THE ORDOVICIAN

IN ESTONIA & SOUTHERN FINLAND

AGE Ma	SERIES	STAGE (age)	Thick-ness m	PREVAILING ROCKS	
				NORTH ESTONIA	SOUTH ESTONIA
443.7 ± 1.5	UPPER ORDOVICIAN	Porkuni	0 -15	bioclastic-, reef- and sandy lime- & dolostone	bioclastic- and ooid lime-stone and silty marl
		Pirgu	0 - 65	clayey & micritic lms.	clayey limestone, reddish marl
		Vormsi	0.3 - 22	clayey & bioclastic lms.	marl, shale
		Nabala	1.5 - 35	clayey & micritic lms.	clayey & micritic lms.
		Rakvere	0.7 - 28	micritic limestone	marl
		Oandu	0 - 8	marls, bioclastic & reef limestones	marl, shale (?)
		Keila	1 - 31	clayey- bioclastic- & reef limestones	marl, clayey limestone
		Haljala	5 - 25	clayey limestone, marl	marl, clayey limestone
		Kukruse	3 - 24	clayey bioclastic lms. & kukersite oil shale	clayey limestone, marl
460.9 ± 1.6	M. ORDOVICIAN	Uhaku	0.6 - 16	clayey bioclastic lms.	micritic limestone
		Lasnamäe	3 - 24	bioclastic limestone	reddish clayey lms.
		Aseri	0.1 - 9	limestone with Fe-ooids	reddish bioclastic lms.
		Kunda	0.1 - 20	limestone with glauconite & ooids	reddish bioclastic lms. & marl
		Volkhov	0 - 21	limestone with glauconite	reddish marl
471.8 ± 1.6	L. ORDOV.	Billingen	0 - 2	glauconitic & limy sandstone	reddish clay
		Hunneberg	0 - 4	glauconitic sandstone	grey clay
		Varangu	0 - 2	clay, claystone	–
488.3 ± 1.7		Pakerort	0 - 17	sandstone, argillite	?

Ordovician stratigraphy of Estonia, thicknesses of stages and main rock types

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THE ORDOVICIAN IN ESTONIA & SOUTHERN FINLAND

Tallinn 2007

The Ordovician in Estonia and southern Finland.
MTÜ GEOGuide Baltoscandia. Tallinn, 2007.

ISBN 978-9985-9867-1-4

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Front cover:	Limestones of Uhaku and Lasnamägi ages exposed in a shore cliff, Osmussaar island
Back cover:	The Pakri cliff exposes Lower to Middle Ordovician rock sequence

Release of this booklet in English was co-financed by European Regional Development Fund ERDF, Estonian Ministry of the Interior and it was accomplished within the framework of INTERREG IIIA Southern Finland and Estonia programme

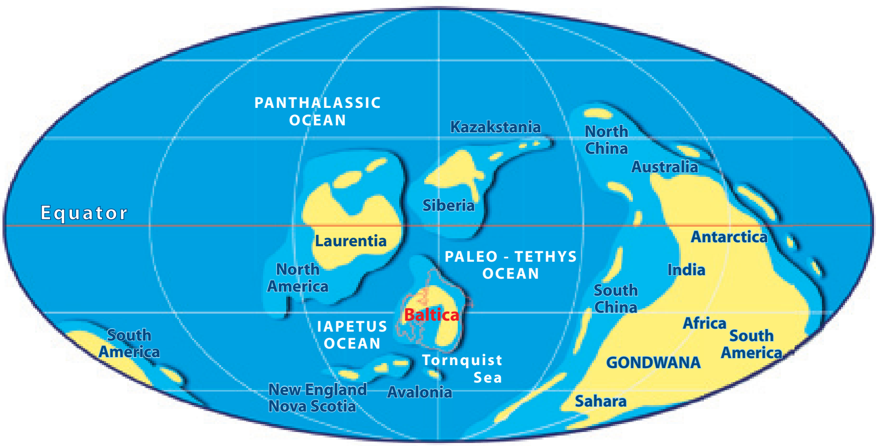
ORDOVICIAN

"The Era of Seas"

The Ordovician is an interval of geologic time from 488 to 443 million years ago characterized by the predominance of seas. (Initially, the period was treated as the Early Silurian until the British scientist Charles Lapworth renamed it in 1879).

Oceans and land masses were in flux. The splitting of Rodinia, a continent that had started at the end of the Proterozoic era, was only half complete. Larger continental blocks (cratons), which had separated from the Gondwana supercontinent – Laurentia (North America), Baltica (Northern and Eastern Europe), Siberia and Kazakhstan – were still drifting apart. All these continents, except Baltica, were in the tropics and extensively flooded by the warm waters of tropical seas, where there were primarily accumulations of lime deposits. In the course of time they evolved into contemporary carbonate rocks (lime- and dolostone). The seas supported the spread of abundant and diverse marine biota, enriching the animal kingdom with several new phyla and classes. In the Ordovician, bryozoans, corals and stromatoporoids made their appearance and afterwards played an important role in reef formation. Among the bottom fauna, the abundance of brachiopods with calcareous shells and attached bottom-living echinoderms (crinoids, or sea lilies, and cystoids) increased explosively. Trilobites – representatives of Cambrian seas – were still rather numerous. Limestone is primarily composed of the calcitic skeletons and skeletal debris of these animal groups.

The Ordovician seas were inhabited by passively floating graptolites with chitinous



Position of continents in the beginning of Late Ordovician, ca 460 Ma (after C.R. Scotese "Plate tectonic maps and Continental drift animations", PALEOMAP Project, www.scotese.com) shells and actively swimming carnivorous cephalopods. The marine biota also included the oldest vertebrates as conodonts and rare early fishes.

In the Ordovician, land formed only 5–10 per cent of the Earth's area; the relief of the continents was relatively shallow and flat. Mountain ridges of volcanic origin occurred only on the margins of some continents, e.g. the first ridges of the Appalachians and British–Scandinavian folded mountains, but also on the eastern coast of Australia and New Zealand forming the northeastern margin of Gondwanaland. Volcanoes were also active in Kazakhstan and in the area which is now the eastern slope of the Urals. Volcanic ash deposited in the area of Estonia as well. However, initially there may have been several volcanic ridges deeper in the ocean, which afterwards joined the continents as a result of subduction. The Ordovician is considered as the period of the most intense volcanic activity, at least during the last 500 million years.

In the Ordovician, the solid land was almost barren, lacking terrestrial animals. Spores assumed to belong to psilophytes – primitive moss-like terrestrial plants – have been found in marine sediments originating from the second half of the Ordovician period.

The marine climate in the Ordovician was warm and humid, however, at the end of the period there was an abrupt cooling. It culminated in the formation of an extensive ice sheet in North Africa, located in the South Polar region. This global cooling, known as the Sahara glaciation, included at least two ice ages and affected the evolution of the Earth, first of all, through the accompanying global drop in sea level by 50 to 100 metres. As a result, many shallow seas on the continents became dry land. In all likelihood, this accounts for the mass extinction of marine biota at the end of the Ordovician period.

The Baltica continent and Palaeobaltic Sea

During the Ordovician, present day Estonia was part of the Baltica continent that is now Northern and Eastern Europe, i.e. the Fennoscandian Shield and Russian Platform. From the east this triangular-shaped continent was bordered by the Ural Ocean, from the south-west by the strait-like Törnquist Sea, and from the north-west by the Iapetus Ocean. In the Ordovician, the waters of the shallow flat-bottomed Palaeobaltic Sea covered most of the Baltica continent, with vast stretches of flat land in only two regions: Kola – Karjala and Ukraine – Belarus. The continent of Baltica, which was located in the Southern Hemisphere during the entire Ordovician period, shifted steadily northwards, passing through the temperate and subtropical zones. The gradual warming of the sea water affected sedimentation processes in the Palaeobaltic Sea. At the end of the Ordovician, Estonia was situated in the rather shallow marginal area of this sea, and had reached latitude 15–20°S; the coast was in the area of Finland and the sea was deepening southwards.

