tons in the coming years.

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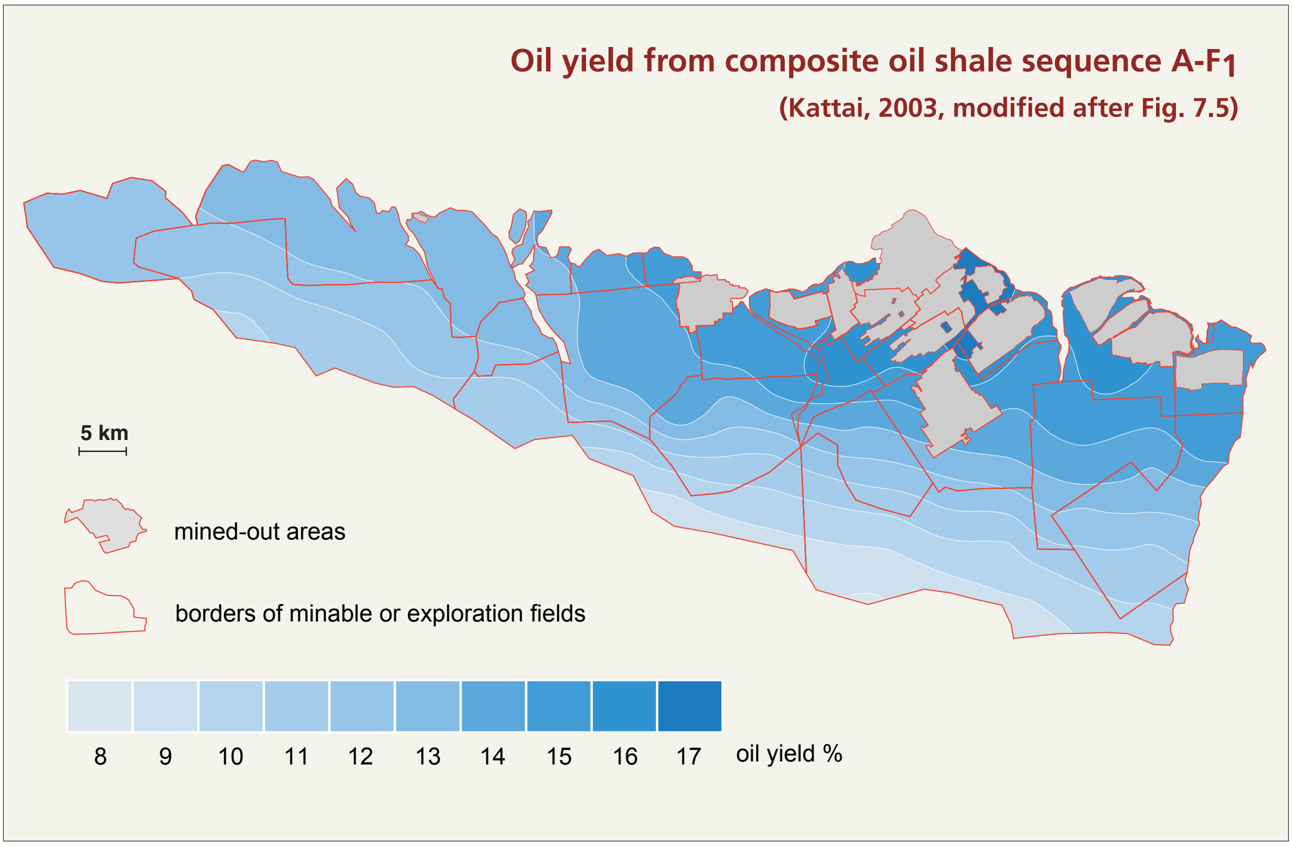
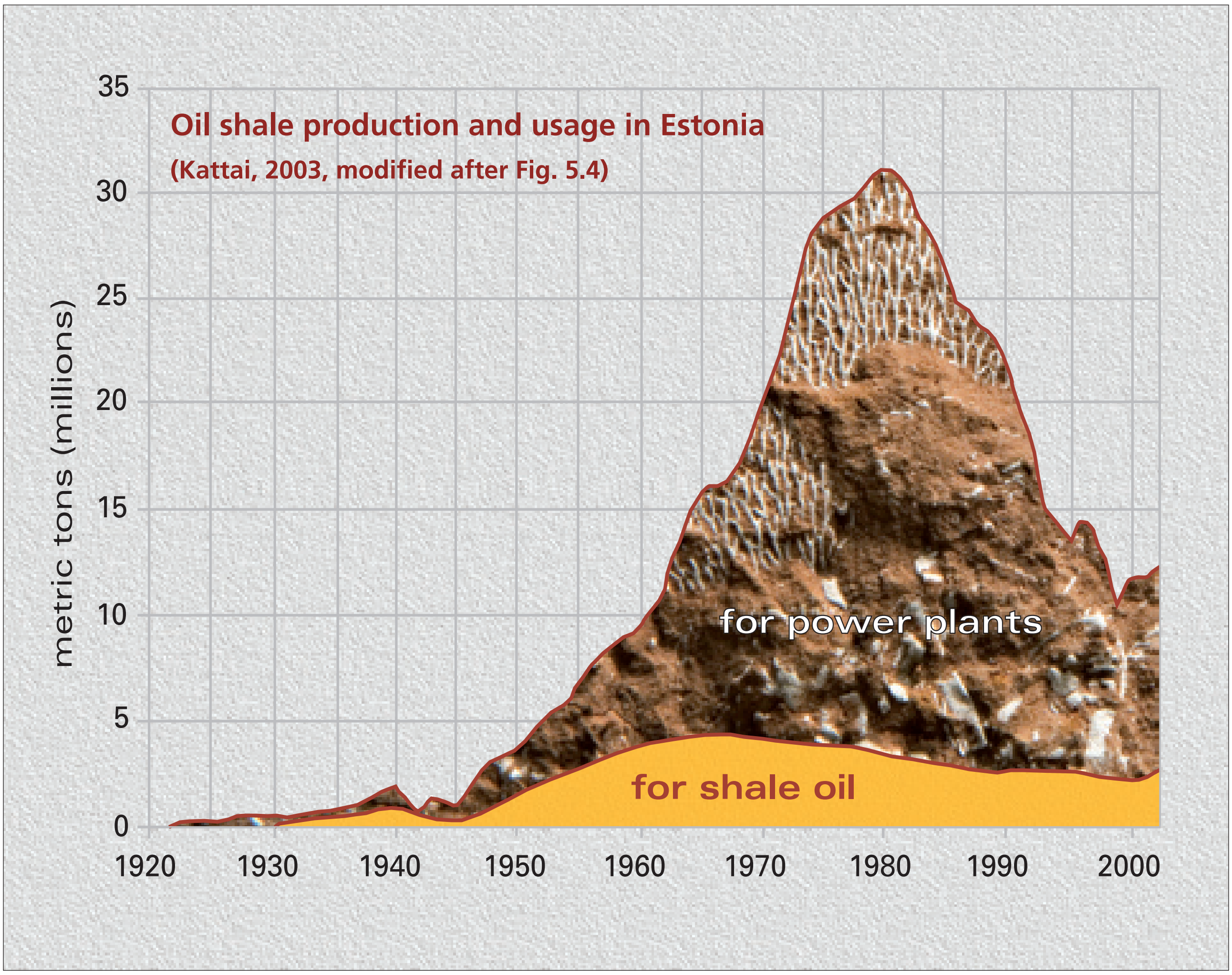
Oil yield isolines of the oil shale bed sequence A-F_1 in the Estonia oil shale deposit. Values refer to minable composite rock, which includes both oil shale and limestone interbeds (above right)


Oil yield from composite oil shale sequence A-F1
(Kattai, 2003, modified after Fig. 7.5)
5 km
mined-out areas
borders of minable or exploration fields
8
9
10
11
12
13
14
15
16
17
oil yield %


Oil shale production and usage in Estonia
(Kattai, 2003, modified after Fig. 5.4)
metric tons (millions)
35
30
25
20
15
10
5
0
1920
1930
1940
1950
1960
1970
1980
1990
2000
for power plants
for shale oil

THE MINERAL RESOURCES OF ESTONIA: PHOSPHORITE

Rein Raudsep

Research into the *Obolus* sandstone (Upper Cambrian to Ordovician in age) in Estonia goes back well over a century. Nevertheless, its utilization lagged behind the studies. In 1861 C. Schmidt stressed the significance of *Obolus* sandstone, which is easy to enrich through sifting, as a possible raw material in the manufacture of fertilizers. However, it was not until the end of World War I that an acute shortage of resources made the German geologists get down to studying *Obolus* sandstone as a potential phosphorite ore.

The high prices of phosphate fertilizers immediately after World War I compelled the Ministry of Agriculture of Estonia to initiate relevant investigations. In 1920, the joint-stock company "Eesti Vosvoriit" ("Estonian Phosphorite") was established, and the first geological investigation was started near Tallinn. It went on for two years. As a result, *Obolus* sandstone was rated as phosphorite ore. In 1924, a mine and plant started to operate at Ülgase. The plant was in operation until the fire of 1938. A new mine and an enrichment plant were built at Maardu in 1940.

During World War II, the annual output of phosphorite was low. However, in the postwar period the Soviet authorities ordered the widening of the phosphorite mines at Maardu. The greatest annual output was 850,000 tons of raw material, most of which was used for producing phosphorite meal, an ineffective fertilizer. A small amount of concentrated phosphorite was added to superphosphate for the neutralization of acid soils. Apatite, the raw material for superphosphate production, was brought from the Kola Peninsula. At the same time, all of northern Estonia was subject to large-scale explorations during which the already known deposits at Maardu, Tsitre, and Aseri were studied and several new ones (Narva, Toolse, and Rakvere) were discovered (Raudsep 1982).

In the 1980s environmental problems attracted increasing attention. In the Maardu mining area, air, soil, and water were contaminated. *Dictyonema* argillite (alum shale), which on phosphorite mining was removed with the overburden and deposited in waste dumps, tended to self-ignite through pyrite oxidation. The burning shale emitted hazardous gases and radioactive substances which were carried many kilometers by wind and water.

In 1991, in light of the circumstances listed above and the exhaustion of phosphorite resources at Maardu, the mining and enrichment of phosphorite were terminated. During the years of operation, 25 million tons of phosphorite ore were extracted at the Maardu deposit.

At the end of the 1980s, the Estonian government, at the urging of scientists and under pressure from the public, succeeded in rejecting the demands of Soviet officials to start the building of gigantic mines in the Rakvere Phosphorite Region, including the Toolse and Kabala deposits. In so doing, the Estonian government and public relied above all on environmental and socio-economic considerations (Raudsep et al. 1991, Raudsep 1994).

Geology

Estonian phosphorite is a slightly cemented sandy deposit finely or coarsely grained. Its color is yellowish-light or dark-grey. The typical shelly phosphorite (Puura 1987, Raudsep et al. 1991) occurs at the boundary of the Upper Cambrian and Lower Ordovician (Kallavere Formation). The basic rock-forming minerals are quartz and biogenic phosphate (fluorcarbonate apatite), represented by remnants of brachiopods. The proportion of these minerals varies by layer and deposit. The content of remnants of brachiopods in the rock ranges from 5–10% to 80–90%. The brachiopod shells and detritus contain up to 35 to 37% P_2O_5; in the whole phosphorite layer, the content of P_2O_5 is in the range of 6 to 20%. In 2006 total phosphorite resources accounted 303 million tons P_2O_5 of passive (subeconomic) proved and possible reserves.

Phosphate rocks also contain dolomite, calcite, pyrite, glauconite, and ferrous hydroxides that

Shelly phosphorite from Maardu deposit (above) and from the temporary Mäekalda outcrop, Tallinn (below)

occur in small amounts but that are sometimes very important in ore enrichment.

The sandy deposits of the Kallavere Formation are spread nearly all over Estonia, except the narrow southwestern and northeastern zone, which extends from Saaremaa Island to Lake Peipsi. The thickness of the formation ranges from 1 to 20 m. The commercial phosphorite bed at a depth of 5 to 200 m is 1 to 12 m thick. The monoclinally bedded sedimentary complex has a slightly southward inclination (10′ to 15′). Some tectonic dislocations occur against the generally peaceful background.

The phosphorite layer is covered by *Dictyonema* argillite, rich in kerogen and pyrite, and by Lower Ordovician clay, glauconitic sandstone, limestone, and dolostone. The Quaternary cover is usually 0.5 to 3.0 m, in the buried valleys 20 to 90 m thick.

The major phosphorite deposits occur in northern Estonia. In order of size, they are Rakvere, Toolse, Aseri, Tsitre, and Maardu.

Problems of development

The opening of new phosphorite mines and plants in Estonia (Toolse and Rakvere deposits) has been widely discussed. The problems to be addressed may be divided into four groups: technological and technical, environmental, economic, and sociological.

The technological and technical problems of development differ by deposit. The phosphorite of the Toolse and Rakvere deposits is easily enriched by flotation. Some types of ore (weathered, high silicate, carbonate) are difficult to enrich and it is impossible to get normal concentrates out of them. In general, all the concentrates have high total impurity (MgO, Fe_2O_3, Cl) content. There is a possibility that the areas contributing to the high impurity content will not be mined. Additional studies are needed.

Another group of problems relates with the mining of phosphorite. In the Rakvere deposit, where the phosphorite seam lies at a great depth, only

underground mining is possible. The main difficulty is the lower nonsolid rock overburden. The oil shale layer some 20 to 35 m above the phosphorite can be removed and utilized.

Open-cast mining is possible only in the Toolse deposit, but several problems need to be addressed before it can be initiated. Among them are the efficient use or, at least, the safe disposal of the *Dictyonema* argillite and other minerals in the overburden.

The above is a topical environmental problem. A terrifying example is the mined-out area at Maardu where the loose *Dictyonema* argillite in the waste dumps is liable to spontaneous ignition. Because of its sulfur content (2 to 3%), the burning *Dictyonema* argillite contaminates the atmosphere with sulfur dioxide. Heavy and radioactive metals, rendered more soluble on ignition, also find their way into surface water and groundwater. The development of satisfactory methods for dealing with the associated rocks, especially *Dictyonema* argillite, is a matter of the highest priority (Veiderma 1993). A solution will determine whether open-cast exploitation of the other Estonian phosphorite deposits (particularly at Toolse) will be introduced.

