10th International Symposium on Fossil Cnidaria and Porifera

Excursion B2: Lower Paleozoic geology and corals of Estonia

August 18-22, 2007

Excursion Guidebook

Edited by Mari-Ann Mõtus & Olle Hints

Tallinn, 2007

10th International Symposium on Fossil Cnidaria and Porifera
Excursion B2: Lower Paleozoic geology and corals of Estonia
Excursion Guidebook

Edited by Mari-Ann Mõtus and Olle Hints

Facts about Estonia *from Wikipedia (2007, http://en.wikipedia.org/wiki/Estonia).*

Introduction *after Puura (2006).*

History of investigation *after Kaljo (1990).*

Ordovician and Silurian stratigraphy *by Olle Hints.*

Ordovician and Silurian carbonate sedimentation basin *modified after Nestor and Einasto (1997).*

Corals and stromatoporoids *modified after Kaljo (1997), Mõtus (2005) and Nestor (1997b).*

Descriptions of excursion stops *are compiled from the following sources: Tinn (2004), Ainsaar (2004), Einasto (1990), Hints (2004), Kaljo and Einasto (1990), Kõrts and Einasto (1990), Nestor (1990), Rubel and Einasto (1990), and Tiirmaa (1997).*

Photos and illustrations are by the editors if not indicated otherwise.

Cover photo: *Halysites junior* Klaamann, 1961 from the Sepise outcrop, Saaremaa (Wenlock).

Acknowledgements
The editors express their special thanks to Dimitri Kaljo, Heldur Nestor, Viiu Nestor, Peep Männik, Tiiu Märss, Leho Ainsaar, Linda Hints, Ivar Puura and Helje Pärnaste for their help in improving this guidebook.

Copies (hard-copy or .pdf) can be obtained from:
Institute of Geology at Tallinn University of Technology
Ehitajate 5, 19086 Tallinn, Estonia
Phone: +372 620 30 10
Fax: +372 620 30 11
E-mail: inst@gi.ee

ISBN 978-9949-430-08-6

Tallinn, 2007

CONTENTS

FACTS ABOUT ESTONIA

Area	
- Total	45,226 km^2 (132nd in the World)
- Water (%)	4.56%
Population	
- 2007 estimate	1,342,409 (151st in the World)
- 2000 census	1,376,743
- Density	29 /km^2 (173rd in the World)
Capital (and largest city)	Tallinn, 59°26′N, 24°45′E
Official languages	Estonian
Government	Parliamentary democracy
- President	Toomas Hendrik Ilves (as of 2007)
- Prime Minister	Andrus Ansip (as of 2007)
Independence	from Russia and Germany
- Declared	24 February 1918
- Recognised	2 February 1920
- Occupied by USSR	16 June 1940
- Re-declared	20 August 1991
Accession to the European Union	May 1, 2004
GDP (PPP)	2006 estimate
- Total	$26.85 billion (106th in the World)
- Per capita	$20,300 (42nd in the World)
Currency	Estonian kroon (EEK)

GEOLOGICAL BACKGROUND

Introduction

Estonia is situated in 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 the mainland of Estonia continue along the seabed, reaching the opposite seashores in Finland and Sweden. A thorough overview of Estonian geology and mineral resources edited by Raukas and Teedumäe (1997) contains most of the information used in this brief introduction.

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 towards Finland, the basement is located closer to the surface, and is exposed in the central part of the Gulf of Finland, lying about 100 m below the water level. Estonia is situated in the central part of a 50–65 km thick block of the Earth's crust, as large as 1 million square kilometres. The structures of this block formed during an orogeny about 2.0–1.8 Ga ago, and during rapakivi magmatism about 1.65–1.5 Ga ago.

The Ediacaran (Vendian; 650 to 540 Ma) and Paleozoic (540 to 360 Ma) sedimentary rocks of Estonia have been formed in a shallow sea basin. All the rocks of the Vendian complex in Estonia have been formed during Ediacaran time. The sea basin has been travelling with an ancient Baltica plate, which has been drifting since Ediacaran time from the high southern palaeolatitudes to its present position in the northern hemisphere, crossing the equator during the Silurian and Devonian. The smooth surface of the crystalline basement is covered by the Upper Vendian sedimentary rocks, represented by sandstones and clays, exposed in the bottom of the Gulf of Finland. The Paleozoic sedimentary rocks usually overlie the Vendian rocks. Only in north-western 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 0.1–0.3 degrees (2 to 5 metres per km), the Paleozoic rocks are exposed as sub-latitudinal belts, successively younger in southward direction.

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 the Hiiumaa Island in the west. Silurian limestones are exposed as

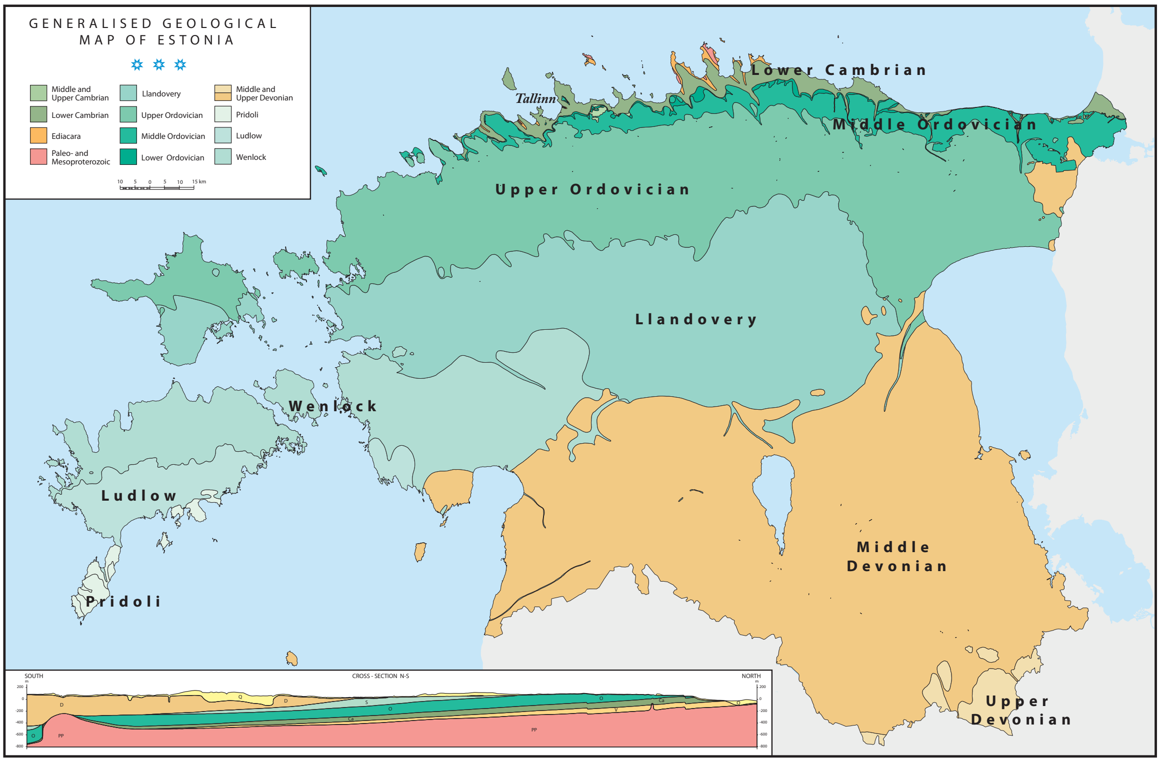


Fig. 1. Generalised geological map of Estonia showing outcrop areas of lower and middle Paleozoic rocks and southward dip of Proterozoic crystalline basement.

a belt in the middle and western Estonia and on the Saaremaa Island. Devonian terrigenous rocks, mostly sandstones, are exposed south of the Pärnu-Mustvee line, extending from southeastern and southern Estonia to the Kihnu and Ruhnu islands in the west. Upper Devonian limestones occur near Narva and in South-East Estonia (Fig. 1).

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 unique field museum of Paleozoic geology.

The Quaternary cover of Estonia consists mostly of glacial, glaciolacustrine, and glaciofluvial deposits of 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, exceeding tens of metres and often 100 m in the Haanja and Otepää heights and in the buried valleys (207 m in Abja buried valley). 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 was influenced by glacioisostatic rebound (neotectonic uplift), most intensive in the north-western part of Estonia. Due to the uplift, the width of Estonia's coastal region exceeds 130 km and ancient coastal formations occur at various elevations.

Estonia is a flat territory, where uplands and plateau-like areas alternate with lowlands, depressions, and valleys. These land forms, 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 75–100 m above the sea level. The highest point in Estonia and the Baltic States, the Suur Munamägi Hill (318 m), is located in the middle part of the Haanja Heights.

The erosional uplands are mostly flat, with relatively thin Quaternary cover, and 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 the relief dominated by hills and valleys, built up of 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.

Higher areas also include the plateaus. The Harju and Viru plateaus are located in northern Estonia and are bordered from the north by the steep escarpment of the Baltic Klint. Both plateaus are about 30–70 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: the 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 waste rock and ash hills. The Ugandi Plateau (40–100 m a.s.l.) 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 Kallaste outcrop on the beach of Lake Peipsi. Other relatively high areas are the Central-Estonian Plain (60–80 m a.s.l.) and Kõrvemaa (50–90 m a.s.l.).

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

Mineral resources. Deposits of the most important mineral resources — oil shale, phosphorite, and carbonate rocks — are located in the northern and north-eastern part of Estonia. Peat, sand, and gravel resources are distributed almost evenly over the country. During the past hundred years, two economically important and geologically unique mineral resources have been (1) Upper Ordovician oil shale and (2) Lower Ordovician shelly phosphorite. Unfortunately, both have been mined and industrially used for more than half a century in environmentally hazardous ways, devastating large regions in northern and north-eastern Estonia. Environmental impact is one of the reasons why phosphorite mining was discontinued in the 1990s and oil-shale based industry and energy production will be decreased. Phosphorite has been excluded from the list of active mineral reserves in late 1990s. Other relevant mineral resources include Ordovician and Silurian limestone, and gravel, sand, peat and sea and lake muds from the Quaternary deposits. Also, mineral water originating from Vendian and Paleozoic sediments is in use in many parts of Estonia.

Most significant geological features of Estonia, in addition to fossil-rich Lower Paleozoic strata, include the ***Baltic Klint*** (Cambrian Ordovician landform over 1000 km long), ***West Estonian Klint*** (Silurian), several ***meteorite craters*** (including Paleozoic Neugrund and Kärdla craters and Holocene Kaali crater), and various ***glacier-shaped landforms*** and ***huge erratic boulders***.

History of investigation

The first publications on Estonian geology date from the end of the 17th century (these were the descriptions of Narva waterfall and a mineral spring at Koorküla). A hundred years later Academician Georgi reported about the discovery of oil shale in North Estonia; however, geological investigations remained sporadic troughout the 18th and first half of the 19th centuries. Of consequence were the works by E. Eichwald (his first paper appeared in print in 1825) who presented a more or less complete stratigraphic subdivision of bedrock and described a great number of fossil species. He was the first to advance the idea that in the diluvial time a part of Estonian territory was covered by glaciers.

The middle of the 19th century brought about the "Golden Age" of investigations marked by the publications of fundamental works by A. Schrenk, F. Schmidt and C. Grewingk, which laid the foundation of modern stratigraphic scheme; in that period the palaeontological monographs by C. Pander (conodonts, agnathans, etc.), H. Asmuss (fishes), I. Nieszkowski (trilobites), W. Dybowski (rugose corals), F. Rosen, H. Nicholson (stromatoporoids), F. Schmidt (trilobites, brachiopods) and several others were published. In Quaternary geology, beside the abovenamed A. Schrenk and F. Schmidt (his first works dealt with the drift theory, and later on he made a great contribution to the glacial theory) one should point out G. Helmersen who studied erratic boulders, the structure and development of coasts and several other problems.

As a result, by the beginning of the 20th century an excellent stratigraphic scheme of the Estonian Lower Palaeozoic had been elaborated (Schmidt 1881) and the main types of Quaternary deposits established. This provided a basis for the compilation of the first geologic sketch maps.

The turn of the century was characterized by a certain slack in scientific activities. Another period of intensive studies began in the 1920s with the first generation of Estonian geologists settling down to work (H. Bekker, A. Luha, A. Öpik, K. Orviku et al.). The stratigraphy of Ordovician and Quaternary deposits underwent an improvement, a considerable number of palaeontological and the first lithological monographs appeared in print. Great attention was paid to the investigations of the mineral wealth of the republic. In the issue, in 1918 an open-cast mining of oil shale (kukersite) was started at Kohtla-Järve. By 1940 a production level of 1.9 million tons of shale annually had been attained. The first phosphorite mine went into operation in 1923 at Ülgase in the vicinity of Tallinn. In 1939 a mine at Maardu was put into use, as a result of which the production level reached 20 thousand tons of phosphorite annually.

After World War II scientific investigations rose to an entirely new level. If before this the leading role was played by the staff of Tartu University and foreign scientists, after there were several specific organizations established - the Institute of Geology of the Estonian Academy of Sciences in 1947 (now the Institute of Geology at Tallinn University of Technology), the Board of Geology of the Estonian SSR (= Geological Survey) in 1957; in addition, groups of engineering geology were founded at several designing institutes, which in 1979 were partly joined into the State Engineering Research Institute.

Regarding corals and stromatoporoids, D. Kaljo, E. Klaamann, H. Nestor and V. N. Riabinin made a history at that time.

Ordovician and Silurian stratigraphy

Ordovician and Silurian regional stratigraphical schemes and correlation with the global timescale are provided on Tables 1 and 2.

The Ordovician and Silurian sequence is relatively complete and represented mosly by carbonate rocks except for the Lower Ordovician which comprises siliciclastics. All global stages can be easily distinguished in Estonian succession and the regional units are often used as proxies for the entire Baltica Continent (Cooper and Sadler 2004, Melchin et al. 2004).

The Ordovician is devided into three regional series and 18 stages and Silurian into 10 stages in Estonia. For overview of particular stratigraphical units, and their rock and fossil content see Raukas and Teedumäe (1997) and references therein.

The regional stages are based on, and correlated using biostratigraphy and at some levels K-bentonites and stable isotope curves. Graptolites are rare for most part of the carbonate succession of Estonia and hence shelly faunas have been traditionally used as the main biostratigraphical tools. In recent decades, however, microfossils have turned most useful and detailed chitinozoan, conodont, and vertebrate biozonal schemes have been elaborated. These microfossil groups also enable correlation with the standard graptolite zonation and with the global timescale.

Table 1. Ordovician stratigraphy of Estonia. Modified after Nõlvak, 1997 and Nõlvak et al. 2007. Global Ordovician timescale according to Cooper and Sadler 2004.

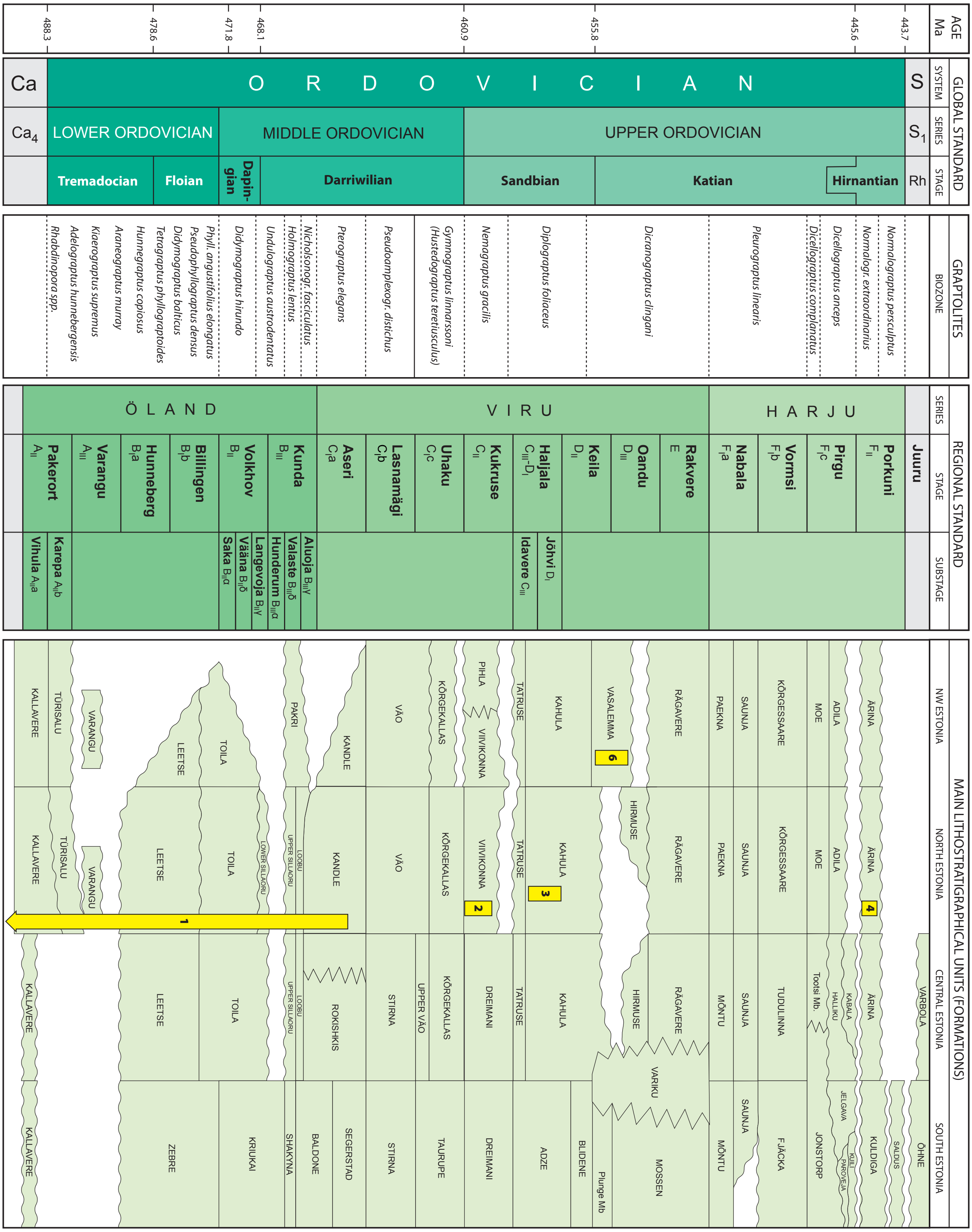
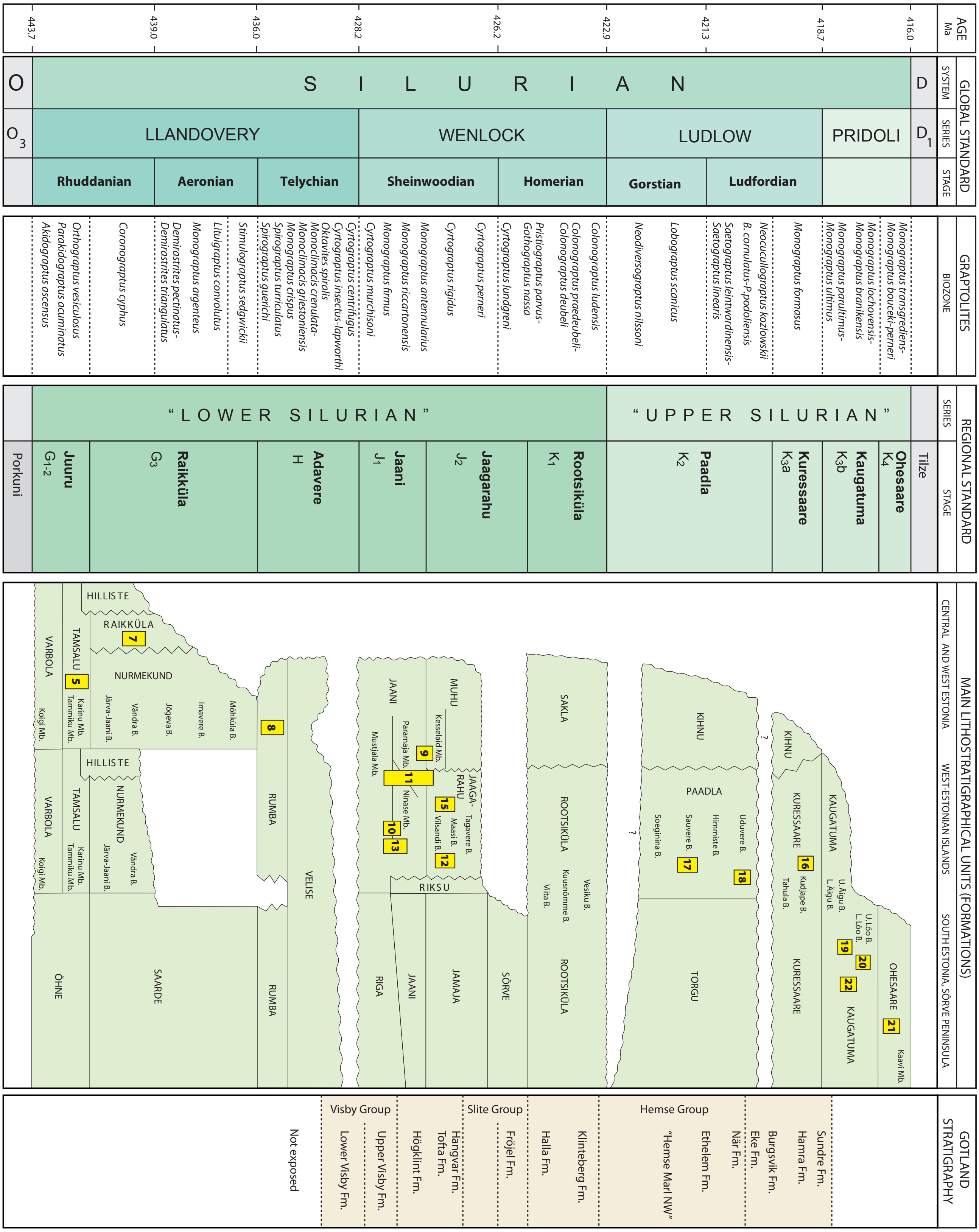


Table 2. SIlurian stratigraphy of Estonia. Modified after Nestor, 1997a and Nestor 2007 (Pers. comm). Global Silurian timescale according to Melchin et al. 2004.



Ordovician and Silurian carbonate sedimentation basin

During the Ordovician and Silurian from the Arenig to the end of the Pridoli and even at the very beginning of the Devonian (Lochkovian), Estonia was part of the northern flank of a shallow cratonic sea in which carbonate and fine-clastic sediments accumulated. In the earlier stages of development this sea extended from Norway to the Volga area, and from the Finnish to the Belarussian-Mazurian Pre-cambrian massif. During the final stages of development, the basin was restricted to the Baltic Syneclise in the East Baltic area and North Poland. The nuclear part of the basin in the Baltic area is treated here as the Palaeobaltic Basin.

Tectonical and facies settings

Two main structural elements of the Baltic Ordovician Basin (*s.s.*) were defined by Männil (1966): (1) the marginal or **Estonian-Lithuanian Confacies Belt**, (2) the central or **Swedish-Latvian Confacies Belt** (= Livonian Tongue). A transitional zone between the above-mentioned belts has also been distinguished. The first belt roughly corresponds to the southern slope of the Fennoscandian Shield and to the northwestern slope of the Belarussian-Mazurian Anteclise (Massif), the second belt — to the Baltic Syneclise. The marginal confacies belt was dominated by shallow-water carbonate sediments with a lot of discontinuity surfaces, while the relatively deeper-water central belt comprised predominantly clayey sediments. The present-day Estonia is situated mostly within the marginal confacies belt and transitional zone. Typical facies of the central belt reach only the southernmost part of Estonia. During the basin development, the limit of the main confacies belts gradually shifted southwestwards.

In the Early and Middle Ordovician, the western part of the East-European Platform as far as the Moscow Syneclise was slowly subsiding and covered by a shallow, epicontinental sea with a comparatively weak bathymetric differentiation and extremely slow sedimentation rate. At the end of the Ordovician, since the Late Caradoc and especially during the Silurian, the upheaval of the northwestern margin of the craton got dominance in connection with the closing of the Iapetus Ocean. At the same time, on the southwestern margin of the craton, belonging to the sphere of influence of the Palaeo-Tethys, the subsidence of the basin floor intensified. As a result of different tectonic movements, a comparatively deep, "starved" of sediments, intracratonic basin depression was formed within the limits of the central (axial) confacies belt in western Latvia, western Lithuania, the Kaliningrad

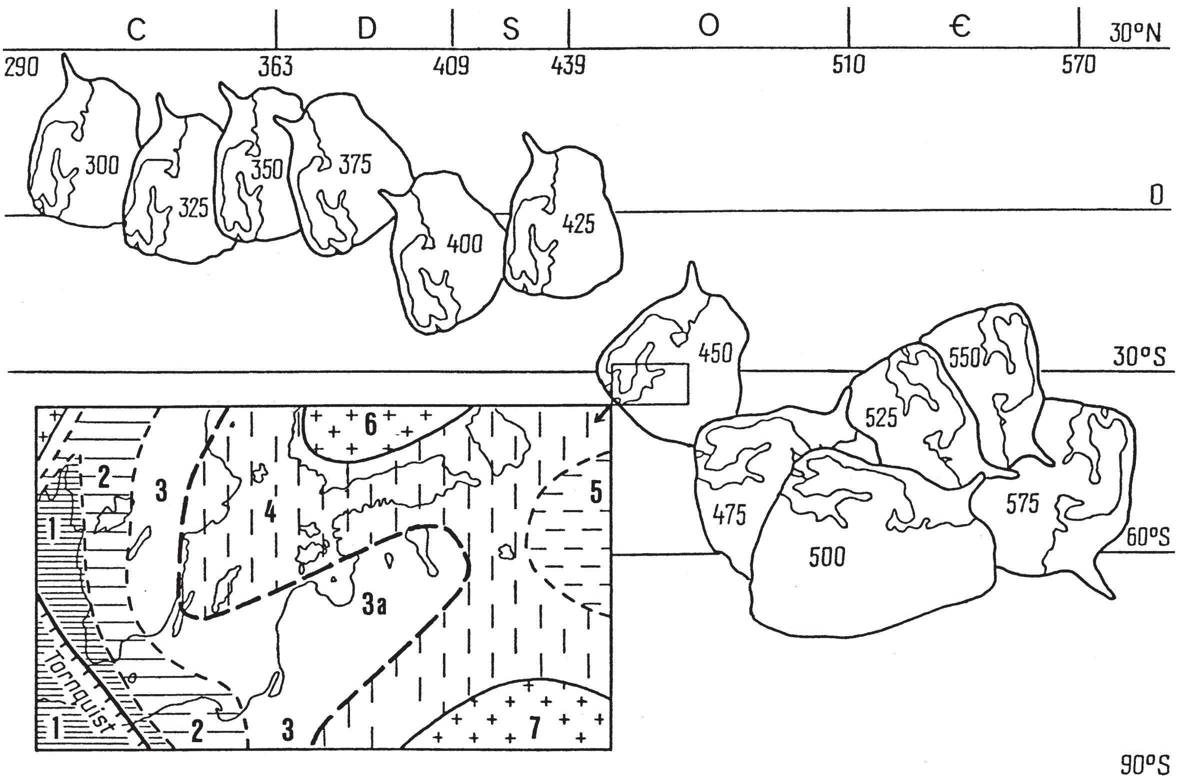


Fig. 2. The main structural elements of the Baltoscandian Ordovician and Silurian basin (from Nestor and Einasto 1997 after Männil 1966 and Jaanusson 1973a) and drift of the Baltica Continent during the Palaeozoic Era (after Torsvik et al. 1992): 1 - Skanian Confacies Belt; 2-3 - central or Swedish-Latvian Confacies Belt including Livonian Tongue or Baltic Syneclise (3a); 4 - marginal or Estonian-Lithuanian Confacies Belt; 5 - Moscow Syneclise; 6 - Fennoscandian Shield; 7 - Belarussian-Mazurian Anteclise (Massif).