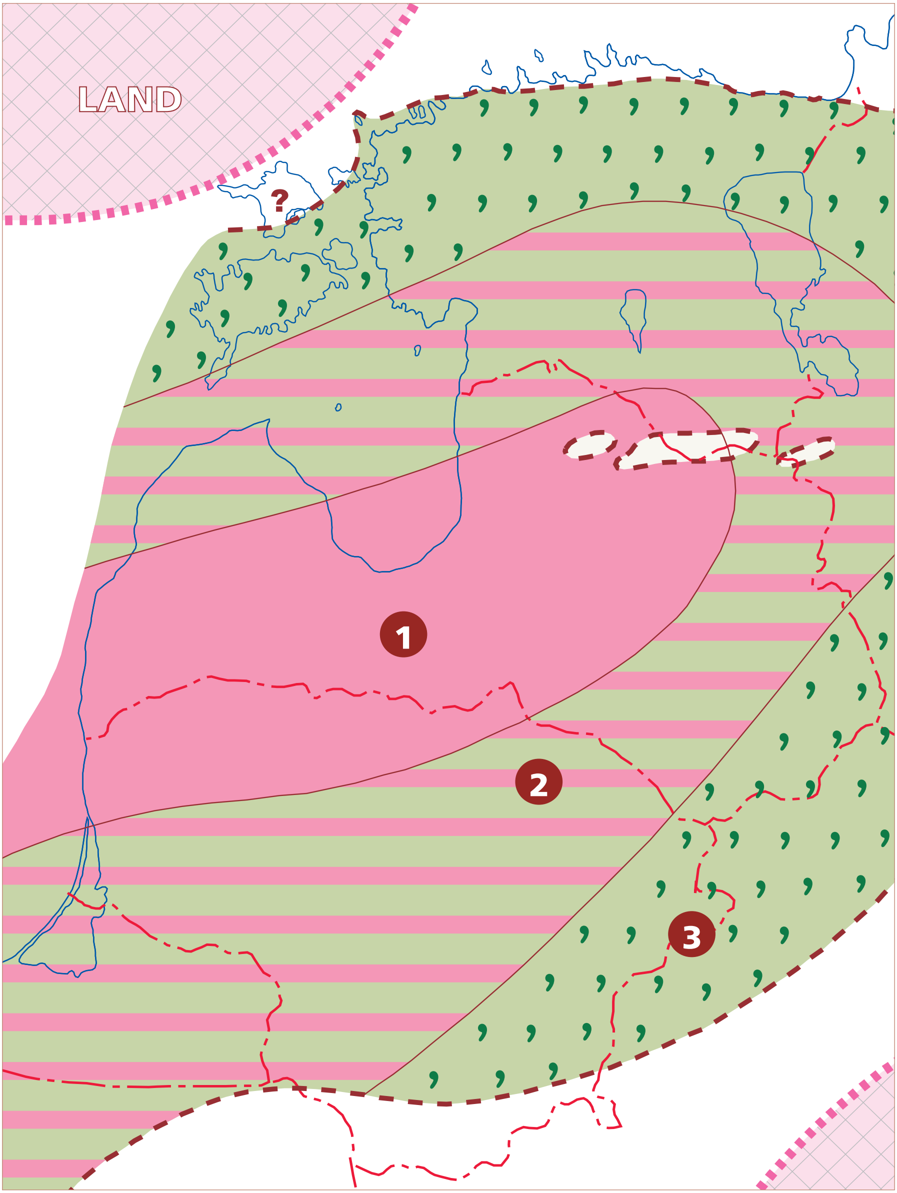
The geological structure and evolution of Estonian territory

In the Early Ordovician (488 – 472 million years ago), the area now comprising Estonia was covered with the waters of the cool Palaeobaltic Sea where only sand and clay deposits with a very low content of fossils accumulated. The sandstones of the Pakerort Stage (the oldest Ordovician stage) were an exception, in places containing an abundance of shells of the lingulate brachiopod *Ungula*, which formed lenticular beds of Obolus Phosphorite. Since organisms with calcareous skeleton were rare in the early Ordovician, sedimentation was a very slow, discontinuous process. In the geological section the light sandstones and brownish slate-like claystones (Dictyonema Shale or argillite) of the Pakerort Stage are overlain by clays of the Varangu Stage, greenish glauconite sandstones of the Hunneberg Stage and sand- and limestone of the Billingen Stage. All these Lower Ordovician stages crop out only on the North Estonian limestone escarpment, in the middle part of the klint.

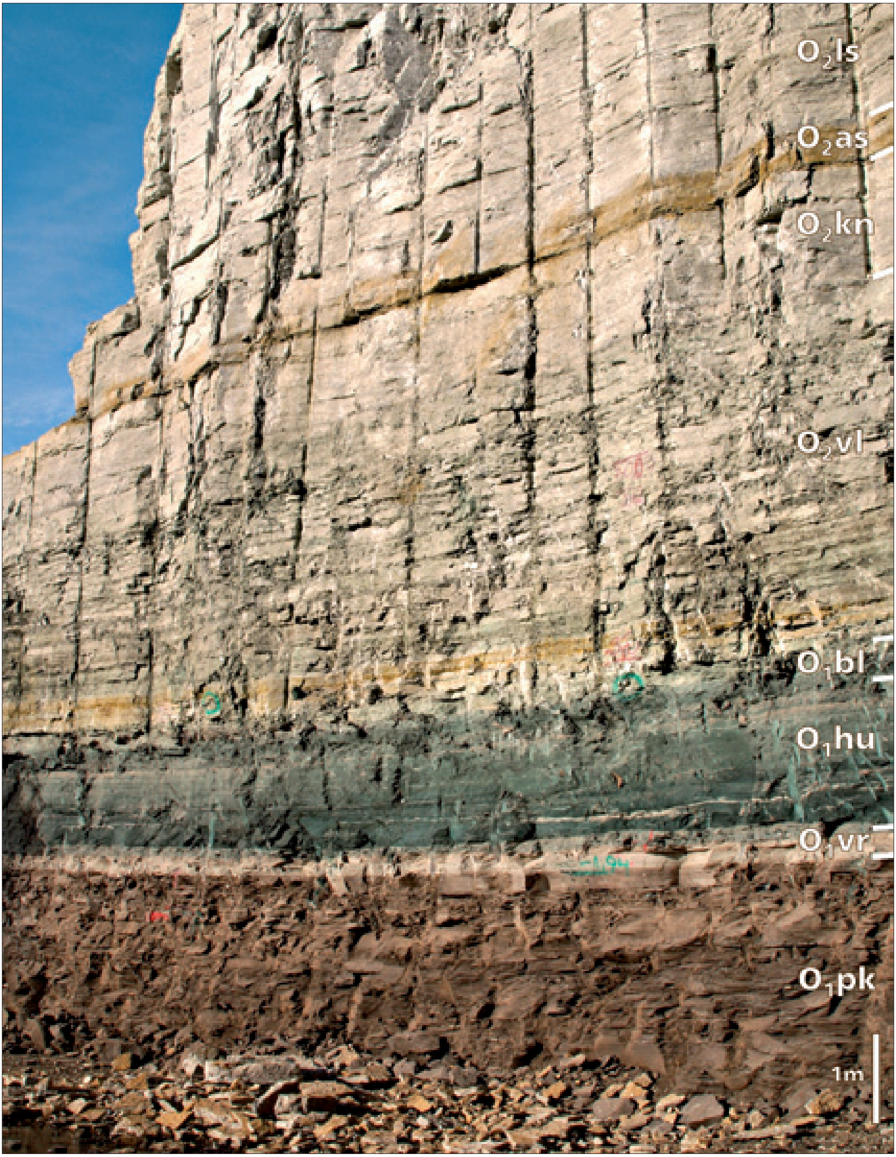
The Middle Ordovician (472–460 million years ago) in Estonia is represented (in ascending order) with the Volkhov, Kunda, Aseri, Lasnamägi and Uhaku stages. In northern Estonia this series is composed of relatively pure limestone, while in the southern region reddish clayey limestone prevails. The total thickness of the complex is 10 m in the north, and up to 60 m in southern Estonia. The clay content in the rocks increases from the bottom upwards in the vertical section. The rocks are rich in skeleton fragments (debris) of trilobites, echinoderms and brachiopods. Hemisphaeric fossils of bryozoans are also abundant, but coral fossils are absent, indicating that sedimentation took place in the conditions of a temperate climatic zone. Evidence is also derived from the slow rate of sedimentation – one metre of rock per million years in northern Estonia and up to five metres in the south.

During the Middle Ordovician, sea transgression took place on the territory of Estonia. The sea gradually deepened and extended, the clay content in the rocks increased and sedimentation became a continuous process. Middle Ordovician limestone beds are exposed in the upper part of the North Estonian Klint and as a narrow belt south of it. The top of the klint consists of hard and resistant limestone of the Lasnamägi and Uhaku stages, which was widely used as a construction material for the medieval city of Tallinn. The limestone plateau dotted with hundreds of limestone quarries extends from the Pakri Cape to Narva town and beyond. Evidence from numerous stone burial places suggests that this was the most densely populated region in Estonia in ancient times. In all likelihood, habitation of the inland areas covered with dense forests proved beyond the strength of our distant ancestors whose only working tool was the stone axe.

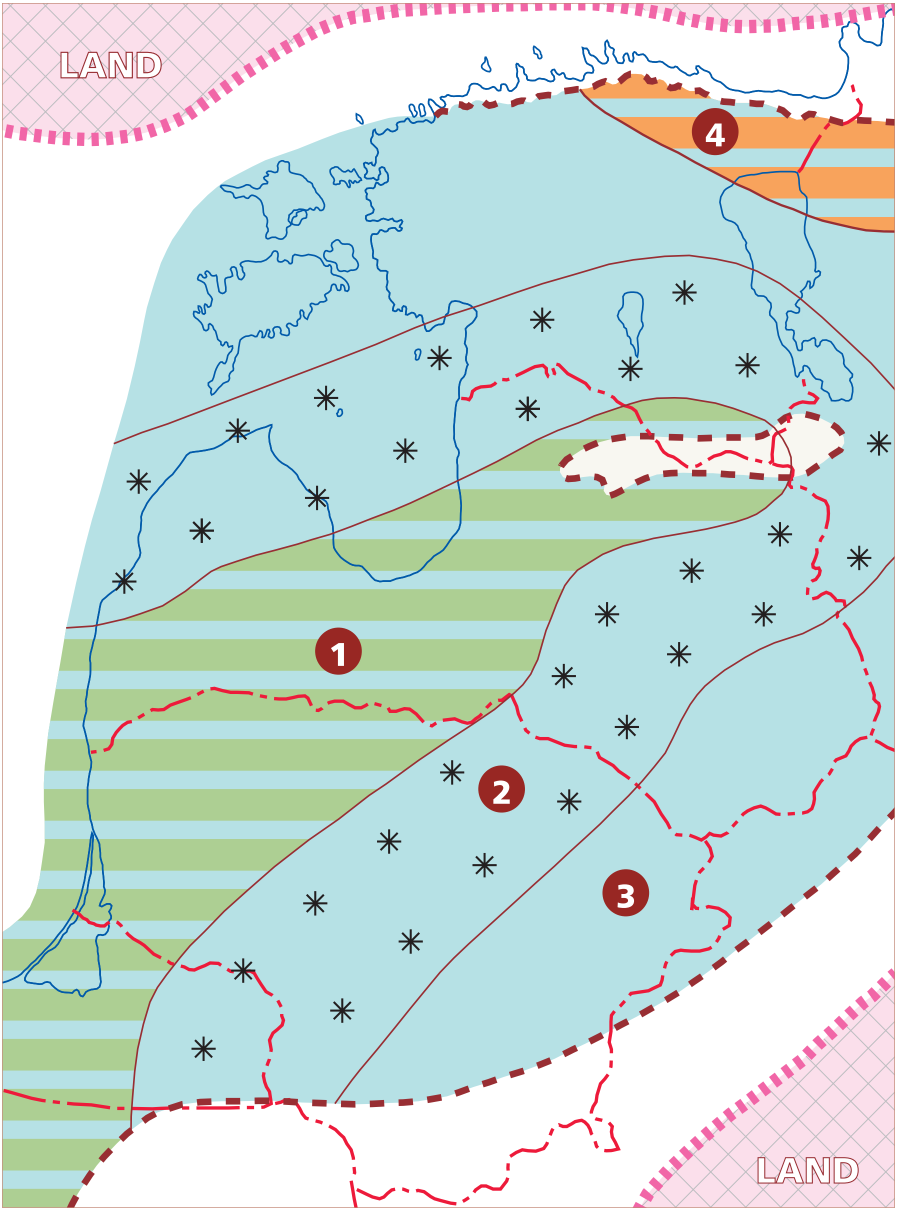
The Late Ordovician (460–443 million years ago) in Estonia is represented by nine