The Toolse and Rakvere deposits are situated in a densely populated and economically advanced region. On the one hand, the convenient location of the deposits deserves attention. On the other hand, one has to consider that these deposits are in the Pandivere Upland, the source of many rivers and a water recharge area for groundwater aquifers. Introduction of phosphorite mining at the Rakvere deposit would create a situation in which water basins over a large area would dry out and the groundwater level of several aquifers would noticeably sink. Thus, for several reasons the agriculture and way of life in a comparatively large area would be destroyed. The situation in the Toolse deposit is less complicated.

From the economic point of view, the production of concentrates from the Toolse and Rakvere deposits will not pay off. Production costs at Toolse may approach or exceed the level quoted for Kingisepp (Russia) concentrates: US$38 to US$56 per ton (IFDC Report, 1993) which is considerably higher than, for instance, in Florida (less than $30 per ton). One factor that might decrease production costs at Toolse is the potential for low-cost electrical power and labor in Estonia.

Sociological factors could be very important for the further development of the Toolse deposit. The impact on the demographic situation in the region will be minor if local people are hired. Some expropriation of land and relocation of residents are expected. However, the number of families directly affected by planned mining activities will not be known until a mining plan is prepared and a detailed land-use survey is conducted (Environmental Review for Toolse Phosphorite Deposit, KBN, USA, 1993).

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THE MINERAL RESOURCES OF ESTONIA: SAND & GRAVEL

Mare Kukk

Sand and gravel are the most common local building materials in Estonia. Sand is used in various building mixtures: as fine aggregate in concrete, ferroconcrete and asphalt concrete, in the manufacture of silica and silicalcite products, ceramics and glass, and in road making. Sands, composed mostly of quartz and feldspars, are the most widespread (Räägel 1997). Gravel consists of magmatic, metamorphic, and sedimentary rock particles. But carbonate varieties dominate.

In Estonia, sand and gravel deposits are mostly glaciofluvial (70 to 80%) and to a lesser extent glaciolacustrine, aeolian, and marine in origin. Glaciofluvial deposits occur in eskers, kames, glaciofluvial deltas, and outwash plains over a wide area (Räägel 1997).

The reserves of sand and gravel and the composition of sediments in eskers vary depending on the shape and size of the esker. Narrow, steep-sloped eskers usually consist of coarse-grained sediments; large flat-roofed eskers consist mostly of sand and fine gravel. In a long ridge both the shape of the esker and the composition of the sediments may vary with the different parts of the ridge. The concentration of coarse particles in eskers may reach 60 to 70%. This kind of material is dominated by carbonate rocks, the content of which may reach 80 to 90%. The proportion of magmatic and metamorphic rocks does not usually exceed 20 to 30%. Generally, the sand fraction is dominated by quartz (more than 60%) and feldspars (up to 25%). Occasionally, the concentration of carbonates exceeds 60% (Räägel 1997).

The sand and gravel resources are of uneven distribution, occurring mostly in a narrow area of long systems of eskers. About two-thirds of the sand and gravel deposits are distributed in northern and southeastern Estonia. In 2005, 347 sand and gravel deposits were known in Estonia, whereas sand deposits accounted for 88% of the explored reserves. Sand deposits made up 65% of the exploitation reserves. About 32.5% of the minable reserves of building sand (621 million m^3) are in the five largest deposits (Tallinn-Saku, Kuusalu, Helmi-Aakre, Mäeküla, and Kõnnu). The reserves of technological sand (7.4 million m^3) have been calculated only in four deposits in Põlva and Võru counties, the largest deposits being Piusa and Imara-Tabina. Currently, sand is found almost everywhere in Estonia, but the minable reserves of gravel are considerably smaller (107 million m^3) and in several regions are almost exhausted.

Sand and gravel form scenic landforms and landscapes, which have been placed under protection in wide areas. This complicates the estimation of the resources and exploitation of deposits.

The use of sand and gravel has always been controlled by the level of construction activity. The largest quantities of sand and gravel were used from 1975 to 1990, when 12 to 15 million m^3 (sand and gravel in equal amounts) was excavated annually from 900 deposits. More than 75% of the gravel was used in road building. From 2000 to 2004, 0.8 to 3.8 million m^3 of sand and about 0.5 to 0.9 million m^3 of gravel were excavated annually, mostly in Harju County. In 2006 these numbers were 3.2 million m^3 and 1.3 million m^3, respectively.

At the beginning of the 1990s, large-scale construction activities decreased considerably in Estonia, and fewer mineral resources were used for construction. However, after a few years the demand for sand and gravel (particularly for sand) began to grow because of the extensive reconstruction of roads and the building of houses.

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Technological sand of Devonian age at Tabina sand pit, Võrumaa

THE MINERAL RESOURCES OF ESTONIA: CLAY

Enn Pirrus

The natural reserves of clay in Estonia are practically unlimited, but the clays have rather similar quality parameters and do not allow a wide range of application. Clays are used in the manufacture of simple construction ceramics (bricks, stove tiles, drainage pipes, ceramic tiles, lightweight aggregate), as a raw material in cement making, and for isolation in waste depositories. In 2005 Estonian active reserves of clay were estimated at 27.3 million m^3 for cement making and at 246.9 million m^3 for the manufacture of ceramics.

The quality parameters of clays depend on their genesis. Cambrian and Lower Ordovician marine clays, the most common clays in Estonia, have the illite-chlorite mineral association persistently dominating in their composition.

The fairly widespread Quaternary glaciolacustrine clays of the last glaciation are richer in illite and poorer in chlorite. Occasionally kaolinite occurs, but its proportion is low (10 to 12%) and does not exert any marked effect on the properties of clay. The granulometric composition of Quaternary clays is inconsistent. Accordingly, the content and composition of loose particles (quartz and carbonates), resulting from the denudation of Ordovician and Silurian rocks, vary widely. This circumstance determines the field of application for these clays (stove tiles, keramsite).

The use of glaciolacustrine clays is restricted by their high natural humidity (40 to 70%), particularly in the area of high-quality clays in western Estonia. For this reason, clay has to be dried before application, but this raises production costs. Another limiting factor is the occurrence of lime concretions formed as a result of the redistribution of carbonate material. These lower the quality of products and need to be ground.

Because of the technological complications and high natural humidity, the glaciolacustrine clays are not currently used, although at the beginning of the twentieth century more than 20 brickyards were operating in Estonia. Six of the clay deposits in Estonia are prospective. Considering local

Temporary outcrop of Cambrian clays in Tallinn needs and increased transportation costs, glaciolacustrine clays may be taken in use again in the near future.

Clay deposits of higher quality occur in the Middle Devonian Burtnieki and Gauja stages cropping out in southern Estonia. These clays are of complicated alluvial (deltaic) and marine genesis. As a result, several grey clay varieties contain up to 30 to 40% kaolinite, which raises the fusing point to 1,380–1,450°C, widens the baking interval, and makes the clays suitable for the manufacture of higher-quality products.

The granulometric composition of Devonian clays varies widely (fraction < 0.01 mm 45 to 77%); the plasticity number ranges from 4 to 28. They also differ in the presence of impurities, such as sandstone and siltstone interlayers and lenses and carbonaceous and phosphorite concretions. The irregular bedding, small dimensions and complicated, lens-like structure of the deposits are a major constraint on the commercial use of the clays. The Devonian clays are suited, above all, for small-scale production at brickworks or local brickyards, known from the last century.

Clays occur of still higher quality, but these deposits are commercially unworkable because of the great bedding depth. Kaolinite is the prevailing component in the weathering crust of metamorphic and magmatic rocks of the pre-Cambrian basement. In places, kaolinite forms pinkish-white clay lenses, some meters in thickness. In the sedimentary rocks of the Vendian complex of subcontinental genesis, resting directly on the weathering crust, the proportion of kaolinite is still substantial, rising often to 40% to 60% and occasionally even to 80% to 90% (Voronka Formation) of the clay component. However, all these occurrences are small in volume and lie at great depths (100 to 300 m); they are therefore practically unworkable. For the same reason, the deposit of illite clays 10 to 40 m thick of the Late Vendian Kotlin Formation in eastern Estonia is only of theoretical commercial value.

The Lower Cambrian clays (so-called *blue clays*), cropping out in a narrow coastal belt in northern Estonia are the most widely used for commercial purposes. The clay body is here 60 to 70 m thick, homogeneous, and easy to reach. The clay of the Aseri deposit is mainly used for the manufacture of bricks and stone roof tiles (also for export); the production of drainage pipes has ceased. Clay mined from the Kunda deposit is used for producing cement. Like other fusible clays, Cambrian clay could be used in producing lightweight aggregate for concrete, but there is no market for such a product today.

The low fusing point (1,200–1,290°C) and the short baking interval (80–120°C) of Cambrian clays causes technological problems. A serious disadvantage is also the relatively low plasticity (8 to 26) resulting from the irretrievable adhesion of the originally finely dispersed clay particles. All this complicates preparation of raw mixture for molding and the regulation of the firing process.

Close-up of Cambrian clays (lower half of sequence)

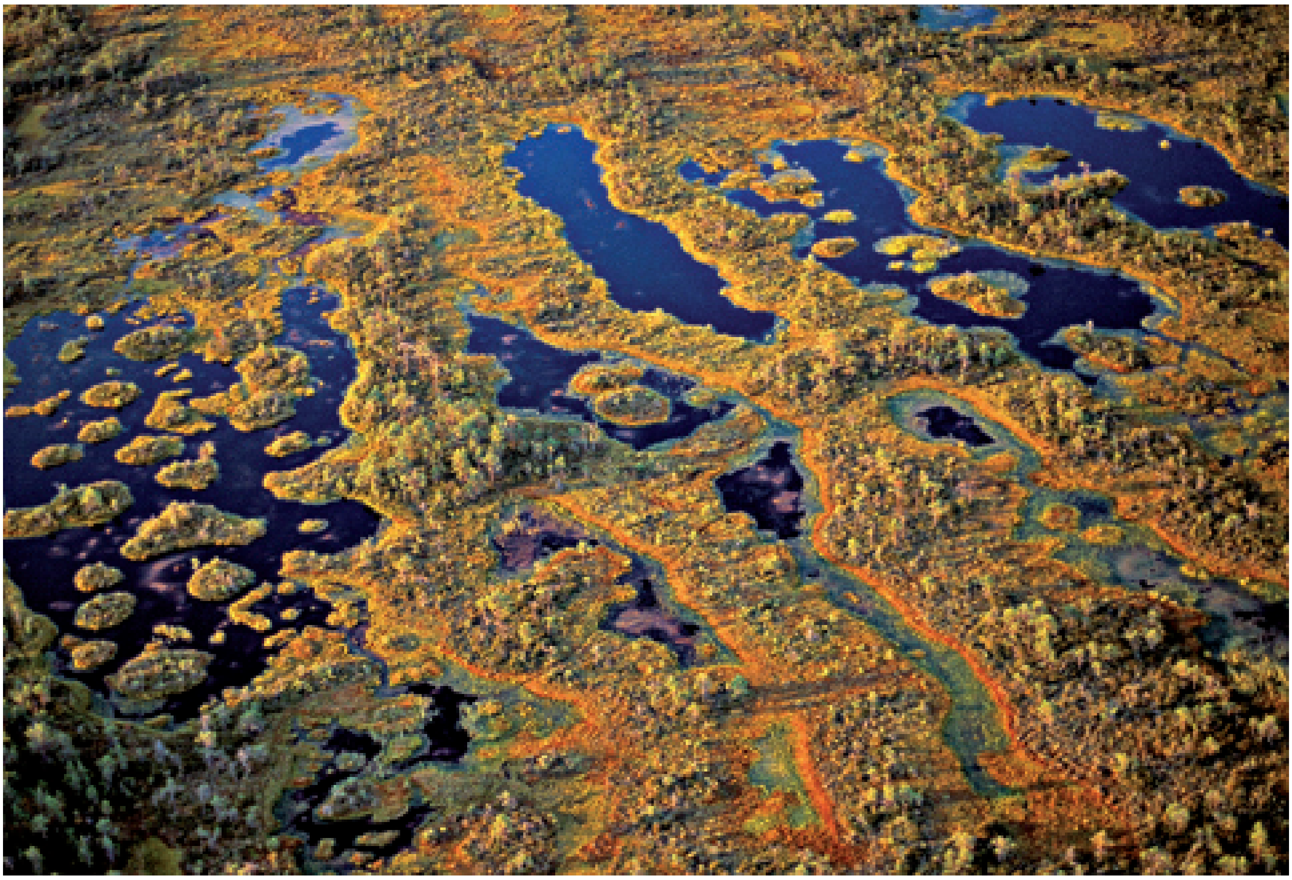
THE MINERAL RESOURCES OF ESTONIA: PEAT

Mall Orru

Estonia is considered to be the country with the second-richest peatland in northern Europe. The area occupied by 9,836 mires is 1 million hectares; 22.3% of Estonia is covered by peatlands. There are 520 large mires with a thick layer of peat. They are of major significance in a number of respects, including commercial and agricultural use and nature conservation. The remaining 1,106 peat deposits are mostly fens with a thin layer. The average thickness of the peat layer in Estonian mires is 3 to 4 m, the greatest thickness is 17 m.

The formation of mires started after Estonia was freed from the ice cover, first in upper Estonia, later in lower Estonia. Throughout the postglacial period, climatic conditions have favored the rise and development of mires. In Estonia, mires formed mostly as a result of the paludification of mineral soils or the filling up of shallow bodies of water. On the basis of the origin and peat-forming species, mires are classified as fens and raised bogs with a transitional mire between them. A fen forms in a low-lying area where the soil is rich in nutrients provided by groundwater. A luxuriant carpet of numerous species of hydrophilous plants grows on it. The main peat-forming plants are sedges, reeds, horsetails, mosses and several species of trees. The ash content of eutrophic peat is high. A raised bog's only supplementary source of minerals is precipitation. The nutrition provided by this kind of "airlift" is inevitably rather meager, and all plants growing in bogs have to cope with a substrate that is extremely poor in nitrogen and lime. Peat mosses flourish under such conditions and provide the major ingredient for peat. To a lesser extent, horsetail, *Scheizeria*, and pine occur. The ash content of ombrotrophic peat is low. A transitional bog is fed by groundwater and precipitation and promotes the development of both fen and raised-bog plants. It also provides favorable habitats for cranberries.

Kaasikjärve bog in the Endla mire system in autumn colours



Total area of mires in Estonia is about 1 million hectares, whereas under protection is about 175 000 hectares:

• Bogs	– 135 000 ha
• Transitional & quaqing mires	– 19 500 ha
• Fens	– 19 000 ha
• Great fen-sedge (*Cladium mariscus* (L.) Pohl) fens	– 1 100 ha
• Spring fens	– 400 ha

Estonia's total peat resources in 1,626 deposits are estimated at 15.24 billion m^3 or 2.37 billion tons. Presently, the environmental register includes 279 peat deposits (total area 359,209 hectares; peat resources 1.61 billion tons) of commercial interest. Currently, 161,575 hectares of peatlands are under conservation. The reserves of peat suitable for use are 627 million tons. The reserves of weakly humified peat are 77 million and strongly humified peat 550 million tons. About 77 deposits are exploited. The distribution of peat resources by counties is uneven.