District and northern Poland where hemipelagic argillaceous deposits accumulated. At the same time, the sea gradually retreated from the northwestern and central parts of the East-European Platform and the basin evolved from an epicontinental to a gulf-like pericontinental sea. During the Silurian, the influx of the fine-clastic material progressed from the Scandinavian Caledonides and it gradually infilled the starved depression.

During the Ordovician and Silurian, drastical climatic changes took place. The Baltica Craton drifted from the southern high latitudes to the tropical realm (see Scotese & McKerrow 1990, Torsvik *et al*. 1992, Fig. 2). It induced the growth of the sedimentation rate of carbonates and development of such types of deposits which are characteristic of the arid and tropical climate (*e.g.* sedimentary dolostones, pelletal and oolitic deposits, coral-stromatoporoid reefs). These characteristics were totally lacking during the Early and Middle Ordovician when the Baltic Basin was situated definitely in the temperate climate zone (Jaanusson 1973). The first signs of warm climate (appearance of tabulate corals, stromatoporoids and reefs) became evident in the Middle Caradoc (Oandu Age), but it was not until the very end of the Ordovician (Porkuni Age) that they got prevalence.

In a sedimentary basin, the facies distribution may be generalized by means of facies models presenting a lateral succession of facies along the reconstructed bathymetric profile. According to the facies model worked out by Nestor and Einasto (1977), five main facies belts can be differentiated in the Baltic Silurian Basin: tidal flat/lagoonal, shoal, open shelf, transitional (basin slope) and a basin depression (Fig. 3). The first three facies belts formed a carbonate shelf or carbonate platform and the latter two - a deeper pericratonic basin with fine-clastic deposits.

Later on, Einasto (Einasto 1986) elaborated two modifications of the basic Silurian facies model: one for the periods of weak and another for the periods of intense supply of terrigenous material. In the first case, the pure lime muds were widespread all over the open shelf and transitional belt; in the second case, argillaceous muds diluted carbonate sedimentation on the open shelf and periodically even in the shoal belt. It also became evident that the Silurian models are not applicable to the Early and Middle Ordovician which climatically and tectonically differed considerably from the Late Ordovician and Silurian. During the Early and Middle Ordovician, sediments accumulated under moderate climatic conditions. The main source of the carbonate component was skeletal material and its production was extremely slow. Therefore, the amount of loose skeletal material on the sea floor was limited. On the other hand, the effect of waves on the bottom was weak, because they subsided gradually in the shallow epeiric sea and lost their energy before reaching the shore. Due to these two circumstances, presumably there did not form notable accumulations of winnowed skeletal sands (grainstones) characteristic of the shoal belt of the basic Silurian facies model. Typical lagoonal carbonate sediments were also lacking, because evaporation was very weak. The position of the lagoonal and shoal facies belts was probably occupied by the belt of nondeposition, represented by a hardground (discontinuity surface). As mentioned above, in the Early and Middle Ordovician, a deeper, sediment-starved axial depression was not developed in the Baltic Basin, and the basin floor formed an evenly and weakly tilted ramp. Accordingly, only three facies belts: a nondepositional belt, an upper and a lower ramp were distinguished in the Early and Middle Ordovician facies models of the Baltic Basin (Nestor 1990b, Nestor and Einasto 1997 and references therein). In the development of the Baltic post-Tremadoc Ordovician and Silurian basin, five stages were differentiated (Fig. 4):

1. The transgression stage (Arenig – Llanvirn). In the marginal part of the basin the deposition was very slow and with many breaks. Within the limits of the upper ramp, micritic skeletal calcarenites accumulated, sometimes containing silt, scattered pebbles and abundant glauconite grains, goethite and francolite ooids and impregnated hardgrounds. On the lower ramp, coinciding with the central confacies belt, mainly red-coloured calcareous-argillaceous deposits (argillaceous limestones and marls) were formed. The deposits of the lower ramp were 2 to 10 times as thick as those in the coeval upper ramp.

2. The unification stage (Llandeilo – Early Caradoc). Along the whole extent of the bathymetric profile (ramp) grey calcareous - argillaceous sediments (argillaceous limestones and marls) accumulated although the general trend towards an increasing clay component and decreasing content of bioclasts in the offshore direction remained. Deposits of the upper ramp contained an admixture of light-brown kukersite kerogen and also pure kukersite interlayers. Interbeds of volcanic ash (K-bentonite) were also characteristic of that stage of the basin evolution.

3. The differentiation stage (Late Caradoc – Middle Llandovery). A deeper axial depression of the basin was formed and facies zonation, typical of the Silurian, developed. The supply of the basin with clastic material was periodically extremely low, and comparatively pure calcareous muds were deposited during those periods on the open shelf and in the transitional belt, while condensed dark graptolitic shales formed in the basin depression. Also an agitated-water shoal belt with pelletal and skeletal sands and a

Main geomorphic units	Shelf (Carbonate platform)			Deeper basin	
Type of sedimentation	Carbonate			Fine - terrigenous	
Facies belts	I Tidal flat/lagoon	II Shoal	III Open shelf	IV Transition	V Depression
Lithogenetic types of sediments	Dolomicrites	Sparitic calcarenites	Micritic calcarenites	Calcareous mudstones	Mudstones
Hydrodynamic zones	Near-shore quiet-water	Agitated-water (high-energy, turbulent)	Quiet-water to storm-agitated (subturbulent)	Calm-water	Stagnant-water
Depositional environments	Tidal (mud) - flats, lagoons, restricted shelf	shoals, reef belts, banks	Open shelf (platform)	Basin slope, shelf/basin transition	Basin depression
Characteristic rocks	Argillaceous dolomites and dolomerites (massive, laminated, bioturbated); dolomitic limestones, bioturbated marls	Skeletal, oolitic oncolitic pelletal grainstones, coquinoid bio- and lithoclastic rudstones, boundstones	Nodular skeletal pack- and wackstones; skeletal calcareous marls; micritic limestones	Argillaceous marls; calcareous mudstones, argillaceous micritic limestones	Mudstones, argillites, clays
Characteristic fossils	Burrows Stromatolites Eurypterids Agnathans Leperditids Scolecodonts Gastropods Lingulids	Stromatoporoids Corals Pelmatozoans Calcareous algae Oncolites Brachiopods Conodonts Vertebrates Bryozoans Bivalves	Brachiopods Pelmatozoans Ostracodes Burrows Corals Stromatoporoids Bryozoans Chitinozoans Conodonts Molluscs	Trilobites Pelmatozoans Burrows Chitinozoans Ostracodes Brachiopods Molluscs Conodonts Graptolites	Graptolites Chitinozoans Cephalopods Burrows Lingulids

Fig. 3. Facies belts and environments in the East Baltic Silurian Basin (Nestor and Einasto 1997).

lagoonal belt with dolomicritic deposits (dolomitic marls, argillaceous dolomites) developed. During this stage, the periods of low terrigenous mud influx cyclically alternated with the phases of more intensive supply with the fine clastic material. In the latter case, deposition followed the basic Silurian facies model characteristic of the stage of stabilization of the basin development.

4. The stabilization stage (Late Llandovery – Early Ludlow). Moderate influx of the fine-clastic material, which partly deposited in the lagoonal and open shelf belts but mostly in the transition belt, resulting in side-filling of the "starved" depression with deposit wedges (lenses) and gradual progradation of the carbonate shelf margin was characteristic of this stage. Facies zonation was clear and the basic Silurian facies model (Figs 3, 4d) reflects the situation during that stage of evolution. However, the facies belts were not equally developed during the different phases of the basin development. The deeper-water facies were widespread during the transgressive phases (the end of the Llandovery and the beginning of the Wenlock), while shallow, marginal-marine facies were best developed during the regressive phases (the end of the Wenlock and the beginning of the Ludlow) of the basin development.

5. The infilling stage (Late Ludlow – Pridoli). Intense influx of terrigenous material filled the basin depression and also diluted carbonate sedimentation on the open shelf where bioclastic limestones were replaced by bioclastic marls. Even in the shoal belt skeletal sands interlayered with marls.

Generally, certain facies models were typical only of certain stages of basin evolution, however, in some cases different types of sedimentation could also alternate. For example, during the Late Caradoc to the Middle Landovery, the periods of low and moderate supply with terrigenous clastic material alternated cyclically and sedimentation followed the models charcateristic of the differentiation and stabilization stages, respectively.

In the following, the evolution history of the basin will be presented with an emphasis on the situation in Estonia. A distinct cyclicity in the basin evolution was summarized by Einasto (1995) and is figured in the present work (Fig. 5). Nine high-rank macrocycles of eustatic origin have been established in the evolution of the Baltic Ordovician and Silurian Basin. They are

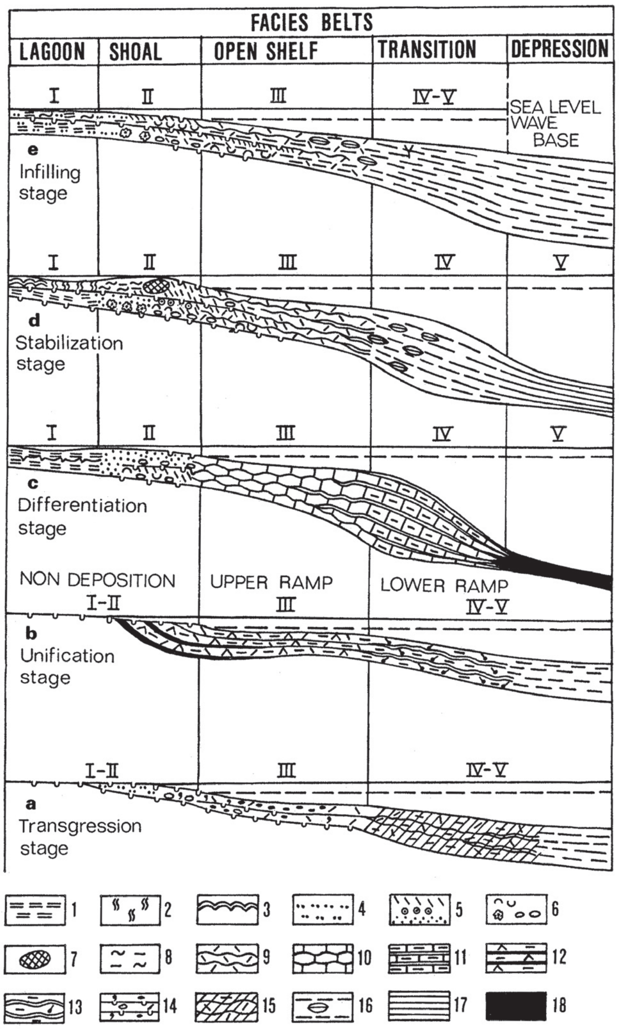


Fig. 4. Facies models for different stages of development of the post-Tremadoc Ordovician and Silurian Palaeobaltic Basin. Rock types: 1 - laminated argillaceous dolomites; 2 - bioturbated argillaceous dolomites; 3 - stratiform stromatolites; 4 - terrigenous silt- and sandstones; 5 - skeletal, oolitic and pelletal grainstones; 6 - coquinoid, oolitic and oncolitic rud- and floatstones; 7 - bioherms, carbonate mounds; 8 - bioturbated clayey wackestones; 9 - nodular biomicritic limestones (skeletal pack- and wackestones); 10 - wave-bedded micritic limestones; 11 - interbedded clayey micritic limestones and kerogenous graptolitic mudstones; 12 - biomicritic limestones with kukersite interlayers; 13 - interbedded argillaceous limestones and marls; 14 - limestones with glauconite, ferruginous ooids, lithoclasts and hardgrounds; 15 - purple argillaceous limestones; 16 - marlstones with limestone nodules; 17 - grey graptolitic mudstones; 18 - dark-brown kerogenous graptolitic shales (Nestor and Einasto 1997).

separated from each other by subregional sedimentation breaks of different duration, increasing in onshore direction. Lower-rank, meso- and microcycles have also been distinguished which, besides the fluctuation of the sea level, were also induced by climatic cyclicity and pulsatory supply with terrigenous material. A meridional cross section of the Ordovician and Silurian rocks across Hiiumaa and Saaremaa islands and the Kuramaa Peninsula (Fig. 6) shows spatial and temporal relations of the main facies commented in the text below.

The basin development stages from the unification (starting from Early – Middle Caradoc substage) to infilling stage are considered here, because the first corals in Estonia appeared in Caradoc.

Unification stage of development

This stage in the basin development covered the Llandeilo and Early Caradoc interval from the Uhaku to Keila ages. It was a period of relative tectonic and eustatic stillstand on the East-European Platform which terminated the general transgressive phase in the development of the Ordovician basin. The most characteristic features of the stage were remarkable intensification of the influx of fine terrigenous material, prevailingly from the northeast, and considerable equilization of environmental conditions in the marginal and central parts of the Baltic Basin (s.s.). All over the Baltic area mainly bioclastic argillaceous-calcareous muds accumulated. Besides lateral variation in the ratio of argillaceous and calcareous components, also a distinct lower rank cyclicity, expressed in alternation of more and less argillaceous deposits, was apparent. The latter reflects the pulsatory supply of the basin with fine terrigenous material rather than the sea-level fluctuation.

Characteristic of the earlier part of the unification stage (**Uhaku** and **Kukruse** ages) was accumulation of light-brown organic matter - kukersine which formed kukersite interlayers and dispersed admixture in calcareous sediments. During the second half of the unification stage (**Haljala** and **Keila** ages), numerous volcanic ash (metabentonite) intercalations formed giving evidence of growing volcanic activity in the adjacent Iapetus Ocean, perhaps connected with its transition from the opening phase to the closing state. It is remarkable that the same phenomenon, *i.e.* the presence of numerous bentonite interlayers, is also characteristic of the highly argillaceous Late Llandovery and Early Wenlock sediments which formed during the Silurian transgression maximum.

First corals *Primitophyllum primum* Kaljo and *Lambelasma dybowskii* (Kaljo) appeared in Haljala Stage (The Early - Middle Caradoc substage).

The **Early - Middle Caradoc substage** of development (Haljala and Keila ages) was a complete eustatic macrocycle with a short transgressive phase at the beginning, longer stillstand period in the middle and drastical shallowing and regression at the end. It began in northern Estonia with the deposition of a thin basal layer of calcareous silt (Kisuvere Member of the Kahula Formation). The silt probably derived from the **Kärdla impact crater** (Nestor and Einasto 1997 and references therein) and was transported eastwards by longshore drift. The macrocycle in consideration is characterised by the occurrence of the most argillaceous sediments in the whole Ordovician sequence and by the presence of numerous bentonite interlayers. Only at the beginning (Tatruse Formation) and at the end of the macrocycle (Pääsküla and Saue members of the Kahula Formation), purer bioclastic calcareous sediments occurred in northern Estonia, in the marginal confacies belt. During the middle part of the macrocycle, bioclastic calcareous-argillaceous muds accumulated in the marginal confacies belt, while in the central belt highly argillaceous bioclastic muds (Adze Formation) deposited.

The macrocycle and the whole unification stage ended with remarkable shallowing and regression. In northwestern Estonia, in the Vasalemma area at late Keila and early Oandu times, a reef complex with bryozoan-microbial carbonate mounds and intermound pelmatozoan grainstones was formed in

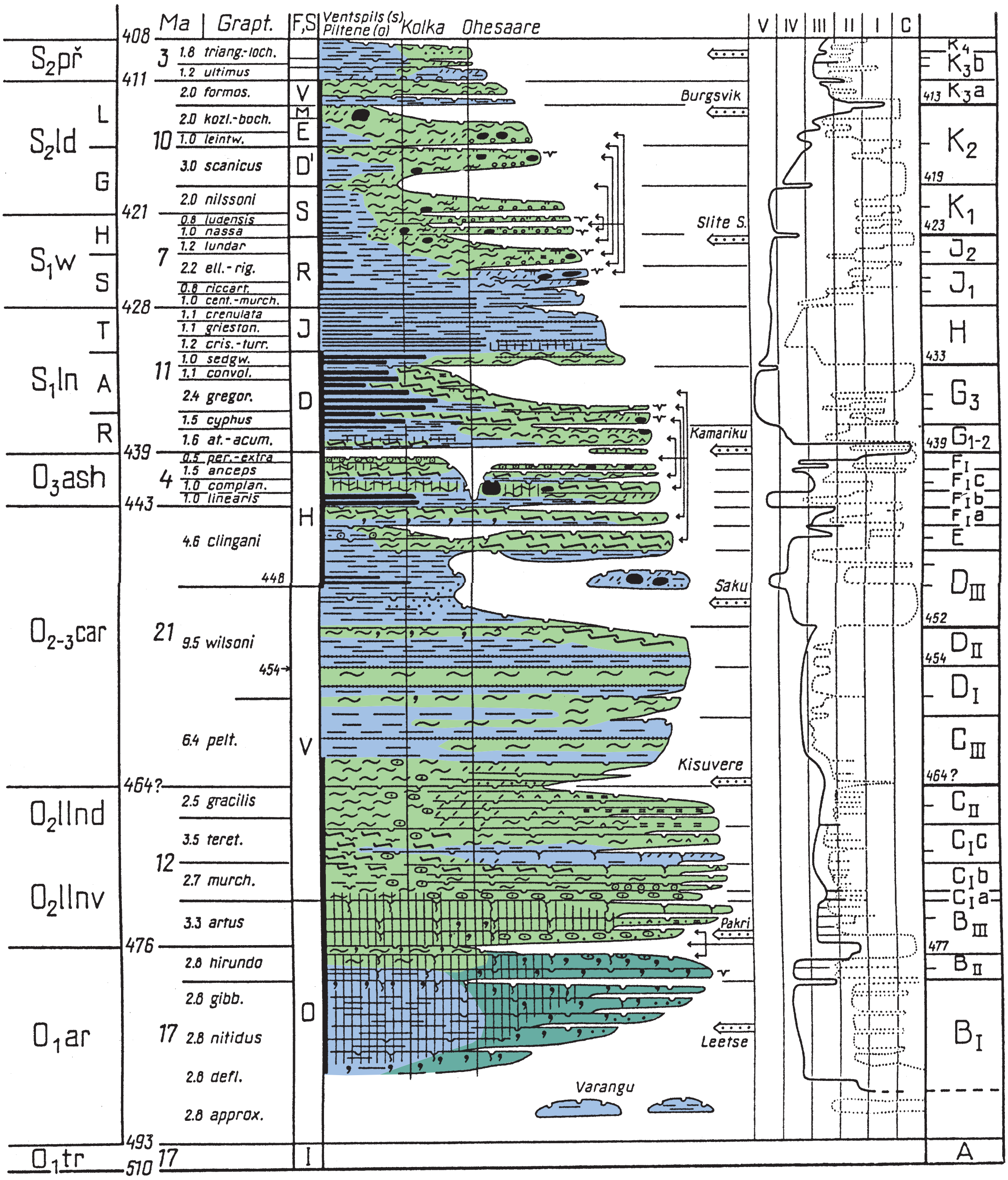


Fig. 5. A generalized sequence of the Ordovician and Silurian rocks in Estonia (by Einasto 1995) shown in time-scale (after Harland et al. 1990 a.o.) with eight higher rank stratigraphical breaks, separating nine eustatic macrocycles of basin development. On the right, two sea-level curves are shown - a dotted line for the marginal and a solid line for the central confacies belts. Facies belts: I - lagoonal, II - shoal, III - open shelf, IV - transitional, V - depression. For lithofacies legend see Fig. 6. Stratigraphical indices: Regional Series: I - Iru, O - Ontika, V - Viru, H - Harju; Silurian Formations: D - Dobele, J - Jurmala, R - Rìga, S - Siesartis, D - Dubysa, E - Engure, M - Mituva, V - Ventspils; Silurian Standard Stages: R - Rhuddanian, A - Aeronian, T - Telychian, S - Sheinwoodian, H - Homerian, G - Gorstian, L - Ludfordian; Baltic Regional Stages: BI - Latorp, BII -Volkhov, BIII - Kunda, Cia - Aseri, Cib - Lasnamägi, Cic - Uhaku, CII - Kukruse, CIII - Idavere, DI - Jõhvi, DII - Keila, DIII - Oandu, E - Rakvere, Fia - Nabala, FIb - Vormsi, Fic - Pirgu, FII - Porkuni, G1-2 - Juuru, G3 - Raikküla, H - Adavere, J1 - Jaani, J2 - Jaagarahu, K1 - Rootsiküla, K2 - Paadla, K3a - Kuressaare, K3b - Kaugatuma, K4 – Ohesaare.

the shallow-water high-energy environment. Elsewhere in northern and central Estonia, a probable hiatus existed between the Keila and Oandu stages. At the same time, highly argillaceous muds of the Blidene Formation (marls and mudstones) formed in the axial part of the Livonian Tongue (Fig. 7). In the wide transitional zone, they were replaced by slightly more calcareous muds which in their most peripheral part in southwestern Estonia, easternmost Latvia and Lithuania contain fine siliciclastic material (Nestor and Einasto 1997 and references therein). The latter deposited at the time of regression maximum when the sea supposedly withdrew from the whole upper ramp area, including northern Estonia.

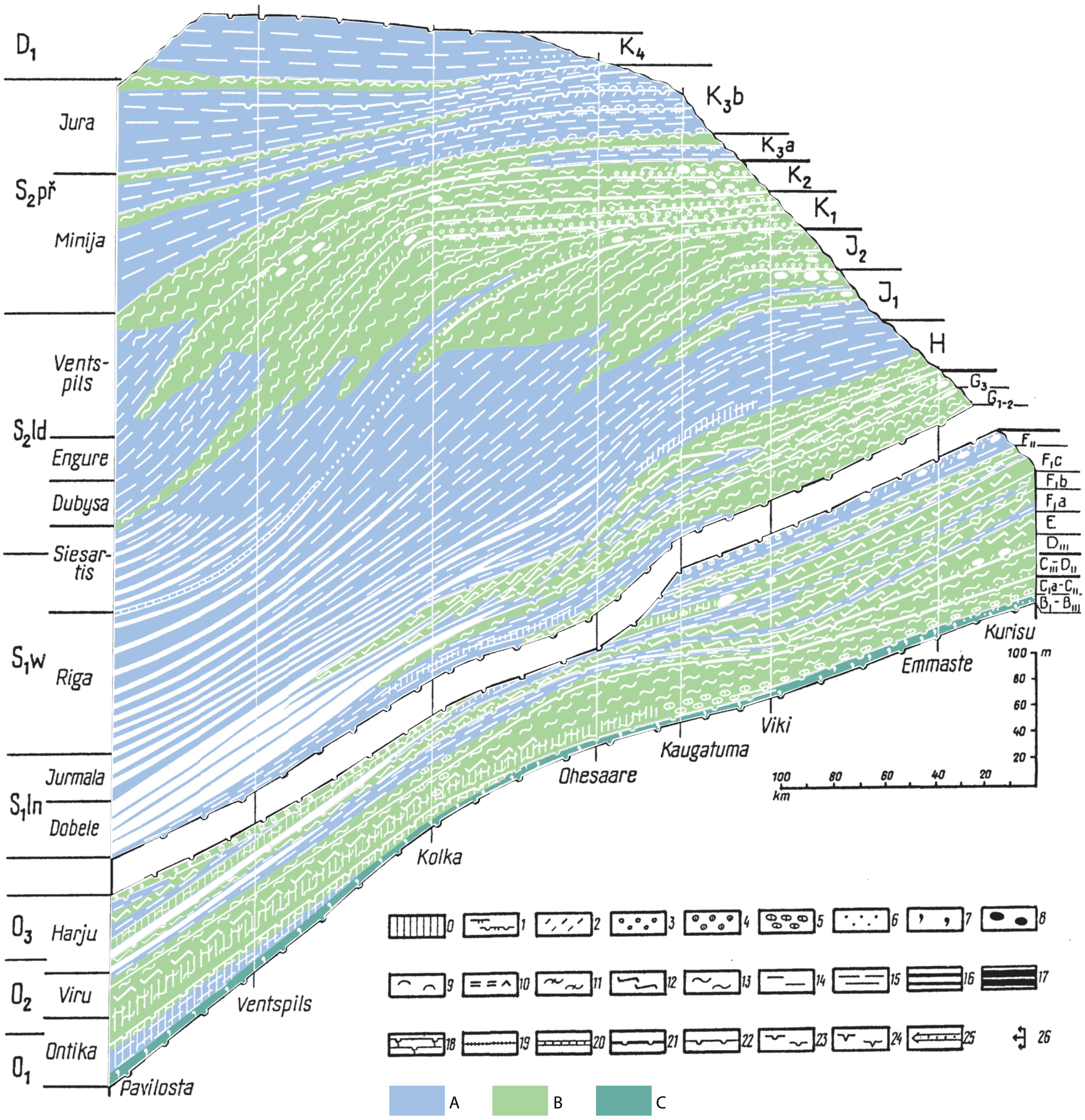


Fig. 6. A meridional cross section throughout the Ordovician and Silurian lithofacies in Hiiumaa and Saaremaa islands and the Kurzeme Peninsula by Einasto (1995), showing drastical differences in thicknesses and sedimentation rates between the Ordovician and Silurian. Lithological legend: 0 - marine redbeds; 1 - lagoonal dolomitic mud; 2 - skeletal sand; 3 - oncolitic and coquinoid gravel; 4 - calcareous ooids; 5 - ferrugenous ooids in calcareous matrix; 6 - terrigenous silt and sand; 7 - glauconitic deposits; 8 - bioherms and carbonate mounds; 9 - brachiopod and bivalve coquina; 10 - kukersine interlayers; 11 - argillaceous-calcareous muds of restricted shelf; 12 - pure lime muds of restricted and open shelf; 13 - bioclastic calcareous muds of open shelf; 14 - argillaceous-calcareous muds at shelf margin; 15 - calcareous-argillaceous muds of transitional belt; 16 - grey graptolitic muds; 17 - dark kerogenous graptolitic muds; 18 - numerous hardgrounds; 19 - metabentonites; 20 - laminated calcareous-argillaceous muds of basin depression; 21 - erosional surfaces and disconformities; 22 - significant discontinuities; 23 - brokened hardgrounds; 24 - mud-cracks, 25 - levels of silt and sand influx; 26 - symmetrical facies successions. A – muds with high content of clay, B – muds with high content of lime, C – clauconitic deposits. Explanation of stratigraphical indices see Fig. 5, (Nestor and Einasto 1997).

Differentiation stage of development

This stage of evolution corresponds to the Late Ordovician and earliest Silurian covering the time interval from the Oandu Age up to the end of the Raikküla Age. The beginning of the evolution stage roughly coincided with the general tectonic inversion in the western part of the East-European Platform, *i.e.* transition from the transgressive to regressive phase in basin development. On the other hand, it also reflected transition from humid, moderate climatic conditions to arid subtropical-tropical climatic conditions. Evidence is derived from the appearance of the first corals and stromatoporoids, beginning of the formation of organic build-ups, pelletal, aragonitic sediments, extensive accumulation of pure lime muds, *etc*.

The most characteristic features of this evolution stage included: 1) development of considerable lateral lithological differentiation of sediments, 2) rapid increase in the sedimentation rate and thickness of deposits, 3) formation of condensed deposits of dark kerogenous muds (shales) in the central confacies belt of the basin, cyclically interbedded with thicker deposits of greenish-grey to purple muds (mudstones and marls), 4) cyclical alternation of deposits of pure lime muds (micritic limestones) with bodies of argillaceous lime muds (marls, argillaceous limestones) in the marginal part of the basin and transitional zone. The former three peculiarities were probably connected with transformation of the western margin of the Baltica Continent from passive to active state due to the beginning of the gradual closure of the Iapetus Ocean. It caused different tectonic movements in the Baltic Syneclise and its surroundings; as a result, deeper intracratonic depression began to form within its limits. A possible reason for cyclical alternation of the deposition of pure and argillaceous lime muds may be an interchange of the arid and humid climate periods characteristic of the big glacial epochs in the Earth history, including the Late Ordovician - Early Silurian glacial epoch. The arid periods caused a relatively low influx of terrigenous material and, consequently, deposition of purer lime muds, while during the humid periods more argillaceous muds were deposited.