Deposits of the Volkhov Age (after Nestor, H. and Einasto, R. 1997, Fig. 142): **1** – reddish marl, **2** – reddish and greenish bioclastic limestone, **3** – glauconite-rich bioclastic limestone



Lower to Middle Ordovician succession at temporary outcrop in Kadriorg, Tallinn (stage boundaries after R. Einasto). O_1pk - kerogenous argillite (Pakerort Stage), O_1vr - greenish clay (Varangu Stage), O_1hu+bl - glauconitic sandstone (Hunneberg & Billingen Stages), O_1vl - glauconite-rich limestone (Volkhov Stage), O_2kn - limestone (Kunda Stage), O_2as - limestone with Fe-ooids (Aseri Stage), O_2ls - limestone (Lasnamägi Stage)

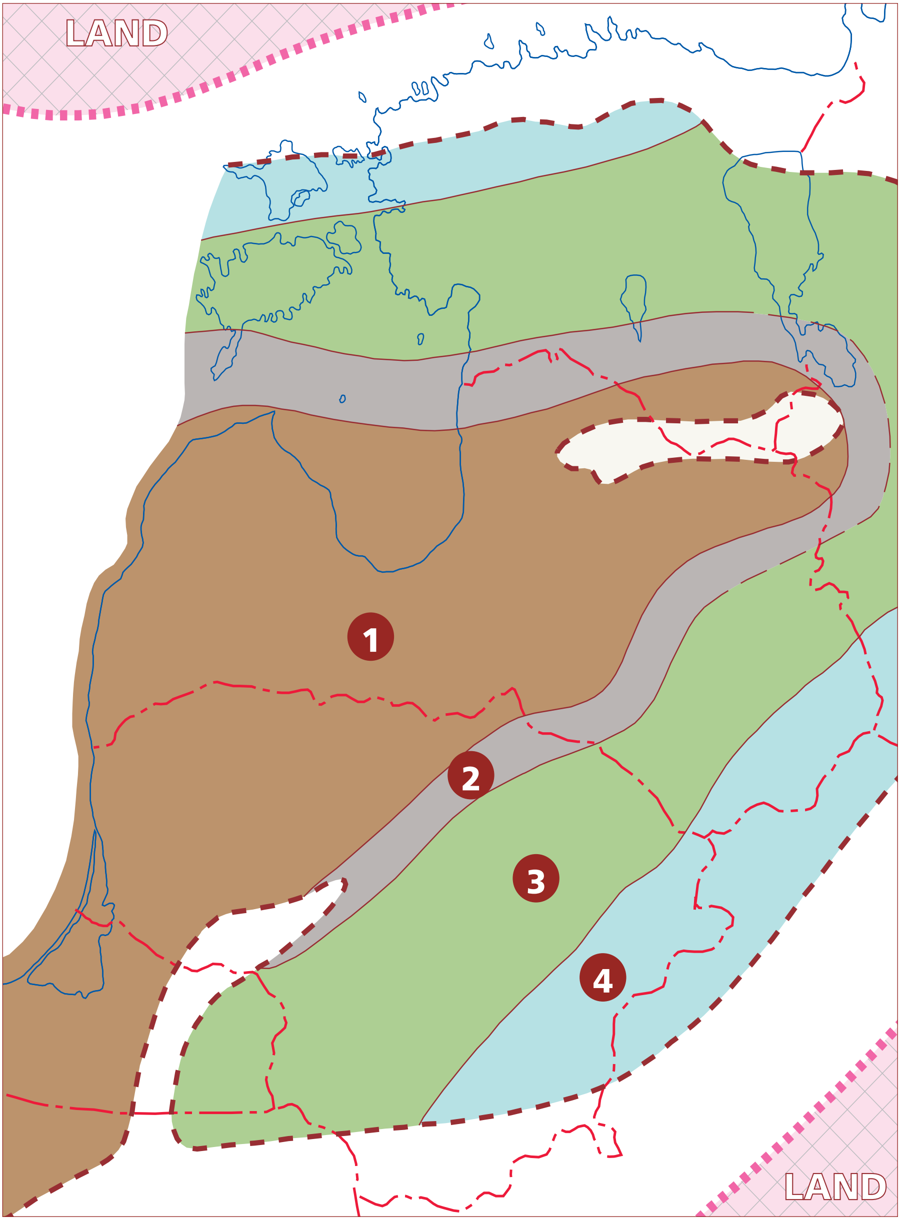


Deposits of the Kukruse Age (after Nestor, H. and Einasto, R. 1997, Fig. 143): **1** – interbedding of clayey and bioclastic limestone, **2** – clayey limestone with pyritized bioclasts, **3** – bioclastic limestone, **4** – bioclastic limestone with kukersite oil shale interbeds stages. From the base to the top they are as follows: Kukruse, Haljala, Keila, Oandu, Rakvere, Nabala, Vormsi, Pirgu and Porkuni. The complex is even thicker than that of the Lower and Late Ordovician combined, reaching 136 m at Rapla in central Estonia and 85 m at Valga on the southern Estonian border, indicating an increased rate of sedimentation due to the warming of sea water. The outcrop areas of the Upper Ordovician stages occur as belts of the west-east orientation, extending approximately to the Haapsalu – Risti – Tamsalu – Mustvee line in the south. In northern Estonia the Upper Ordovician rocks are represented by pure to clayey limestone; in the south, by clayey limestone and marls.

At the beginning of the Late Ordovician, in the Kukruse Age (age is a time interval during which the rocks of the corresponding stage were deposited) oil shale formed in northeastern Estonia. The formation of oil shale is associated with the sinking of seafloor, deepening of the sea basin and more intensive input of clay material from the adjacent mainland. (Up to the present, oil shale resource has satisfied the needs of Estonia for electrical energy, and is one of the cornerstones of Estonia's rapid economic growth).

The accumulation of oil shale continued during the following Haljala Age and in the first half of the Keila Age. This time interval was characterized by intense volcanic activity in the seas adjacent to the continent of Baltica. Some of the volcanic ash (dust, more precisely) reached Estonia and fell on the sea floor, forming interlayers of volcanic ash or bentonite. The thickness of these clay-like interlayers ranges from a few millimetres to several centimetres. The thickest bentonite interbed, up to 60 cm on the Island of Hiiumaa, occurs on the boundary of the Haljala and Keila stages. Its thickness increases in westward direction, which suggests that the source of ash was located either on the British Islands or in the area of North America's east coast. Volcanic material is spread over a huge area extending from the Great Lakes in America to Lake Peipsi on Estonia's eastern border. Some scientists believe that this was the most powerful volcanic eruption during Phanerozoic.

A bit earlier, in the beginning of the Haljala Age (ca 455 million years ago), Estonian territory experienced another catastrophic event. A large meteorite hit the ground in the vicinity of present day Kärdla town on the Island of Hiiumaa and generated an explosion crater, 4 km in diameter and 540 m in depth. By the end of the Ordovician, the crater, which was formed at a depth of 20 m in the sea, was filled with marine sediments. It is only partially visible in the present topography but can be observed as an interrupted ring wall at Paluküla and Tubala. From the Haljala Stage some world's first, earliest representatives of some animal groups have been recorded. From the Aluvere limestone quarry in the vicinity of Rakvere town, the most ancient sea urchin – *Bothriocidaris* has been found. The earliest horn-like solitary rugose corals



Deposits of the Vormsi Age (after Nestor, H. and Einasto, R. 1997, Fig. 145): **1** – kerogenous claystone, **2** – clayey marl, **3** – clayey limestone, **4** – bioclastic limestone have been established from the same stage as well.

In the second half of the Keila Age, the Paleobaltic Sea subjected to an abrupt shallowing and lime sand, consisting mostly of the skeletal debris of ecinoderms, started to accumulate in the vicinity of Vasalemma in north western Estonia. After petrification of the sand, a complex of coarse-grained, pure, detrital limestones was formed, which is now named the Vasalemma Formation. It contains the oldest reefs or bioherms in Estonia. These are lenticular or irregular massive rock bodies which mostly consist of fine lime mud produced by microorganisms, but bryozoans, calcareous algae, as well as earliest in Estonia colonial corals and stromatoporoids also participated in their formation.