Peat is produced for use as litter in animal husbandry, for substrate in horticulture, and for fuel. It is also mixed with manure and used for improving agricultural soils. The area of peat-production fields is 20,549 hectares. Estonian peat is exported to 110 countries.

Besides the peatlands, there are many small mires with a thin layer of peat. They cover an area of 107,453 ha. The peat reserves of those small mires have not yet been estimated.

Within the framework of the Natura 2000 project, 211,421 hectares of Estonian mires have been placed under protection. Most (72%) of them are natural raised bogs.

As the natural accumulation of peat in mires is slow and natural sites for its accumulation are dwindling rapidly, the government of Estonia has adopted regulations for the sustainable use of peat, with annual output quotas for every county. For the entire country, the quota is 2.65 million tons per year.

It is expected that peat will find new uses in the future, since it shows promise for producing growth stimulators and peat wax. There are rich resources of well-humified eutrophic peat suitable for making growth stimulators (about 57 million tons), and the production technology is not very complicated. The resources of cotton-grass peat for producing peat wax are estimated at 1.6 million tons, for balneology, 0.9 million tons.

Extensive peat production may damage the natural ecological balance. When planning peat milling in new fields, one has to take into consideration the groundwater regime and other local conditions so as to avoid the destruction of natural cranberry bogs. Cranberry plantations are to be laid out in the exhausted peat-milling fields. Experiments of this kind have already been made in Estonia and the results are good.

One of common peat mosses
Sphagnum magellanicum **Brid.**

EXCURSION STOP: VÄO LIMESTONE QUARRY

Rein Einasto

The Ordovician carbonate rocks of Estonia lie under a thin Quaternary cover and are therefore easy to reach. Since the thirteenth century, these rocks, remarkable for their unrivaled durability and great variety, have been widely used for building (strongholds, castles, churches, townhouses, bridges, fireplaces), making sculptures, road building and paving, the production of lime and cement, the glass and paper industry, and export.

The quarries are operated in northern Estonia, where the Middle Ordovician building stone crops out as a continuous belt with an average thickness of 8.0 to 8.6 m. The belt thins gradually from Tallinn toward Osmussaar Island and to the southwest. Long traditions of stonemasonry have provided a detailed, bed-by-bed stratification of the quarried rocks (Table 1), according to their properties, composition, color, textural features, and possibilities for usage. Altogether, 58 beds (Vilbaste 1954; Einasto 2002) have been distinguished. They range from the lower part of the Väo Formation (Lasnamägi Stage) to the lower part of the Kõrgekallas Formation (Uhaku Stage).

The section of building stones (beds 16 to 56) is well-exposed in the Tondi–Väo quarry (Väo deposit) near Tallinn. The Väo Paas (1) drill hole, penetrating beds 15 to 56 (Table 1) and terminating in the carbonate rocks of the Volkhov Stage (depth 14.8 m), lies southeast of the quarry. The Väo Formation, overlain by Quaternary sediments, is well-represented, and the core section is used as the type section of the formation.

The building-stone sequence of medium- to thick-bedded limestones with numerous discontinuity surfaces in northern Estonia was first thoroughly described by Jaanusson-Orviku (1927). The same succession and lithological variation of beds in combination with characteristic discontinuity surfaces can be observed over a wide area

Production at the Väo quarry

Indexed limestone beds (for usage see Table 1)

Table 1. Bed-by-bed stratification of the Väo Paas (1) section, and characteristics of the building stone

Regional stage	Formation	Depth of the lower boundary (m)	Bed number	Local bed name	Traditional applications / remarks
Uhaku	Kõrgekallas	–	1	Nutu	– / crumbles easily
		–	2	Hakantkirju	Masonry / argillaceous, with a PDS
		–	3	Topeltkirju	Masonry / argillaceous
		–	4	Kollane lõug	Masonry / argillaceous, on the PhDS kukersite-containing
		–	5	Ratsatäkk	Masonry / argillaceous, with a hard middle interbed
		–	6	Papa	Masonry / argillaceous
		–	7	Mamma	Masonry, indoor steps / argillaceous, with a hard middle interbed
		–	8	Tussualune (Mapa)	Masonry / argillaceous, with a hard middle interbed
		–	9	Tõusandus	Masonry, indoor steps / argillaceous, with a hard middle interbed
		–	10	Karvakord	Masonry, internal wall cladding / with a distinct rugged PDS
		–	11	Reinukord	Indoor steps in a light traffic area / –
		–	12	Seitsmetolline	Indoor steps in a light traffic area / –
		–	13	Laksupealne	Indoor steps in a light traffic area / –
		3.58	14	Laksu	Indoor steps / with a distinct PDS, very picturesque
		3.67	15	Nahakord	Internal wall cladding / with two PDSs, very picturesque
	Väo	3.85	16	Tulikord	Outdoor paving in a heavy traffic area / dark
		3.90	17	Nahakord	– / crumbles easily
		4.00	18	Mädakord	– / crumbles easily
		?	19	Nõtku	Masonry / brittle
		4.25	20	Rabandus	Outdoor steps in a heavy traffic area / –
		4.38	21	Lõhkumine	Outdoor steps in a heavy traffic area / –
		4.58	22	Paks hall	Outdoor steps in a heavy traffic area / outermost beds crumble easily
		4.88	23	Kirjukord	Outdoor steps in a heavy traffic area / –
		5.13	24	Trepp	Masonry, indoor steps in a heavy traffic area / with a distinct PDS?, very picturesque
		5.29	25	Viiene	Masonry, outdoor paving in a heavy traffic area / with a distinct PDS?
		5.40	26	Neljane	Masonry, outdoor paving in a heavy traffic area / with a distinct PDS?
		5.47	27	Pealmine nahakord (arssin)	Internal masonry / –
		5.63	28	Tige seitsmene	Wall cladding and flooring / with a hard middle interbed and a PDS in the middle, very picturesque
		5.67	29	Alumine nahakord	Masonry, outdoor wall cladding / –
		5.95	30	Pealmine muldvalge	Suitable for all outdoor building applications / thick-bedded
		6.25	31	Alumine muldvalge	Suitable for all outdoor building applications / thick-bedded
		6.55	32	Kassikord	Outdoor wall roofing tile and steps / split into three, with a hard middle interbed
		6.80	33	Lutt	– / crumbles easily
		7.00	34	Laksu-punane	Outdoor usage in severe exposure areas, steps in a heavy traffic area / peculiar vertical sedimentary structures, very picturesque
		7.21	35	Kirjukärn	Suitable for severe exposure areas / peculiar vertical sedimentary structures, two distinct PDSs, very picturesque
		7.42	36	Trepp-kalk	Outdoor steps in a heavy traffic area, wall cladding and flooring / with two hard interbeds, set upside down
		7.64	37	Sauekord	Internal masonry / –
		7.75	38	Hall arssin	Outdoor usage, flooring in a heavy traffic area, wall cladding / very picturesque
		7.84	39	Valge arssin	Outdoor usage, paving in a heavy traffic area / –
		8.20	40	Nahakord (Sajakordne)	– / crumbles easily
		8.36	41	Tulikord	Indoor steps in a heavy traffic area / crystal size is larger than 0.05 mm, contains pyrite
		8.47	42	Poriarssin	Outdoor paving / the upper interbeds harder than lower, pyrite-rich
		8.60	43	Poriarssina alune	Masonry / brittle, pyrite-rich
		8.75	44	Ristikord	Memorials and carving (sculpture), outdoor usage / –
		8.81	45	Nahakord	– / crumbles easily
Lasnamägi		9.08	46	Raudsüda (Üheksane)	Outdoor usage, wall cladding and flooring / split into three, the middle interbed harder than outer, flexibility values of the bed high
		9.24	47	Kuuetolline	Memorials and carving (sculpture) / homogeneous
		9.40	48	Seitsmetolline	Memorials and carving / the lower interbed harder than upper, heterogeneous with a PDS in the upper part
		9.57	49	Neljane	Outdoor paving / –
		9.67	50	Viiene	Outdoor paving / –
		9.85	51	Pealmine põhjavalge	Masonry / in the uppermost part a PDS
		10.00	52	Alumine põhjavalge	Masonry / pyrite-rich, with marlstone films
		10.15	53	Põhjatrepp	Masonry, outdoor steps / contains pyrite, often dolomitized
		10.40	54	Pealmine põhjapunane	Masonry, outdoor steps / hard, porous, dark brown
		10.55	55	Alumine põhjapunane	Masonry, outdoor steps / hard, porous, dark brown
		10.80	56	Pukisarv	Masonry / split into three

PDS – pyritized discontinuity surface; PhDS – phosphatized discontinuity surface; – bed missing; ? – boundary of the bed not recognized.

(Orviku 1940). Bed-by-bed stratification of the building stone known from the Väo deposit was described in the Väo Paas (1) core in the part of the Väo Formation at a depth of 3.67 to 10.80 m.

Light grey, medium- to thick-bedded, very finely crystalline and finely crystalline limestones with rare marlstone films and interbeds (thickness 0.2 to 0.5 cm) contain 25 to 50% bioclasts, abundant discontinuity surfaces, dolomitized intervals in the lower part of the Väo Formation, and pyrite impurities. Fifty-five distinct phosphatized discontinuity surfaces were recognized in the Väo Formation of the Väo Paas (1) core. Pyritized discontinuity surfaces (10) are all related to transgressive sediments.

The limestones of the quarry are intersected by two-directional (toward the southwest and southeast) vertical fractures characteristic of the entire sedimentary cover of Estonia. Fractures provide a path for fluid flow, so a variety of rock alteration and mineralization products are found along them. Often karst develops along fractures, arising from percolating waters or underground streams.

The territory of the Väo deposit is 3.1 km^3. In 2004 685,500 m^3 of limestone was mined out, and at the end of the year active reserves amounted to 14,835,000 m^3. Because of its good quality and original physico-mechanical properties, limestone from the Väo quarry is highly valued on the domestic construction market. It is considered a pure and strong natural material. Crushed limestone is the basic material used in most construction and civil-engineering operations and is key raw material for the production of asphalt and concrete.

Finely crushed stone and limestone blocks are widely used in construction works as well. Filler is a very important component for ready-mixed asphalt and concrete production. End products of various sizes are tested and supplied in accordance with customer specifications as well as governmental regulations regarding the environment and quality control.

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EXCURSION STOP: AIDU OIL SHALE OPEN-CAST MINE

Vello Kattai, Kalmer Sokman

The Aidu open-cast mine pit (active reserve: 12 million tons) is in the central part of the Estonian deposit. The northern boundary of the pit is erosional, the western boundary is cut by the Purtse ancient buried valley, and the southern and eastern parts border the Ojamaa exploration field and the old Kohtla mine. Mining conditions are the most favorable in the western part of the pit, where the overburden is less than 15 m thick; southward the overburden reaches 20 to 25 m and open-cast mining becomes more complicated. On the northern boundary the productive bed crops out from below the Quaternary deposits at a depth of 1 to 10 m from the land surface.

The kukersite formation embraces the Kiviõli Member of the Kukruse Stage (Upper Ordovician), where indexed kukersite seams (A–F_1) form the commercial bed of the Aidu open-cast mine. Major characteristics of the commercial bed are presented in the table.

The territory of the Aidu open-cast mine is 25.6 km^2, of which about 21.2 km^2 has been mined out already. Extensive surveys for new oil shale prospects were carried out in 1948 and 1949, 1970, and 1979. Mining of commercial beds A–F_1 began in 1974. The entire commercial bed is mined out at once. With later beneficiation, material is obtained for thermal processing, cement production, and use in power plants.

In 1982 more than 3.7 million tons of oil shale were mined out. The current annual output is less than 1.5 million tons.

The oil shale of the Aidu open-cast mine is consumed by the Baltic Power Plant (80%), Viru Keemia Grupp (15%), and Kunda Nordic Cement (5%).

Recultivation of the mined-out area is part of the mining process. The Estonian Oil Shale Company Ltd. levels the excavated ground, which is left for a couple of years so that it becomes stable. A forest is then planted on it. Afforestation is performed by local foresters, recultivation of farmlands by scientists from the Estonian University of Life Sciences. The recultivated area is about 19.4 km^2, including 18.0 km^2 of afforested land and 1.4 km^2 of farmland. Wildlife has returned to the recultivated areas with coniferous and broadleaved forests. Farmlands with recovered soil 50 cm thick and a risen subsoil water level have been turned into grasslands.