In the evolution of the Baltic Basin, the cyclically alternating periods of low and high influx of terrigenous material are well recognizable. During the low influx ("limy") phases rather pure, light lime muds (micritic or calcilutitic limestones) deposited on the open shelf and in the transitional facies belt (see Fig. 4c). During the high influx ("clayey") phases, on the open shelf bioclastic argillaceous-calcareous muds (nodular argillaceous biomicritic limestones) were deposited, while in the transitional belt prevailingly terrigenous muds (marlstones, mudstones) accumulated (Fig. 4d). Nine of such cycles of alternating low- and high-influx phases have been recognized in the development of the Baltic Basin during Late Ordovician - earliest Silurian times.

The low-influx ("limy") phases were: 1) Rakvere (Rägavere Formation), 2) late Nabala (Saunja Formation), 3) early Pirgu (Moe and Svėdasai formations), 4) mid-Pirgu (Oostriku, Baltinava, Parovėja formations), ?5) latest Pirgu (Taučionys Formation), 6) early Juuru (Koigi, Ruja, Sturi members), 7) early Raikküla (Järva-Jaani beds, Slītere Member), 8) mid-Raikküla (Jõgeva beds, Ikla Member), 9) late Raikküla (Mõhküla beds, Staicele Member).

The high-influx ("clayey") phases were correspondingly: 1) Oandu (Hirmuse, Lukštai formations), 2) early Nabala (Saunja, Mõntu formations), 3) Vormsi (Kõrgessaare, Tudulinna, Meilūnai formations), 4) early-mid Pirgu (Adila, Halliku, Ukmerge formations), 5) mid-late Pirgu (Ludza, Kuiļi formations), 6) Porkuni (Ärina, Kuldiga, Saldus formations), 7) middle and late Juuru (Varbola, Tamsalu formations, Rozeni Member), 8) early-mid Raikküla (Vändra beds, Kolka Member), 9) mid-late Raikküla (Jõgeva

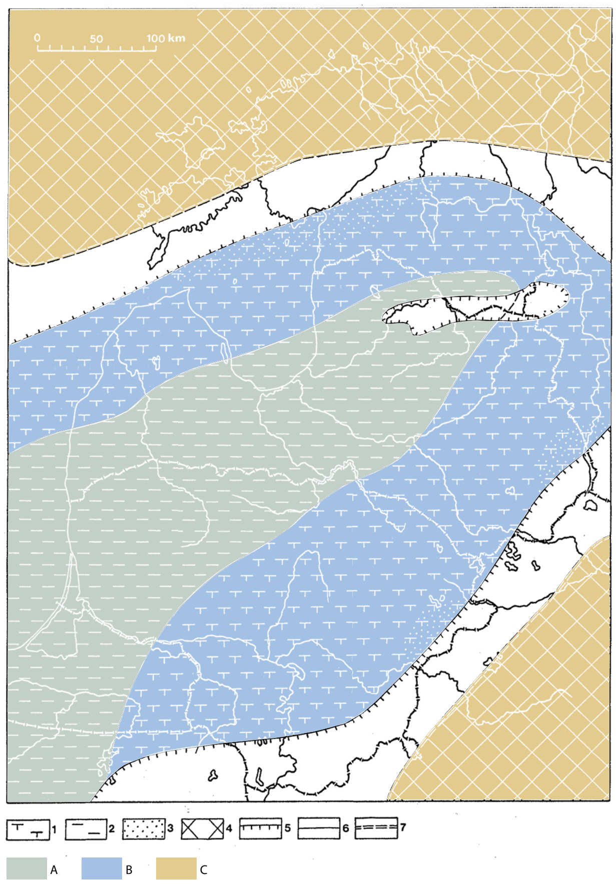


Fig. 7. Distribution of the late Middle Ordovician late Keila (top Pääsküla) sediments and facies belts in the Baltic Basin: 1 - calcareous-argillaceous mud; 2 - terrigenous mud; 3 - admixture of silt; 4 - presumable land; 5 - boundary of the present extention of rocks; 6 - facies boundaries; 7 - shoreline. A- terrigenous mud, B - calcareous-argillaceous mud, C - presumable land (Nestor and Einasto 1997).

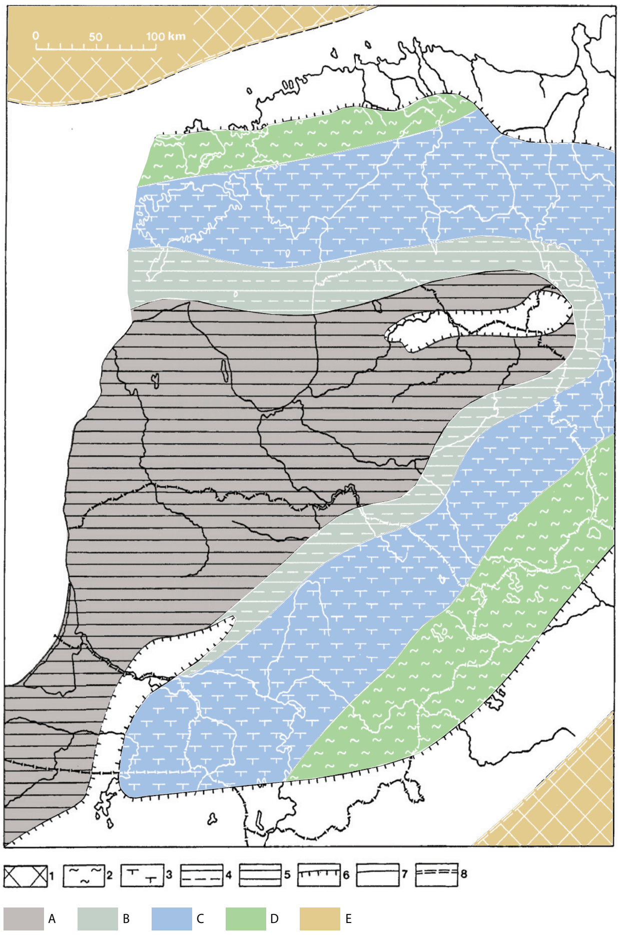


Fig. 8. Distribution of the Late Ordovician Vormsi Age sediments and facies belts: 1 - presumable land; 2 - bioclastic calcareous mud; 3 - calcareous-argillaceous mud; 4 -grey terrigenous mud; 5 - dark kerogenous argillaceous mud with graptolites; 6 - boundary of the present extension of rocks; 7 - facies boundaries; 8 - shoreline. A - kerogenous argillaceous mud with graptolites, B - grey terrigenous mud, C - calcareous-argillaceous mud, D - bioclastic calcareous mud, E - presumable land (Nestor and Einasto 1997).

beds, u. pt., Lemme Member).

In most cases, the distribution of the pure lime muds was restricted to the open shelf and transitional facies belt (see Fig. 4c). Basinwards the lime muds were replaced by dark brown kerogenous graptolitic muds (Mossen Formation of the Rakvere Stage, Dobele Formation of the Raikküla Stage) or by purple calcareous-argillaceous muds (Jonstorp Formation of the Pirgu Stage, Remte Formation of the Raikküla Stage). However, in some cases light lime muds covered also extensive areas in the central part of the basin (Saunja Formation of the Nabala Stage, Parovėja Formation of the Pirgu Stage, Stūri Member of the Juuru Stage); more deeper-water deposits are not represented in the Baltic area. Lateral transition of the open shelf lime muds into the deposits of the nearshore agitated-water shoal belt has been established only in the Raikküla Age (Fig. 7). In this case, they were gradually replaced by fine-grained skeletal-pelletal deposits, in places containing numerous corals and stromatoporoids.

The deposition of the pure lime muds probably proceeded under somewhat specific hydrochemical conditions. The deposits of the micritic limestones (calcilutites) contain extremely sparse organic remains. Most frequently, the Late Ordovician micritic limestones comprise skeleton particles of specific dasycladacean algae *Cyclocrinites*, *Vermiporella, etc*. The micritic limestones of the Raikküla Stage often contain detritus of problematic dendroid graptolites. The presence of such specific biotic elements suggests that a certain generative role of the biochemical factor in the formation of pure lime muds is not excluded. The micritic limestones of the Pirgu Stage, especially those of the Moe Formation, are richest in skeleton particles of *Vermiporella* and other dasycladaceans. The latter and the adjacent Tootsi Formation also contain specific carbonate mounds (Hoitberg, Niiby, Ruunavere, Kaugatuma, Paatsalu, Võhma) which are analogous to the well-known Boda mounds in Central Sweden (see Nestor 1995).

The differentiation stage of the basin development consisted of two similar bathymetric macrocycles, one corresponding to the Late Caradoc - Ashgill from the Oandu to the Porkuni stages, and another to the Early-Middle Llandovery from the Juuru to the Raikküla stages. These macrocycles began with a slow, gradual deepening of the basin and finished with a rapid shallowing, regression and, in places, with intensive erosion of the older deposits.

The **Late Caradoc-Ashgill macrocycle** began with a short transgressive episode in the Oandu Age when for the first time in the post-Tremadoc history of the basin development typical anoxic depression facies - dark-brown kerogenous graptolitic muds (Mossen Formation) were formed in the Baltic Syneclise. At the slope of the Belarussian-Mazurian Anteclise the Oandu deposits transgressively overlap the older strata and in northern Estonia they also disconformably overlie the Keila deposits.

After a rapid initial deepening during the Oandu Age, there followed a relative stabilization and levelling of sedimentation conditions culminating during late Nabala time when monotonous pure lime muds (Saunja Formation) expanded over the whole East Baltic area. A new deepening impulse and bathymetric differentiation followed in the Vormsi Age when deposition of dark kerogenous muds with graptolites (Fjäcka Formation) was restored in the central depression of the Baltic Syneclise (Fig. 8).

The Pirgu Age was a variable period in the basin evolution with two distinct episodes of accumulation of pure lime muds. A general regressive trend of basin development is recognizable in the Pirgu Age. During the first, early Pirgu phase of deposition of lime muds (Moe Formation) purple terrigenous muds (Jonstorp

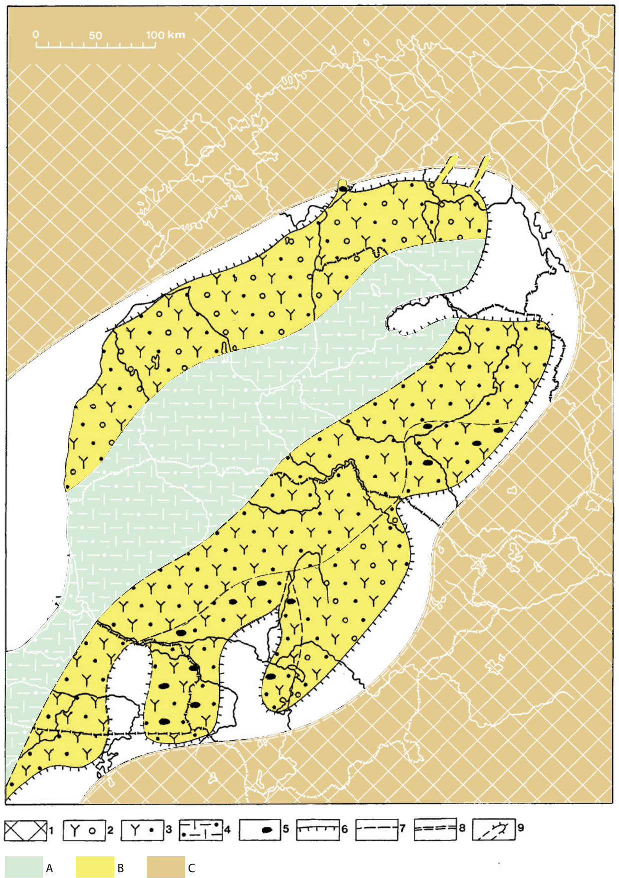


Fig. 9. Distribution of the end-Ordovician late Porkuni (Saldus Formation) sediments and facies belts: 1 - presumable land; 2 - calcareous sand with oolites; 3 - calcareous sand with siliciclastic admixture; 4 - microlayered silty calcareous and terrigenous muds; 5 - conglomerate; 6 - boundary of the present extension of rocks; 7 - boundaries of sediment types; 8 - shoreline; 9 - erosion channel. A - silty calcareous and terrigenous mud, B - calcareous sand, C - presumable land (Nestor and Einasto 1997).

Formation) were deposited in the central confacies belt, while during the second, mid-Pirgu phase of lime mud deposition (Oostriku, Baltinava, Parovėja formations), monotonous pure lime muds spread all over the Baltic Basin. The Pirgu Age ended with an obvious sedimentation break of different duration in different places. Extensive local sedimentation gaps with considerable erosion of lower-lying strata have been established in the areas of the Lower Nemunas and Irbe structural elevations (see Männil 1966, Kaljo *et al*. 1988). In these and some other places, the Porkuni rocks rest disconformably on the Pirgu strata showing that the Porkuni Age began with a certain transgression event. During the first half of the Porkuni Age a diverse complex of shallow, agitated-water carbonate sediments (skeletal sand and silt, coral-stromatoporoid bioherms, bioclastic calcareous muds of the Ärina Formation) formed in the marginal confacies belt. In the central belt bioclastic calcareous-argillaceous muds (Kuldiga Formation) deposited at the same time. An abrupt shallowing took place in the middle of the Porkuni Age and deposition of shallow-water calcarenitic sediments (bioclastic, oolitic, lithoclastic sand, silt and gravel) with remarkable admixture of siliciclastic silt and sand shifted into the central confacies belt, forming high-energy shoal deposits of the Salduse Formation (Fig. 9). In the peripheral part of the Baltic Basin, including northern Estonia, subaerial conditions existed at that time. In the mid-Estonian transitional zone some 15-to-30-m-deep erosion channels (Tootsi, Jõgeva, Ruskavere) were recently discovered (Nestor and Einasto 1997 and references therein). The end-Ordovician drastical shallowing event (or events) in the Baltic Basin was definitely connected with the global glacio-eustatic drop of the ocean level (Nestor and Einasto 1997 and references therein), perhaps combined with certain tectonical upheaval, especially at the end of the Pirgu Age.

The **Early-Middle Llandovery macrocycle** began with a glacio-eustatic rise of the sea level and deposition of pure lime muds (Stūri, Rūja, Koigi members) on wide areas of central and eastern East Baltic. Only in the deepest-water residual depression (South Estonia - Kurzeme) the lime muds were replaced by calcareous-argillaceous muds (Õhne Formation). During the Juuru Age, a bathymetric differentiation and development of regular facies zonation, interrupted by the end-Ordovician hiatus, denudation and levelling of the sea floor topography, were gradually restored, but it was not until mid-Raikküla time (Ikla/Jõgeva beds) that a deep-water central depression with dark kerogenous graptolitic muds was finally restored and since then, until middle Ludlow time, it functioned as a sediment-starved depression where deposition rate could not keep pace with the subsidence of the sea floor. A full set of five main facies belts (Fig. 3) was completely established and a shelf-type sedimentation finally replaced the ramp-type sedimentation which prevailed during most of the Ordovician. The most characteristic feature of the shelf-type sedimentation was formation of thick deposit wedges in the transitional facies belt which led to the side-filling of the basin depression and gradual progradation of the carbonate shelf edge. A gradual side-filling effect is well visible in the cross-section of the Llandovery rocks in western Estonia (Fig. 6).

The Early-Middle Llandovery macrocycle ended with extensive local sedimentation breaks and denudation of earlier deposited strata in the marginal parts of the basin. One area of denudation was situated in western Estonia where the north-westwards increasing erosional hiatus cut the older strata down to the Järva-Jaani beds. Still more remarkable erosional break was developed on the opposite flank of the Baltic Basin, in eastern Lithuania, where the Early and Middle Llandovery deposits were subject to denudation all over the carbonate shelf as far as the eastern

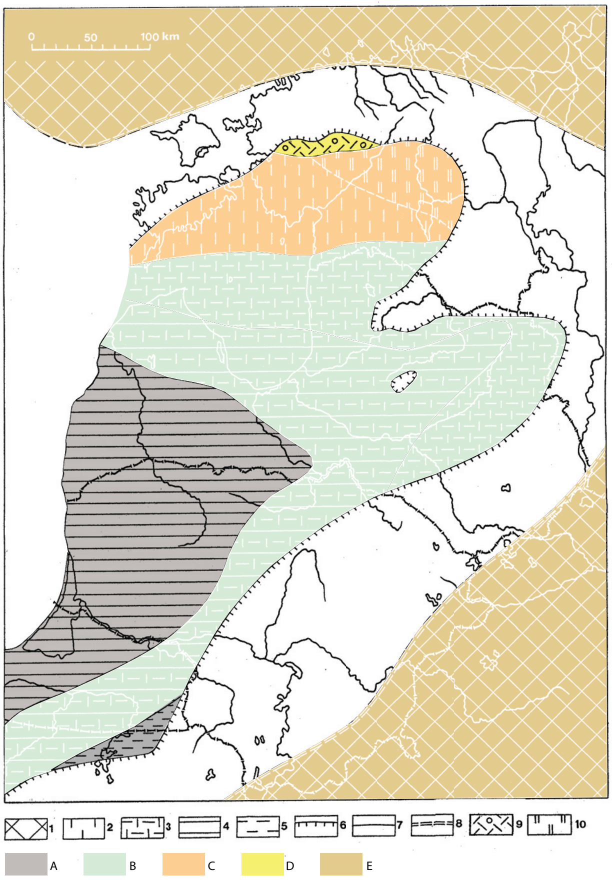


Fig. 10. Distribution of the Llandovery mid-Raikküla (Ikla Member) sediments and facies belts: 1 - land; 2 - pure lime mud; 3 - interbedded lime mud and dark kerogenous mud with graptolites; 4 - dark kerogenous graptolitic mud; 5 - grey graptolitic mud; 6 - boundary of the present extension of rocks; 7 - facies boundaries; 8 - shoreline; 9 - pelletal-skeletal sand and silt; 10 - dolomitized lime mud. A - kerogenous argillaceous mud with graptolites, B - interbedded lime mud and dark kerogenous mud with graptolites, C - pure lime mud and dolomitized lime mud, D - pelletal-skeletal sand and silt, E - presumable land (Nestor and Einasto 1997).

limit of the Baltic Syneclise with depression facies of dark graptolitic shales of the Dobele Formation (Fig. 10). The local (subregional) character of the nondeposition and changeable extent of deposition breaks suggest the tectonic nature of the upheaval, most probably induced by the beginning of the collision of the Laurentia and Baltica continents.

Stabilization stage of development

The stabilization stage of basin evolution embraced the main part of the history of the Baltic Silurian Basin from the beginning of the Late Llandovery (beginning of the Adavere Age) up to the end of the Middle Ludlow (end of the Paadla Age). The most characteristic features of the stabilization stage of evolution were: 1) a moderate influx of the fine terrigenous material, 2) the presence of a comparatively deep, starved axial basin depression with continuous sedimentation of dark-grey argillaceous deposits (mudstones and shales) with graptolites, 3) a perfect shelf-type facies zonation beginning from marginal-marine, lagoonal dolomitic muds and ending with dark -grey graptolitic muds in the depression belt (see Figs 3, 4d). At the beginning of the stabilization stage, during the transgressive phase of the basin development, deeper-water facies had a wide distribution. During the regressive phase, in the second half of the stabilization stage, shallow near-shore facies were well developed.

In the marginal part of the basin, a general regressive trend of evolution was characteristic to the stabilization stage and it led to the transformation of the Baltic Basin into a gulf-like pericontinental sea. On the background of the general shallowing trend, smaller-scale sea level fluctuations were characteristic of the basin evolution. The stabilization stage may be subdivided into two eustatic macrocycles of unequal duration and completeness. The first, perfect deepening-shallowing macrocycle corresponds to the Late Llandovery - Middle Wenlock (Adavere to Jaagarahu ages) and the second, uncomplete one to the Late Wenlock and Early Ludlow (Rootsiküla and Paadla ages).

The **Late Llandovery - Middle Wenlock macrocycle** began in the Baltic Basin with a rather long transgressive (deepening) phase, lasting from the beginning of the Adavere Age up to the mid-Jaani time. The transgression proceeded in two steps (Nestor and Einasto 1997 and references therein). It began with an extensive deposition of bioclastic argillaceous-calcareous muds with coquinite accumulations of the brachiopod *Pentamerus oblongus* (Rumba Formation) in the the open shelf facies belt, transgressively overlying different strata of the Raikküla Age. In the central depression of the basin, condensed dark-brown kerogenous graptolitic muds of the Dobele Formation continued to deposit. During the next step of deepening, corresponding to late Adavere (Velise) time, argillaceous sediments of the depression (Jurmala Formation) and transitional facies belts (Velise and Švenčionys formations) covered the whole East Baltic area. The transgression was especially extensive in eastern Lithuania where marly deposits of the Švenčionys Formation disconformably overlie the Ordovician strata. The Late Llandovery - Early Wenlock transgression expanded even into the Moscow Syneclise (Kaljo 1987). During the late Adavere time, purple terrigenous muds accumulated in the western part of the Baltic Basin (Kurzeme, Sõrve, Gotland areas).

Deposition of the deeper-water, highly argillaceous sediments continued also at the beginning of the Wenlock, Jaani Age (Tõlla beds of the Rīga Formation, Mustjala Member of the Jaani Formation, Sutkai beds of the Paprieniai Formation). The highly

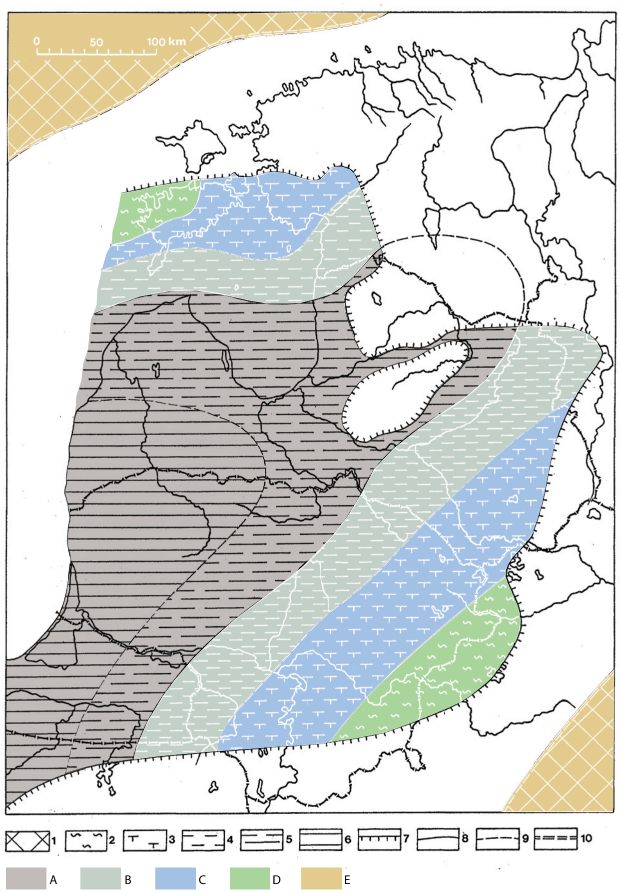


Fig. 11. Distribution of the Wenlock mid-Jaani (base of Ninase Member) sediments and facies belts: 1 - land; 2 - bioclastic calcareous mud; 3 - argillaceous-calcareous mud; 4 - green terrigenous mud; 5 - grey terrigenous mud with graptolites; 6 - dark kerogenous graptolitic mud; 7 - boundary of the present extension of rocks; 8 - main facies boundaries; 9 - boundary of sediment types; 10 - shoreline. A - terrigenous and kerogenous mud with graptolites, B - terrigenous mud, C - argillaceous calcareous mud, D - bioclastic mud, E - presumable land (Nestor and Einasto 1997).

argillaceous sediments of the Late Llandovery and the earliest Wenlock contain numerous thin metabentonite interlayers. It leads to the supposition that the Late Llandovery – Early Wenlock sea-level high-stand was probably induced by the acceleration of the sea-floor spreading accompanied by intensification of volcanic activity in the Iapetus Ocean.

In the middle of the Jaani Age, an abrupt shallowing developed in the peripheral part of the Baltic Basin. Reefs and skeletal sand bar deposits of the shoal facies belt began to form in the Gotland area (Högklint Formation), northwestern Saaremaa (Ninase Member of the Jaani Formation) and eastern Lithuania (Jačionys Formation). However, in the basin depression the facies of dark-grey graptolitic muds even expanded its area at that time (Fig. 11). As a result, extremely rapid early-mid Wenlock regression along the perimeter of the basin finally transformed the Baltic Basin s.s. into a gulf-like pericratonic sea (the "Baltic Gulf"). The most drastic upheaval and regression took place in the Scandinavian part of the sea due to the progressing rise of the Caledonides.

During the Jaagarahu Age, the gradual shallowing continued at the margins of the basin, interrupted by short deepening episodes. This resulted in a cyclical alternation of high-energy shoal deposits (winnowed skeletal-pelletal sand and silt, coral-stromatoporoid banks and reefs) with different lagoonal-littoral dolomitic muds (*Eurypterus*- and bioturbated pattern-dolomites). The *Eurypterus*-dolomites probably formed in a brackish-water environment (Nestor and Einasto 1997 and references therein). Three of such shallowing-up mesocyclithes have been recognized in the Jaagarahu Formation and are treated as the Vilsandi, Maasi and Tagavere beds. Basinwards these intercalating shoal and lagoonal deposits of the Jaagarahu Formation were successively replaced by the bioclastic argillaceous-calcareous muds (Riksu Formation), greenish-grey calcareous-argillaceous muds (Jamaja Formation) and finally by dark grey terrigenous muds with graptolites (Rīga Formation). During late Jaagarahu time, a long sedimentation break and erosion of the earlier deposits took place all over the shelf plateau (Nestor & Nestor 1991). At the moment of the maximum shallowing, at the end of the Jaagarahu Age, a band of thinly interbedded marls and limestones (Ančia Member) was formed in the central depression of the basin, marking the end of the Late Llandovery - Middle Wenlock macrocycle in the basin development.

The **Late Wenlock - Middle Ludlow macrocycle** corresponds to the Rootsiküla and Paadla ages. It is represented by the cyclical alternation of winnowed skeletal-pelletal grainstones with sedimentary argillaceous dolostones (*Eurypterus*-, pattern- and microlaminated dolomites). Unlike the Jaagarahu cycles, the shoal and lagoonal facies of the Late Wenlock - Middle Ludlow mesocycles extended over a very wide area of southwestern Estonia, covering the whole levelled shelf plateau. Southwards these marginal-marine facies were rapidly replaced by the dark-grey graptolitic muds of the Siesartis and Dubysa formations which shows that at that time a rather steep gradient existed between the shelf plateau and basin depression. The open shelf and transitional facies belts were heavily reduced (Fig. 12). It means that a platform-type sedimentation with a very wide belt of marginal-marine facies was typical of the Late Wenlock - Middle-Ludlow macrocycle of basin development.