The second half of the Late Ordovician is characterized by the cyclic alternation of pure and argillaceous limestone. Purer limestone is represented by crypto- or microcrystalline (micritic) rocks formed from lime mud which are practically devoid of visible fossil particles. These rocks alternate with muddy-detritic, clayey limestone or marls comprising fossil fragments, lime mud and clay material. Rocks with higher clay content occur in the Oandu, Nabala (lower half), Vormsi and Pirgu (upper half) stages. Pure micritic limestones are represented in the Rakvere, Nabala (upper half) and Pirgu (lower half) stages. It is assumed that the alternation of pure and argillaceous rocks observable in the section was caused by the interchange of arid and humid climate periods. During arid periods the influx of terrigenous material was relatively low or even nonexistent; a greater amount of argillaceous mud was deposited in humid periods.

As previously stated, at the end of the Ordovician, North Africa was subject to the Sahara glaciation, which evidently consisted of two ice ages and one interglacial period. During the ice ages, there was a global drop in sea level (50–100 m). In all likelihood, abrupt climatic cooling in the polar regions and temperate zone did not significantly affect the temperature of water in the Palaeobaltic Sea, which at that time was situated close to the equator. On the contrary, shallower seas allowed the intensive tropical solar radiation to warm the comparatively thin water layer down to the sea bottom. In northern Estonia, this promoted the development of massive shallow-water detritic limestone with reef formations rich in corals and stromatoporoids. These limestones of the Porkuni Stage were evidently formed during the interglacial period of Sahara glaciation. During the preceding and following ice ages the global sea level lowered dramatically, retreating from all of northern and central Estonia; no sediments were formed there. In other words, the Porkuni Stage is sandwiched between sedimentation breaks.

THE MOST SIGNIFICANT ORDOVICIAN OUTCROPS IN ESTONIA

Western coast of the Pakri Cape

One of the best-known bedrock outcrops in Estonia is situated on the western coast of the Pakri Cape. It starts from the northern boundary of the town of Paldiski, extends as an continuous escarpment to the tip of the Pakri Cape and continues along the coast of Lahepera Bay. On the western coast of the peninsula it occurs as a 3.5-km-long continuous coastal escarpment. Its southern end reaches a height of 8–9 m, while the northern end on the Pakri Cape rises to 24.5 m high. The thickness of the section increases from south to north and older layers are gradually added to its lower part. The southern part of the escarpment is named Uuga cliff, the northern part, Pakerort cliff. The latter exposes almost the whole Middle and Lower Ordovician section, and even the Lower Cambrian Tiskre sandstone crops out in its lowermost part.

The overall section is divided into two parts: the upper third is represented by Middle Ordovician limestone, the lower part by Lower Ordovician and Cambrian sand- and claystones. Middle Ordovician limestone can be better studied on the Uuga cliff rather than the Pakerort cliff, where the limestone beds rise to an inaccessible height.

The topmost 4.5 metres of the Uuga cliff are formed from resistant platy building limestone of the Uhaku and Lasnamägi stages. It rests on the 20-cm-thick clayey limestone of the Aseri Stage, which contains brownish grain-shaped Fe-ooids. Still lower, the Kunda Stage (1.0 m) consists of fissured sandy limestone with brownish kerogene (burning organic matter) patches. This kind of limestone, the result of an earthquake, is found only in northwestern Estonia. The base of the limestone complex is formed by the limestone of the Volkhov Stage (1.3 m), which contains fine green glauconite grains. The lowermost bed cropping out in the southern end of Uuga cliff is formed by the

Lower to Middle Ordovician sequence at the Uuga cliff (right)


Uuga cliff at the Pakri Cape

greenish-grey fine-grained glauconitic sandstone of the Lower Ordovician Hunneberg Stage, which in the upper (0.3 m) part turns into harder calcareous sandstone of the Billingen Stage. All older beds on Uuga cliff are buried under the talus.

The Lower Ordovician and Cambrian sand- and claystones can be studied in the northern part of the outcrop, which is situated near the lighthouse on the Pakri Cape. Here, the Middle Ordovician limestone beds are located higher, in the upper part of the Pakerort cliff. Below, 4-m-thick greenish glauconitic sandstones of the Billingen and Hunneberg stages are exposed and underlain by greenish- to light grey sandy claystone of the Varangu Stage (0.5 m) are exposed. The thick Pakerort Stage lies below that. The upper 4.5 metres of the Pakerort Stage are formed of brown shale, which was previously named Dictyonema Shale but is currently known as the Türisalu Formation. Actually, this is a variety of oil shale with a rather low calorific value, but it contains several rare earth elements, including uranium. So far, there is no environmentally-friendly and economically viable technology for its exploitation. The lower part of the Pakerort Stage is formed by the Kallavere Formation (3.7 m), represented by yellowish-grey fine-grained sandstone with thin argillite interbeds. Accumulations of phosphatic brachiopod shells, which in this stage occasionally form Obolus Phosphorite deposits, are absent in the section under discussion.

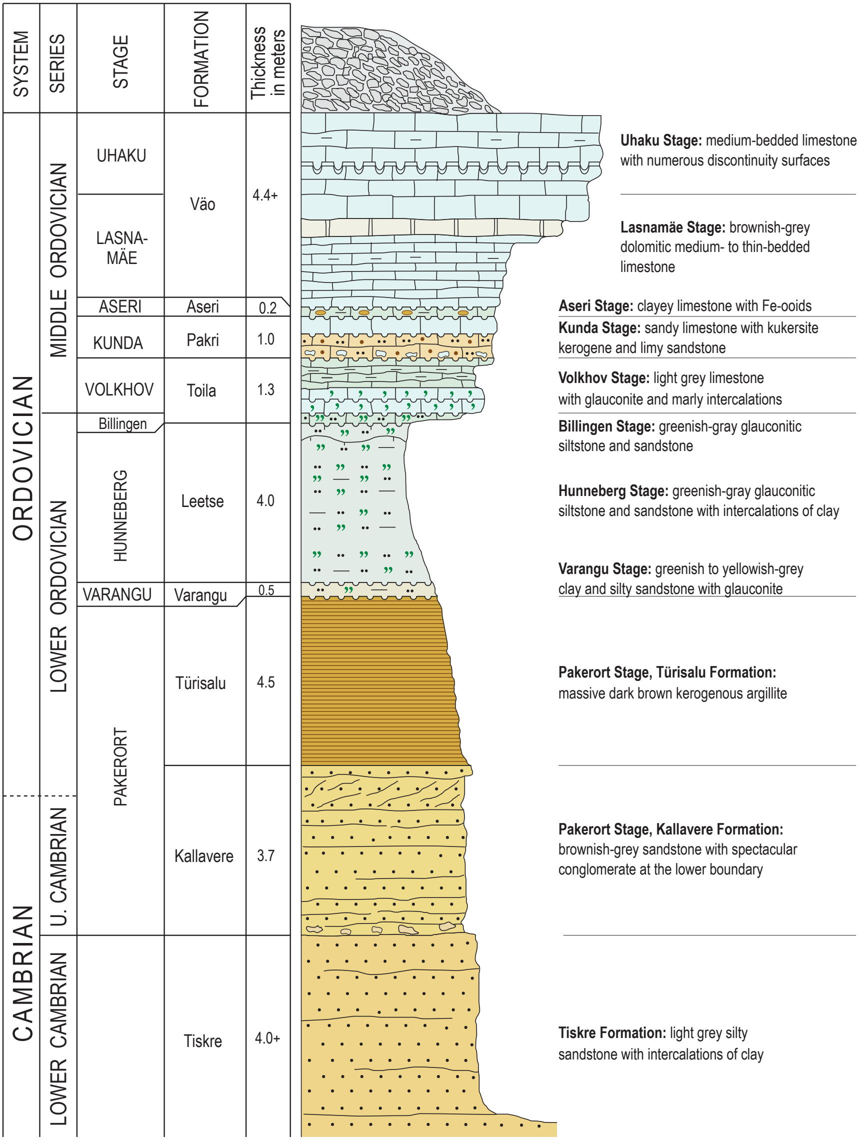
According to recent studies, the lower part of the Kallavere Formation comprises Cambrian fossils and must be assigned to the Cambrian system. There is no noteworthy lithological change on the Ordovician-Cambrian boundary; this refers to continuous sedimentation in the territory of Estonia. A long-term sedimentation break occurs three metres lower, on the lower boundary of the Pakerort Stage and Kallavere Formation, where conglomerates with big sandstone pebbles occur. Below this boundary, the section displays ca 4-m-thick yellow sandstones of the Lower Cambrian Tiskre Formation. Thus, in the Pakri section, as elsewhere on the North Estonian Klint, rock beds characteristic of the greater part of the Upper Cambrian, the whole of Middle Cambrian and the upper part of the Lower Cambrian are absent. This extensive sedimentation break covers ca 30 million years.