Index of the kukersite bed	Thickness (m)	Calorific value (MJ/kg)	Oil yield (%)	Volumetric weight (t/m^3)
F_1	0.53	6.9	12.4	1.82
E	0.55	10.8	19.3	1.61
D/E	0.11	3.1	–	2.09
D	0.10	8.6	15.5	1.73
C/D	0.22	0.0	–	2.41
C	0.34	8.9	15.7	1.72
B/C	0.11	3.1	–	2.09
B	0.50	17.5	31.1	1.38
A′/B	0.12	1.5	–	2.25
A′	0.08	7.9	14.2	1.76
A/A′	0.03	3.0	–	2.11
A	0.14	14.7	26.1	1.46
A–F_1 (m)	**2.83**	**8.3**	**14.7**	**1.75**
Σ kukersite beds	**2.24**	**10.8**	**19.1**	**1.62**

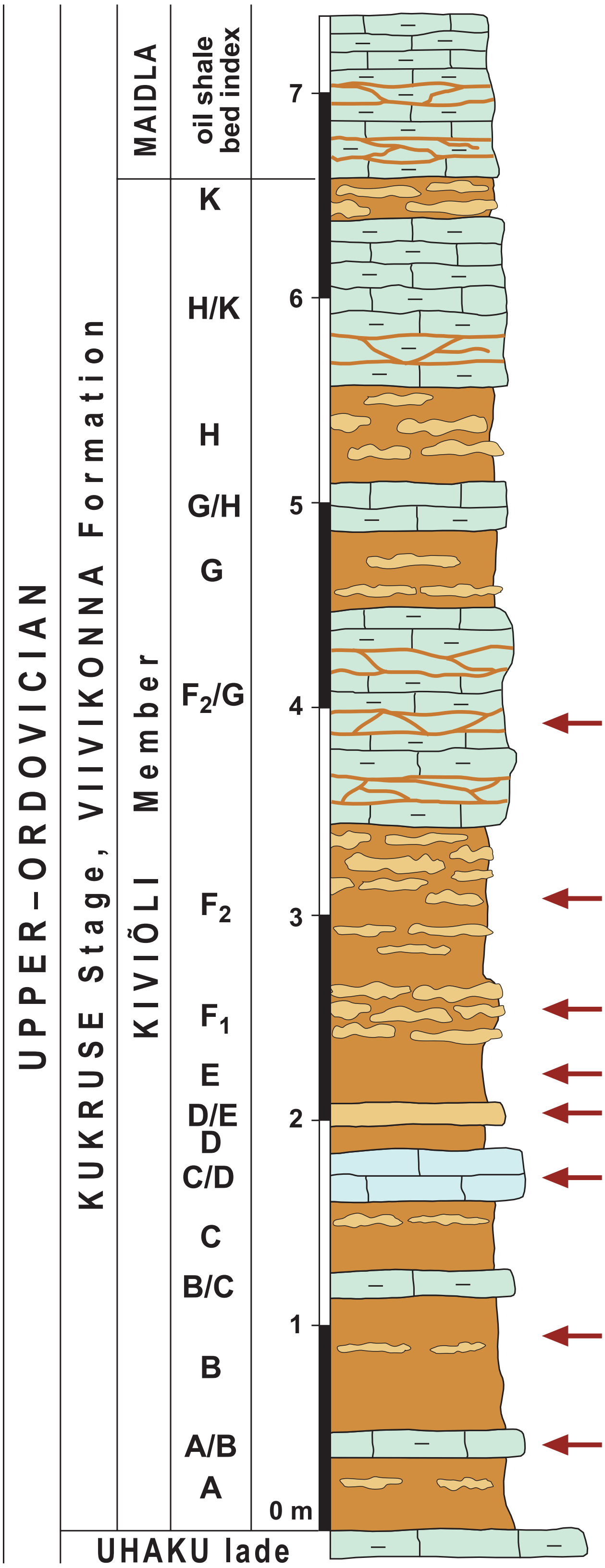
Mining operation at the Aidu (Vanaküla) open-cast mine

Dragline removing overburden

Afforested areas of the Aidu open-cast mine

VANAKÜLA oil shale open-cast mine

Upper part of kukersite oil shale seam C is penetrated by numerous burrows (trace fossils)



LEGEND:

← clayey limestone with thin wavy and nodular interbeds of oil shale

← oil shale with nodular limestone interbeds

← particular bed of kerogenous limestone nodules "Devil's skin"

← pure oil shale bed

← kerogenous limestone interbed ("pink limestone")

← bluish-gray limestone interbed ("double limestone")

← oil shale with a few kerogenous limestone nodules

← grey clayey limestone interbed (blue limestone")

Geological succession of oil shale beds exposed at the Vanaküla oil shale open-cast mine, near the Kohtla Mining Park-Museum

EXCURSION STOP: KOHTLA MINING PARK-MUSEUM

Enn Käiss

A closed Kohtla underground oil shale mine east of the Aidu open-cast mine has been converted into the Kohtla Mining Park-Museum. During excursions in the mining shafts of the former oil shale mine, tourists can learn about the history of mining and get an idea about the underground working conditions in late 1980s. It is possible to get a ride on an underground train, try one's hand at drilling with real miner's equipment, watch how several mining devices can be operated, and taste a miner's lunch in the underground environment.

The mine shafts of the museum are 8 to 35 m deep. In the present-day underground mines, the mining shafts can reach depths of 70 m. The excavation of oil shale in Estonia and the use of oil shale for the production of electricity began in 1916. The main users of oil shale have been electric power plants. About 96 to 98% of the electricity in Estonia is produced from oil shale. About 1.5 kg of oil shale has to be mined to produce a kilowatt-hour of electricity.

The Kohtla underground mine was opened in 1937. A limestone separation tower was built next to the mine. There, limestone slabs were sorted out from the mined kukersite oil shale by hand. While men worked mainly underground, women were involved in work at the sorting tower.

The mine was known for its high-level working culture, the low price of oil shale and its well-planned operations. Altogether 48,329,542 tons of oil shale have been mined in 64 years. This amount would provide electricity for our country for 14 years.

The guided tour, 1.6 km long, in the former Kohtla mine shafts shows the following:

- oil shale mining environment
- mining equipment used in the 1980s
- underground transportation vehicles
- underground explosive storage

Racing with miner's bicycles: photo E. Käiss

Fossils from the kukersite oil shale formation that can be found from nearby oil shale tailings:

a. fragile, branched bryozoa (photo A. Liivamägi)

b. inner view of brachiopod valve

c. large trilobite on kukersite oil shale surface

Photos **b** and **c** are from the image bank of the Institute of Geology at Tallinn University of Technology

EXCURSION STOP: VALASTE WATERFALL

Kalle Suuroja

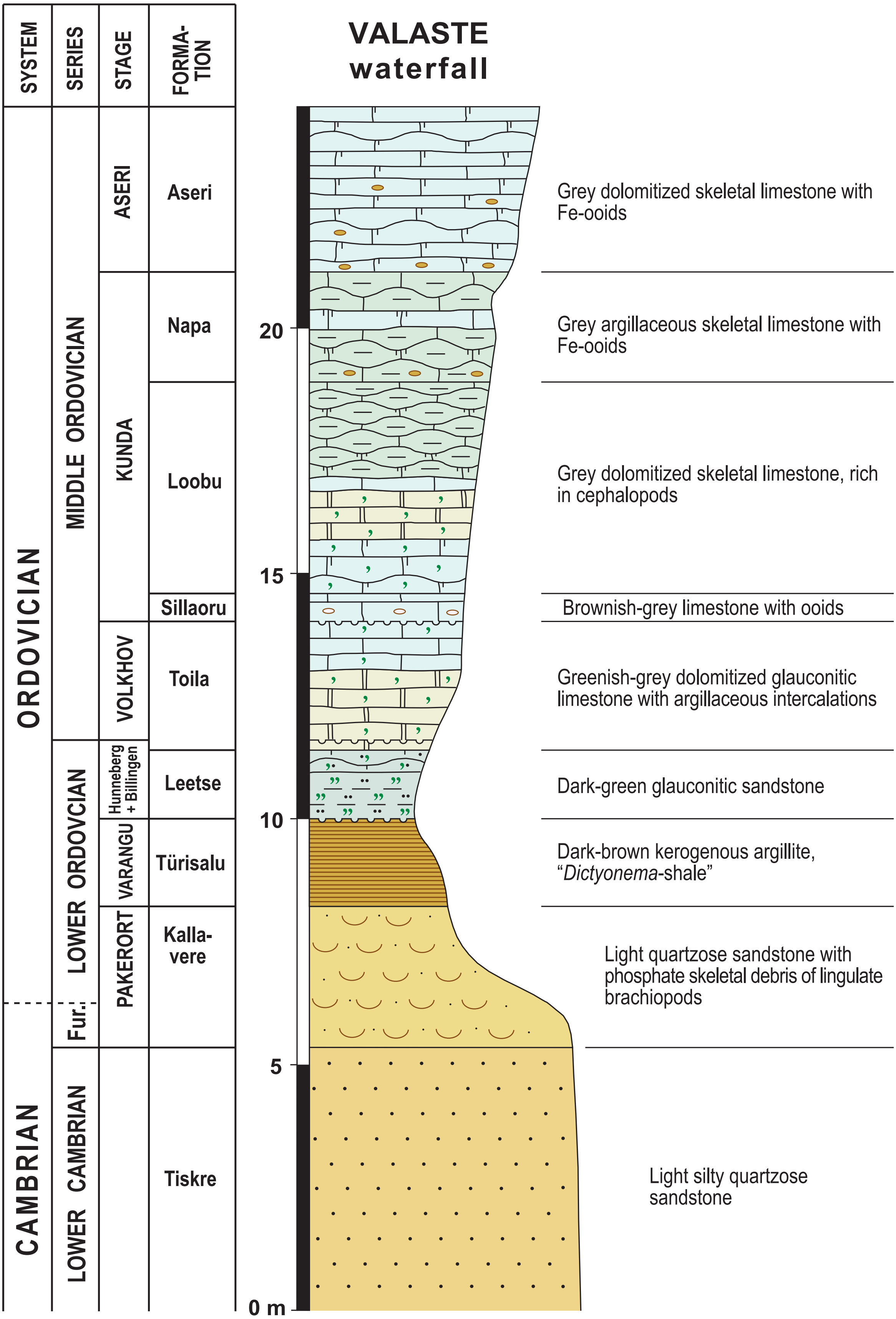
Valaste, the highest waterfall in Estonia, is on the western edge of Valaste village, Kohtla Municipality, Ida-Viru County, 2 km east of the Ontika Manor House. The water of the 7 km-long Kaasikvälja main ditch (also known as Valaste Brook), which comes from a 16 km^2 catchment area, runs in a canal more than 2 m deep cut into the limestone. The water from the canal falls off the edge of the 54 m high Saka-Ontika Klint plateau. The Valaste Waterfall has existed for more than 160 years. As early as 1840 the local German newspaper Inland wrote about it, calling it a "world wonder." A maximum height of the waterfall of 30 m was measured in the rainy month of August 1998, when the surging water cleared fallen rocks from the area underneath the falls and carved a cavity up to 3 m deep into the soft sandstone. The height of the waterfall has been 26 to 28 m. After the water tumbles from the main falls, it reaches a lower fall of 10 to 15 m, below which it turns into rapids just before reaching the sea. Of course, this happens only when there is enough water. At times (as during the dry summers of 1999 and 2002), not a single drop of water makes it over the falls. With ample water, the Valaste Waterfall is beautiful and powerful; without water it is just beautiful. This applies mostly to the wall behind the fall, which is more than 35 m high. Here multicolored rock layers of Estonia's crust are exposed. They layers formed over 80 million years (460 to 540 million years ago).

A beautiful bridge has been built directly in front of the waterfall. From the bridge, a complete and panoramic view can be had of the water as it falls from the plateau. The bridge is called *The Bridge of Sighing*.

The cross-section of the earth's crust revealed in the Valaste Waterfall escarpment starts with a layer almost 2 m thick of the surface cover consisting of both moraine and sea shingles. The presence of moraine shows that the continental glacier was once here. The shingles tell us that the sea has followed the glacier. The surface cover is succeeded by a layer more than 13 m thick of Middle Ordovician limestone. The upper 3.5 m is grey limestone (Aseri Stage), which is followed by 6.5 m of the limestone of the Kunda Stage containing numerous petrified cephalopods, and 2.5 m of glauconite limestone (Volkhov Stage). The limestone is underlain by softer Lower Ordovician layers comprising 0.6 m of multi-colored glauconite limestone (Päite Member of the Billingen Stage), 1.3 m of green glauconitic sandstone of the Leetse Formation of the Hunneberg Stage, 2 m of dark brown Dictyonema Shale of the Türisalu Formation of the Varangu Stage, and 0.5 m of Obolus sandstone or phosphorite of the Pakerort Stage corresponding to the Kallavere Formation. Below that level lie Lower Cambrian rocks reaching 530 million years in age. The rock succession is composed of 12 m of yellowish-grey quartz sandstone of the Tiskre Formation followed by 11 m of quartz sandstone, with the layer of blue clay corresponding to the Lükati Formation. When the water level is normal, the upper layers of the latter formation are the last ones that are exposed. However, during the spring melt, the upper part of the blue clay layer can be exposed within the range of a couple of meters. On the shores of the valley downstream of the waterfall the *blue clay* (Lontova Formation) is exposed; the thickness is about 10 m. That layer is a famous feature of the Estonian Cambrian, even though the clay is not as blue as the name implies. Rather, it is greenish-grey with some purple stains.

During the spring melt in the afternoon sunlight it is possible to see the extent to which the seawater around the mouth of the brook has obtained a reddish color. The reddish color is probably caused by floating particles that have broken loose from the brook bed and been carried out to sea. Sometimes the fan-shaped discoloration in the sea around the mouth of the brook can cover an area up to half a kilometer wide.

Everything described above can be recognized, admired, and even touched in the waterfall's steps



Geological section of the Baltic Klint at Valaste waterfall (Tinn, O., Stop 10. Valaste waterfall, WOGOGOB-2004 Conference Materials, Tartu 2004, modified after Fig. 138)

View of the Valaste waterfall

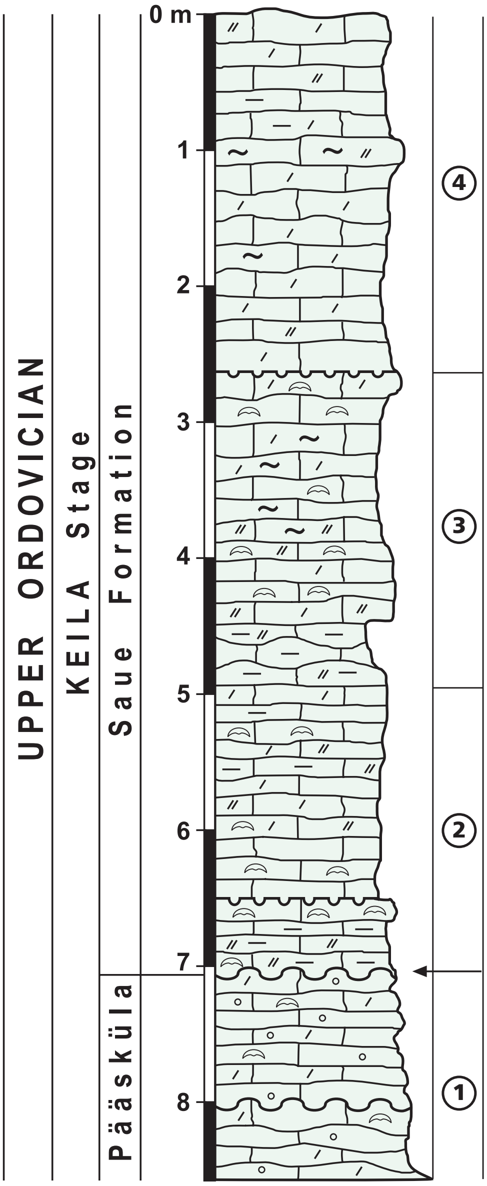
and the walls of the valley underneath it. However, an even more striking experience can be obtained when standing at the foot of the waterfall with one's head tilted back, looking up at the amphitheatre-shaped falls. If one hears the rushing sound of falling water and sees the rainbow in the mist among the trees, then one has experienced everything that Valaste has to offer.