On the background of the cyclical sea-level fluctuations a faintly expressed regressive-transgressive trend is perceivable in the basin evolution. The break point, *i.e.* the regression maximum was probably reached by the end of the Vesiku time (mid-Rootsiküla) and further a very slow, gradual transgression followed. It is likely that several sedimentation gaps existed during the time-interval in consideration, but

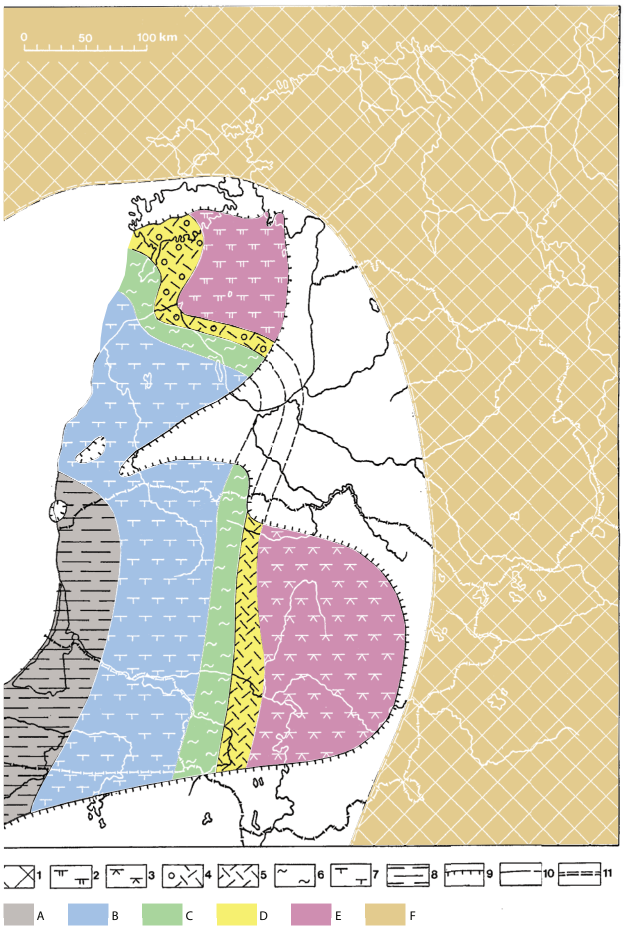


Fig. 12. Distribution of the Ludlow mid-Paadla (base of Himmiste beds) deposits and facies belts: 1 - presumable land; 2 - lagoonal dolomitic mud; 3 - high-salinity, gypsiferous dolomitic mud; 4 - pelletal-skeletal sand and silt; 5 - skeletal sand; 6 - bioclastic calcareous mud; 7 - calcareous-argillaceous mud; 8 - grey terrigenous mud with graptolites; 9 - boundary of the present extension of rocks; 10 - facies boundaries; 11 - shoreline. A - terrigenous mud with graptolites, B - calcareous-argillaceous mud, C - bioclastic calcareous mud, D - silt and skeletal sand, E - dolomitic mud, F - presumable land (Nestor and Einasto 1997).

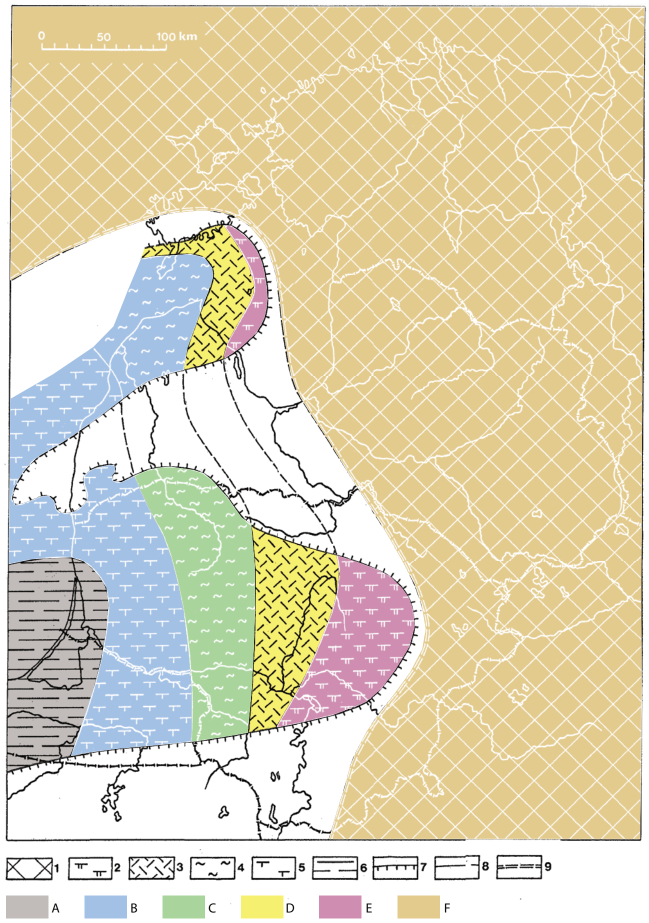


Fig. 13. Distribution of the Pridoli earliest Kaugatuma sediments and facies belts: 1 - land; 2 - lagoonal dolomitic mud; 3 - skeletal sand and gravel; 4 - bioclastic calcareous mud; 5 - green calcareous-argillaceous mud; 6 - grey terrigenous mud with graptolites; 7 - boundary of the present extension of rocks; 8 - facies boundaries; 9 - shoreline. A - terrigenous mud with graptolites, B - calcareous-argillaceous mud, C - bioclastic calcareous mud, D - skeletal sand and gravel, E – dolomitic mud, F - presumable land (Nestor and Einasto 1997).

direct evidence is still lacking and only a probable hiatus has been revealed between the Rootsiküla and Paadla stages.

Infilling stage of development

It was the final epoch in the evolution of the Ordovician-Silurian carbonate sedimentation basin at the western margin of the East-European Platform which corresponded to the time interval from the Late Ludlow (Kuressaare Age) up to the earliest Devonian (Tilžė Age). An abrupt increase in the supply of the basin with terrigenous material, coming from the Scandinavian Caledonides, was a characteristic feature of the infilling stage. The previous side-filling of the basin depression was changed by the total infilling and shallowing all over the central part of the Baltic Syneclise where the deposition of terrigenous graptolitic muds was now replaced by the accumulation of the greenish-grey calcareous-argillaceous muds with benthic biota. The formation of the graptolitic muds of the depression belt migrated to the platform margin in northeastern Poland where a thick clayey-silty complex of distal turbidites (Siedlce beds) was formed. Even in the shelf area, corresponding to the open shelf and shoal environments, the accumulation of the terrigenous material was so heavy that it diluted the carbonate sedimentation. As a result, the formation of bioclastic marls got dominance all over the shelf area. However, from time to time rather thick (3 to 5 m) deposits of crinoidal grainstones, coquinite banks with *Atrypoidea prunum*, thickets of rugose and tabulate corals were formed. Such thick deposits of crinoidal grainstones, containing cross-bedding, ripple marks and other signs of the agitated-water environment mark the end of several shallowing-up mesocycles. They are most typically developed in the Kaugatuma Stage where four of such cyclithes (Lower and Upper Äigu beds, Lower and Upper Lõo beds) have been distinguished. A clear facies zonation was characteristic of the moments of the formation of crinoidal grainstones in the shoal belt (Fig. 13), while during the rest of time with intensive influx of clayey component, the lateral differentiation of facies was much poorer.

The infilling stage began with a brief transgressive event during the Kuressaare Age. This Late Silurian transgression reached its maximum at the beginning of the Pridoli (early Kaugatuma time). The transitional facies belt with deposition of calcareous-argillaceous muds (Šilalė beds of the Minija Formation) was very wide and extended from southwestern Latvia to northwestern Poland. In onshore direction it was gradually followed by open shelf biomicritic marls, coarse-grained crinoidal gravel and sand of the shoal belt and lagoonal dolomitic muds. The latter have preserved only in the Lithuanian part of the basin. During the late Kaugatuma and Ohesaare times, the general facies pattern remained the same but all facies belts migrated gradually southwestwards.

By the beginning of the Devonian (Tilžė Age), only a remnant lagoon-like body of water was preserved in northern Kurzeme and south-western Lithuania. It was characterized by a clastic-dominated near-shore belt and argillaceous-dolomitic muds in its offshore part.

Favosites pseudoforbesi Sokolov, 1952, from Katri cliff, Saaremaa Island (Excursion Stop 18)

CORALS AND STROMATOPOROIDS

Rugose corals

Knowledge of the Ordovician and Silurian rugose corals of Estonia is mainly based on the studies by Eichwald (1854-1860), Dybowski (1873), Weissermel (1894), Reiman (1956, 1958) and Kaljo (1996, 1958, 1970). During the recent decades, Neuman (1969, 1986), Scrutton (1988) and Weyer (1973, 1982, 1983, 1993) have published several papers describing only a few new taxa but improving considerably the taxonomy of corals identified earlier. The number of the known species-level taxa, slightly exceeds one hundred, but the share of undescribed forms might be at least 20-30%.

Rugose corals made their first appearance in the Middle Ordovician of North America. In Estonia, they are represented by *Primitophyllum primum* Kaljo and *Lambelasma dybowskii* (Kaljo) occurring in the Haljala Stage and undoubtedly having the habitus of the most primitive tetracorals. In general, the Ordovician rugose coral assemblages were dominated by simple streptelasmatid corals provided only with tabulae between septa and often having a dilated septal apparatus. The first corals with well developed dissepimentarium appeared at the very end of the Late Ordovician and gained predominance later in the Silurian. The Ordovician Period, however, ended with a serious extinction of corals (first of all species- and genus-level taxa, particularly streptelasmatids), and the earliest Silurian (Rhuddanian) was a low-diversity period dominated by Ordovician carry-overs. Later, a stepwise increase in the diversity followed until the maximum was reached in the Wenlock (Kaljo 1996). Morphological differentiation was remarkable. New types of septa, stereozones, calices, many colonial forms, *etc*. appeared which formed a base for taxonomical diversity. The most characteristic were different cystiphyllids, kodonophyllids, entelophyllids, lykophyllids, arachnophyllids, *etc*. The Late Silurian shows a decline of rugose corals in general, but a few new elements appeared in the Pridoli, among them the so-called “Devonian” elements (*Acanthophyllum*, *Lyrielasma*, *etc*., Scrutton, 1988).

The above general evolutionary pattern is well observable in Estonia. Apart from the above-mentioned primitive rugosans, *Kenophyllym* and *Streptelasma* appeared in the Keila Age, and *Borelasma* and the first tryplasmatid *Estonielasma*, in the Oandu Age. The first *Grewingkia* was identified at the end of the Middle Ordovician. It means that rugose corals were scarce in the Middle Ordovician of Estonia, but their diversity was already comparatively high.

The Late Ordovician was mostly dominated by streptelasmatids (*Kenophyllum*, *Streptelasma*, *Grewingkia*, *Helicelasma*, *Dalmanophyllum*), but there occurred also rare lambelasmatids or calostylids s. l.: *Coelostylis* (*Vormsistylis*), *Neotryplasma*, *Calostylis*, *Estonielasma*. The end of the period (Porkuni Age) was marked by the incoming of the first paliphyllids (*Paliphyllum, Strombodes*) and staurids (*Palaeophyllum*).

The Silurian rugose corals in Estonia are the most diversified in the following stratigraphical units: (1) the upper Aeronian Rumba Formation (*Dinophyllum*, *Entelophyllum*, *Prodarwinia*, *Phaulactis*, *etc*.); (2) the Middle Wenlock Jaagarahu Formation (*Acervularia*, *Spongophylloides*, *Microplasma*, *etc*.); (3) the Ludlow - Pridoli (*Entelophyllum* and *Tryplasma* were most common, but in the Kaugatuma Stage also *Cystiphyllum*, *Holmophyllum*, *Strombodes* and the first representatives of *Acanthophyllum* appeared).

The distribution of these corals shows a distinct facies control. Reliable records of rugose corals from the Silurian lagoonal and shelf depression facies are lacking. These corals were scarce also in the *Borealis* and *Pentamerus* banks and stromatoporoid biostromes, but rich assemblages occurred in the reefs and their surroundings (*e.g*. Hilliste reefs of the Juuru and Raikküla stages, Sepise outcrop of the Jaagarahu Stage, *etc*.). A diverse assemblage of rugose corals occurred also in the shallow part of the open shelf. However, the share of solitary corals in it was higher than in reef environments, and the role of colonial corals decreased. Up to now, only a few species have been identified from the deeper (outer) shelf (*Porpites porpita* from the Velise Formation, *etc*.), but many new taxa have not been described yet.

By now, no suggestions for the biozonations of rugose corals have been made, but Kaljo (1996, 1970) has listed the characteristic species for stratigraphic units.

Biogeographically, Estonian rugose corals belonged to the Baltoscandian (or North European) Province which had some connections with the North American - Siberian and also with the Middle Asian provinces. These connections, as well as the share of the widely distributed and endemic corals, were changing during the time under discussion. The importance of endemic corals was relatively high before the Wenlock.

Tabulate corals

The East Baltic and Dniestr River basins are the areas of the Baltica plate with abundant, well preserved and well known tabulate corals. The largest taxonomical studies in Estonian tabulate corals were carried out by Klaamann (1962a,b, 1964, 1966) and Sokolov (1951, 1952, 1955). Estonia and Gotland together comprise the most complete section with diverse tabulate fauna known throughout the Silurian. The Ordovician corals are exposed in outcrops of Estonia. The best tabulate bearing Ludlow sections are in the Dniestr River basin.

Tabulate corals are distributed predominantly in the shallow part of the basin and occur mainly in the high-energy, shoal facies, although they also occur less frequently in all other facies belts except the depression. The corals are rare in tidal flats and transition facies belts and achieve maximum diversity in the belts of shoal to open platform (Klaamann et al. 1980).

The changes in composition of tabulate faunas of the East Baltic at the Ordovician and Silurian boundary were mainly expressed at the generic level (Fig. 14). The Ordovician tabulate taxa did not disappear simultaneously. Some taxa disappeared much earlier than the beginning of the Silurian. In total, 16 Upper Ordovician genera disappeared towards the end of the period and 5 genera continued into the Silurian (Fig. 14) in the Estonian sequence. The Upper Ordovician lichenarids, tetradiids, sarcinulids and heliolitids disappeared, but several species of paleofavositids continued into the Silurian and became more diverse than the extinct cateniporids (Klaamann 1964, 1966). A few heliolitid genera also continued from the Ordovician into the Silurian.

The widespread transgressions and ameliorating climates at the beginning of the Silurian induced a rapid emergence of the cosmopolitan species and genera among corals (Copper 1994). In East Baltic, small bioherms are known in Estonia in the Hilliste Member of the Juuru Stage, Rhuddanian. In the early Llandovery the tabulate faunas in Estonia are characterised by low generic diversity, although the species diversity of *Paleofavosites* increased. The early-middle Llandovery macrocycle began with the glacio-eustatic sea level rise and ended with the denudation in marginal areas of the basin (Nestor and Einasto 1997).

According Johnson (1996) and Johnson et al. (1998), the first Silurian sea-level rise took place at approximately the beginning of the Aeronian. The renewal of faunas in the upper part of the Raikküla Stage occurred at this time in Estonia (Fig. 14); the genera *Parastriatopora, Multisolenia*, *Syringopora, Vacuopora* and *Sinopora* appeared. *Favosites* is more abundant than *Paleofavosites* in the Raikküla Stage than in the Juuru Stage. The Adavere Stage (Rumba Member) displays the highest diversity of tabulates and the highest ratio of cosmopolitan taxa for the whole Llandovery. This is the beginning of stabilisation stage in the basin development (Nestor and Einasto 1997). The upper part

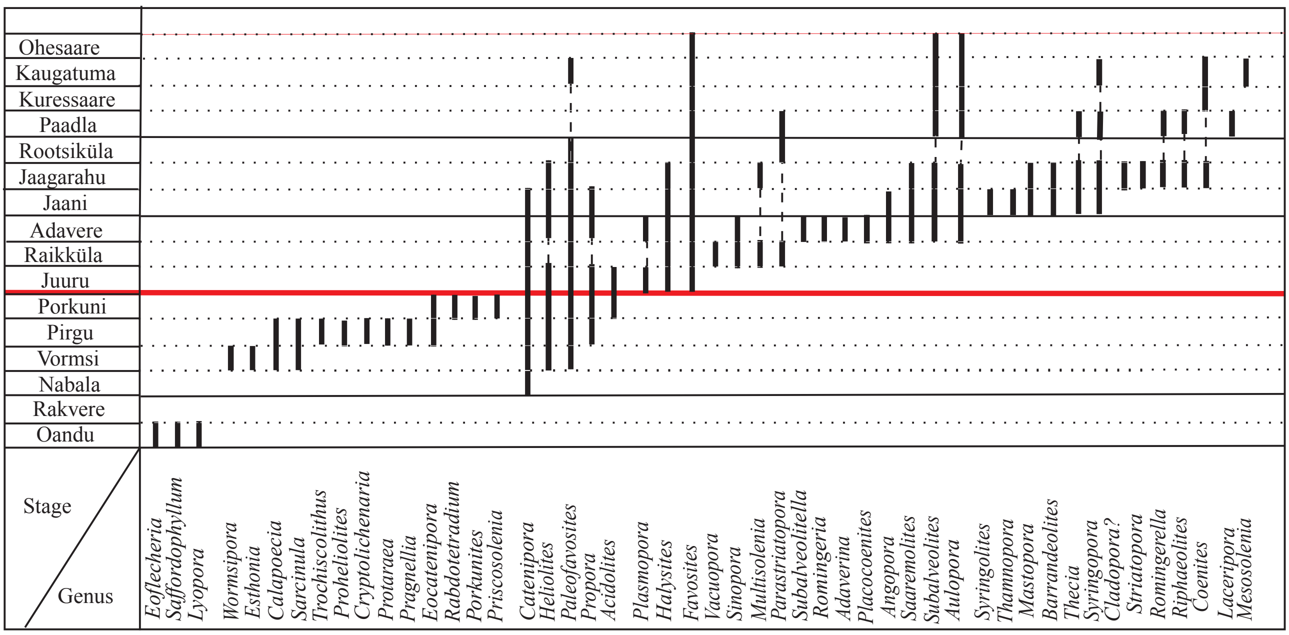


Fig. 14. Ranges of tabulate coral genera in the sequence of Estonia (Mõtus 2005).

of the Adavere Stage in Estonia comprises marl- and mudstones of deeper facies and contains very few corals. Corals are more abundant in the in the Vik Formation in Oslo Region, which is the same age .

The major Silurian sea-level rise in uppermost Llandovery is reffered to as the fourth sea-level event by Johnson et al. (1998). The sea-level lowered again at the beginning of Wenlock The Ireviken event in Gotland, which spanned the Llandovery-Wenlock boundary, caused the major extinction of conodonts and trilobites (Jeppsson, 1998). In East Baltic basin, the tabulate fauna changed considerably, new genera appeared (*Thecia*, *Syringolites*, *Mastopora*) and only one of the widely distributed Llandoverian species of *Paleofavosites* continued from the Adavere Stage into the Jaani Stage (Klaamann 1970).

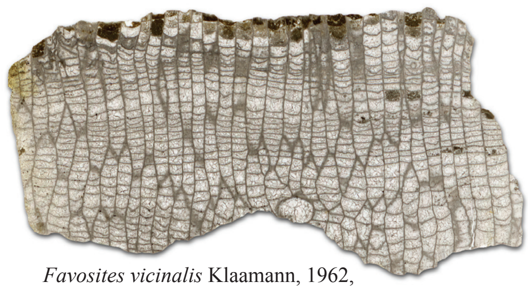
The species and genera of tabulate corals were highly diverse and abundant in the Wenlock. Reefs became widespread and abundant in mid-continental North America and in the Urals during the Wenlock (Copper and Brunton 1991). The correlation between the carbon isotopic changes and environmental cyclicity in the Silurian of East Baltic was investigated by Kaljo et al. (1998). The sea-level declines, associated with glaciations, were periods of more vigorous circulation and enhanced oxygenation of ocean-bottom waters. The relationship between the positive carbon isotopic peaks and intensive reef growth in Gotland has been confirmed by Sambtleben et al. (1996). The conditions for corals were more favourable in Gotland than in Estonia. Spectacular reefs rich in tabulate corals occur in the Högklint Formation on the northern coast of Gotland (Laufeld and Martinsson 1981). The high-energy shoal facies, which are the most favourable for corals, were absent on Saaremaa at that time. Smaller biostromes of open shelf facies, rich in heliolitids and halysitids, were spread instead in the Jaani Beds, Ninase Member (Mõtus 2006).

The Jaagarahu Stage in Estonia is characterised by the largest generic diversity of tabulates in the Wenlock (Fig. 14). The most widespread tabulates were favositids, theciids and coenitids. *Palaeofavosites* dominated many bioherms on Gotland and was also abundant on Saaremaa.

The global sea level fall culminating near the top of the *Cyrtograptus lundgreni* Zone and the following rapid transgression in *Gothograptus nassa-Pristiograptus parvus* Zone is marked by transgressive oolites in lowermost Halla Formation on Gotland (Calner 1999, Calner and Säll 1999). A global extinction and disappearance of graptolites, conodonts, chitinozoans and shelly fossils, named the Mulde event by Jeppsson (1998), also affected the reefs on Gotland. The low-diversity biostrome from the Halla Beds of Blåhäll 1 is the first re-appearance of reefs on Gotland after the Mulde event. A common feature of the Halla and Mulde Formations as well as for the middle of the Klinteberg Formation is their small size (Klaamann and Einasto 1982). A lowering of the sea at the end of the Wenlock is suggested from the appearance of the lagoonal facies in the Rootsiküla Stage on Saaremaa, which contains abundant branching parastriatoporids (Klaamann 1986).

The diversity of tabulate corals in Estonia was low during the Ludlow Epoch (Fig. 14), when the sea was narrowing in Baltoscandia. The high-energy shoal facies with more favourable conditions for corals existed in Gotland, in the Dniestr River Basin and in the Podljassk-Brest area. Heliolitids and halysitids are not found in the Ludlow successions in Estonia, although the former reached the end of Devonian elsewhere and halysitids have been found in the Ludfordian in Gotland and also in the Pridoli of Southern Gaspe Peninsula in Canada. Disappearance of *Thecia* and *Subalveolitella* is recorded in Estonia at the end of the Wenlock, but they occur in Ludlow of the Dniestr River Basin. Large reefs were characteristic of this time in Gotland and Podolia.

The halysitids from the Eke Formation in Gotland are the youngest in Baltoscandia (Mõtus and Sandström 2005). The Lau event is one of the largest extinction events among conodonts, graptolites, chitinozoans, some fishes, and brachiopods (Jeppsson 1998). It is noteworthy that the halysitids survived the early parts of the Lau extinction event in Gotland.



Favosites vicinalis Klaamann, 1962, from Kaugatuma cliff, Saaremaa Island (Excursion Stop 19)

Stromatoporoids

In the Ordovician and Silurian strata of Estonia, 88 valied species of stromatoporoids have been described (Rosen 1867, Nicholson 1886a,b, Riabinin 1951, Nestor 1960, 1964, 1966). The full list of the species, belonging to 26 genera and 16 families, and representing all orders of stromatoporoids except fine-cylindrical amphiporids, was published recently (Nestor 1990d). Stromatoporoids are continuously present in all regional stages of Estonia beginning from the Lower Ashgill (Vormsi Stage) and ending with the Lower Pridoli (Kaugatuma Stage). However, some earliest representatives of stromatoporoids (*Stromatocerium canadense* and *S. sakuense*) occur in the Middle Caradoc (Oandu Stage) already. Shorter gaps in the distribution, explained with unfavourable ecological conditions or local stratigraphical hiatuses, occur at the Llandovery/Wenlock and Wenlock/Ludlow boundaries.

Stromatoporoids appeared in the Estonian sequence later than in North America, North China or Australia where the earliest indubitable stromatoporoids have been recorded from the Llanvirn - Llandeilo strata already. It has been explained with the location of the Baltica Continent in the southern temperate climate zone until the Ashgill time when it migrated finally into the equatorial belt (Webby 1980).

In the Ordovician of Estonia, stromatoporoids are rare, except its topmost part - the Porkuni Stage. A few species of the most primitive, vesicular stromatoporoids (Order Labechiida) have been recorded from the Oandu (*Stromatocerium*), Pirgu (*Cystostroma*) and Porkuni (*Pacystylostroma*) stages. *Plumatalinia,* a problematic intermediate form between labechiidae and reticulate stromatoporoids (Actinostromatidae), occurs in the Pirgu Stage (Fig. 15). In the latest Ordovician, representatives of the sublaminate stromatoporoids (Order Clathrodictyida) became rather common: *Clathrodictyon* appeared during the Vormsi Age and *Ecclimadictyon* in the Porkuni Age.

In the Llandovery, clathrodictyids flourished. *Clathrodictyon* Nich. *et* Murie and *Ecclimadictyon* Nestor became dominating genera. They formed more than 80% of stromatoporoid specimens. Labechiids (*Pachystylostroma*, *Forolinia*, *Rosenella* and *Labechia*) were the second abundant group. During the Llandovery, the first representatives of several families appeared in the Estonian sequence. Thus, during Raikküla time, *Intexodictyon* - the earliest known representative of the Family Atelodictyidae (Fig. 15), and *Plectostroma*, the first certain representative of the Order Actinostromatida, made their appearance. During the Adavere Age, *Petridiostroma* was added among clathrodictyids as the most ancient representative of the Family Gerronostromatidae. At the same time, a very peculiar form "*Stromatopora" elegans* Rosen (=*Pachystroma*) appeared, showing the closest affinities to the Family Pseudolabechiidae. Thus, during the Llandovery, the first genuine laminate stromatoporoids (Atelodictyidae and Gerronostromatidae) and different branches of reticulate stromatoporoids (Actinostromatidae, Pseudolabechiidae) were gradually added to the prevailing fauna of the sublaminate and vesicular stromatoporoids.

During the Wenlock, the enrichment and diversification of the stromatoporoid fauna continued. In Jaani time, the first known microreticulate stromatoporoid *Densastroma* appeared. It belonged to the family Densastromatidae and played an important role later in the Silurian. At the same time, *Stromatopora* appeared in the Estonian sequence, being one of the earliest representatives of the Order Stromatoporida, *i.e.* stromatoporoids with irregularly amalgamated skeletal elements. *Simplexodictyon validum* Nestor, an early representative of the tripartite-laminated stromatoporoids (Order Stromatoporellida), has been recorded from the Maasi beds of the Jaagarahu Stage. *Vikingia tenuis* (Nestor) was the main frame builder in the Jaagarahu reefs (Vilsandi beds); it may be treated as a possible ancestor of the Order Syringostromatida with clinoreticulate microstructure of vertical skeletal elements (Nestor 1994). During the Wenlock the role of clathrodictyids decreased considerably; labechiids have not been recorded from Estonia.

During the Early Ludlow (Paadla Age), the diversity of the stromatoporoid fauna reached its maximum (13 genera from 12 families) in Estonia. In different taxonomical branches new elements were added, *e.g.* *Lophiostroma* among labechiids, *Plexodictyon* among clathrodictyids, *Pseudolabechia* in Actinostromatida, *Syringostromella* among stromatoporids, and *Parallelostroma* - the first representative of the Order Syringostromatida in the Estonian sequence. However, representatives of all the above-mentioned genera are known from somewhat earlier strata in other regions (Nestor 1994). In the Late Ludlow (Kuressaare Age) and Early Pridoli (Kaugatuma Age), the diversity of stromatoporoid assemblages decreased considerably due to an increase in the clay content of sediments and bad exposure of the corresponding strata. Stromatoporoids have not yet been recorded from the Silurian Ohesaare Stage.

The above leads to the conclusion that favourable climatic conditions for constant colonization of the Estonian area by stromatoporoids were established during the Ashgill. The beginning of the Silurian was characterized by comparatively unilateral fauna of sublaminate clathrodictyids (*Clathrodictyon, Ecclimadictyon*) with an admixture of labechiids. During the Llandovery and Wenlock, representatives of most of the orders and families were gradually added, and in the Early Ludlow (Paadla Age) the diversity of the stromatoporoid fauna reached its maximum, falling after that rapidly due to a progressive increase in the influx of clayish clastic material from the raising Caledonides.