Vasalemma limestone quarry

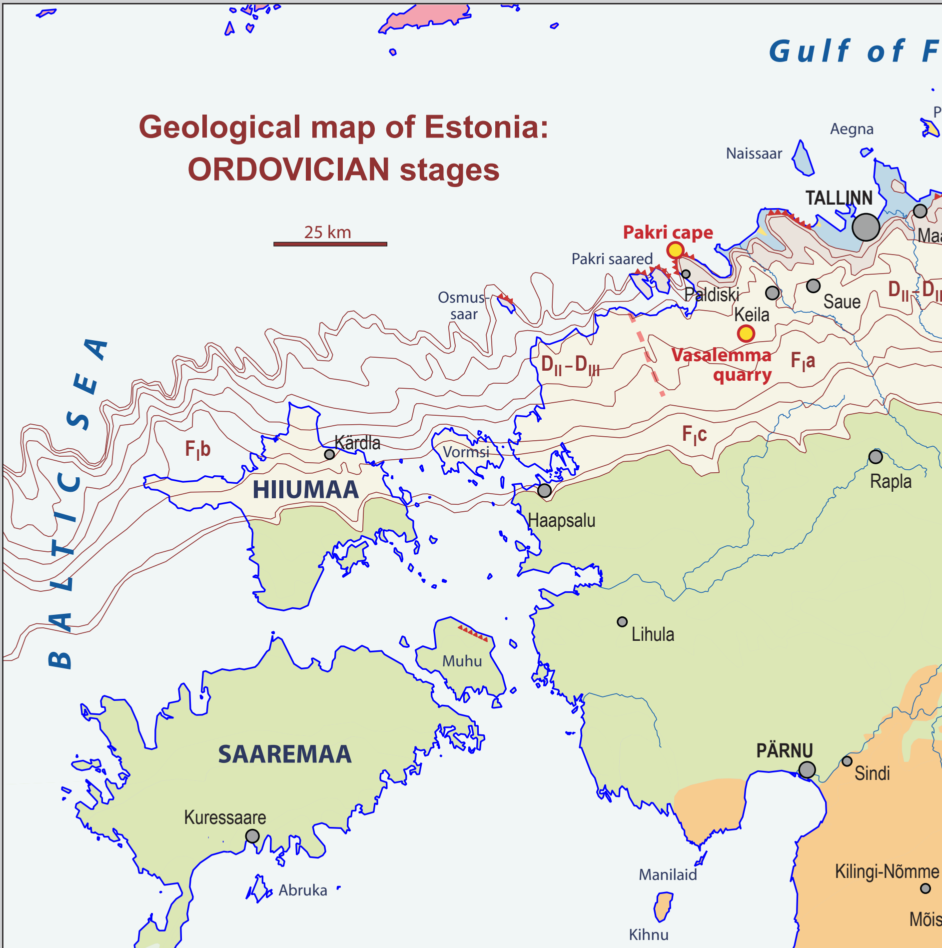
The Vasalemma limestone quarry measures four square kilometres in area. It is situated east of the Vasalemma settlement, just across the railway. The quarry exposes detrital and reef limestones of the Late Ordovician Keila and Oandu stages. The northern wall of the quarry displays wave-bedded to nodular argillaceous detrital limestone formed from lime mud and fossil fragments of the Saue Member, Keila Stage. Well-preserved wave ripple marks on the lower boundary of the member, which forms the quarry floor, show that the formation of limestone took place in shallow water conditions and was affected by wave action.

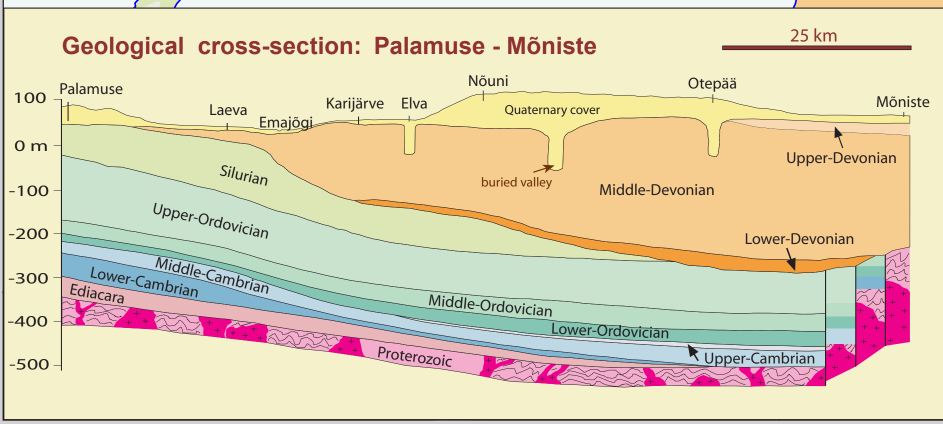
Moving along the eastern quarry wall southwards, there appear interlayers of

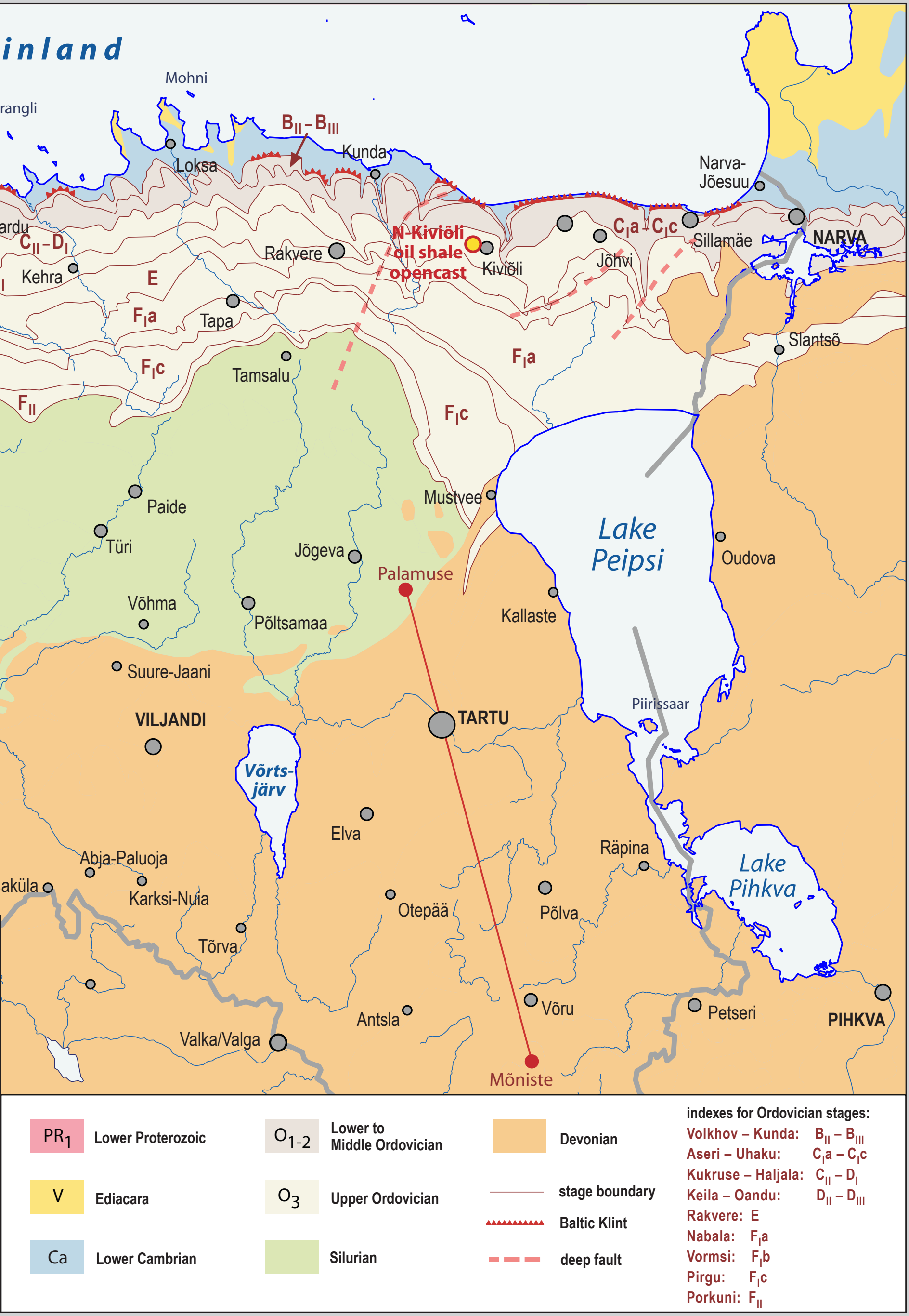
PAKRI cape (composite section)



The composite section at the Pakri Cape (after Puura, I., 2004. Stop 2. North Estonian Klint on the Pakri Peninsula, WOGOGOB-2004 Conference Materials, Tartu, 2004, Fig. 119).

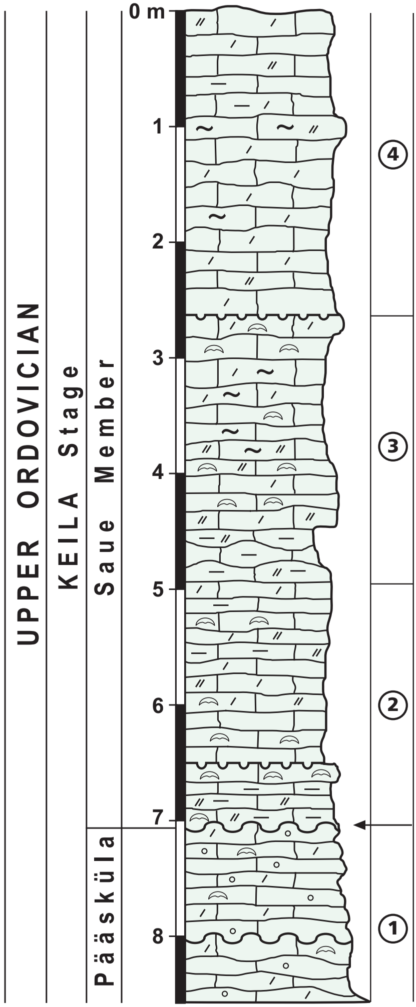

Geological map of Estonia:
ORDOVICIAN stages
25 km
BALTIC SEA
Aegna
Naissaar
TALLINN
Pakri cape
Pakri saared
Osmus-saar
Paldiski
Keila
Saue
Vasalemma quarry
F_Ia
D_{II}-D_{III}
F_Ic
F_Ib
Kärdla
HIIUMAA
Vormsi
Haapsalu
Rapla
Lihula
Muhu
SAAREMAA
Kuressaare
Abruka
PÄRNU
Sindi
Manilaid
Kihnu
Kilingi-Nõmme