With the first serious frosts, a huge ice monument begins to form, extending down from the top of the falls. It is surrounded by a shiny lace of icicles that hang down for about 5 m against the backdrop of the cliff. Any substantial melt or more serious temperature drop adds new details to the construction. In early spring nothing new might be seen, yet a faint noise of rushing water somewhere underneath the thick icicle covering can be heard. Then, without notice, the invisible becomes visible once again, as the water that comes from underneath the ice castle gives it a final push off the edge and down the side of the cliff.

EXCURSION STOP: VASALEMMA LIMESTONE QUARRY

Linda Hints

Ordovician Ordovician limestones have been quarried in the vicinity of Vasalemma settlement since the thirteenth century. The limestone has been used as local building material for Padise monastery, Risti and Madise churches, and Vasalemma and Laitse castles. The increasing need for limestone caused the opening of a new quarry close to the Paldiski–Tallinn–Narva–Gatchina railway in 1920. Now there are five abandoned old quarries in the limits of Vasalemma settlement. Some quarries have been filled with water and are used for swimming. In one quarry a rally tract has been built.



The quarry to be visited by our excursion is east of Vasalemma. Here a small quarry was opened in 1931. Since 1946, exploitation of the quarry has increased considerably. Nowadays, the quarry is owned by the company Nordkalk Corporation, which is active in Germany, Finland, Sweden, Poland, and Estonia and is the leading manufacturer of limestone-based products in northern Europe. The production of crushed limestone for building works is the main business of the Nordkalk Corporation in Vasalemma. The territory of the Vasalemma deposit is 5.4 km^2; the territory of the Nordkalk Ltd. quarry is 3.4 km^2. In 2005, 167,700 m^3 of limestone were mined out. At the end of the year, active reserves amounted to 15.2 million m^3.

In the Vasalemma quarry the Ordovician section (Kahula and Vasalemma formations) is exposed; the thickness is 13 to 14 m. The upper parts of the northern and southern quarry walls are of somewhat different age because of the dipping of strata by about 4 to 5 m per 2 km. The Kahula Formation and the main part of the Vasalemma Formation correspond to the Keila Stage. The uppermost part of the latter formation exposed in the quarry belongs to the Oandu Stage.

The lowest strata exposed in the northern part of the quarry (about 1.5 m) are represented by seminodular pelletal cryptocrystalline to very finely crystalline limestones, in places rich in silt and very fine sand-size quartz of the Pääsküla Member of the Kahula Formation. Spotty distribution of hemispheric bryozoan colonies in life position and large valves of the strophomenid *Keilamena* on some bedding planes are characteristic of the

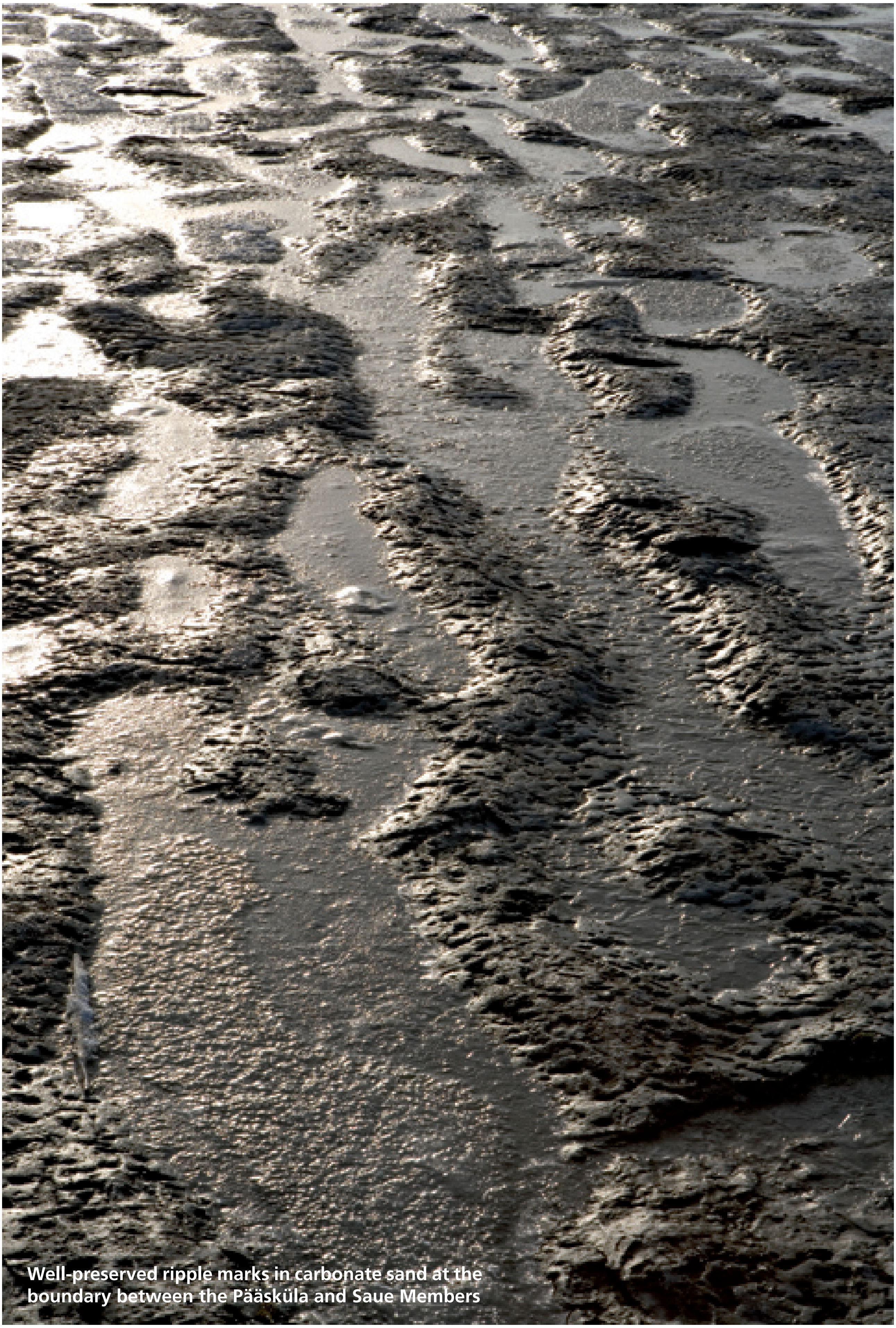
Geological section of the northern wall of the Vasalemma limestone quarry (Hints, L. et al., Stop 3. Vasalemma quarry, WOGOGOB-2004 Conference Materials, Tartu 2004, modified after Fig. 123).
1- pure limestone, with abundant bryozoan colonies, **2** - alternation of bioclastic and argillaceous limestone, **3** - bioclastic limestone, in places bioturbated and with abundant brachiopod shells, **4** - limestone with different bioclasts content and wavy bedding planes

uppermost part of these limestones. The trilobite *Conolichas* can also be found in the quarry. Some argillaceous bedding planes are covered with numerous valves of brachiopods (*Sowerbyella*, *Keilamena*, *Horderleyella*, *Clinambon*) and their fragments, sometimes concentrated in large horizontal burrows. The dense set of burrows indicates active bioerosion by various organisms.

In the northern part of the quarry, the rocks of the Pääsküla Member are capped by a surface with impregnated ripple marks exposed in a wide area. The ripples are oriented north to south and seem to be asymmetrical (Hints & Miidel 2004). Southward, close to carbonate buildups, the ripple marks become indistinct, the quarry floor starts to undulate, and in some places the corresponding bedding plane disappears under younger strata. The dense occurrence of *Trypanites*-type burrows on the upper surface of the ripple marks points to the existence of shallow water before the formation of the younger strata of the Kahula and Vasalemma formations.

Most of the section (about 7 m) in the northern part of the quarry contains bioclast-bearing interlayers and lenses in more or less argillaceous limestone (Saue member of the Kahula Formation). The sequence in the southern part of the wall is represented by small carbonate buildups. In the lowest part, the trilobites *Pseudobasilicus*, *Asaphus* (*Neoasaphus*), and *Leiolichas* have been identified (Hints et al. 2004). The biodetrital limestones and bedding planes are rich in fragments of various fossils. The Vasalemma Formation with its typical features is exposed in the central and southern parts of the quarry. The formation consists of white to dark grey, bedded, finely to coarsely crystalline grain stones. The grain stones include distinctive irregular bodies of various sizes, formed by massive pure limestones. The lower part of the formation contains an argillaceous interlayer, sometimes with fossils indicative of Keila age (e.g., the brachiopod *Estlandia*). The massive limestones, tentatively identified as carbonate buildups, have been interpreted as reefs, bioherms, or mud mounds. Younger buildups sometimes contain echinoderms *Cyatocystis* (Edrioasteroidea), which seem to form their frames. Several other fossils are present as well, for example sponges, corals, stromatoporoid-like structures, the alga *Solenopora*, and in some "caves" cephalopods, which altogether form the reef-like carbonate bodies. In the uppermost part of the Vasa-

Limestones of the Saue Member are exposed on the northern wall of the quarry



Well-preserved ripple marks in carbonate sand at the boundary between the Pääsküla and Saue Members lemma Formation are the oldest corals in Estonia (*Lyopora*, *Eofetcheria*) and brachiopods (*Rhynchotrem*, *Rostritsellula*), common in the marls of Oandu age (Rõõmusoks 1970).

The carbonate buildups contain a relatively low-diversity association of trilobites. The illaenids are most common, forming small coquinas (e.g., one about half a meter in diameter) in pockets on the outer surfaces of the buildups (Hints et al. 2004).

In the older literature the Vasalemma Formation has been described as *Hemicosmites*-limestone. In the Vasalemma quarry *Hemicosmites* has been found in the argillaceous limestones surrounding the carbonate buildups. However, in the Rummu quarry west of Vasalemma, the limestone consists mainly of the polygonal plates of *Hemicosmites calyx*.

The possible upper boundary of the Vasalemma Formation is preserved only in a few limited areas in the westernmost part of the quarry. The pyritized discontinuity surface with deep burrows filled with greenish-grey marl marks this boundary in the areas with buildups. The younger deposits have been removed by the Pleistocene ice, which has left ice scratches on hard limestones.

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Massive carbonate buildup in contact with bedded detrital limestones (horizontal size of bioherm is about 10 m)

EXCURSION STOP: LAVASSAARE PEAT DEPOSIT

Mall Orru

Lavassaare mire, 21,868 ha in area, is one of the largest mires in Estonia. The area of the Lavassaare peat deposit is 19,746 ha. The mire system includes a 196 ha lake and mineral soil islands.

The mire was formed through the overgrowing of the freshwater lagoon that had separated itself from the Litorina Sea. It is fed by groundwater and surface water. In some places the peat layer is underlain by a layer of lake mud 0.1 to 0.2 m thick. The peat and lake mud are underlain by sandy loam, loamy sand, and sand.

The Lavassaare mire system is dominated by the open mire (50 to 60%). Fen forest grows at its margins. The spruce-birch forest of the transitional mire is rich in raised bog plants (marsh rosemary, heather, cranberry, etc.).

The area of the fen is 7,490 ha, of the transitional mire 4,794 ha and of the raised bog 9,584 ha. Eutrophic peat occurs in the region of the peat-milling fields in the middle of the mire and in the marginal areas. The peat layers, 3.1 to 8.2 m thick, are formed of wood, wood reed, wood sedge, sedge, reed sedge and reed *Hypnum* peat. The upper layers of the transitional mire are composed of weakly humified *Sphagnum* peat, which lies on mesotrophic and eutrophic grass peat. The total thickness of the peat layers is 4.5 to 9.1 meters. More than half of the raised bog peat consists of weakly humified *Sphagnum* peat, which is underlain by mesotrophic and eutrophic grass peat. The total thickness of the raised bog peat is 4.5 to 9.9 m.

Peat has been produced for fuel at Lavassaare since 1922. In 1939, a peat briquette plant was launched at Tootsi.

The present peat-production field takes up 3,400 ha. It is exploited by several companies, the largest of those being AS Tootsi Turvas with the mining area of 2,400 ha.

Weakly humified peat with active reserves of 6.6 million tons is distributed on 14,768 ha and well-humified peat with active reserves of 25.8 million tons on 19,746 ha. Peat mining has been stopped on 178 ha, which are being reclaimed.

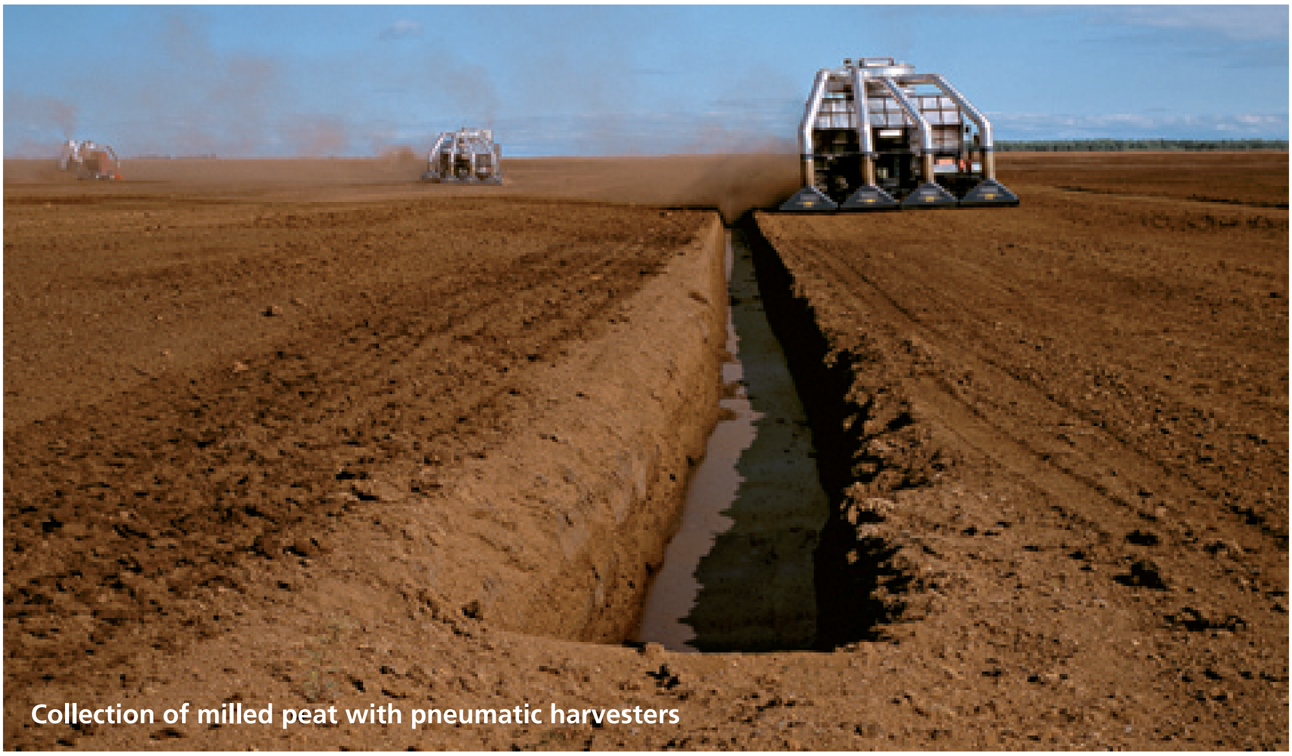
The contents of hazardous elements are below the average values for Estonia (As, 0.89; Co, 0.12; Cr, 0.7; Cu, 1.2; Mn, 7.3; Mo, 0.18; Ni, 1.0; Pb, 2.7; Sr, 12.3; Zn, 5.6; Th, 0.12; U, 0.08 and V, 0.5 mg/kg). Only the levels of Cd and Hg (0.103 and 0.04–0.07 mg/kg, respectively) are a bit higher than the permissible limits. The content of sulfur is higher in the bottommost fen peat but very low in the middle and upper layers (0.050% to 0.170%).