Stromatoporoids were highly facies-dependent organisms with comparatively narrow ecological niche. The richest and most diverse stromatoporoid association occurred in the high-energy shoal facies belt, represented in fossil record by coral-stromatoporoid boundstones, skeletal and coquinite grain- and rudstones (Nestor 1990d). They were rather numerous also in the moderate- to low-energy open-shelf facies belt where biomicritic deposits (nodular skeletal packstones) were accumulated. Parallel successions of imperfectly deliminated lateral communities have been distinguished for shoal and open-shelf environments, consisting of 23 stromatoporoid communities (Nestor 1990d). Up to now, no definite biogeographic provinces have been established for the Late Ordovician and Silurian stromatoporoids (Nestor 1990c).

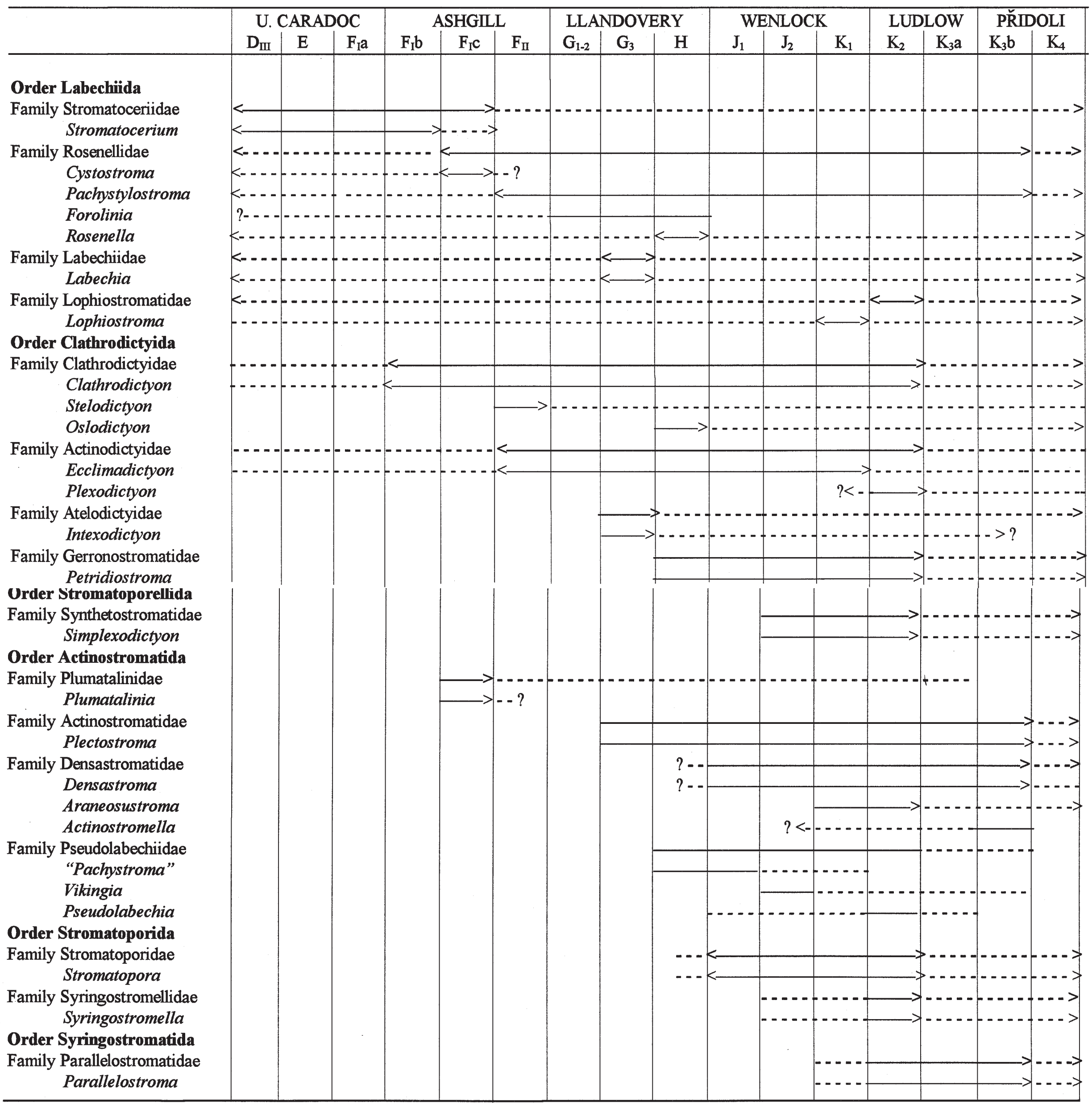
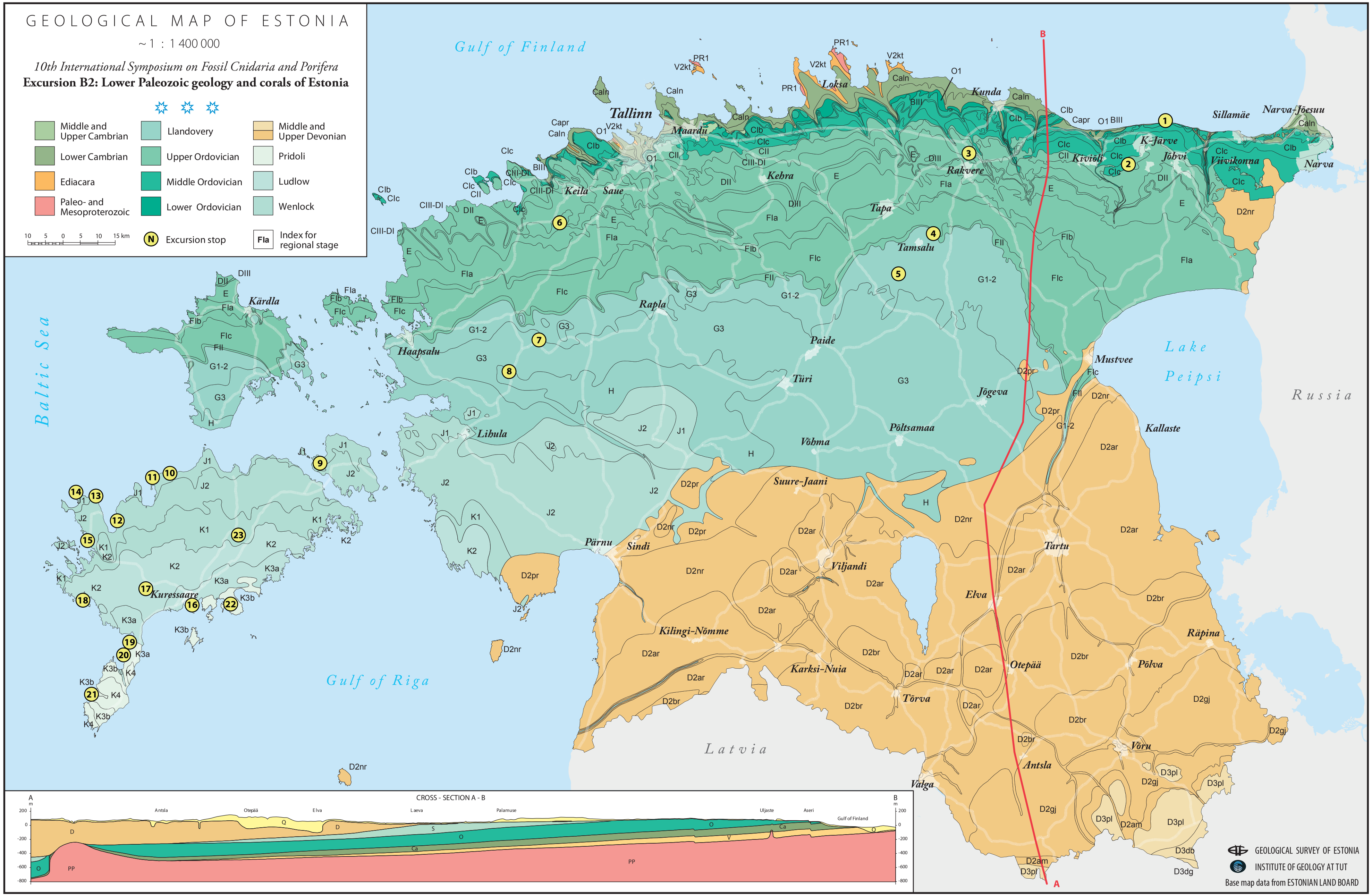


Fig. 15. Stratigraphical ranges of higher stromatoporoid taxa in Estonian sequences.

Excursion Stops


GEOLOGICAL MAP OF ESTONIA
~1 : 1 400 000
10th International Symposium on Fossil Cnidaria and Porifera
Excursion B2: Lower Paleozoic geology and corals of Estonia
Middle and Upper Cambrian
Lower Cambrian
Ediacara
Paleo- and Mesoproterozoic
Llandovery
Upper Ordovician
Middle Ordovician
Lower Ordovician
Middle and Upper Devonian
Pridoli
Ludlow
Wenlock
N Excursion stop
Fla Index for regional stage
10 5 0 5 10 15 km
Gulf of Finland
Baltic Sea
Gulf of Riga
Lake Peipsi
Russia
Latvia
Tallinn
Maardu
Keila
Saue
Kehra
Loksa
Kunda
Rakvere
Tapa
Tamsalu
Kiviõli
K-Järve
Jõhvi
Sillamäe
Narva-Jõesuu
Narva
Viivikonna
Haapsalu
Rapla
Paide
Türi
Jõgeva
Põltsamaa
Võhma
Mustvee
Kallaste
Lihula
Kärdla
Kuressaare
Pärnu
Sindi
Suure-Jaani
Viljandi
Kilingi-Nõmme
Karksi-Nuia
Tõrva
Elva
Tartu
Otepää
Räpina
Põlva
Võru
Antsla
Valga
CROSS - SECTION A - B
Antsla
Otepää
Elva
Laeva
Palamuse
Uljaste
Aseri
Gulf of Finland
GEOLOGICAL SURVEY OF ESTONIA
INSTITUTE OF GEOLOGY AT TUT
Base map data from ESTONIAN LAND BOARD

Day 1, August 18, 2007

Stop 1. Baltic Klint at Valaste waterfall (Lower Cambrian to Middle Ordovician)

The North-Estonian Klint is a part of a 1,200 km long limestone cliff, the **Baltic Klint**, that begins from the western coast of the Öland island in Sweden, extends under the sea to the western coast of Estonia, and then runs through Estonia to NW 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. The klint is dissected by river valleys and klint-bays, and its present form is the result of the abrasion by the Baltic Sea.

The artificial **Valaste waterfall**, falling from the 54 m high North Estonian Klint is the highest waterfall in Estonia (Fig. 16). Its height is usually between 26 and 28 m, but after exceptionally heavy rainfalls the strong flow may erode a deep pit in the sandstone on the foot of the klint and the total height of the waterfall can be up to 30 m. Downwards, the waterfall continues as a 10–15 m high rapid, flowing into the sea. Due to the slight southward dip (3–4 m per 1 km) of the limestone layers and the absence of water outlet, the fields in the klint area have been suffering from excessive water during rainy seasons. At the beginning of the 19th century, a 7 km long and up to 2 m deep drain was made to aid water to run off the manor's fields nearby. As a result, the water flow has cleaned and eroded the klint wall, exposing the wonderful Lower Cambrian to Middle Ordovician sedimentary section.

The section exposes the Lower Cambrian sandstone (Tiskre Formation), Furongian to Lower Ordovician sandstone (Kallavere Formation), black shale (Türisalu Formation) and glauconitic sandstone (Leetse Formation), and Middle Ordovician limestone and dolomite (Volkhov, Kunda and Aseri stages; Fig. 17). The banks of the stream below the klint expose locally the "blue clay" of the Lower Cambrian Lükati Formation. In 1999 a platform was constructed in front of the waterfall to make the observation of this site safer and more attractive.

Fig. 16. Valaste waterfall. Photo by O. Hints.

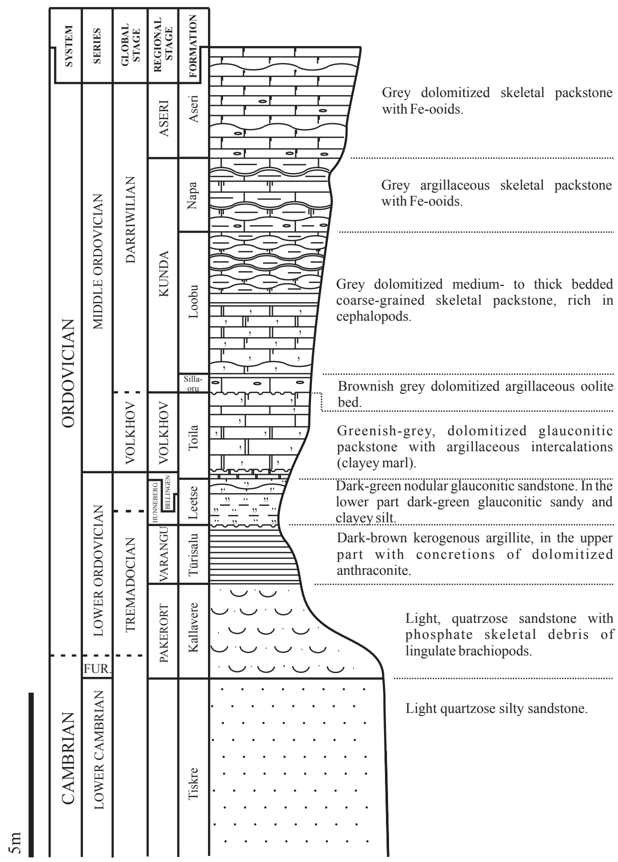


Fig. 17. Stratigraphy of the Valaste waterfall section (Tinn 2004).

Stop 2. Kohtla Mining Museum and Estonian oil shale (Upper Ordovician)

The Baltic Oil Shale Basin is situated in north-eastern Estonia, with a part of it extending eastward into Russia. Three well-explored oil shale deposits – Estonia, Leningrad and Tapa – are distinguished within this basin. The first two deposits are mineable, while the Tapa deposit in central Estonia is considered to be a prospective one. At present, the Estonia deposit, with an area of nearly 3000 km^2, is the largest commercially exploited oil shale deposit in the world. Total reserves of the deposit are approximately 5 gigatonnes, which include active reserves about 1.5 gigatonnes. Nowadays oil shale is excavated in two underground mines – Estonia and Viru – and in three open cast mines – Narva, Aidu and Vanaküla (Fig. 18A). In the year 2005 the total amount of excavated oil shale was 14.6 million tonnes. The Kohtla quarry works as a part of the Aidu open cast pit. Estonian oil shale – kukersite – is a unique mixed rock, widely distributed in the northern Estonian Ordovician sequence. It consists of the following main components: organic matter of algal and/or cyanobacterial (*Gloeocapsomorha prisca* Zalessky) origin (15–70%); terrigenous matter, mostly clay (10–75%); calcareous component, consisting mainly of calcitic matrix and skeletal detritus (10–75%; Bauert and Kattai 1997).

The oldest Ordovician occurrence of kukersite is in the sandy limestones of the Pakri Formation, Kunda Stage. Especially rich in kukersite is the sequence of the Middle–Upper Ordovician boundary beds of Llandeilo–Early Caradoc (Uhaku and Kukruse stages) age. Here up to 50 laterally continuous kukersite seams are registered. The seams can be traced laterally for 250 km in the east–west direction and 40–50 km in the north–south direction.

The Uhaku and Kukruse stages are characterized by frequent rhythmical alternation of different rock types:

Fig. 18A. Oil-shale open cast mine.

Fig. 18B. Kohtla Mining Museum. Photo by H. Pärnaste.

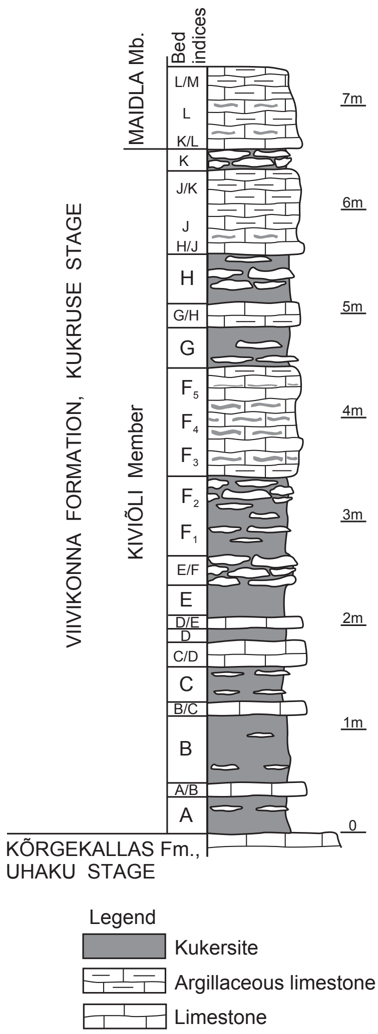


Fig. 18C. Kohtla quarry section (Kõrts and Einasto 1990, modified by Ainsaar 2004).

limestone with different contents of the argillaceous component and kerogene, kukersite and marl. The rocks are often dolomitized within tectonic disturbances and karstification zones. Both bedding structures and nodular textures of oil shale can be observed. The limestones are mainly medium-bedded (2–10 cm), marls – thin- to thick-bedded, of seminodular texture. Kukersite is thin- to thick-bedded, frequently also of nodular and seminodular (net-like) texture. The deposits have been bioturbated before lithification. Frequent burrows and discontinuity surfaces are registered in the sequence. The sequence is extremely rich in fossils: over 300 species have been identified in the Kukruse Stage, which is the most fossiliferous Ordovician stage of Estonia (Rõõmusoks 1970).

The commercially exploited beds (seams) of the Kukersite oil-shale occur in the Kiviõli Member which forms the lower part of the Kukruse Stage in northeasten Estonia and is exposed in the territory of Kohtla mining park-museum (Fig. 18B). The Kiviõli Member is the richest in kukersite, especially its lower part. Here seven thick kukersite layers (A, A', B, C, D, E and F_1) form the commercial seam of the Estonian Oil Shale Deposit (Fig. 18C). The kukersite beds in the upper part of the Kiviõli member (F_2, F_3, F_4, F_5, G, H, J and K) have no commercial value, though some of them (G and H) are considerably thick (20–40 cm). Kukersite of the lower part of the succession (Fig. 18C, beds "B", "C") is rich in cryptostome (*Graptodictya, Pachydictya, Phaenopora*) and some ramose bryozoans (*Homotrypa, Nematotrypa*) as well as pelmatozoan debris (*Ristnacrius, Baltocrinus*). Especially the latter accumulations refer to the fluctuating energy levels that existed during the Kukruse Age. Kukersineous limestone beds contain mostly trepostome bryozoans, microgastropods, small trilobites, and brachiopods. The middle part of the section (beds "D", "E", "F") is dominated by brachiopods (*Sowerbyella, Bekkerina*). Here *Bilobia musca* and *Paucicrura navis* appear. Another good stratigraphical marker level follows, where ostracodes *Sigmoopsis rostrata, Polyceratella bicornis* and *Airina amabilis* make their first appearance in beds "F_2/F_3" - "F_3". Starting with the beds "F_4" - "G_1" *Kullervo panderi* can be distinguished. Kukersite beds "F_4", "G_2" and "H_2" show a remarkable content of echinoderm debris (eocrinoids, stylophorans, homoiostelean and asteroid species).

The commonest species of the Kiviõli Member (Rõõmusoks 1970): bryozoans - *Chasmatopora furcata, Pseudohornera bifida, Diplotrypa petropolitana petropolitana, Mesotrypa excentrica*; brachiapods: *Bicuspina dorsata, Bilobia musca, Cyrtonotella kuckersiana kuckersiana* and trilobites: *Asaphus (N.) nieszkowskii, Cybellela rex, Chasmops* aff. *odini*.

Stop 3. Aluvere quarry (Upper Ordovician)

In the abandoned Aluvere quarry near Rakvere, south of the Tallinn–Narva road, the limestone succession of the Kahula Formation, Haljala Stage (Caradoc) is exposed (Fig. 19). In the southern wall of the quarry a 6 m thick section of the Aluvere and Pagari members of the Kahula Formation can be studied (Fig. 20). The limestone can be classified as argillaceous wackestone to packstone. The siliciclastic content varies from 10 to 25 %, forming 10–20 cm thick cycles, clearly observable in the weathered walls of the quarry. In the northern part of the quarry, in an old railway cut, the Vasavere and Aluvere members of the Kahula Formation are exposed. Two thin (2–4 cm) K-bentonite beds outcropping in the middle part of this wall belong to the Grefsen K-bentonite complex (Bergström *et al.* 1995). The rhythmically bedded argillaceous wackestones–packstones of the Haljala Stage have been deposited in the temperate climate open marine conditions on the open shelf. The abundance and high diversity of benthic shelly fauna refers to the depositional environment at a moderate depth, probably within the photic zone. The Aluvere

Fig. 19. Aluvere quarry.

quarry has been a well-known fossil site since the beginning of the 20th century. More than 150 species of macrofossils are reported from the locality, especially brachiopods, bryozoans and various micro-fossils being abundant and diverse. The most common macrofossils are *Porambonites baueri* Noetling, *Platystrophia lynx lynx* (Eichwald), *Clinambon anomalus* (Schlotheim), *Estlandia pyron silicificata* Öpik, *"Chasmops" wenjukovi* (Schmidt), *Pyritonema subulare* (Roemer), *Diplotrypa petropolitana* (Nicholson), *Ischadites murchisoni* (Eichwald), *Conichnus conicus* Männil. The earliest corals of Estonia have been recorded from this locality.

The oldest **rugose corals** from Estonia are found from this locality:

Primitophyllum primum Kaljo, 1956 and *Lambelasma dybowskii* (Kaljo, 1956)

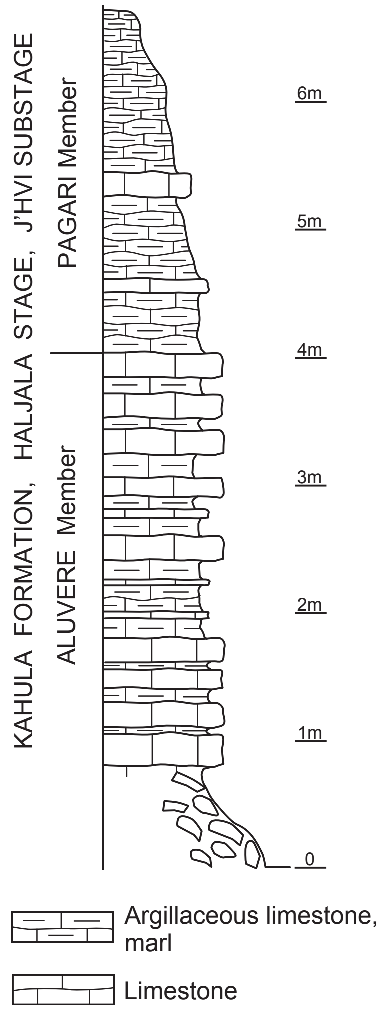


Fig. 20. Aluvere quarry section, southern wall (Ainsaar and Meidla 2004).

Stop 4. Porkuni quarry (Upper Ordovician)

The old Porkuni quarry is located near the Porkuni village by the Tamsalu–Kullenga road, some 20 km SW of Rakvere (Fig. 21). The locality was known already to Eichwald who first mentioned the Borkholm dolomite as a specific type of rocks (Borkholm is the old German name for Porkuni). Schmidt (1858) established the "Borkholm'sche Schicht" (=Porkuni Stage), which formed the roof of his "Untersilurische Formation" (=Ordovician). Schmidt recognised a succession of four different types of rocks in the Porkuni quarry. Later on, geographical names were provided for these units: the Röa, Vohilaid, Siuge and Tõrevere members, respectively (Fig. 22). All four members belong to the Ärina Formation which represents the youngest Ordovician rocks in northern and central Estonia. In southern Estonia, the Porkuni Stage is represented by the Kuldiga and Saldus formations. Based on the biostratigraphical and stable isotope data the Ärina Formation exposed in the Porkuni quarry most likely correlates with the lower part of the Kuldiga Formation, thus representing only the early Porkuni time (Nõvak and Grahn 1993; Kaljo *et al*. 2001). The description of the Porkuni quarry section from base to top according to Hints *et al*. (2000) is following (thickness shown in parentheses):

Adila Formation 5.47–5.83+ m (0.36+ m): yellowish-grey to yellow micro- to fine-crystalline variably calcitic and argillaceous dolostone. Skeletal debris consists of fragments of bryozoans, brachiopods and echinoderms.

Ärina Formation, Röa Member 4.00–5.47 m (1.47 m): yellowish, thick-bedded, predominantly fine-crystalline dolostone contains unevenly distributed crinoid ossicles. The upper boundary of the Röa Member is marked by a wavy discontinuity surface without impregnation. Brachiopods, trilobites and some other fossils occur in the upper half of this interval.

Vohilaid Member 3.00–4.00 m (1.00 m): yellowish, light grey, middle- to thick-bedded slightly dolomitic skeletal grainstone.

The shelly fauna of the Vohilaid Member consists of rugose and tabulate corals, bryozoans and brachiopods, but skeletal fragments of echinoderms are also

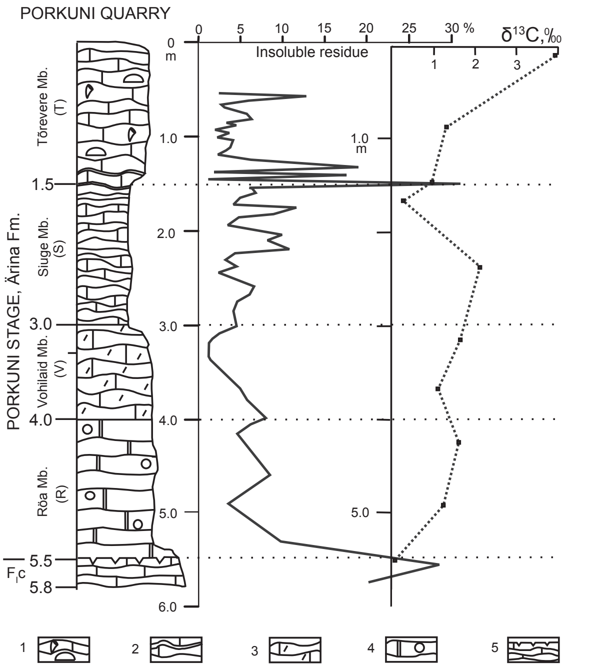


Fig. 22. Porkuni quarry section after Hints et al. (2000). Analyses of the insoluble residue and δ13C composition. Legend: 1, reef limestone with corals; 2, biomicritic dolomitic limestone with interlayers of calcitic marl; 3, dolomitic skeletal limestone; 4, dolomite with crinoid ossicles; 5, argillaceous dolomite with discontinuity surface. FIc, Pirgu Stage; indexes of the members are given in parantheses.

common. Coral species in the Vohilaid Member are *Paliphyllum rhizobolon* (Dybowski), *Palaeophyllum fasciculum* (Kutorga), *Priscosolenia prisca* (Sokolov). In the southernmost end of the quarry wall the formation of a bioherm begins in this member with a large type specimen of *Mesofavosites dualis* Sokolov, 1951 at the base.

The Siuge Member 1.50–3.00 m (1.50 m): yellowish-grey, beige to brownish-grey, dolomitic micro- to fine-crystalline wackestone and packstone contains wavy or branching, thin interlayers of slightly kerogenous marl (2–10 cm in thickness). The Siuge Member contains a diverse association of corals and brachiopods. Characteristic to Siuge Member are brachiopods and graptolites. Corals include *Palaeofavosites porkuniensis* Sokolov, *Porkunites amalloides* (Dybowski), *Paliphyllum sokolovi* Reiman. Characteristic are also delicate reticulate or branching bryozoans and dendroid graptolites. Most of the fossils are silicified.