Geological cross-section: Palamuse - Mõniste
25 km
100
0 m
-100
-200
-300
-400
-500
Palamuse
Laeva
Emajõgi
Karijärve
Elva
Nõuni
Otepää
Mõniste
Quaternary cover
buried valley
Upper-Devonian
Middle-Devonian
Lower-Devonian
Silurian
Upper-Ordovician
Middle-Ordovician
Lower-Ordovician
Upper-Cambrian
Middle-Cambrian
Lower-Cambrian
Ediacara
Proterozoic



inland
Mohni
rangli
Loksa
Kunda
Narva-
Jõesuu
B_II – B_III
ardu
C_II – D_I
Kehra
E
Rakvere
N-Kiviõli
oil shale
opencast
Kiviõli
Jõhvi
C_Ia – C_Ic
Sillamäe
NARVA
F_Ia
Tapa
F_Ic
Tamsalu
F_II
Slantsõ
Paide
Türi
Mustvee
Lake
Peipsi
Jõgeva
Palamuse
Oudova
Võhma
Põltsamaa
Kallaste
Suure-Jaani
VILJANDI
TARTU
Piirissaar
Võrts-
järv
Elva
Räpina
Abja-Paluoja
Lake
Pihkva
akula
Karksi-Nuia
Otepää
Põlva
Tõrva
Võru
Petseri
PIHKVA
Antsla
Valka/Valga
Mõniste
PR_1 Lower Proterozoic
V Ediacara
Ca Lower Cambrian
O_1-2 Lower to Middle Ordovician
O_3 Upper Ordovician
Silurian
Devonian
stage boundary
Baltic Klint
deep fault
indexes for Ordovician stages:
Volkhov – Kunda: B_II – B_III
Aseri – Uhaku: C_Ia – C_Ic
Kukruse – Haljala: C_II – D_I
Keila – Oandu: D_II – D_III
Rakvere: E
Nabala: F_Ia
Vormsi: F_Ib
Pirgu: F_Ic
Porkuni: F_II

VASALEMMA limestone quarry (northern wall)



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

Bioclastic limestone with fossils.

Level of large ripple marks with pyritized surface at the upper boundary of the Pääsküla Member is in places well visible on the quarry floor.

Geological succession of the northern wall of the Vasalemma limestone quarry (after Hints, L. et al., 2004. Stop 3. Vasalemma quarry, WOGOGOB-2004 Conference Materials, Tartu 2004, Fig. 123)

1 - relatively 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 varying share of bioclastic material and wavy bedding planes

light, pure, coarse-grained limestone consisting of skeletal debris of echinoderms, particularly sea anemons and cystoids, without muddy material between skeletal grains. Therefore such rock is called lime grainstone or pure detrital limestone and initially it was a lime sand. The muddy and pure detrital limestones interlayer in vertical section. The thickness and number of pure detrital limestone interlayers increase southward and where they become dominant in section, the Saue Formation is replaced by the Vasalemma Formation. The light, thick-bedded, coarse-grained limestone of the Vasalemma Formation contains irregular lens-like or nodular lime mud formations, known as mud-mounds or bioherms. These formations may reach 10 metres in thickness and 300 metres in length. It is assumed that microorganisms precipitated lime material from sea water and played an important role in the formation of bioherms. The stems of cystoids and other echinoderms attached to these mud-mounds and formed peculiar thickets on the seafloor. When the organisms died, their calcareous skeletons disintegrated into plates and columnals, which accumulated around bioherms and formed pure detrital limestone. But root systems of echinoderms remained on the surfaces of bioherms, protecting them from wave and current erosion. The surface of the bioherms emerged slightly above the seafloor. Since organisms played an important role in the formation of these mud accumulations, the latter can be treated as peculiar reef formations. Besides microorganisms and holdfasts of echinoderms, fossil assemblages of bryozoans and calcareous algae also participated in some reef formations. Due to the gentle southward inclination (ca 3 m per km) of the bedrock strata, the thickness of the Vasalemma Formation increases towards the south. Younger layers with a total thickness of 6 m are added in the southern part of the quarry. These belong in part to the Oandu Stage. At that time the oldest colonial honeycomb-like corals – in Estonia started to participate in the formation of reefs, indicating that the territory of present day Estonia, which was part of the Baltica continent, had reached the tropical climate zone.

In the past, the pure light-grey, coarse-grained bioclastic limestone of the Vasalemma Formation, known as the "marble of Vasalemma", was widely used as building material and ornamental stone. For instance, Padise monastery, Harju-Risti and Harju-Madise churches, Vasalemma and Laitse manor houses and even the wing of Marienburg castle in Eastern Prussia were built from this limestone. However, it is not weatherproof, proving unsuitable as an ashlar, grave slab, or ornamental stone. Furthermore, the manual labor required for its use in building construction is prohibitive. Thus most limestone currently produced in the Vasalemma quarry is widely used in the chemical industry.

Ontika cliff and Valaste waterfall

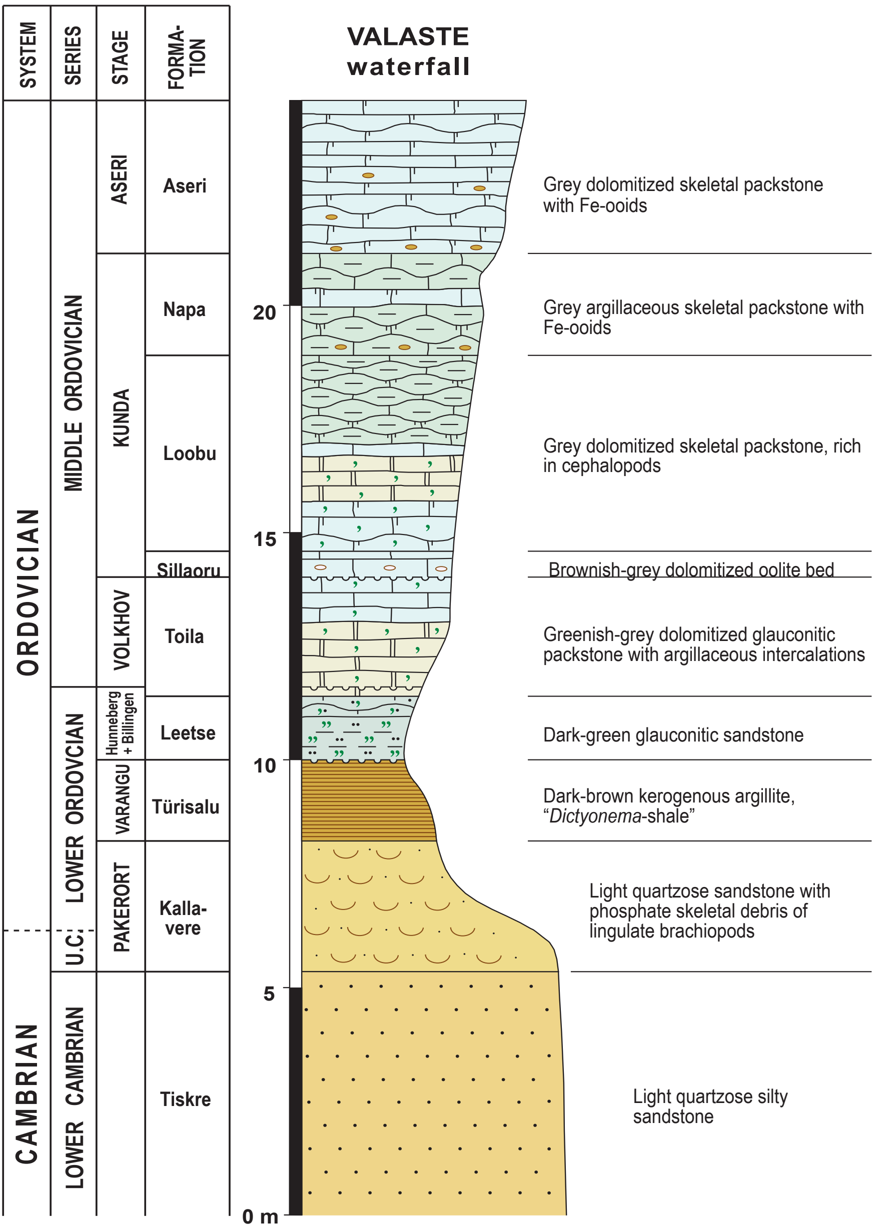
The North-Estonian Klint reaches its greatest height (56.5 m) at Ontika. To offer a better view from the cliff, a sightseeing platform was erected adjacent to Valaste waterfall, the highest in Estonia. In this waterfall, water drops from the mouth of a man-made ditch on the third kilometer of the road leading from Ontika village to Toila. The height of the waterfall ranges from 26 to 30 m depending on the amount of precipitation and falling water. The main part of the waterfall (ca 20 m) consists of Middle Ordovician limestone beds (ca 13 m) and Lower Ordovician sand- and claystones (ca 7 m). Below this is Lower Cambrian sandstone, about 25-metres thick, which for the most part is buried under thick talus, and crops out only in an eroded hollow under the waterfall.

In West Estonian sections, including Pakri Cape, the dark brown shale belongs to the Pakerort Stage. Here it was formed later and is of Varangu age.

Kohtla Mining museum

The Kohtla Mining Museum, located on the site of an former underground mine at the western boundary of Kohtla-Nõmme settlement, offers a good introduction to the history and technology of the oil shale production industry in Estonia.

Oil shale is Estonia's most important mineral resource. It is called kukersite in Estonian, named for Kukruse village, located in the centre of the Estonian Oil Shale Basin. The mining of oil shale at Kohtla was started in 1937, using both underground and opencast methods. By now, oil shale reserves have been exhausted here.