The peat mined at Lavassaare is used in horticulture and as a fuel, both in Estonia and abroad.

Horticultural peat blocks

Horticultural peat blocks collected on pallets

Freshly cut sod peat drying on a peat field



Collection of milled peat with pneumatic harvesters

EXCURSION STOP: TUHU MIRE

Mati Ilomets

Tuhu mire system is located on the western Estonian lowland at the border of Läänemaa and Pärnumaa Counties. The total area of the mire system is about 6540 ha, from which 3660 ha was taken under conservation as a landscape protection area in 1981. The Tuhu mire system is borded from south and east by a coastal ridge (with a relative height up to 10 m) which formed during the Litorina stage of the Baltic Sea.

Almost one third (mainly fen areas) of the whole mire system was drained for agricultural purposes (NE part) and for forestry (NW part) in the 1950ies.

The Tuhu mire system is split into two parts by a buried coastal ridge along which a gravel road passes the mire: the western Tuudi bog and the eastern Tuhu mire. The nearly round-shaped Tuudi bog (with a diameter of ca 5 km) is characterized by almost tree-less central part which is borded by marginal bog pine forest belt.

The eastern part of the mire system, Tuhu or Oidrema mire, is characterized by a minerotrophic fen vegetation with prevailing *Betula–Myrica–Carex* community. In the western part, close to the buried coastal ridge, the mire development is reached the ombrotrophic stage already.

About 1 km long wooden track takes visitors over this part of the Tuhu mire. Starting from the south-western end of the track visitors can get acquainted with a common West-Estonian mires sequence: from open rich-fen over pure fen to bog communities. The fen part is dominated by *Betula pubescens* with some *Pinus sylvestris* in the tree layer, and *B. humilis*, *Salix species*, *Juniperus communis*, *Myrica gale* in the shrub layer. *Carex acutiformis*, *C. nigra*, *C. hostiana*, *C. davalliana*, *Menyanthes trifoliata*, *Comarum palustre*, etc. are present in the grass layer. Ombrotrophic plant communities have developed in the Tuhu mire in a rather short time period, perhaps in less than 2000 years. Therefore the marginal slope, characteristic to Estonian bogs, is not yet developed and the bog surface is only slightly convex.

Several bird species can be seen in the Tuhu mire system. In southeastern part of the Tuudi bog, nesting colonies of Common Snipes (*Gallinago gallinago*) Black-tailed Godwits (*Limosa limosa*), Wood Sandpipers (*Tringa glareola*), Spotted Redshanks (*T. erythropes*), Northern Lapwings (*Vanellus vanellus*) etc have been recorded. Prevailing are two species - Tree Pipet (*Anthus trivialis*) in the forested part and Meadow Pipet (*A. pratensis*) in the open areas of the mire system.

View at the Tuhu mire

Cranberries

Sphagnum moss
Sphagnum cuspidatum Ehrh. Ex Hoffm.

Bog pools in the Männikjärve bog,
Endla mire system in eastern Estonia

KUNDA CLAY PIT

Kalle Kirsimäe, Kaisa Mens, Avo Miidel

North of the town of Kunda, Lower Cambrian clay sediments crop out along a narrow belt of the Baltic-Ladoga Klint.

On the basis of lithological and paleontological data, the Lower Cambrian sediments in the northern Baltic area are divided into eight formations (Mens et al. 1990). In northern Estonia the Lontova, Lükati and Tiskre formations form the Lower Cambrian succession (Mens & Pirrus 1997). These three formations are represented also in the vicinity of Kunda.

The Lontova Formation consists mostly of up to 100 m-thick pelagic marine greenish-grey and variegated clays with interbeds of coarse- to fine-grained sandstones in the lowest and uppermost parts. The Lontova succession forms a nearly complete transgressive-regressive sedimentary cycle. The near-shore facies equivalents of the Lontova clays in northwestern Estonia are represented by the Voosi Formation.

The Lontova Formation is transgressively succeeded by the Lükati Formation, consisting of lithologically similar, rhythmically interbedded greenish-grey clays and very fine-grained sandstones or siltstones up to 20 m thick. The Lükati sediments were probably deposited under alternating water-energy conditions in shallow, gulf-like basins. The Lower Cambrian in northern Estonia is completed by the shallow-water silty sandstones of the Tiskre Formation. The greenish-grey clayey sediments of the Lontova and Lükati formations have traditionally been called the Cambrian *blue clay*.

The Lontova Formation corresponds biostratigraphically to the zone of the tubular agglutinated fossil *Platysolenites antiquissimus*, and the Lükati Formation, unconformably overlying the Lontova Formation, corresponds to the lower part of the zone of the problematic fossil *Mobergella* and the *Schmidtiellus mickwitzi* trilobite zone.

In northwestern Estonia, sandstones 5 to 50 m thick containing thin clay interbeds of the Sõru Formation, corresponding to the *Rusophycus parallelum* trace fossil zone, occur between the Lontova/Voosi and Lükati formations (Mens et al. 1990).

The *blue clay* deposits are typically ascribed to the Lower Cambrian Tommotian and Atabanian stages (534 to 524 million years ago). However, there is paleontological evidence supporting an older age (545 to 530 Ma, Nemakit-Daldynian and Tommotian) for these sediments (Moczydlowska & Vidal 1988; Volkova et al. 1990).

The sequence of greenish-grey and reddish-violet spotted homogeneous clays in the old abandoned upper Kunda quarry was suggested by Armin Öpik in 1933 as the stratotype of the Lontova beds (Formation), named after a small village next to Kunda. The lower part of these beds is exposed today in the new lower Kunda quarry, where the fine-grained unlithified clays lithologically defined as the Kestla Member represent the Lontova Formation.

The Kestla member is paleontologically characterized by the tubular agglutinated fossils *Platysolenites antiquissimus* and *Platysolenites lontova*, *Sabellidites cambriensis*, numerous pyritized worm tracks and hyolithid casts, an early gastropod *Aldanella kunda* Öpik, hornlike chitinous? sclerites, and *Leiosphaerides* and *Tasmanites* acritarchs.

The *blue clay* is a unique sediment. Despite its old age, the clay has retained natural plasticity and a high water content/porosity and is used as a raw material for the cement and brick industry. The clays were never deeply buried nor strongly heated. This conflicts with the high diagenetic grade of the clay minerals found in the sediment.

Today, the company Kunda Nordic Cement uses the Lontova clay from the Kunda quarry for cement production in a mixture with Ordovician limestone from the Kunda-Aru quarry a few kilometers south of Kunda.

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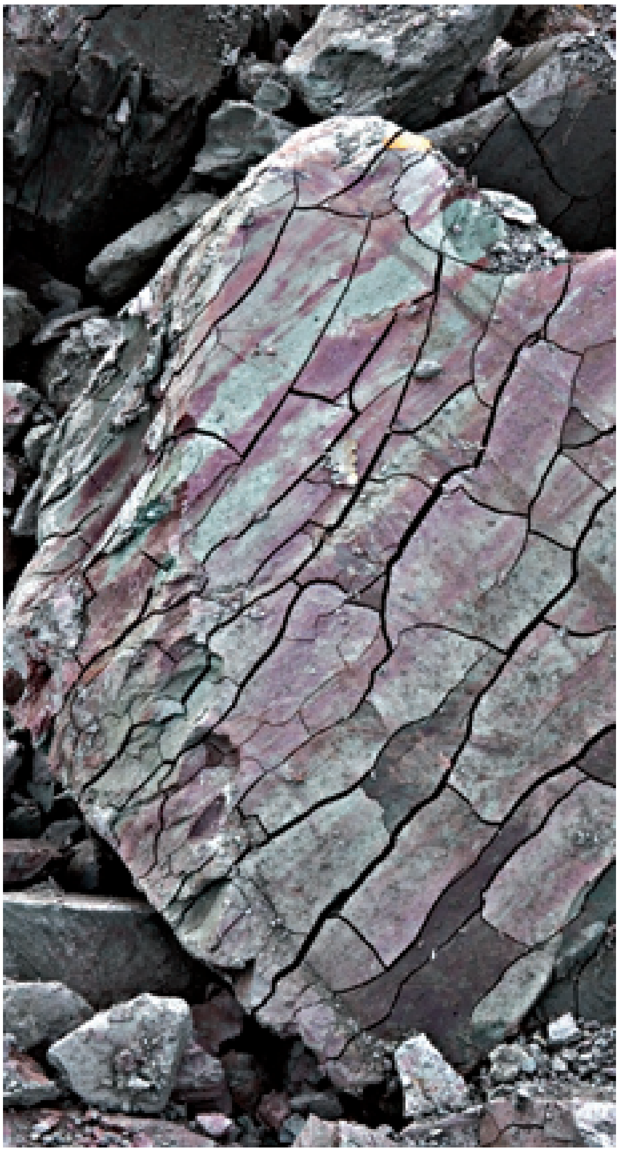


ARUMETSA CLAY DEPOSIT

Maris Rattas, Kalle Kirsimäe

The Arumetsa clay deposit and Arumetsa quarry are in southwestern Estonia near Häädemeeste, about 40 km south of Pärnu. The area of the deposit is 29.23 ha, with the active reserves of ceramsite clay amounting to 2.9 million m^3 (southern part of the deposit) and of ceramic clay 590,000 m^3 (northern part of the deposit). This clay is an important raw material for the production of lightweight expanded clay aggregates (ECA), widely used in construction. The clay is also suitable for making facade bricks, drainage pipes, and roof tiles (Peikre & Korbut 2003).

The clay quarry and factory are run by the maxit Group AB company maxit Estonia AS (formerly known as Leharu, Fibo ExClay, Optiroc AS). Production of ECA started in 1994; the production capacity was about 430,000 m^3 of exclay in 2006 (www.maxit.ee).

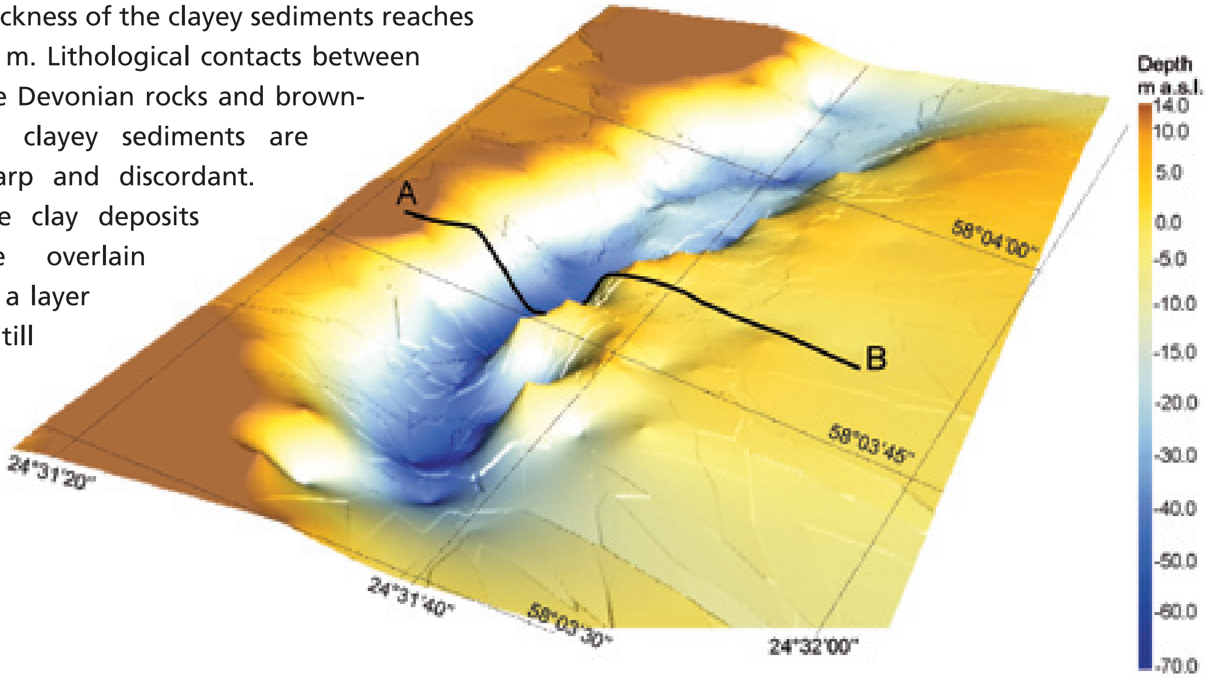
The clay deposit is in an arc depression incised into the Middle Devonian bedrock. The depression is oriented north to south and is 1.5 km long, 300 m wide, and up to 80 m deep. The reddish-brown, weakly cemented sandstones and siltstones of the Aruküla Regional Stage are up to 10 m thick. They are underlain by brownish-red sandstone intercalated with siltstone, dolomitic marl, and clay of the Narva Regional Stage. In the depression, the thickness of the clayey sediments reaches 80 m. Lithological contacts between the Devonian rocks and brownish clayey sediments are sharp and discordant. The clay deposits are overlain by a layer of till up to a meter thick or glaciolacustrine silt and Holocene marine sands.