Tõrevere Member 1.5–0.00 m (1.5 m): brownish-grey, micro- to finecrystalline coral-stromatoporoid limestone with wavy-bedded to massive structure. The most characteristic fossils are *Clathrodictyon gregale* Nestor, *Ecclimadictyon porkuni* (Riabinin), *Eocatenipora parallela* (Schmidt), *Paleofavosites nikitini* (Sokolov), *Rhabdotetradium frutex* Klaamann, *Tryplasma tubulum* (Dybowski), *Strombodes middendorfi* (Dybowski).

Fig. 21. Porkuni quarry. Photo by G. Baranov.

Species of brachiopods as *Thaerodonta nubila* (Rõõmusoks), *Pirgumena martnai* Rõõmusoks, *Streptis undifera* (Schmidt), *Ilmarinia ponderosa* Öpik, *Vellamo silurica* Öpik, *Aphanomena luna* (Lindström), *Schmidtomena acuteplicata* (Schmidt); trilobites *Valdariops eichwaldi* (Schmidt), *Encrinurus moe* Männil and graptolites *Callograptus kaljoi* Obut et Rytzk, *Dictyonema delicatulum* Lapworth, *Mastigograptus crinitus* Obut et Rytzk are found in this locality except corals and stromatoporoids.

Besides above named species more stromatoporoid and coral species are described from this locality among them many new species:

stromatoporoids *Clathrodictyon mammillatum* (Schmidt, 1858) (type),
Clathrodictyon zonatum Nestor, 1964 (type),
Ecclimadictyon porkuni (Riabinin, 1951) (type),
Clathrodictyon gregale Nestor, 1964;
tabulates *Palaeofavosites porkuniensis* Sokolov, 1951 (type),
Paleofavosites rugosus Sokolov, 1951 (type),
Palaeofavosites legibilis Sokolov, 1951 (type),
Palaeofavosites corrugatus Sokolov, 1951 (type),
Mesofavosites dualis Sokolov,1951 (type),
Rhabdotetradium frutex Klaamann, 1966 (type),
Priscosolenia prisca (Sokolov, 1951) (type),
Palaeofavosites haapsaluensis Klaamann, 1961,
Eocatenipora parallela (Schmidt, 1858);
Propora conferta Milne-Edwards and Haime, 1851 (type);
rugose corals *Porkunites amalloides* (Dybowski, 1873),
Paliphyllum sokolovi (Reiman, 1956),
Tryplasma tubulum (Dybowski, 1873),
Strombodes middendorfi (Dybowski, 1874),
Palaeophyllum fasciculum (Kutorga, 1837),
Paliphyllum rhizobolon (Dybowski, 1873).

Stop 5. Võhmuta quarry (Llandovery)

A few years ago a new quarry exposed the coquina limestone of the Tamsalu Formation, Juuru Stage, Llandovery, near the Järva-Jaani–Tamsalu road in Võmuta village (Fig. 23). The main part of the section exposes white massive coquinoid rudstone of *Borealis borealis* (Tammiku Member) in a thickness of 5 m (Fig. 24). The rock is composed of complete and fragmental valves of the brachiopod *B. borealis*. Interestingly, *B. borealis* is represented in the Tamsalu coquina almost exclusively by ventral valves. The valves of *B. borealis* may comprise up to 64% of the coquina rock of the Tammiku Member. The matrix contains pellets and rounded skeletal particles in sparry calcite. The bedding planes are usually stylolites, with occasional thin marl coatings. The fossil assemblage of the Tammiku Member is of a very low diversity. Besides *B. borealis* there occur big, scattered skeletons of stromatoporoids *Ecclimadictyon microfastigiatum* (Riabinin) and tabulate corals *Catenipora septosa* (Klaamann). The upper boundary of the Borealis-bank is a wavy erosional surface. The Karinu Member covering the Borealis-bank (Tammiku Member) is exposed in the north-eastern and south-western corners of the Võhmuta quarry in a thickness of up to 0.8 m (Fig. 24). It comprises a yellowish biostromal stromatoporoid bank of irregular nodular skeletons (lower part) and fine-grained pelletal grainstone with stromatoporoids (upper part). The most common stromatoporoids in the Karinu Member are *Clathrodictyon boreale* Riabinin, *C. kudriavzevi* Riabinin and *Ecclimadictyon microvesiculosum* Riabinin, heliolitid corals *Acidolites* can be found in the biostromal limestone. The shell bank of the Tamsalu Formation was deposited in a shallow-water high-energy environment in the shoal belt of the Silurian Baltoscandian Sea. The *B. borealis* accumulation zone is distributed in the east–west direction all over central Estonia, being about 200 km long and 30 km wide. The Borealis-bank is up to 13.5 m thick. It represents the first Silurian shallowing in the Baltoscandian Basin, lying on the argillaceous limestones (pack- and wackestones) of the Varbola Formation, Juuru Stage, about 10–20 m higher than the Ordovician–Silurian boundary. The massive Borealis-bank, resistant to erosion, has later given shape to the core of the Pandivere Upland in this part of Estonia. The limestone of the Borealis-bank contains minor amounts of dolomite (1–10%) and siliciclastics (clay; usually <2%) in the Karinu–Tamsalu area. It has been used for lime production for over a century as pure calcitic material. The Võhmuta quarry is exploited by the enterprise AS EDK and the material extracted is used in chemical industry.

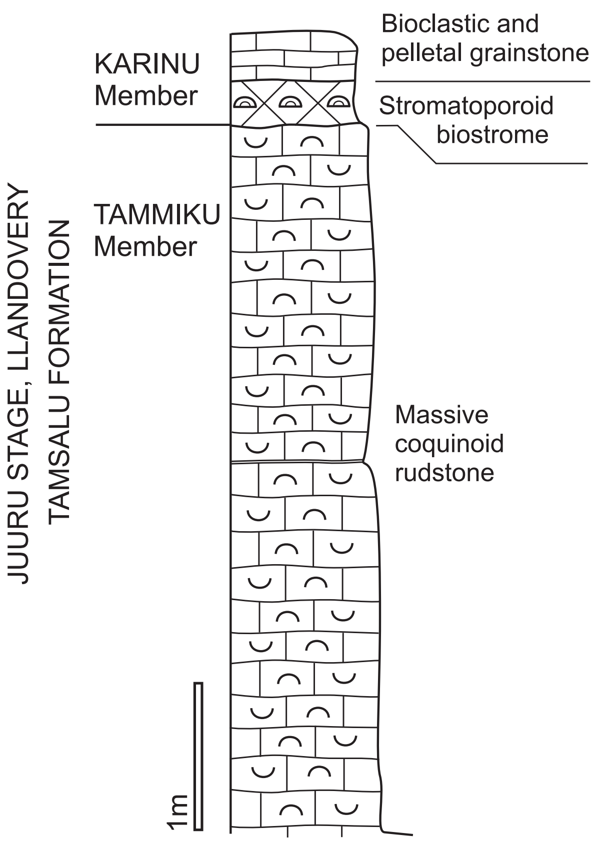


Fig. 24. Võhmuta quarry section (Ainsaar 2004).

Fig. 23. Võhmuta quarry.

<u>Common **stromatoporoids** and **tabulate corals** in Tammiku member are</u>:

Ecclimadictyon microfastigiatum (Riabinin, 1951),
Catenipora septosa (Klaamann, 1959).

<u>Common **stromatoporoids** and **tabulate corals** in Karinu member are</u>:

Ecclimadictyon microvesiculosum (Riabinin, 1951),
Clathrodictyon boreale Riabinin, 1951,
Clathrodictyon kudriavzevi Riabinin, 1951,
Acidolites.

Day 2, August 19, 2007

Stop 6. Vasalemma quarry (Upper Ordovician)

Fig. 25. Vasalemma quarry.

In the vicinity of the Vasalemma settlement (first mentioned already in 1241), Ordovician limestones have been quarried since the 13th century. The limestone has been used as building material for the Padise monastery, Risti and Madise churches and Vasalemma and Laitse castles. The quarry to be visited by our excursion is located east of Vasalemma (Fig. 25). The quarry is owned by the Swedish company Nordkalk, which is acting in Finland, Sweden, Poland and Estonia and is the leading manufacturer of limestone-based products in Northern Europe. The size of the quarry is about 2x2 km.

Fig. 26. Carbonate buildup with surrounding skeletal grainstone in Vasalemma quarry. Photo by L. Hints.

The strata of the Kahula and Vasalemma formations are exposed in the quarry walls. The Kahula Formation and the main part of the Vasalemma Formation correspond to the Keila Stage, and the uppermost part of the latter formation exposed in the quarry belongs to the Oandu Stage. The Kahula Formation is divided into Pääsküla (below) and Saue (above) members. The Pääsküla Member consists of micritic pelletal seminodular limestones rich in silty to very fine sand-size quartz and crops out only in the northern part of the quarry. The occurrence of *Trypanites* type burrows refers to very shallow water conditions in the region at the end of time. The upper boundary

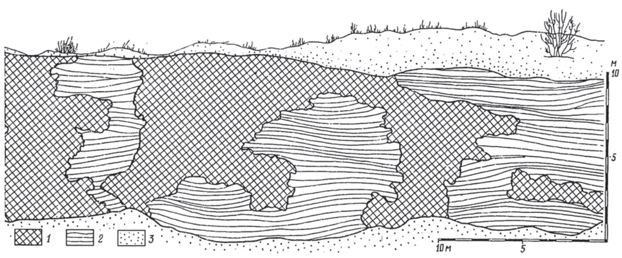


Fig. 27. Section of the Vasalemma Formation in the western part of the quarry. 1 - carbonate buildup, 2 - skeletal grainstone, 3 – dump (Hints 1990).

of the Pääsküla Member is marked by large, impregnated and partly eroded ripple marks.

Spotty distribution of hemispheric bryozoan colonies in life position and large valves of the strophomenid *Keilamena occidens* (Oraspõld) on some bedding planes are characteristic of the Saue Member. Trilobites occur in the lowermost part of the Saue Member. Most of the section in the northern part of the quarry corresponds to the Saue Member of the Kahula Formation. In the surrounding areas of the Vasalemma Formation the Saue Member is characterised by the occurrence of grainstone interlayers and lenses in more or less argillaceous limestones. The argillaceous biodetrital limestones of the Saue Member, with brachiopod *Sowerbyella* coquinas are gradually replaced by grainstones in the lower part of the Vasalemma Formation containing also a bed with numerous *Sowerbyella* towards the south.

The Vasalemma Formation with its typical characteristic features is exposed in the middle and southern parts of the Vasalemma quarry. The formation consists of white to dark grey, fine- to coarse-crystalline bedded grainstones. The grainstones include distinctive irregular bodies of different size formed of massive pure limestones. The lower part of the formation contains an argillaceous interlayer, sometimes with fossils as brachiopod *Estlandia* indicative of Keila age. The massive limestones, tentatively named here as carbonate buildups, have been interpreted as reefs or mud-mounds (Figs 26, 27). Some buildups contain holdfasts of *Cyathocystis* (*Edriasteroidea*), which seems to form their frame. Also several other fossils are present, such as sponges, corals, the alga *Solenopora*, in some "caves" cephalopods, etc., which all together form the reef-like carbonate bodies. The Oandu age of the uppermost Vasalemma Formation in the quarry is indicated by the appearance of the oldest tabulate corals in Estonia (*Lyopora tulaensis* (Sokolov), *Eofetcheria orvikui* Sokolov). However, no stromatoporoids have been recorded from the Vasalemma buildups yet. Their earliest representatives in the Estonian sequence appear in the stratified limestones of the Saku Member, laterally replacing Vasalemma formation in southern direction. The carbonate buildups contain a relatively low-diversity association of trilobites. Brachiopods *Rhynchotrema parva* Oraspõld and *Rostritsellula nobilis* (Oraspõld), are common in the Oandu marls (Rõõmusoks 1970).

Tabulate corals: *Lyopora tulaensis* Sokolov, 1951, *Eofetcheria orvikui* (Sokolov, 1951).

Stop 7. Pakamägi cliff (Llandovery)

An ancient inland cliff of the Yoldia Sea stage of the Baltic Sea, 5 km north-east of the Koluvere castle at Tallinn-Virtsu road exposes flaggy micritic and coral-stromatoporoid limestones from the middle part of the Raikküla Formation (middle Llandovery) (Fig 28).

The description of the locality is following (Fig. 29):

1. 0-1.0 (1.0m) - coral-stromatoporoid biostromal bank of a micritic matrix and nodular structure, consists of tabulates *Parastriatopora celebrata* Klaamann, *Sinopora operta* Klaamann, *Palaeofavosites balticus* (Rukhin) and stromatoporoids *Ecclimadictyon macrotuberculatum* (Riabinin), *Intexodictyon avitum* Nestor, *Intexodictyon olevi* Nestor buried only partly in life position.
2. 1.0-1.7 (0.7 m) - light-grey medium-bedded flaggy micritic (pelletal?) limestone containing scattered skeletal particles. Thickness of the layers is decreasing downwards.
3. 1.7-2.2 (0.5 m) - grey argillaceous limestone with marl partings in the upper part.
4. 2.2-2.5 (0.3 m) - flaggy micritic limestone, similar to bed 2, but more thin-bedded.
5. 2.5-2.6 (0.1 m) - interlayer of greenish-grey soft argillaceous marlstone.
6. 2.5-2.9 (0.3 m) - interlaminated micritic limestone and marlstone with polygonal mud cracks on the upper surface of the bed.
7. 2.9-3.4 (0.5 m) - light-grey massive micritic (pelletal?) limestone with scattered skeletal particles.
8. 3.4-3.75 (0.35 m) - interlaminated micritic limestone and marlstone, the same as layer 6.
9. 3.75-4.05 (0.3+ m) - massive argillaceous dolomitic limestone.

Fig. 28. Pakamägi cliff.

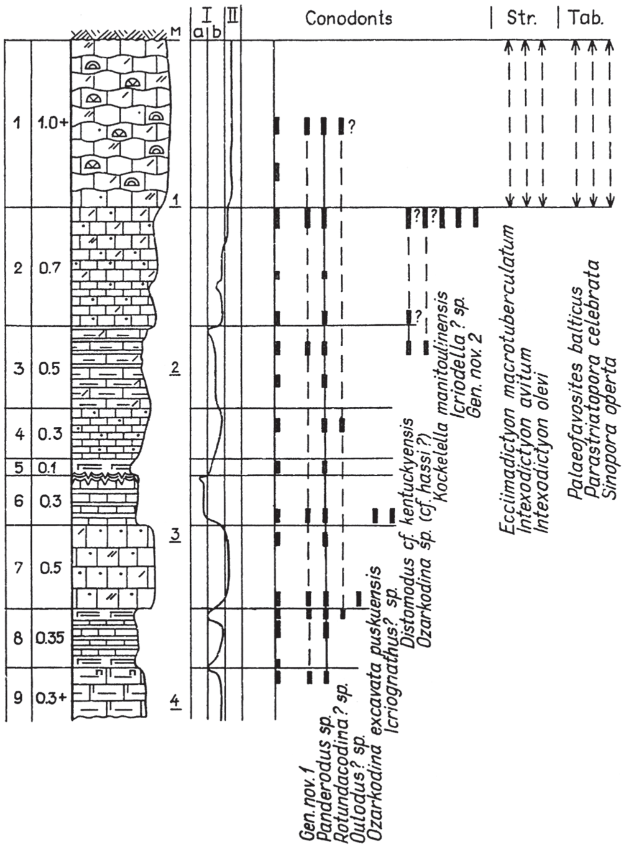


Fig. 29. Lithological log, facies curve and distribution of fossils in the section of Pakamägi cliff (Nestor 1990g). For legend see Fig. 30.

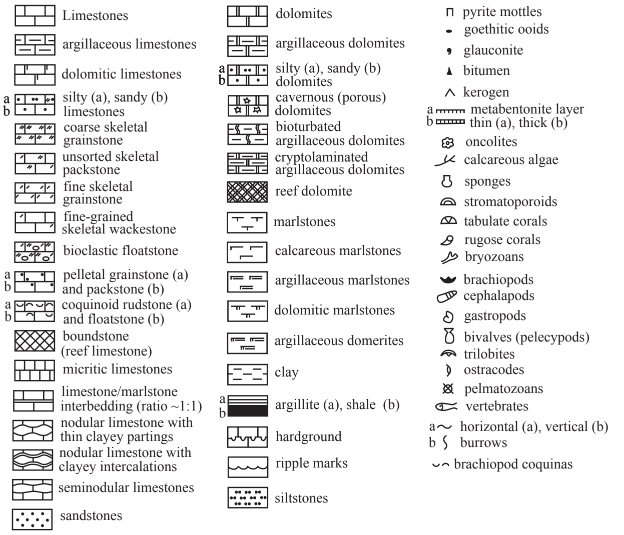


Fig. 30. Lithological legend to the logs of the outcrops for figs 29, 32, 35, 39, 41, 46, 49, 52, 55 (Nestor 1990a).

Excluding the uppermost bed (1) rich in corals and stromatoporoids, the rest of the section contains a very poor assemblage of fossils. Only conodonts (see Fig. 29) and in some beds fragments of leperditian ostracodes have been recorded.

The exposed rocks have been formed during a regressive phase of the development of the Baltic Silurian Basin and are related to the first tongue of lagoonal/restricted shelf deposits which is preserved in the Estonian sequence. The section shows a transition from lagoonal and restricted shelf deposits (most of the section) to more or less normal-marine sediments at the top.

Common stromatoporoids and tabulate corals in Pakamägi cliff:

stromatoporoids *Ecclimadictyon macrotuberculatum* (Riabinin, 1951),
Intexodictyon avitum Nestor, 1964,
Intexodictyon olevi Nestor, 1964;
tabulate corals *Parastriatopora celebrata* Klaamann (1962b),
Sinopora operta Klaamann (1966),
Palaeofavosites balticus (Rukhin, 1937).

Stop 8. Päri quarry (Llandovery)

A broad, shallow, disused quarry is located 5 km south-west of Kullamaa village on a flat limestone hillock (Fig. 31). In earlier German literature the outcrop was known by the name Kattentack and it serves as a type locality of several coral and stromatoporoid species

Argillaceous nodular limestones, containing brachiopods *Pentamerus oblongus* (Sowerby), are exposed in this outcrop. They belong to the upper part of the Rumba Formation of the Adavere Stage (Fig. 32A). The following section can be observed in the deepest part of the quarry:

1. 1.30 m - irregularly nodular, argillaceous limestone (skeletal packstone) with lense-like interlayers of *Pentamerus* rudstone and skeletal grainstone. The basal 15 cm is highly argillaceous rock, in the uppermost 40 cm grainstone lenses are rare. Fig. 32B shows a detail through a ripple mark filled by a *Pentamerus*-rudstone.
2. 0.05 m - argillaceous marlstone lying on a double discontinuity surface.
3. 1.05 m - different grey argillaceous, mostly irregularly nodular limestones (packstones; containing pentamerid and stromatoporoid rudstone lenses, some beds of microcrystalline limestones and thin marl intercalations.
4. 0.10 m - grey argillaceous limestone with marl intercalations.
5. 1.15 m - greenish-grey, irregularly nodular, argillaceous skeletal limestone (packstone) with lenses

of skeletal grainstone (*Pentamerus*-coquinas). Upper 15 cm contains purer limestone with a pyritic discontinuity surface at the top.

6. 0.06 m - bioturbated metabentonitic bed with fragments of pentamerids.
7. 0.1 m - grey calcitic marl with grainstone nodules.
8. 0.1 m - brownish grey microcrystalline irregularly nodular limestone (packstone).

A detailed study of the section has revealed a rather distinct microcyclicity. Usually a cycle begins with a thin marlstone layer, upwards the clay content decreases and grainstone or coquinoid rudstone lenses appear. The cycle ends with a distinct discontinuity surface.

The section is rich in fossils although intense sampling has considerably reduced their abundance. Particularly common are typical members of the *Pentamerus oblongus* community, including numerous corals e. g. *Paleofavosites obliquus* (Sokolov), *Calostylis luhai* Kaljo and stromatoporoids *Clathrodictyon variolare* (Rosen). Rather common are the gastropods *Boiotremus* cf. *longitudinalis* (Lindström) and *Hormotoma* sp. and trilobites *Calymene frontosa* Lindström, *Encrinurus* (*Nucleurus*) *rumbaensis* Rosenstein. Practically no ostracodes and chitinozoans have been found and only scanty conodonts (*Panderodus* sp., *Ozarkodina* sp.) and thelodonts (*Thelodus* sp.) have been recorded.

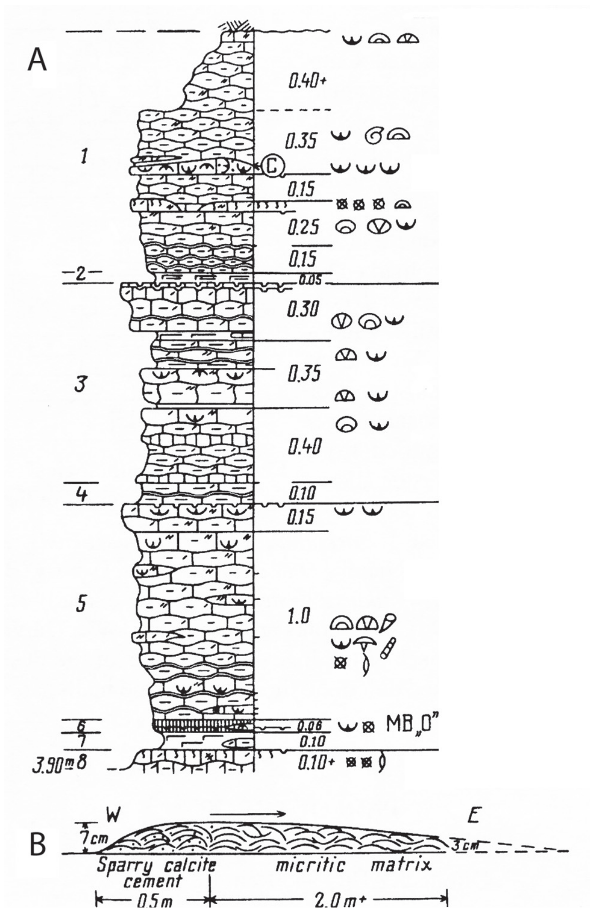


Fig. 32. Lithological column of the Päri quarry (A), ripple mark filled by a Pentamerus rudstone (B) (Modifyed from Kaljo and Einasto 1990). For legend see Fig. 30.

Many species of stromatoporoids and corals are described or found from this outcrop, including

stromatoporoids: *Clathrodictyon delicatulum* Nestor, 1964 (type),
Ecclimadictyon fastigiatum (Nicholson, 1886b),
Clathrodictyon regulare (Rosen, 1867),
Clathrodictyon variolare (Rosen 1867),
Forolinia pachyphylla (Nicholson, 1886a),
Oslodictyon suevicum (Nicholson 1886a);

Fig. 31. Päri quarry.

tabulate corals: *Palaeofavosites aliquantulus* Klaamann, 1962b (type),
Palaeofavosites septosus Sokolov, 1952,
Palaeofavosites jaaniensis Sokolov, 1952,
Mesofavosites validus Klaaman, 1964 (type),
Mesofavosites obliquus Sokolov, 1951,
Favosites igens Klaamann, 1962b (type),
Subalveolites panderi Sokolov, 1955,
Subalveolites eichwaldi Sokolov, 1955,
Subalveolitella majuskula Klaamann, 1962b (type),
Placocoenites pellicula Klaamann, 1964 (type),
Catenipora exilis Eichwald, 1829 (type),
Catenipora elegans (Ficher-Benzon, 1871),
Catenipora maxima (Fisher-Benzon, 1871) (type),
Propora exiqua (Billings, 1865) is found there,
Aulopora assueta Klaamann, 1966 (types),
Adaverina adaverensis (Klaamann, 1966) (type),
A. acclinis (Klaamann, 1966) (type),
Sinopora callosa Klaamann,1966 (type);

rugose corals: *Prodarwinia speciosa* (Dybowski, 1873),
Calostylis luhai Kaljo, 1958.

Stop 9. Koguva quarry (Wenlock)

Koguva quarry is situated on the north-western coast of Muhu Island, 2 km northeast of the Koguva village. It exposes a contact of the Wenlock Jaani and Jaagarahu stages represented by dolomitic marlstones of the Paramaja Member and reef and flaggy dolomites of the Kesselaid Member, correspondingly (Fig. 33, 34).

The lowermost strata crop out at the north-eastern end of the quarry (Fig. 35A, B, point 1) indicating the contact between the Paramaja argillaceous dolomitic marlstones and the Kesselaid mud-mounds and surrounding rocks.

The south-eastern quarry wall exposes the upper contact of the mud-mounds and above-lying flaggy dolomites (Fig. 35A, C, point 2).

At the point 1 dark-grey massive argillaceous dolomitic marlstones (1) crop out at the bottom of the quarry (Fig. 35B). The upper surface of the dolomitic marlstone is wavy, dipping down below the mud-mounds of the Kesselaid Member and rising in between (amplitude is up to 1.7 m). The best exposed mud-mound (2) begins from the upper surface of the Paramaja dolomitic marlstones and expands upwards (visible dimensions are 4.7x11 m) in the middle of the north-eastern wall of the quarry. It consists of dark-grey pyrite-mottled massive fine- to microcrystalline dolomite. The mound lacks visible skeletal framework of fossils. The mound rock contains thin discontinuous curved partings of dolomitic marlstone. Surrounding rock for the lower part of the mud-mounds (3) is medium-porous coarse-crystalline dolomite - probably dolomitized pelmatozoan grainstone. Upwards and further from the mounds the rock becomes more fine-grained and seemingly grades from the dolomitized grainstone into packstone.

Fig 33. Koguva quarry.

Fig. 34. Mud mound in Koguva quarry.

A lenticular body of comparatively massive porous dolomites (4) appears at the same level with the stratifies surrounding rocks. Its relict texture confirms that it consisted originally of fine-dendroid fossils (?*Coenites*) in the lower part and of shells (?brachiopods) in the upper part, while the adjoining stratified rock (3) originally consisted mostly of the fragments of pelmatozoans.

Above the described lenticule a peripheral section of a mud-mound (5) crops out with numerous curved partings of dolomitic marlstone marking irregular stratification of mound rock in its periphery. In the upper part of the section the intermound rock (6) is represented by flaggy, slightly kerogenous argillaceous dolomite.

At point 2 (south-eastern quarry) wall topmost part of a mud-mound and above-lying flaggy dolomites can be observed (Fig. 35C). In the ascending order there are exposed:

(1) 1.2 m - dack-grey pyrite-mottled massive fine-

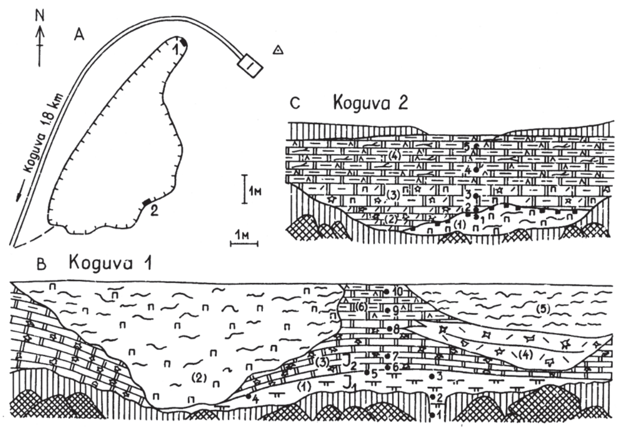


Fig. 35. Location of the Koguva quarry (A) at the points 1 (B) and 2 (C). Numbers in brackets indicate lithological units described in the text (Modifyed from Nestor 1990e).

grained dolomite of the upper part of a mud-mound. The upper surface of the mound has very intense pyrite impregnation and may be erosional.
(2) 0.2-0-7 m - grey dolomite with relict fine-grained texture (dolomitized packstone or grainstone) which occurs only on the sloping upper surface of the mound.
(3) 0.8 m - brownish-grey flaggy fine-crystalline slightly argillaceous dolomite (dolomitized wackestone or packstone), which contains specific tubular stylolitic structures in the upper part.
(4) 2.30 m - brownish-grey flaggy argillaceous dolomite with partings of brown kerogenous argillaceous dolomite on the bedding planes.