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

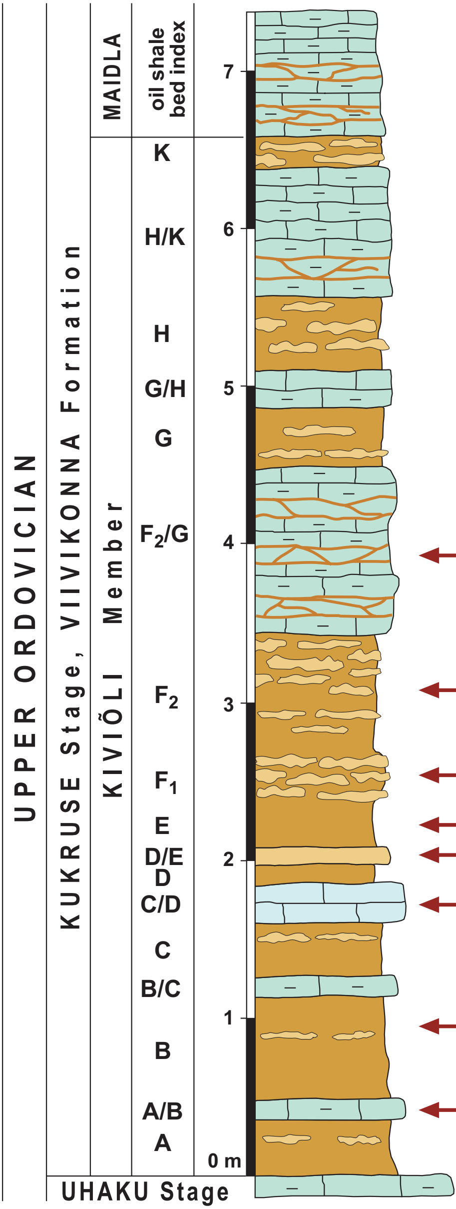

Geological section at the Valaste

In the Oil Shale Basin, the oil shale forms intercalations in the limestone deposit of the Uhaku and Kukruse Stages. Commercial limestone beds occur in the lower half of the Kiviõli Member belonging to the Kukruse Stage. In this region the Kiviõli Member is ca 6.5 m thick. In its section, brown kukersite layers alternate with hard, heavier grey limestone layers, which may contain varying amounts of kerogene – organic matter that gives them a yellowish or pinkish tinge. Oil shale beds contain nodules of kerogenic limestone. Traditionally, the oil shale beds are marked with capital letters A – K. In some cases lowercase indices are used: F_1–F_5, G_1-G_2, H_1-H_2. The Kiviõli Member includes a total of 14 oil shale seams. The section is divided into two parts. In the lower part, up to seam F_1, the oil shale beds are thicker (15–20 cm), purer, with lower limestone content. These seams form a commercial bed and are mined. The upper part of the Kiviõli Member is predominantly composed of argillaceous nodular limestone. Oil shale seams in this part which are rather thin or contain numerous limestone nodules are not mined.

In Kohtla mine, oil shale seams from A to F_1 can be observed. These form the commercial bed with a total thickness of 3.0 metres. The thickest and purest seams are B (50 cm), C (40 cm) and E (30 cm). In seam A (30 cm) the content of clay material is rather high and its calorific value is lower. It is separated from the upper layers with a hard thick blue limestone interbed and is sometimes left unmined. The same may happen to seam F_1 that is rather thick (50 cm), but relatively rich in limestone nodules (20–30%). The limestone interbeds between seams bear the idiomatic names as follows: A/B – blue limestone, B/C – fist , C/D – twin limestone, D/E – pink limestone, E/F – devil's skin. Blue limestone and particularly light-coloured "twin limestone"

Kukersite oil shale mining at the Aidu (Vanaküla) open-cast

VANAKÜLA kukersite oil shale open-cast mine



The uppermost part of kukersite 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 level of kerogenous limestone nodules "Devil's skin"

pure oil shale bed

kerogenous limestone interbed ("pink limestone")

bluish-gray limestone interbed ("twin limestone")

oil shale with few kerogenous limestone nodules

gray clayey limestone interbed (blue limestone")

Geological succession of the Aidu (Vanaküla) oil shale open-cast near Kohtla Mining museum stand out with their smooth bedding planes and low kerogene content. The 30 cm thick C/D interlayer, actually consisting of two separate layers, is the best reference level for those interested in following the layers in the sequence.

Porkuni limestone quarry

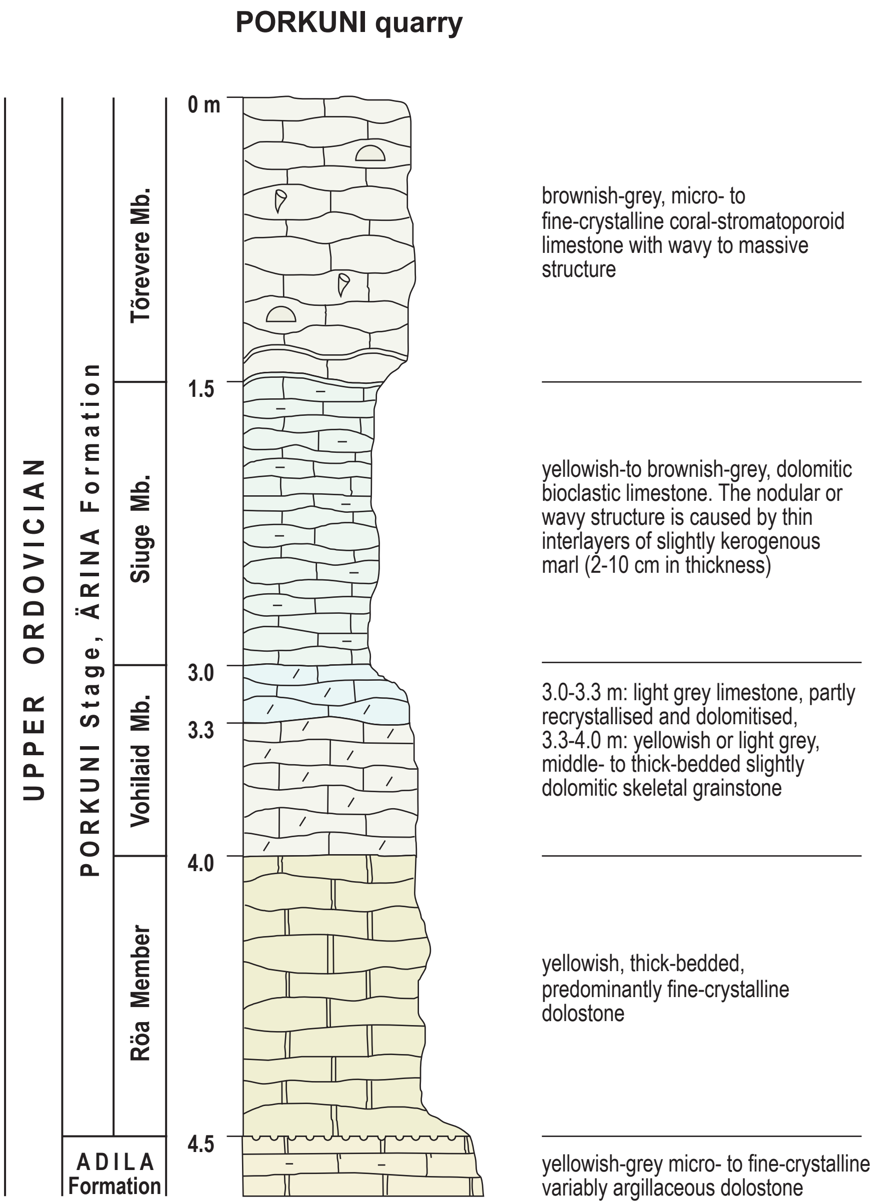
The old Porkuni quarry in the northwestern corner of the old forest park of Porkuni manor is situated on the western slope of the ancient Valgejõgi valley east of the Kullenga – Tamsalu road, ca 200 m towards Tamsalu from the bridge leading over the Valgejõgi River. The quarry was in operation since the 15th century when limestone was quarried for building of the Porkuni episcopal stronghold. Currently, its gate tower accommodates the limestone museum.

The recently cleaned wall of the outcrop exposes 5.5 m of the Porkuni Stage, which is the uppermost Ordovician stage in Estonia. The Porkuni limestone quarry is one of the few outcrops where the Porkuni Stage is exposed nowadays. The pure coarse-grained limestones of the Porkuni Stage and associated reef-like coral-stromatoporoid limestones have been formed in very shallow water conditions, where lime sands with abundant corals and stromatoproids deposited. The abrupt sea level fall in the Porkuni Age is associated with the formation of continental ice cup in Africa, which was located near the present day South Pole. The sea level lowered 100 m, many shallow seas turned into dry land and therefore outcrops of the rocks of the Porkuni age have been preserved in only a few places in the world. Porkuni quarry with its abundant fossils is considered one of the richest in fossils among them. Here, over the years, more than 150 type specimens of fossil species have been described for the first time, and contribute to the understanding of the composition and evolution of the biota at the end of the Ordovician, ca 450 million years ago.

The extraordinary geological riches of Porkuni limestone quarry have attracted many foreign scientists and excursions. The most noteworthy were arranged for participants of the International Geological Congress held in St. Petersburg in 1897 and the joint excursion of the Ordovician and Silurian sub-commissions of the International Geological Union in 1990.