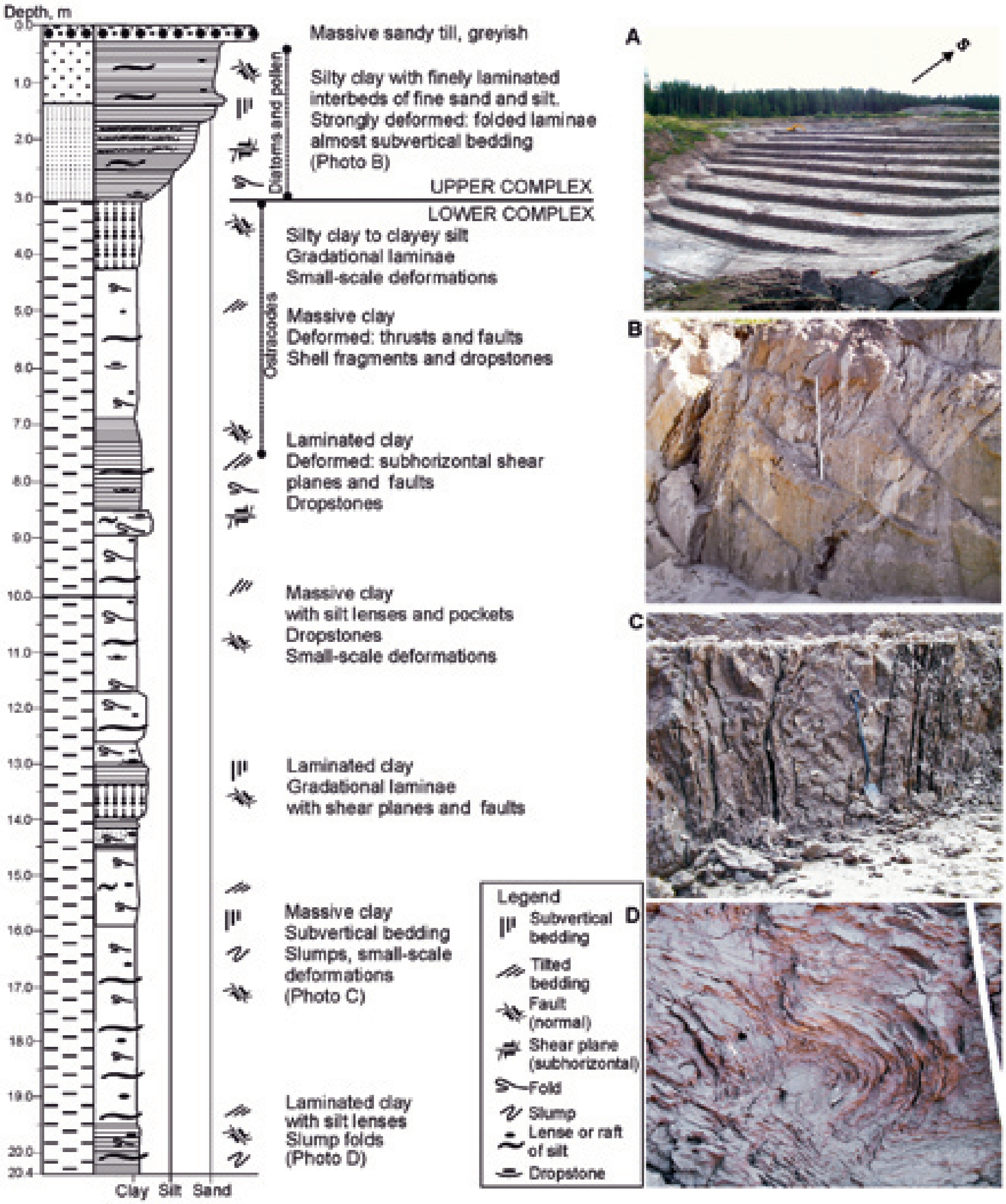
The clayey complex is divided into two parts: (1) the upper complex (grey, silty clay and clayey silt with finely laminated interbeds of yellowish-grey fine sand and silt, varying in thickness from 0.5 to 7 m); (2) the lower complex (brown, silty clay, which downward grades into homogeneous massive clay with silt lenses and pockets and fills most of the depression).

The whole-rock mineral composition of the brownish clay (lower complex) is dominated by illitic clay minerals (illite and illite-smectite), which form on average 40 to 60% of the sediment. Kaolinite is the second-most abundant clay mineral, accounting for 5 to 15%. The average contents of quartz, K-feldspar, and plagioclase are 20 to 30%, 5 to 10%, and 1 to 3%, respectively. The clay fraction (< 2 μm) is characterized by the assemblage of illite, kaolinite, and chlorite (Rattas et al. 2001).

The originally more-or-less regular lamination has been heavily disturbed by a number of deforma-

Morphology of the Arumetsa depression cut into the Middle Devonian siltstone and sandstone





Generalized lithological log of the Arumetsa clay section exposed in the quarry (to a depth of 20 m)

tional features, sedimentary as well as glaciotectonic. Deformation mechanisms and driving forces are related essentially to gravitational instabilities, dewatering, liquefaction, and brittle deformations. The structures occur in a large variety of morphologies (e.g., slumps, load and pillow structures, folds, faults, shear planes, and slides). The upper complex of the section is glaciotectonically folded. The orientations of folds and fractures suggest the ice pressure from the north (Rattas & Kalm 2004).

The deposit itself has been known since the late 1940s and has been interpreted as a synsedimentogenetic clay lens within the Middle Devonian reddish-brown siltstones and sandstones of the Aruküla Regional Stage, or as a river valley of the Aruküla Age which has been filled with clays of the Middle Devonian Burtnieki Age. This viewpoint is officially accepted today. However, the microfossil and palynological investigations do not confirm the Devonian age of the sediment. Two ostracod species (*Cytherissa lacustris* and *Ilyocypris bradyi*) were found in the depth interval of 3.0 to 7.5 m (Rattas et al. 2001). The stratigraphic range of these species is from the Pliocene and Pleistocene to the Recent. The diatom flora found in the uppermost part (up to 3 m) consists of typical Quaternary freshwater oligohalobes, mainly represented by the planktonic species *Aulacoseira islandica*, *Aulacoseira granulata*, and *Stephanodiscus astraea* (Tänavsuu 2002). The palynological composition of the uppermost part resembles the Holstenian pollen assemblage.

The structure and the mineral and paleontological composition of the sediment prove that the Arumetsa deposit is not of Devonian but of Quaternary age. Deformations of probably glacial origin and the palynological signatures suggest a pre-Weichselian, probably as old as Holsteinian age of the deposits. According to sedimentological interpretations, the lower, clayey complex, in part resembling varved clays with dropstones, was evidently deposited in periglacial conditions. The upper complex was probably deposited in a freshwater lake during the interglacial conditions.

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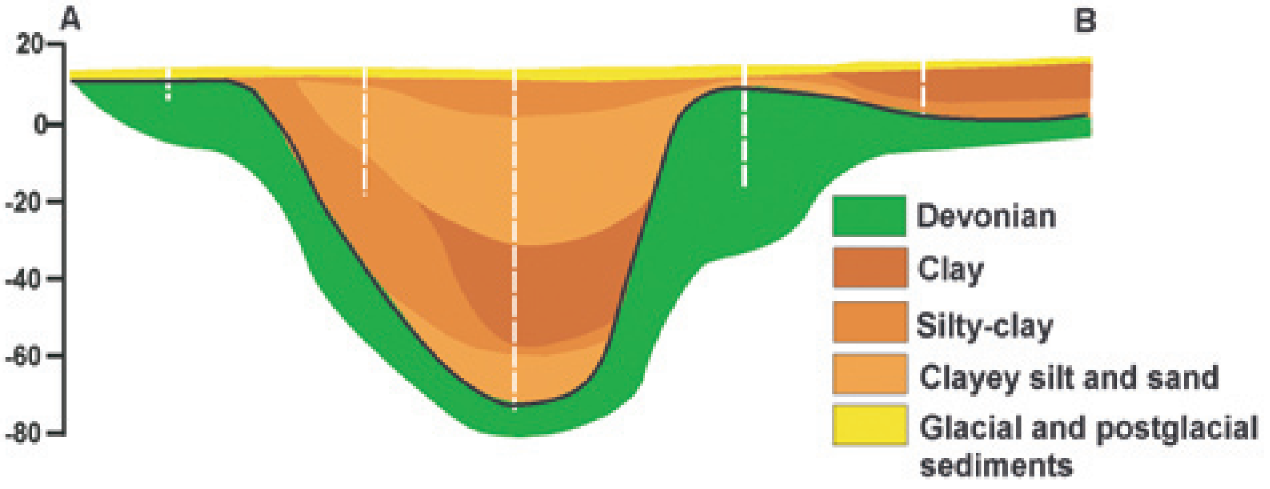


Cross-section of the bedrock depression filled with Pleistocene clayey sediments in a thickness of up to 80 meters

Close-up of Arumetsa clay

BALTIC KLINT IN NORTH ESTONIA

Kalle Suuroja

The Baltic Klint is a system of erosional escarpments in Lower Paleozoic (Vendian to Ordovician) sedimentary rocks. The system generally follows the boundary between the Fennoscandian (Baltic) Shield and Russian Plate. The Baltic Klint, 1,200 km long in a beeline, starts from the sea bottom near Öland Island in Sweden and runs across the bottom of the Baltic Sea and the North Estonian coast up to the vicinity of Lake Ladoga (the Syass River) in Russia.

The Baltic Klint is a *cuesta*-like structure (Spanish *cuesta*, "escarpment"), formed largely due to a slight (1 to 5 m/km) southward dip of the sedimentary rocks cropping out on the escarpments. Even more important in the formation of the escarpments than the dip of strata has been the resistance of the rocks to weathering. The escarpments have formed in largely the same rock complexes regardless of their altitude. The boundary between limestone and sandstone complexes lies more or less at the sea level on Osmussaar Island, while in the depression of the Neugrund meteorite crater it lies at 24 m below sea level. East from the northern part of Väike-Pakri Island, it is above sea level everywhere: elev. 1 m on Cape Pakri, 38 m at Lasnamäe in Tallinn, 32 m at Jägala Waterfall, 40 m on the Muuksi Klint Cape, 60 m at Sagadi, 50 m near Kunda, 43 m at Ontika, and 10 m in Narva. On the Öland Klint, this surface is 20 m below to 30 m above sea level, dropping down to 170 m below sea level at the bottom of the Baltic Sea. On the Ingermanland Klint, in the vicinity of St. Petersburg in Russia (in Koporye), which is the highest point of the limestone plateau of the Baltic Klint, this boundary rises to 130 m above sea level. Thus, the differences in altitude of this boundary surface at the Baltic Klint range up to 300 m!

The formation of escarpments on the Baltic Klint is associated with several long-term processes: land uplift has alternated with subsidence, rise of sea level with fall, invasion of glaciers with melt, formation of escarpments with leveling. A great part of the North Estonian Klint visible on land has been shaped during the period following the latest glaciation (i.e., during the last 12,000 years or so). The Baltic Ice Lake began to abrade escarpments on the side of the North Estonian

Limestone Plateau at the levels that currently extend to the slope of the Pandivere Upland, at up to 70 m above sea level. Escarpments are never formed in an empty place; they all presuppose the existence of an earlier, steeper slope. Postglacial abrasion has strongly reshaped the earlier escarpments; they have decreased in number and become steeper and higher. In the higher areas of the Ingermanland Klint (elev. 60 m and more) and at the bottom of the Baltic Sea, where the escarpments have not been reshaped by postglacial abrasion, they slope gently; that is, they slope more or less as they sloped after the retreat of the last continental glacier.

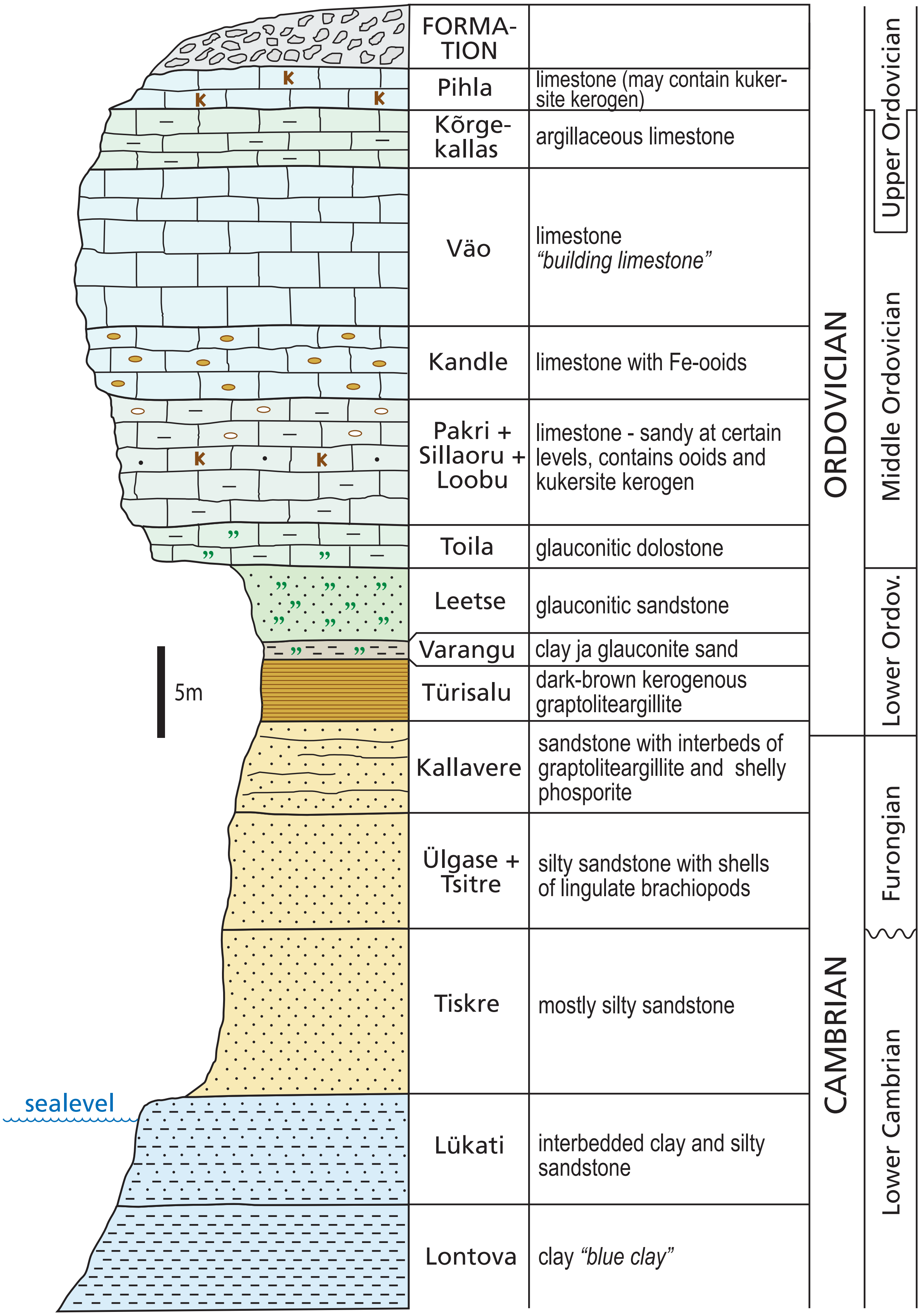
The few places on the Baltic Klint the sea is still abrading escarpments into bedrock: in just about 160 km of the 1,700 km of the escarpment line, with most of it (about 130 km) located on the North Estonian Klint and the remaining 30 km on the Öland Klint. The 130 km are distributed across the North Estonian Klint as follows: 17 km fall within the North–West Estonian Klint section (Osmussaar, Suur-Pakri and Väike-Pakri Islands), 43 km in the West Harju Klint section (Pakri, Türisalu, Suurupi, and Kakumägi Klint Peninsulas) and 70 km in the East Viru section between Kalvi and Udria.