The fauna in the Koguva quarry is poor containing brachiopods *Leptostrophia filosa* (Sowerby), *Atrypa reticularis* (L.), *Leptaena* sp., chitinozoans *Conochitina claviformis* Eisenack, *C*. cf. *mamilla* Laufeld, *C*. cf. *leptosoma* Laufeld, *Margachitina margaritana* (Eis.), *Ancyrochitina* sp. and trilobites *Encrinurus punctatus* (Wahlenberg), *Calymene* sp. indet.

The replacement of dolomitic marlstones of the transitional facies belt with the peculiar facies of mud-mounds can be examined in the regressive succession of the outcrop. And they are replaced with the kerogenous argillaceous dolomites of probably restricted shelf genesis in the upper part of section. The deposits of the mud-mound facies, which resemble sediments of semi-isolated patch-reef environments are represented here. No skeletal remains of frame-building organisms have been found in the massive reef bodies of the Kesselaid Member therefore the latters are treated as mud-mounds of microbial origin, formed in restricted shelf environment.

Day 3, August 20, 2007

Stop 10. Liiva cliff (Wenlock)

The locality is situated in the northern coast of Saaremaa, few hundred meters from the road between Võhma and Leisi. It is about a kilometer long and only 1.5 meters high coastal cliff (Fig. 36). The Ninase Member forms the most part of the cliff section above the Mustjala Member. The latter forms the base of the locality. Two different types of facies occur in the Jaani Stage (Wenlock), the shoal facies (Ninase Member) and the open shelf facies (Mustjala Member).

The thickness of the Ninase Member is about 1 m. It consists of grainstones with the fragments of brachiopods and crinoids (Fig. 37). A few tabulate corals *Paleofavosites secundus*? (Klaamann) (Mõtus 2006)are found from the layers of marlstone, intercalating with grainstone.

The Mustjala Member above the sea level is approximately 50 cm thick when the shoreline is not covered by pebbles and the sea level is relatively low. Marls with interlayers and nodules of biomicritic limestones form the upper part of the Mustjala Member (Fig. 37). It contains rich fauna of tabulate corals, stromatoporoids, rugose corals, brachiopods and crinoidal debris.

<u>Common stromatoporoids and tabulate corals in the Liiva cliff:</u>

stromatoporoids *Clathrodictyon affabile* Nestor, 1966 (type),
Clathrodictyon kudriavtsevy Riabinin, 1951,
Petridiostroma simplex (Nestor, 1966) (type),
Densastroma pexisum (Yavorsky, 1929),
Stromatopora impexa Nestor, 1966 (type);

tabulate corals *Thecia tenuicula* Klaamann, 1961 (type species),
Mesofavosites obliquus Sokolov, 1951,
Syringolites kunthianus (Lindström, 1896),
Subalveolites sokolovi Klaamann, 1961 (type),
Catenipora oriens Klaamann, 1961 (type),
Heliolites interstinctus (Linnaeus, 1767),
Propora tubulata (Londsdale, 1839),
Mesofavosites secundus Klaamann, 1961.

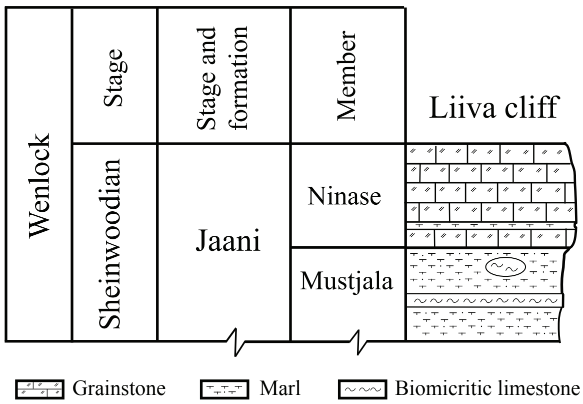


Fig. 37. Stratigraphical scheme with the lithological column of Liiva cliff (Modifyed from Mõtus 2006).

Fig. 36. Liiva cliff.

Stop 11. Panga cliff (Wenlock)

The Panga cliff is the highest (20 m) and the most prominent land-form on the northern coast of Saaremaa Island near Mustjala village ranging arch-shaped about 3 km from north-east to south along the seashore (Fig. 38). As a wonderful sight and an important object for scientific studies, the Panga cliff (also called the Mustjala cliff) has been taken under state protection. In the Panga cliff the Jaani and Jaagarahu stages of the lower Wenlock are exposed. The outcrop consists of two escarpments.

The first escarpment on the seashore is composed of variably argillaceous limestones and dolomites of the Jaani Stage. Porous dolomites of the Vilsandi Beds of the Jaagarahu Stage containing single bioherms crop out in a smaller escarpment, remaining inland of the main section. One more 10 m high underwater escarpment marked by a surf zone is in the sea. It is composed of highly argillaceous dolomitized limestones.

The section given in the figure represents the eastern part of the cliff (Fig. 39) and it is following:

Mustjala Member

1. 10 m - underwater part of the cliff, which consists of grey dolomitic marlstone containing argillaceous dolostone nodules, lenses and interbeds.
2. 0.6 m - grey argillaceous dolostone.
3. 1.0 m - bioturbated argillaceous dolostone with dolomitic marlstone interbeds.
4. 1.8 m - dolomitic marlstone with argillaceous dolostone interbeds and nodules and erosional surface at the top.

Ninase Member

5. 1.9 m - similar to bed 3 but contains 35 cm high small "bioherms" formed by encrusting bryozoans and fine-grained dolostone (grainstone) at the base.
6. 1.2 m - analogous to bed 5 with bryozoan bioherms (1.3x1.2 m) in the upper part.
7. 2.0 m - interbedding of coquinoid biomorphic to skeletal secondary dolostone and argillaceous dolostone with dolomitic marlstone interbeds.
8. 1.3 m - similar to bed 7

Paramaja Member

9. 0.4 m - bioturbated skeletal argillaceous dolostone.
10. 1.2 m - dolomitic marlstone with scarce skeletal debris and interbeds of skeletal argillaceous dolostone.
11. 2.3 m - grey thinbedded highly argillaceous dolostone containing scarce and fine skeletal debris.

Fig. 38. Panga cliff.

Jaagarahu Formation

12. 1.5 m thick-bedded skeletal dolostone.
13. 1.0 m - slightly argillaceous dolostone with unevenly distributed skeletal debris.
14. 1.3 m - porous dolostone containing small bioherms.

The Mustjala Member is the most fossiliferous. A lens-like interlayers containing abundantly tabulate and stromatoporoid colonies occur in several outcrops and core sections in the upper part of the Mustjala member there occur a lens-like interlayers containing abundant tabulate and stromatoporoid colonies. The species list is given below. Loose material at the coast has yielded *Clathrodictyon variolare*, *Clathrodictyon delicatulum* and *Oslodictyon suevicum*, which is supposed to be an erratic material from the Adavere Stage. The brachiopods in the locality are known

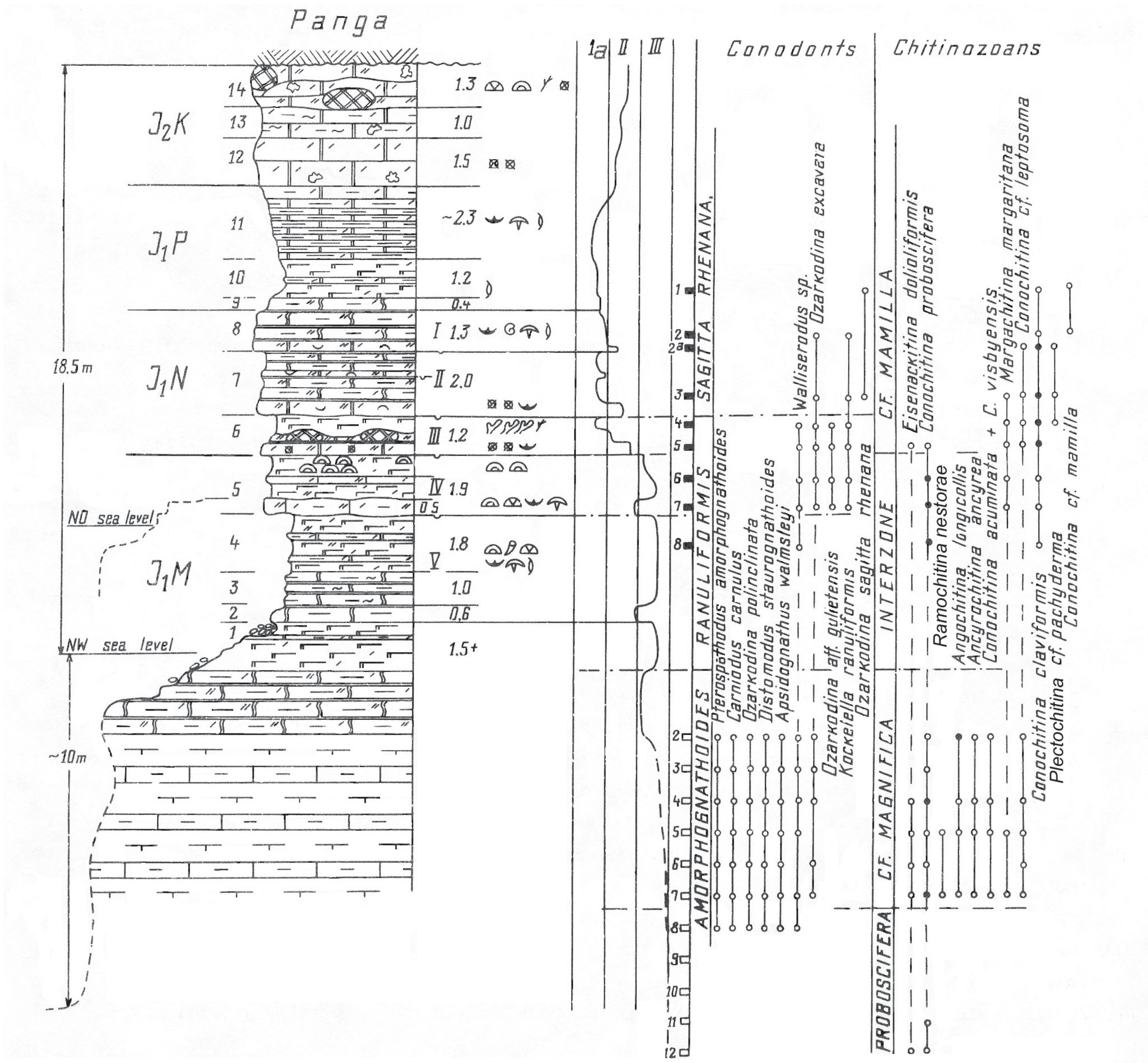


Fig. 39. The Panga Cliff section. The facies curve corresponds to the facies belts: Ia - restricted shelf, II - shoal. III - open shelf (from Rubel and Einasto 1990). For legend see Fig. 30.

from all members of the Jaani Stage (*Estonirhynchia estonica*, *Stegerhynchus borealis, Atrypa reticularis*, *Dolerothis rustica*, *Microsphaeridiorhunchus nucula*, *Dalejina hybrida*, *Whitfieldella* sp., *Resserella* sp., *Leptaena* sp. From the loose material of the Ninase Member also trilobites *Calymene blumenbachi* and *Proetus concinnus osiliensis* have been recorded. The conodont zones established permit good correlation of the section with the Silurian standard. The chitinozoan zones, in turn, link the section to the regional stages. Thus the distinction of the *Conochitina proboscifera* zone in the lower part of the subwater escarpment confirms the assignment of the corresponding beds already to the Adavere Stage.

Common stromatoporoids and tabulate corals in Panga cliff:

stromatoporoids *Petridiostroma simplex* (Nestor, 1966),
Densastroma pexisum (Yavorsky, 1929),
Eostromatopora impexa Nestor, 1966,
Oslodictyon suevicum (Nicholson, 1886a);
tabulate corals *Catenipora panga* Klaamann, 1961,
Catenipora quadrata (Fischer-Benzon, 1871),
Halysites senior Klaamann, 1961 (type),
Syringopora novella Klaamann, 1961 (type),
Syringolites kunthianus (Lindström, 1896),
Subalveolites sokolovi Klaamann, 1961 (type),
Thecia tenuicula Klaamann, 1961.

Stop 12. Abula cliff (Wenlock)

The Abula cliff (Figs 40-41) is situated on the eastern coast of Tagalaht Bay, 3 km north of Mustjala-Veere road. The cliff exposes topmost lagoonal dolomitic marls of the Vilsandi Beds and the basal part of the Maasi Beds belonging to the Jaagarahu Stage. Luha (1934) referred to these rocks as to Kurevere Limestone.

Fig. 40. Abula cliff.

The section is as follows:

1. 0.4+ m - skeletal wackestone, rich in stromatoporoids, with 0.1 m thick lenses of skeletal marl in the lower part; at the base - a distinct discontinuity surface.
2. 0.7 m - light-grey wavy-bedded limestone with pelletal structure and several discontinuity surfaces in the upper 15-20 cm, stromatoporoids are common, in the middle of the bed brachiopod-shell accumulations occur.
3. 0.6 m - light yellowish-grey fine-nodular pelletal limestone with stromatoporoids, tabulate corals (*Favosites mirandus* is the commonest), ostracodes and calcareous algae; the lower 0.1 m contains marl; the upper 0.2 m comprises irregularly nodular skeletal wackestone with 0.15 m thick and 1.5 m long skeletal grainstone lenses; large *Megalomus* shells are found.
4. 0.10 - 0.15 - grey fine-grained pelletal limestone.
5. 0.5 - yellowish-grey fine-nodular pelletal and skeletal, slightly argillaceous limestone; brachiopods are common, while tabulate corals are rare; the basal 10-15 cm is more argillaceous; a discontinuity surface occurs at the base.
6. 0.2 - thin-bedded skeletal (ostracode-) packstone with 1-2 cm thick calcareous marl laminations.
7. 0.5 - yellowish-grey wavy-bedded- pelletal limestone containing large ostracodes and gastropods at the base a 3 cm thick ostracode grainstone layer with small oncolites.

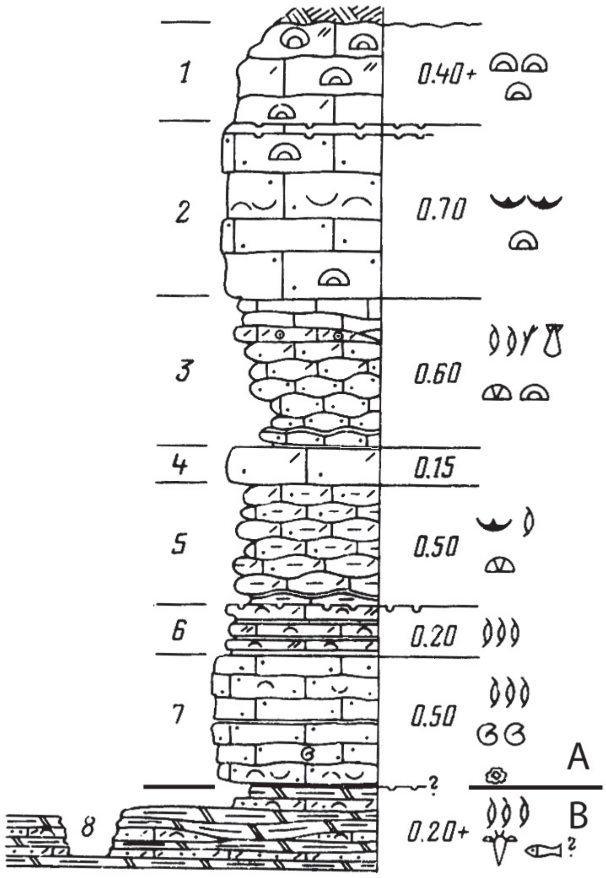


Fig. 41. The section of Abula cliff with the Maasi (A) and Vilsandi (B) beds of the Jaagarahu Stage (Einasto 1990a). For legend see Fig. 30

8. 0.2 (exposed on the sea bottom) - greenish-grey calcareous domerite with 1-2 cm lenses and laminations of fine-grained skeletal and pelletal packstone; large ostracodes and *Eurypterus* fragments occur.

The last bed (= the top of the Vilsandi Beds) forming the first lagoonal complex in the Estonian Wenlock - is presumably of the same age as the *Pterygotus* Marl on Gotland. Just below these lagoonal dolomitic marlstones a stromatoporoid limestone bed with *Vikingia tenuis* occur, exposed north of Abula cliff.

<u>Common stromatoporoids and tabulate corals:</u>

stromatoporoids *Clathrodictyon kudriavzevi* Riabinin, 1951,
Vikingia tenuis (Nestor, 1966) (type),
Ecclimadictyon macrotuberculatum (Riab., 1951);
tabulate corals *Thecia confluens* (Eichwald, 1854),
Favosites mirandus Sokolov, 1952.

Stop 13. Suuriku and Kuriku cliffs (Wenlock)

Suuriku

Suuriku cliff is located in the north-eastern coast of Tagamõisa peninsula in Saaremaa. The outcrop is 1.6 km long and about 8 m high (Fig. 42). In this locality the Ninase and Mustjala members of the Jaani Stage (Wenlock) are exposed. Coarse-grained skeletal grainstones with interlayers of marls of Ninase Member form the largest upper part of the section. The rock is mainly composed of pelmatozoans fragments. Brachiopods and gastropods are abundant, rugose corals are less frequent. Bioherms with abundant bryozoans (*Ceramopora*, *Lioclema*) occur in the middle part of the Ninase Member. The lower part of the Suuriku section consists of marlstones of the Mustjala Member. Both, Ninase and Mustjala members contain tabulate (favositids) and rugose corals. Besides, in the upper part of the Mustjala Member halystids are abundant. Many loose, eroded specimens of heliolitids, favositids and halysitids are spread along the coast.

Fig. 42. Suuriku cliff.

Common stromatoporoids and tabulate corals in Suuriku cliff:

stromatoporoids *Petridiostroma simplex* (Nestor, 1966),
Densastroma pexisum (Yavorsky, 1929),
Eostromatopora impexa Nestor, 1966;
tabulate corals *Mesofavosites imbellis* Klaamann, 1961,
Heliolites interstinctus (Linnaeus, 1767),
Subalveolites sokolovi Klaamann, 1961,
Propora tubulata (Londsdale, 1839),
Palaeofavosites suurikuensis Klaamann, 1961 (type).

Kuriku

Kuriku cliff is very close to the Suuriku cliff. The outcrop is smaller and lower (about 2 meters high). The Ninase Member of the Jaani Stage is exposed in Kuriku cliff. Cavernous dolomites and dolomitic boundstones with the layers of marls are characteristic to the upper part of section. Tabulate corals, rugose corals and bryozoans are found. Lower part of section consists of crinoid dolomites and coarse-grained skeletal grainstones. Small bioherms are found in the middle part of section.

Similar species as in Suuriku cliff are present also in Kuriku.

Stop 14. Undva cliff (Wenlock)

Undva cliff is situated in the northern end of Tagamõisa peninsula, few kilometers north from Suuriku and Kuriku cliffs (Fig. 43). The cliff is 350 m long and 2.5 m high. The Mustjala and Ninase members of the Jaani Stage (Wenlock) are exposed here as in the most cliffs of the northern coast of Saaremaa Island (Liiva, Panga, Suuriku and Kuriku cliffs). The Ninase member is 1.5 m thick consistsing of coarse-grained skeletal grainstones with interlayers of marls. Bryozoans, brachiopods, crinoids and few rugose corals can be found. About 50 m to the east, a 45 cm large bryozoan bioherm is exposed in the upper part of section.

If the sea level is low and limestone pebbles are not covering the beach, Mustjala beds below the Ninase beds are well exposed. Marls of blue-green colour contain nodules of biomicritic limestone in the upper part of member. Marls contain abundant brachiopods, crinoids, bryozoans, corals and stromatoporoids (see Liiva, Suuriku and Panga cliffs).

Fig. 43. Undva cliff.

Corals and stromatoporoids are same as in Liiva, Panga and Suuriku cliffs.

Stop 15. Jaagarahu quarry (Wenlock)

The Jaagarahu old quarry is situated on the western coast of Saaremaa, 6 km northwest from the Kihelkonna settlement. In the 1930-s limestone was quarried (about 300 tons per day) and exported mainly to Sweden, Finland, Poland and Germany. The quarry exposes bioherms and the surrounding limestone with algae, corals and stromatoporoids from the Jaagarahu Stage (Figs 44, 45).

In the southern corner of the quarry, lagoonal dolomitic marlstones of the topmost Vilsandi Beds are exposed, as well as the basal part of the overlying Maasi Beds (Fig. 46). In this point the following section is described (from base):

1. 1.6+ m (mostly under the water; except in the eastern part of the quarry) - light-grey massive boundstone of shoal reef facies. The commonest fossils of the reef are *Vikingia tenuis*, *Favosites mirandus*, *Solenepora filiformis*, *Wetheredella multiformis*, *Rothpletzella munthei.*
2. 0.8 m (0.4 m above the water) - bluish-grey dolomitic skeletal argillaceous packstone of backreef origin. The rocks have fine pyritic pattern and contain calcite crystals. Stromatoporoid and tabulate coral colonies are not in the living position bearing erosion marks.
3. 0.5 m - greenish- or bluish-grey thin-bedded argillaceous dolostone with little skeletal debris are exposed. Numerous big ostracodes *Leperditia* occur on some bedding planes. The upper surface of the bed shows mud cracks with abraded edges. It marks the boundary of the Vilsandi and Maasi beds.

Fig. 44. Jaagarahu quarry.

Fig. 45. Stromatoporoids in Jaagarahu quarry.

4. 0.8+ m - bluish-grey thickbedded or massive microcrystalline pelletal limestone with slight pyritic patterns are exposed next. The rock contains abundant abraded stromatoporoids and dolomite pebbles from the underlying strata. The lower part of the bed is more argillaceous, contains ostracode debris and abundant *Cladopora perrara*.

Elsewhere in Saaremaa (except Sõrve Peninsula) this basal part of the Maasi Beds consists of floatstones and skeletal limestones with discontinuity surfaces and oncolites. It corresponds to the Tofta Limestone of Gotland. Accordingly, the topmost Vilsandi Beds are of the same age as the Pterygotus-Marl (Högklint d) of Gotland.

<u>Common stromatoporoids and tabulate corals in Jaagarahu quarry</u> (the fauna is similar to that in Abula cliff):

stromatoporoids *Clathrodictyon kudriavzevi* Riabinin, 1951,

Vikingia tenuis (Nestor, 1966) (type),

Ecclimadictyon macrotuberculatum (Riabinin, 1951);

tabulates *Thecia confluens* (Eichwald, 1854),

Favosites mirandus Sokolov, 1952.

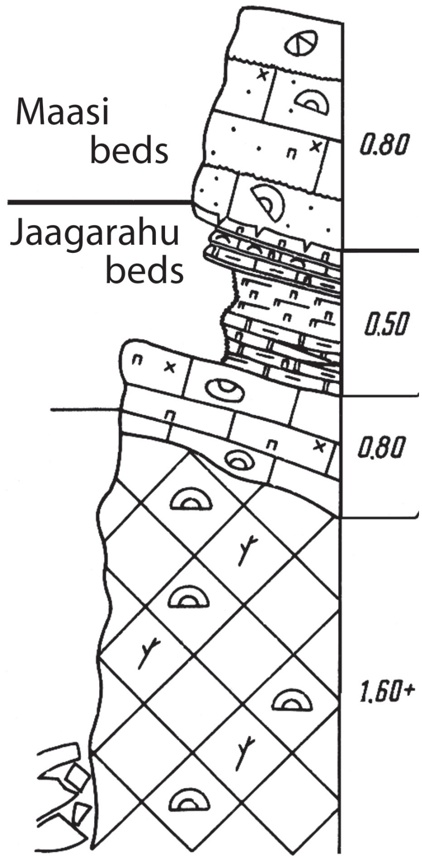


Fig. 46. The section of Jaagarahu quarry (Modifyed from Einasto 1990b). For legend see Fig. 30

Stop 16. Lennujaama trench (Ludlow)

This is a small locality near the Kuressaare - Roomassaare road outside Kuressaare town (Fig. 47). It contains Kudjape beds of the Kuressaare Stage (upper Ludlow). Kudjape beds are represented by nodular argillaceous biomicritic limestones containing coquinoid interlayers with *Atrypoidea* and numerous colonial rugose corals *Entelophyllum*. Also some favositids can be found in this locality.

Rugose coral: *Entelophyllum articulatum* (Wahlenberg, 1821)

Fig. 47. Lennujaama trench.

Day 4, August 21, 2007

Stop 17. Kogula quarry (Ludlow)

The new Kogula quarry (Fig. 48) is situated 1 km south-west of the main Kogula crossroad. The middle part of the Sauvere Beds of the Paadla Stage is exposed.

Fig. 48. Kogula quarry.

The sequence is as follows (Fig. 49):

1. 0.2+ - brownish-grey kerogeneous and bioturbated argillaceous dolostone with lenses of domerite, discontinuity surface at the top.
2. 0.2 - bioturbated slightly argillaceous dolostone. The upper part of the bed is more calcareous; brachiopods *Hermannina*, *Didymothyris* and branching and massive tabulate corals occur.
3. 0.2-1.0 - light-grey massive rudstone with small bioherms (height 1 m, width from some meters to 20 cm), the base of the bioherm consists of rounded tabulate corals and stromatoporoids.
4. 0.25 - greenish-grey bioturbated packstone alternating with wavy dark-grey interbeds of fine-grained skeletal grainstones; from the base towards the top packstone beds become thinner and those of grainstone thicker.
5. 0.7 m - greenish-grey bioturbated dolomitic argillaceous wackestone forming wavy beds; in the lower part two 1-2 cm interbeds of argillaceous domerite can be distinguished.
6. 0.5 m - grey bioturbated unsorted packstone at the base and skeletal grainstone at the upper part of the beds, a pyritic discontinuity surface occurs at the top.
7. 0.15 - dark limestone, occurring between discontinuity surfaces, at the base - fine-grained skeletal grainstone, in the upper part - unsorted skeletal packstone.
8. 0.3 - strongly bioturbated argillaceous wackestone resembling bed 5, marlstone interlayers on both surfaces.