The Palaeozoic sedimentary rocks of southern Finland

The thickness of the Neoproterozoic and Palaeozoic platform sediments, that once covered most of the present southern Finland could reach 200 – 500 metres. However, these sediments were mostly destructed and eroded either due to the uplift of a foreland bulge in the Devonian or as a consequence following the isostatic uplift after denudation of the Caledonides in the late Palaeozoic and Mesozoic. The Palaeozoic sedimentary rocks occur sporadically in southwestern Finland, in the



Geological section of an abandoned Porkuni quarry (after Hints, L. and Oraspõld, A., 2004. Stop 6. Porkuni quarry, WOGOGOB-2004 Conference Materials, Tartu 2004, Fig. 127) places protected from erosion: meteorite craters and fissures of the Precambrian bedrock. The contact of the Vendian and younger sediments with the Precambrian peneplain is discordant, and the structures in the Precambrian basement are cut in the contact with these younger sediments.

Erratic boulders derived from the Palaeozoic sedimentary rocks occur on the coast of southwestern Finland. They have a diameter from a few centimetres to one metre. In the coastal erratics from the Luvia and Hanko area, the amount of the Cambrian sandstones reaches 10% and the amount of the Ordovician limestones is about 1%. The erratic boulders are unevenly distributed. However, most erratic sandstones in southwestern Finland and the Åland Islands are not Palaeozoic, but originate from the 1300 Ma old Jotnian sandstone, which forms the depositional platform for the Palaeozoic sedimentary rocks in the Bothnian Sea and is exposed in Pori-Luvia mainland.

The Ordovician limestones of southern Finland

Towards the Ordovician and Silurian, an extensive carbonate platform developed at the margin of the Precambrian craton. The Ordovician limestone deposited in an environment of regressive epicontinental sea, which was shallower and more limited than the same sea in its transgressive phase.

The carbonate platform extended from Estonia to the Bothnian Sea and possibly to Central Finland. As the thicknesses of the Cambrian-Ordovician strata in the Bothnian Sea and in Estonia are almost even, and since there neither systematic decrease of bed thickness nor facies change towards north, the sedimentary cover in the Bothnian Sea may represent rather a tectonically preserved part of an originally extensive Palaeozoic sedimentary sequence than a separate Palaeozoic sedimentary basin. The Early Palaeozoic marine basin may have been connected to passive-margin type of development resulting later into foreland subsidence developing alluvial-fluvial deposition since Devonian (at 400 Ma).

In the Swedish part of the Bothnian Sea, offshore near Gävle, the Ordovician bedrock sequence is penetrated by the drill cores of Finngrundet and Västra Bänken. The extent of the early Palaeozoic sediments in the Bothnian Sea has been established by geophysical studies.

In southwestern Finland and in the Turku archipelago, erratics derived from the Palaeozoic rocks of the Bothnian Sea occur. The Ordovician limestone deposited in the meteorite crater of Lumparn in the Åland Islands gives some insights into the still unknown possible occurrences of bedrock limestones in Finland.

The limestone erratic boulders collected from the coast 70-100 kilometres NW from Turku, from Pyhäranta, Pyhämaa, Kalanti and Kustavi, have been studied in detail by Estonian and Finnish palaeontologists.

Palaeozoic sedimentary rocks and Jotnian sandstone under the Baltic Sea and Gulf of Bothnia (figure adapted from: Flodén, T. & Winterhalter, B. 1981. Pre-Quaternary geology of the Baltic Sea. In: In the Baltic Sea, Voipio, A. (ed.), Elsevier Oceanogr. Ser. 30, Amsterdam)

These rocks are similar to the limestones in of the northern Estonia. By microfossils, (chitinozoans, conodonts, ostracods and acritarchs), the boulders are biostratigraphically correlated with the transition interval of the Lasnamägi to Uhaku stages and to the interval from the Oandu to the late Rakvere stages in the Upper Ordovician. The chitinozoans and acritarchs were most valuable in dating the Ordovician deposits and erratics, although in some Baltic limestones (with red spots) organic-walled microfossils are not preserved and the only available fossils are ostracods.

In situ locations of limestone

The Lumparn structure in the Åland Islands is a round depression with a diameter of 10 kilometers, which has been formed into the rapakivi granite massif. The Lumparn limestone occurrence is the only known in situ occurrence of Ordovician limestone in southern Finland (although other occurrences have been suggested to exist in the bottom of the sea). The limestone in Lumparn is not exposed on the surface, and cannot be reached reachable without diving. The Lumparn crater holds a 30-70 meters thick Ordovician limestone deposited partly on siltstone, partly on at least 60 meters thick layer of clay. The diameter of this occurrence occupying the crater is at least 2 kilometers.

Another underwater limestone location may occur south of Isokari in front of Uusikaupunki, where large boulders have been found and sampled.

USEFUL TERMS

Age – a specific time period in the geological development of a region; a subdivision of an epoch

Aleurolite/siltstone – sedimentary rock with a finer grain-size than sand

Argillite – shale, consolidated claystone, which has lost its plasticity

Barrier reef – a coral reef, an elongated offshore ridge built up from calcareous skeletons of marine organisms (corals, calcareous algae, sponges, etc.)

Bentonite – sedimentary rock formed of volcanic ash deposited on the seafloor

Bioherm – a sea-floor elevation composed of fossil organisms (see also reef, mud-mound)

Biostrome – a layer of calcareous skeletons of organisms attached to each other

Carbonate rocks – rocks composed of carbonate (H_2CO_3) minerals (calcite, dolomite); popularly known as limestone

Cavern – a hollow in a rock usually resulting from the dissolution of a fossil

Cavernous dolomite – dolomite with an abundance of solution cavities

Cliff – a bedrock escarpment produced by sea erosion

Commercial bed – part of a mineral resource subject to mining

Conglomerate – a sedimentary rock consisting of consolidated gravel

Conodont – a member of an extinct group of small primitive fishlike chordates, preserved primarily in the form of their conelike teeth

Craton – a core of a stable continental crust, which in the geological past occurred as an independent supercontinent in the context of the continental drift. When cratons are discussed as parts of the modern goelogical structure of certain regions, outside the historical context of continental drift, the traditional term „platform" is also often used

Detrital (bioclastic) limestone – limestone with skeletal remains of organisms; divided into muddy detrital limestone if lime mud deposited between skeletal particles during sedimentation, and pure detrital (bioclastic) limestone if initially there was no clay but only pure lime sand. In the first case, sedimentation took place under deeper calm-water conditions, in the latter case in the shallow zone of wave action

Detritus – crushed skeletal remains of organisms

Dictyonema Shale – historical name of organic-rich shale (argillite) occurring in the Lower Ordovician of Estonia

Dolostone – a rock consisting of mineral dolomite

Dolomite – both a carbonate rock and mineral (Ca/MgCO_3) consisting of calcium-magnesium carbonate

Domerite – dolomite-marl, dolomitic stone rich in clay material

Epoch – a subdivision of a geological period; often used in conjuction with descriptors, e.g. Early, Middle, Late

Eurypterid – a sea scorpion; a large, jointed-limbed extinct scorpion-like arthropod

Formation – a rock mass with a more or less uniform composition named after the geographic locality where it was first recognized and described and occurs in its typical form

Glauconite – a green siliceous iron mineral with granular structure and complicated composition

Graptolite – an extinct colonial marine animal with a planktonic mode of life

Iron ooid – rounded grain-like formation composed of iron minerals

Kerogene – lithified organic matter

Klint – an extensive bedrock escarpment on cliffed coast or inland, partially buried or terraced

Kukersite – an oil shale mined in Estonia

Marl – a carbonate rock formed of lime and clay material, also known as floating limestone

Member – a subdivision of a formation

Micritic limestone – a muddy, micro- or cryptocrystallline limestone formed of lime mud and almost devoid of skeletal fragments of organisms (detritus)

Mud-mound – a reef-like build-up formed due to microorganisms on the sea floor

Muddy detrital limestone – limestone where the space between skeletal remains of organisms (detritus) is filled with muddy material

Obolus Phosphorite – the historical name of the phosphorite formed of the shells of brachiopods and occurring in the Lower Ordovician of Estonia

Ostracode – a tiny crustacean; its body was enclosed in a bivalved carapace

Outcrop – an area where rocks of a certain age or composition appear above the surface of surrounding land or are covered with a thin layer of unconsolidated Quaternary deposits

Period – a division of geologic time; a distinct segment of time in the evolution of the Earth, lasting tens of millions of years

Plateau – part of platform (craton) where the bedrock of metamorphic and igneous rocks is covered with younger sedimentary rocks

Psilophyte – a primitive plant

Pure detrital limestone – a limestone without muddy material between the skeletal remains of organisms, i. e. initially there was lime sand

Reef – a mound on the seafloor composed of the skeletons of carbon-secreting organisms (corals, calcareous algae, sponges, etc.)

Reef hillock – a bedrock hillock formed of hard reef rocks in contemporary relief

Regression – retreat of the sea

Rugose – a horn-shaped, commonly solitary coral

Shield – part of platform (craton) where the bedrock made up of metamorphic or igneous rocks is not covered with younger sedimentary rocks

Series – a subdivision of a system, rocks formed during a relevant time priod; the name of the series is mostly formed by placing an adverb (Lower, Middle, Upper) in front of the name of a corresponding system

Silica concretion – a spherical mineral inclusion made up of silica within a limestone or dolomite stratum

Stage – a subdivision in the classification of stratified rocks formed concurrently in a certain region; the name of the stage is derived from the name of the locality where it occurs in its typical form

Stromatoporoid – a large loaf-like fossil; an extinct colonial form belonging to sponges

Supercontinent – a large landmass, which combined most of the continental crust of the Earth, e.g. Pangaea

System – rocks, formed during a certain period of geological time and bearing the same name as the period, e.g. Ordovician System/Ordovician Period

Thalassocratic period – an era when seas reigned/predominated

Tentaculite – a problematic fossil with a small conical shell

Transgression – advance of the sea

Trilobite – an extinct arthropod, very common in early Palaeozoic seas

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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

ISBN 978-9985-9867-1-4