Abrasion was particularly intensive in places where hard Ordovician limestones are underlain by softer Lower Ordovician and Cambrian sandstones. Here the rate of the retreat of the escarpments is determined by the resistance of relatively soft sandstones to weathering. Good reference points for measuring the rate of the retreat of escarpments, which is a rather slow process, are scarce. Still, the lighthouse built on Osmussaar in 1765 provides one such reference point. E. Eichwald writes in his travelogue (1840) that the lighthouse is said to have been built at a distance of 7 fathoms (1 Russian fathom = 2.16 m) from the escarpment edge. Today, the retreating klint escarpment has "swallowed" the old lighthouse so that only a few blocks of its foundation have been preserved. Thus, the klint escarpment has retreated by nearly 17 m in 240 years, or about 7 cm per year.

The speed of the retreat of the klint varies, reaching in places up to 10 and even more centimeters per year. For instance, during the storm of

Baltic Klint from air

Composite section of North Estonian Klint

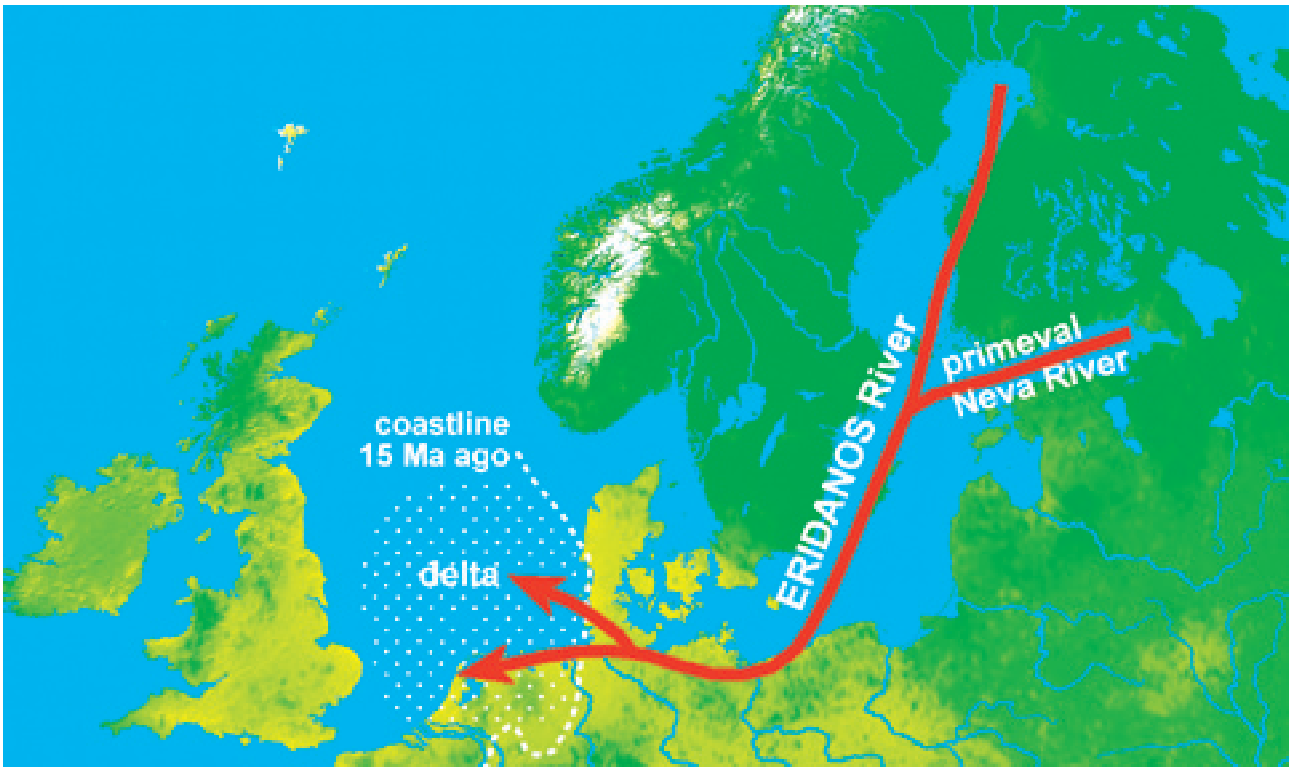


FORMATION	
Pihla	limestone (may contain kukersite kerogen)
Kõrgekallas	argillaceous limestone
Väo	limestone *“building limestone”*
Kandle	limestone with Fe-ooids
Pakri + Sillaoru + Loobu	limestone - sandy at certain levels, contains ooids and kukersite kerogen
Toila	glauconitic dolostone
Leetse	glauconitic sandstone
Varangu	clay ja glauconite sand
Türisalu	dark-brown kerogenous graptoliteargillite
Kallavere	sandstone with interbeds of graptoliteargillite and shelly phosporite
Ülgase + Tsitre	silty sandstone with shells of lingulate brachiopods
Tiskre	mostly silty sandstone
Lükati	interbedded clay and silty sandstone
Lontova	clay *“blue clay”*

January 2005, the sandstone escarpment at the top of the Kakumägi Klint Peninsula retreated by up to a meter in places (Suuroja & Suuroja 2005), and not only due to the downfall of single megablocks but as a general process.

The Baltic Klint emerged from the last continental glacier some 11,000 years ago, with the Öland Klint and Ingermanland Klint emerging somewhat earlier and the Baltic Sea Klint and North Estonian Klint a bit later still. If we knew the position of the klint immediately after the retreat of the ice, it would be easy to calculate the rate of its retreat. In the North–West Estonian Klint section (Osmussaar and Pakri islands) and the West Harju section (Pakri Peninsula, Türisalu, etc.) and in some more places farther to the east, limestone or sandstone terraces a few dozen to a few hundred meters wide occur in the sea in front of the klint. On klint peninsulas extending far into the sea (Osmussaar, Pakri, etc.), this terrace can be even wider than a kilometer. It is possible that this is where the escarpments of the Baltic Klint started their postglacial retreat after their emergence above sea level.

Baltic Klint at Martsa, NE Estonia



Several hypotheses on the reasons for and time of the formation of the Baltic Klint have been put forth, with most of them associating it with the erosive action of water, either in its fluid or solid state. Few authors have made an attempt to associate the formation of the Baltic Klint with a single phenomenon, yet one reason has usually been preferred to others. The following names, rather arbitrarily attributed to the hypotheses, refer to the phenomenon regarded as the dominating one.

The **tectonic hypothesis** is one of the most widespread hypotheses explaining the formation of the klint. Supporters of this hypothesis suggest that the formation of the Baltic Klint (and, naturally, the North Estonian Klint also) is in one way or another connected with a tectonic fault running nearby along the southern border of the klint zone.

The joints and faults shaping the formation of the klint have been sought from the zone of the Baltic Klint with a variety of methods, mainly from the sea bottom, but they have not been found. There exist joints and faults there, of course, yet their direction does not coincide with that of the Baltic Klint but intersects with it at some angle. Besides, it is difficult, if not impossible, to explain the multitude of escarpments in the klint zone and the formation of the broad (up to 40 km) terraces in between with faults only.

According to the **glacial hypothesis**, continental glaciers contributed to the formation of the Baltic Klint. As supposed, the North Estonian Klint was lifted up by a glacier arriving from the north across the Gulf of Finland and gliding along the surface of Cambrian sandstones.

There is no doubt that continental glaciers have swept over the Baltic Klint repeatedly and shaped it in some way. But their impact has been a secondary factor (i.e., it has leveled the already existing escarpments rather than created new ones). When depicting the Baltic Klint as a bank of a glacier valley, as the supporters of the glacial hypothesis have done, one is immediately faced with difficulties, as the more or less southwest-northeast trending Baltic Klint runs transverse to rather than parallel with the roughly north–south movement of continental glaciers that once swept across it. The action of continental glaciers is traceable also in klint bays and valleys incised into klint escarpments, but this action has been limited to the reshaping of the already existing (i.e., preglaciation), valleys and bays.

The supporters of the **abrasional hypothesis** state that the escarpments of the Baltic Klint were shaped primarily by abrasion, with waves abrading the rocks and currents carrying off the clast. This hypothesis is weak. It fails to explain where the huge quantity of clastic matter from the abraded escarpments has gone, because it is not found at the bottom of the Baltic Sea.

According to the **denudational hypothesis**, the Baltic Klint was formed mainly by denudation – the leveling of ground surface by external impacts (temperature, wind, water). The escarpments of the Baltic Klint began to form about 40 million years ago in the Paleogene. The supporters of that hypothesis associated the process with the jointing and divergence of the Earth's crust in the East Atlantic (west of Norway) in this period, which in turn led to a significant rise (up to 400 m) in the Earth's surface in the region of the future Baltic Sea. The escarpment on the boundary between the crystalline basement and sedimentary rocks was formed first, and the other, more southerly escarpments were formed later, as the invasion of the sea progressed or the erosional basis of the giant river increased.

According to the **Pra-Neva hypothesis**, the Pra-Neva River emanated from the area of the White Sea and flowed west along the boundary between hard crystalline rocks of the Baltic (Fennoscandian) Shield and the softer sedimentary rocks covering the Russian Plate. The Pra-Neva, flowing on a hard, more weathering resistant crystalline basement (gneisses, granites, migmatites, etc.) with a slight southward dip (2 to 3 m per km), was denuding its southern bank (consisting of softer sedimentary rocks) more intensively and therefore itself shifted, too, gradually southward. The Pra-Neva hypothesis explained the removal of the clastic matter from the Baltic Klint area but failed to explain where it went. A giant complex (up to 1.5 km thick, on about 100,000 km^2) of clastic deposits about 1 to 10 million years old has been found in recent years at the bottom of the North Sea west of the Danish Straits, in an area called the Eridanos Delta. This has been supposed to be the "lost material" carried off the denudation area of the Baltic Klint by the hypothetic giant (up to 2,700 km long) river Eridanos, which began somewhere in the area of Lapland and ran across the eastern part of the Gulf of Bothnia and the western part of the Baltic Sea down to the Polish coast and from there across Denmark and the north German coast into the North Sea. The Pra-Neva was merely one of the few eastern tributaries of this giant river. The Eridanos River ceased to exist about a million years ago, after the invasion of a continental glacier.

The Eridanos River got its name from an Old Greek legend according to which Phaeton (Faeton), son of Helios, was pushed down from the Vault of Heaven by Zeus with a lightning bolt and fell into this very river invisible to the human eye. The Heliades (daughters of Helios, god of the sun) came to the banks of the river to bewail their slain brother. Their bodies turned into poplars and their tears into amber. In the legends, the Eridanos River has been most often associated with the River Daugava (or Gauja). However, it is difficult, if not impossible, to explain the formation of both the Baltic Klint and the other klint escarpments on the Baltic Sea as well as the terraces separating them with the Eridanos only. If it was the Eridanos, then why did it not flow across the Baltic Deep but across a limestone plateau more than 100 m higher? Neither the Eridanos nor the tectonic fault zones at the bottom of the Baltic Sea cared about the Baltic Klint, as both of them intersected it without leaving any traces. Also the formation of the high escarpments and broad terraces abraded into limestones and clays is difficult to explain by river erosion only.

ERRATIC BOULDERS

Enn Pirrus

Owing to the proximity of the Fennoscandian Shield, Estonia's territory is bespeckled with numerous huge granite blocks of great height and thousands of erratic boulders. In northern Europe, most of the gigantic (circumference above 25 m or length more than 10 m) boulders occur in Estonia, where their number is about 100. Almost 1,900 boulders with a circumference over 10 m and length over 3 m have been registered. Their location, composition, size, etc. have been documented and included in the database "Book of Primeval Nature" (in Estonian *Ürglooduse Raamat*). As many as 349 large boulders and boulder accumulations are under state protection.

The accumulations of sharp-edged gigantic boulders of the same type suggest that extremely large blocks were dragged along by the glacier, which during the drift or after the melting of the ice were crushed into smaller blocks. One such boulder accumulation, identified on the Island of Hiiumaa, was termed the "Boulders of Helmersen" after the famous geologist Gregor Helmersen (1803–1885), who was the first to describe them and ask for protection of nature objects.

On the basis of the petrographic composition and texture, more than 50 types of boulders can be distinguished in Estonia. Granites (including rapakivi), in which large boulders account for about 90%, prevail. These are followed by gneisses (6%) and pegmatites (3%). Some of the boulders have been studied in the area of initial location in clearly marked places. These are indicator (index) boulders that show precisely the direction of the movement of the ice. They provide a solution to several stratigraphical and paleogeographical problems.

The largest boulders in Estonia are derived from Finland (Vyborg and southwestern Finland rapakivi massifs, Ålandian granite and rapakivi massif). Among smaller boulders, other indicators can be found: red and brown quartz-porphyries from the bottom of the Baltic Sea, the Satakunta olivine diabase, the Bothnian porphyries, the uralite-porphyrites of Tammela and Pellinki, and several other types of rock.

The distribution of indicator boulders in till beds and the orientation of clasts in tills suggest that the movement of glaciers during the glaciations in Estonia was mainly from north to south and from northwest to southeast. Naturally there were different local movements depending upon the bedrock topography.

Vainupea Kaarnakivi on the shore of Gulf of Finland as drawn by G. Helmersen, 1853 (below) and as photographed in December, 2006 (next page)

Letipea Ehalkivi is the largest erratic boulder on mainland Estonia (volume – 930 m^3)

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

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

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

Simplified geological map of Estonia