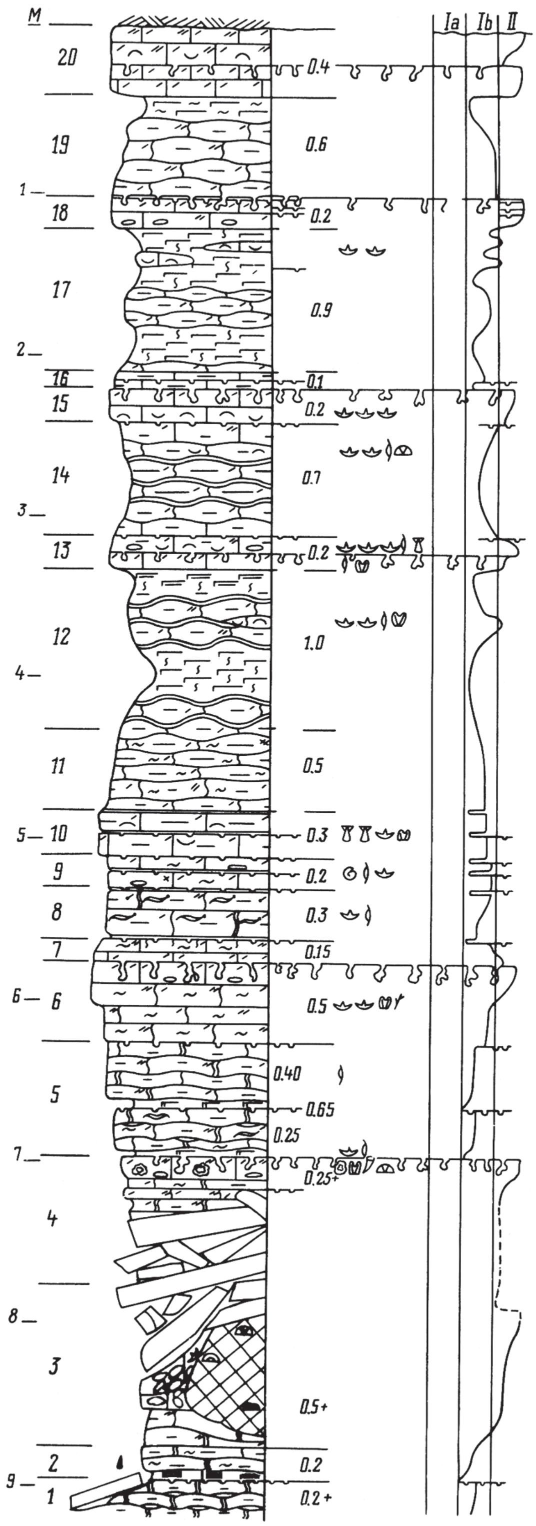


Fig. 49. The Kogula quarry section: middle part of the Sauvere Beds of the Paadia Stage. The facies curve corresponds to the facies belts: Ia - lagoonal, Ib - restricted shelf, II – shoal (Einasto 1990c). For legend see Fig. 30.

9. 0.2 - limestone like bed 7, with some pebbles, discontinuity surfaces occur.
10. 0.3 - homogeneous fine-grained skeletal argillaceous packstone with abundant *Ilionia*, discontinuity surface and marl interbed occur in the middle.
11. 0.5 - wavy-bedded to lenticular nodular bioturbated unsorted skeletal wackestone, higher becoming more argillaceous.
12. 1.0 - lenticular nodular bioturbated argillaceous wackestone alternating with burrowed marlstone, the most argillaceous part in the section, in the upper part containing lenses of *Didymothyris*-Limestone.
13. 0.2 - fine-grained skeletal grainstone at the base argillaceous *Didymothyris*-Limestone with pebbles in the upper part, strongly pyritized discontinuity surface occurs in the middle.
14. 0.7 - resembles bed 12, the middle part is the most argillaceous, on the upper surface a discontinuity surface.
15. 0.2 - grey limestone, at the base *Didymothyris*-Limestone, in the upper part purer limestone, a sharp discontinuity surface occurs on the upper boundary.
16. 0.1 - argillaceous packstone with a discontinuity surface in the middle.
17. 1.9 - like bed 12 with the maximum clay content.
18. 0.2 - packstone with pebbles containing two discontinuity surfaces at the base, fine-grained skeletal grainstone in the upper part, a strongly pyritized double discontinuity surface on the upper boundary.
19. 0.6 - wavy-bedded bioturbated argillaceous wackestone and marl on the top.
20. 0.4 - fine-grained skeletal grainstone at the base, distinct discontinuity surface in the middle and unsorted skeletal packstone in the upper part.

From the old quarry, situated 1 km northward and corresponding to beds 5 to 11 in the present quarry, the abundant fauna is recorded: stromatoporoids and tabulate corals see below; brachiopods *Didymothyris*, *Protochonetes, Salopina*, *Morinorhynchus*; molluscs *Ilionia*, *Holopea*, *Murchisonia,* fishes *Phlebolepis*, *Thelodus* sp.; conodonts *Ozarkodina confluens*, *O. excavata excavata*, *Oulodus siluricus*, etc.

Stromatoporoids and tabulate corals are following:

stromatoporoids *Araneosustroma stelliparratum* Nestor, 1966,
Stromatopora bekkeri, Nestor, 1966,
Parallelostroma typicum (Rosen, 1867);
tabulate corals *Thecia swinderniana* (Goldfuss, 1829),
Favosites kogulaensis Sokolov, 1952,
F. forbesi, Milne-Edwards & Haime, 1851,
F. psuedoforbesi, Sokolov, 1952,
F. subgothlandicus, Sokolov, 1952,
Syringopora schmidti Chernyshev, 1937,
Parastriatopora coreaniformis (Sokolov, 1952),
Thecia confluens (Eichwald, 1854)

Stop 18. Katri cliff (Ludlow)

Katri cliff is located in the south-western coast of Saaremaa, 4 kilometers south from the Karala village. The section is up to 1 meter high when the coast is not covered by eroded limestone pebbles (Fig. 50). The Uduvere beds of the Paadla Stage (Ludlow) are exposed. The largest part of the section is represented by biostrome. It includes abundant fauna of stromatoporoids corals, brachiopods and algae.

Fig. 50. Katri cliff. Photo by G. Baranov.

Common stromatoporoids and tabulate corals in Katri cliff:

stromatoporoids *Parallelostroma typicum* (Rosen, 1867),
Plexodictyon katriense Nestor, 1966 (type),
Pachystylostroma sp.,
Petridiostroma convictum (Yavorsky, 1929),
Simplexodictyon yavorskyi (Nestor, 1966) (type),
Plectostroma intermedium (Yavorsky, 1929),
Plectostroma mirificum Nestor, 1966 (type),
Syringostromella borealis (Nicholson, 1891);
tabulate corals *Laceripora cribosa* Eichwald, 1854,
Favosites pseudoforbesi Sokolov, 1952,
F. kogulaensis Sokolov, 1952,
Syringopora multifaria Klaamann, 1962a,
Syringopora affabilis Klaamann, 1962a (type),
Thecia swiderniana (Goldfuss, 1829),
Alveolites sp.

Stop 19. Kaugatuma cliff (Pridoli)

The 2.5m high Kaugatuma cliff is situated on the western coast of Sõrve Peninsula, some kilometers south from its neck and about 100 metres from the sea (Fig. 51). Rocks of two different facies types in the regressive succession can be seen representing the middle part of the Äigu Beds of the Kaugatuma Stage (Fig. 52A):

1. 05+ m - greenish-grey nodular argillaceous wackestone of open shelf origin. Skeletal debris consists mostly of echinoderm and brachiopod fragments. Ostracodes, trilobites, gastropods, bryozoans and fishes are not so common.

2. 1.5+ m – yellow-grey coarse-grained wavy-bedded crinoidal limestone of forereef origin is exposed. Grain size and sorting degree of skeletal debris is variable. Some bedding plains show erosion marks. Large colonies of *Syringopora blanda* Klaamann (30 cm in diameter) occur.

A great number of fossil species has been recorded from the Kaugatuma locality including trilobites, *Proetus nieszkowskii, Calymene schmidti, C. kaugatumensis, C. dnestroviana, Acaste dayiana*, *Eophacops helmuti*, tabulate corals and stromatoporoids (see below). However, they are collected from the loose material at the beach and they obviously came from the lower-laying strata. The following vertebrate remains have been found from the cliff: *Nostolepis striata*, *Gomphonchus sandelensis*, *Poracanthodes porosus*; *Thelodus parvidens* from the lower part and *Nostolepis gracilis* from the upper part. Most of chitinozoans identified from the section (*Angochitina echinata*, *Eisenackitina lagenomorpha*) belong to the wideranging species, only *Eisenackitina filifera* is

Fig. 51. Kaugatuma cliff.

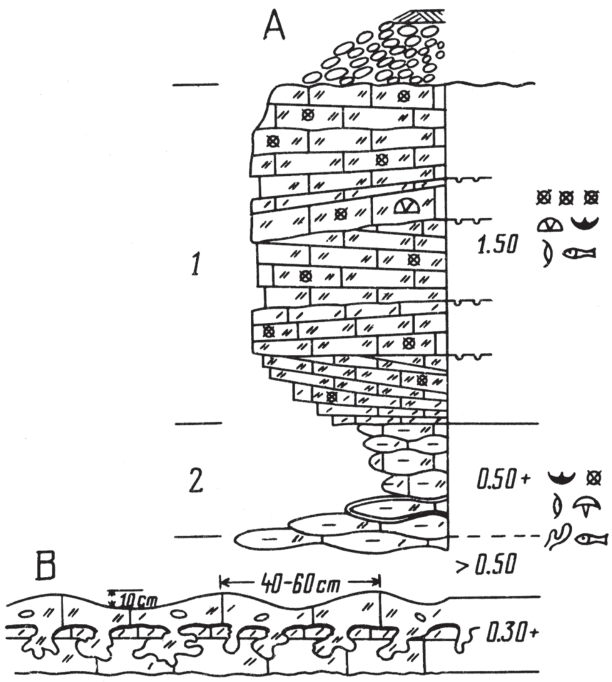


Fig. 52. (A) The Kaugatuma Cliff section: Upper Äigu Beds of the Kaugatuma Stage. (B) Ripple marks exposed at the present sea level (Einasto 1990d). For legend see Fig. 30.

characteristic of the upper Äigu Beds.

About 1 km south of the cliff large east-west directed well-preserved Silurian ripple marks are exposed on a 200 m long seashore, observable only when the sea level is low. Ripple marks are best preserved in a 30 cm thick interval of the section, immediately underlying the basal part of the cliff. Distance between the rounded crests is 40-60 cm (max up to 80 cm), height up to 10 cm. Under the uneven discontinuity surface that forms the base of this ripple mark bed, up to 10 cm of dark-grey unsorted skeletal packstone is exposed.

Common stromatoporoids and tabulate corals in the Kaugatuma cliff:

stromatoporoids *Actinostroma astroites* (Rosen, 1867) (type),
Stromatopora astroites Rosen, 1867 (type);
tabulate corals *Palaeofavosites finitimus* Klaamann, 1962a (type),
P. moribundus Sokolov, 1952,
Favosites similis Sokolov, 1952,
Favosites vicinalis Klaamann, 1962 (type),
F. forbesi Milne-Edwards & Haime, 1851,
F. terraenovae Chernyshev, 1937,
Multisolenia reliqua Sokolov, 1952,
Syringopora blanda Klaamann, 1962a,
Aulopora sp.

Stop 20. Lõo cliff (Pridoli)

Lõo cliff is situated south of Kaugatuma cliff in the Sõrve peninsula (Fig. 53). A 1.5 meters thick section of the Kaugatuma Stage (Pridoli) is exposed in the distance of 250 meters. It consists of coarse grained skeletal grainstones of crinoids with interlayers of marl. Brachiopods, ostracods, crinoids, stromatoporoids and tabulate corals are found. Abundant *Syringopora blanda* colonies are spread in the layer of marl (Fig. 54).

Common stromatoporoids and tabulate corals in the Lõo cliff:

stromatoporoids *Parallelostroma tuberculatum* (Yavorsky, 1929);
tabulate corals *Syringopora blanda* Klaamann, 1962 (type species),
Favosites pseudoforbesi Sokolov, 1952,
F. forbesi Milne-Edwards & Haime, 1851,
F. eichwaldi Sokolov,1955,
F. vicinalis Klaamann, 1962a,
Multisolenia reliqua Sokolov, 1952.

Fig. 54. Corallum of *Syringopora blanda*.

Fig. 53. Lõo cliff.

Stop 21. Ohesaare cliff (Pridoli)

The Ohesaare cliff is located on the western coast of Sõrve Peninsula near Ohesaare village, 2.5 km southwest of Jämaja church (Figs 55-56).
The lower beds of the Ohesaare Stage, the latest stage in the Silurian of Estonia are exposed here. The outcrop serves as a stratotype of the Ohesaare Stage, being one of the best-known Silurian localities in Estonia. As a famous fish locality it is known a1ready since the pioneering work by C. Pander (1856). It also has attracted attention as the topmost Silurian outcrop in the whole Baltic area containing a rich association of different fossils - fishes, ostracodes, conodonts.

The Ohesaare cliff is over 600 m long and up to 4 m high, it is located immediately by the sea in the zone of storm abrasion. The total thickness of the exposed bedrock is 3.5 m, whereas the thicknesses of separate layers are rather variable throughout the outcrop. The lithological log (Fig. 55) presents the thicknesses of layers in observation points 1 and 2 (the first ones in brackets). The section is almost completely observable in the northern part of the cliff in a small inlet (point 1).

The section is characterized by the intercalation, of thin-bedded limestones and marlstones. The intervals containing relatively few or thin marlstone interlayers form three cornices in the cliff section: I - beds 2 and 3, II - beds 5-7, III - beds 10-13. In the niches the marlstone/limestone ratio changes from equal to predominance of marlstones. In the middle part of the section limestones are mostly with a biomicritic texture (skeletal packstones), but in its upper and especially in the lower parts they are biosparitic (skeletal grainstones). A few lens-shaped intercalations of cross-bedded fine-grained pelletal-skeletal grainstones are found also in the middle part of the section, in beds 7 and 9.

Marlstone interlayers are highly argillaceous, in places reaching the condition of the plastic carbonate clays. In the upper beds of the outcrop (1-4) the rocks are somewhat dolomitized.

In this rather monotonous section there are some distinct interlayers. The lower part of the section reveals a layer of coarse-grained skeletal grainstone to coquinoid rudstone (10) with a 3-5 cm thick interbed of argillaceous marlstone in the middle. 0.5-1.0 m higher of it there is a 2-5 cm thick interlayer of fine-

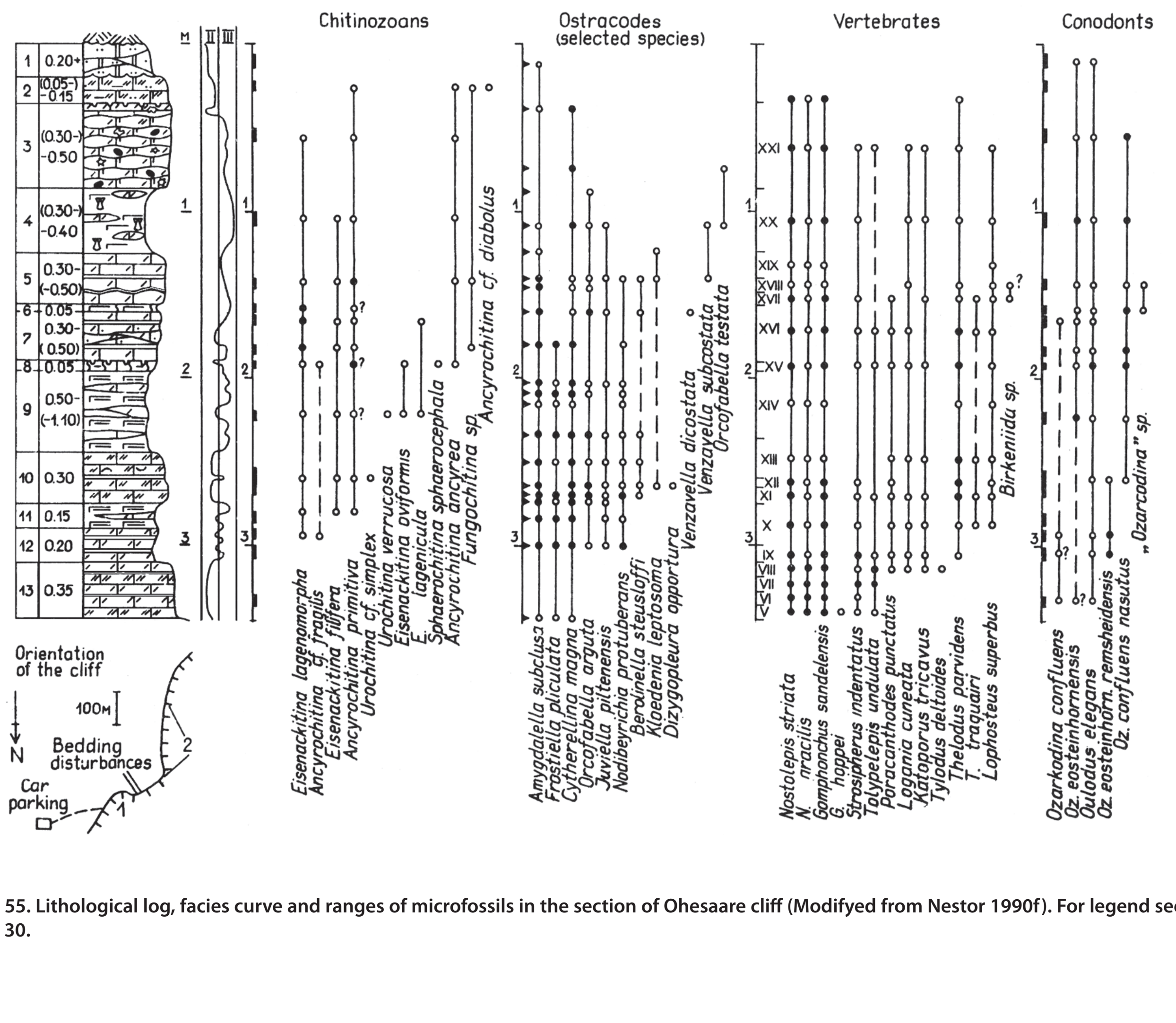


Fig. 55. Lithological log, facies curve and ranges of microfossils in the section of Ohesaare cliff (Modifyed from Nestor 1990f). For legend see Fig. 30.

grained limestone (8) pierced by thin vertical burrows filled with light-green marl. Still higher (0.3-0.5 m) there is a thin (5 cm) interlayer (6) of light-green calcareous marlstone containing vertical cracks with brownish granular infilling.

In the upper half of the cliff a layer of greenish-grey marlstone forms a distinct niche containing abundantly shells of *Grammysia obliqua* (McCoy) buried in living position.

The section ends up with an up to 20 cm thick layer (1) of fissile wavy- to cross-bedded-laminated calcareous siltstone which has preserved only in the southern end of the observation point 2. It is underlain by a 5-15 cm thick interbed (2) of light-grey silty skeletal grainstone, the upper surface of which bears large ripple marks and the lower boundary displays a hardground.

The Ohesaare cliff is rich in diverse shelly fauna which has given the main part of the fauna recorded from the topmost Silurian Stage in the East Baltic. The most abundant macrofossils are brachiopods, represented by *Delthyris magna* Kozlowsky, *D. elevata* Dalman, *Homoeospira baylei* (Davidson), *Morinorhynchus* orbignyi (Dav.), *Isorthis ovalis* (Paškevicius), *Dalejina hybrida* (Sowerby), *Shaleria (Janiomya) ornatella* (Davidson), *Collarothyris collaris* (Modzalevskaya). As compared to other Silurian sections, relatively numerous here are bryozoans *Fistulipora tenuilamellata* (Bassler), *F. aculeata* Astrova, *Eridotrypa parvulipora* Ulrich and Bassler, *Trematopora porosa* (Dybowski) and others and also bivalves *Grammysia obliqua* (McCoy), *Cardiola interrupta* Sowerby, *Palaeopecten danbyi* (McCoy), *Modiolopsis complanata* Sowerby and others. Trilobites are most often represented by *Calymene conspicua* Schmidt, *C. soervensis* Männil, *Acaste dayiana*. Stromatoporoids have not been recorded from the cliff section, corals occur at certain levels in the middle part and are represented by species having an extensive stratigraphical distribution (see below). *T. loveni* occurs in the Oheassaare and Kaugatuma stages, but here it is found from deeper beds and can be of Kaugatuma age. The middle part of the section (beds 5-10) has yielded also tentaculites *Tentaculites scalaris* (Schlotheim) and *Lowchidium inaequale* Eichwald. Very diverse and rich is the characteristic association of microfossils (particularly ostracodes) (Fig. 55). Characteristic of the section is the high content of terrigenous material, possibly caused by intense influx of fine siliciclastic material into the basin at the final stage of its development.

<u>Common corals in Ohesaare cliff</u>:

tabulate corals *Favosites forbesi* Milne-Edwards and Haime, 1851,
F. pseudoforbesi Sokolov, 1952,
F. vectorius Klaamann, 1962a;
rugose corals: *Entelophyllum articulatum* (Wahlenberg, 1821),
E. pseudodianthus (Weissermel, 1894),
Spongophylloides sp.,
Tryplasma loveni (M. Edwards & Haime, 1851).


Fig. 56. Ohesaare cliff.

Day 5, August 22, 2007

Stop 22. Väike-Rootsi (Pridoli)

Small outcrop near village of Väike-Rootsi. It is situated close to the end of peninsula, before the sign of Väike-Rootsi village. Facing the sea, the locality is left from the road of Pihtla, after Kailuka village. The beds of crinoid limestone of the Kaugatuma Stage are exposed.

Many favostids and stromatoporoids are to be found in this outcrop (e.g., *Favosites pseudoforbesi* Sokolov, 1952; *Densastroma astroites* (Rosen, 1867); *Parallelostroma tuberculatum* (Yavorsky, 1929); *Parallelostroma minosi* (Nestor, 1966).

Stop 23. Kaali meteorite craters (Quaternary)

Until the 1960s, the craters at Kaali on Saaremaa Island were the only known meteorite craters in Europe which had attracted scientists since the first half of the 19th century. The first description of the Kaali main crater appeared in 1827 in J.W.von Luce's book dealing with the nature and history of Saaremaa (Luce 1827).

Different hypotheses about the origin of the craters were advanced between 1827–1928, some of which suggested also their volcanic origin or the emption of gas and steam (Hofman 1837, Teichert 1927b). Eichwald (1843), Schmidt (1858) and Kraus (Kraus *et al*. 1928), who were well acquainted with the geology of Estonia, considered the dislocation zones and karst phenomena most important. In 1854, Eichwald suggested that there had been an ancient stronghold, in which a natural karst lake with man-made walls served as a well.

Fig. 57. View to the main Kaali meteorite crater from air. Photo by Ants Kraut.

Fig. 58. Main Kaali meteorite crater. Photo by G. Baranov.

In 1927, I. Reinwald carried out geological investigations in the craters. In 1937, he collected 30 fragments of meteoritic iron from craters 2 and 5. The chemical analysis showed, that in these pieces Fe and Ni made up 91.5 and 8.3%, respectively. Minerals, characteristic of iron meteorites, were also found (Spencer 1938). According to more recent determinations, the Kaali meteorite belongs to the class of coarse octahedrite (Buchwald 1975).

Up to now, 3.5 kg of meteoritic material has been collected from the craters; the largest piece weighed 28.4 g. In the late 1970s and early 1980s, the types and distribution of the pulverized meteoritic matter were investigated and their preliminary classification compiled (Tiirmaa 1997 and references therein, Shymanovich *et al.* 1993).

In 1955, Ago Aaloe (1927–81) proceeded with the studies started by Reinwald. During the course of the succeeding 25 years, he devoted to this work, the geological structure of the craters was studied in particular detail. In 1959, a geological protection area of craters was founded at Kaali and an exhibition pavilion was built near the main crater. In 1984, a memorial stone was opened to Ivan Reinwald and Ago Aaloe.

The Kaali metorite craters, 9 in all, are located within one square kilometre. On the bottom of the main crater there is a natural body of water known as Lake Kaali (Fig. 57, 58). The diameter of the lake depends on the water level and ranges from 30 to 60 m. The depth of the lake is 1...6 m, the maximum thickness of lake sediments is 5.8 m. The smaller craters, locally known as dry lakes, are shallow hollows bordered in places with the remains of a low wall. The craters have formed in the clayey basal till and underlying thick micro-bedded Upper Silurian dolomites. The main crater measures 105...110 m in diameter at the top of the mound, and is at least 22 m deep. The upper part of the mound consists of the material ejected from the crater during the explosion and of partly overhanging dolomite layers tilted at an angle of 25–90°. The uplifted bedrock complex with an average thickness of 10 m has been split into nine shifted blocks, each up to 50 m wide (Tiirmaa 1997 and references therein).

The diameters of the secondary craters range from 12...40 m being 1...4 m deep. On the bottom of craters 4 and 5 meteorite impact traces have been discovered.

The energy at the formation of the Kaali craters has been estimated at $4x10^{19}$ ergs for the main crater (Tiirmaa 1997 and references therein). Based on the main crater's energy of formation and the supposed angle of incidence of 45°, the following ranges of values were obtained: initial mass of meteorite 400 to 10,000 tonnes, mass at impact 20 to 80 tonnes, initial velocity upon entering the atmosphere 15 to 45 km/s, velocity at impact 10 to 20 km/s. The meteorite pieces causing the small secondary craters separated at an altitude of approximately 5...10 km, and their combined mass did not exceed 18 to 20% of the total mass.

Opinions differ as to the direction and angle of incidence of the Kaali meteorite. The sizes of the craters led the first investigators to believe that the direction of movement was from the southeast to the northwest (Tiirmaa 1997 and references therein). Aaloe, basing primarily on the study of impact traces at the bottom of craters 4 and 5, maintained that the probable angle of incidence had been 35–40° relative to the horizon (Tiirmaa 1997 and references therein). The morphology of the wall of the main crater, the geophysical data available on the destruction zones of the main and secondary craters 1 and 6 and the distribution of dispersed material in the craters and outside the crater field suggest that the meteorite fell from the east-northeast (Tiirmaa 1997 and references therein).

Various methods have been used to determine the age of the craters. As neither deformed remnants from the explosion nor more recent sediments of marine origin had been found in the crater, Linstow (1919) estimated the age of the crater at about 4000 to 8000 years. Since the craters or their embankments did not reveal any traces of marine erosion or accumulation, Reinwald (Tiirmaa 1997 and references therein), basing on the data available on the history of the Baltic Sea at that time, considered the craters some 4000–5000 years in age. In his first papers, Aaloe expressed the same opinion, but some years later he maintained that the age of the craters could not be more than 3000 to 4000 years. ^{14}C dating of charcoal discovered in 1961, yielded an age of 2660±200 years; the later dates 2530±130 and 2920±40 years allowed Aaloe to place the age of the craters erroneously at about 2800±100 years (Tiirmaa 1997 and references therein).

As it was not excluded that the dated charcoal was much younger than the craters themselves, great hopes were placed on drilling and dating of lake sediments in the main crater. Palynological analysis by Kessel (Tiirmaa 1997 and references therein) showed that the bottommost sediments are Sub-Boreal in age and the craters are more than 3500 years old. Simultaneous ^{14}C and palynological investigations initiated by L. Saarse, placed the craters' age at approximately 3500...4000 years (Saarse *et al.* 1990) or 4000 years BP (Saarse *et al.* 1992).

Recent investigations have shown that the Kaali area was freed from the waters of the Baltic Sea already some 8000 yr BP. In 1994, a high concentration of microimpactites was detected in the peat of the Piila Bog, about 10 km to the northwest from the Kaali craters. The age of the layer with microimpactites was established by means of palynological and radiocarbon methods. The studies suggest that the Kaali craters were formed probably close to 7500 BP (Raukas *et al.* 1995a).

The mid-1970s witnessed an ever growing interest of historians in the Kaali Crater. Impetus was given by Lennart Meri's books "Hõbevalge" (1976) and "Hõbevalgem" (1984) and by the first archaeological finds in the east wall of the main crater in 1976. In 1978, excavations were begun on the discovered fortification which is located on the outside slope of the northeastern wall of the main crater. From the side of the lake it is protected by a steep slope and from outside by a semi-circular wall. Archaeological finds in the fortress area are limited, few earthenware fragments are dated from the 7th century BC, most of the pottery dates from the Iron Age, the beginning of which is considered to be 600 years BC locally (Lõugas 1978, 1980).

REFERENCES

Ainsaar, L. 2004. Stop 5. Võhmuta quarry. 126 pp. *In* Hints, O. and Ainsaar, L. (eds), *WOGOGOB-2004 8th Meeting on the Working Group on the Ordovician Geology of Baltoscandia May 13–18, 2004, Tallinn and Tartu, Estonia*. Tartu University Press.

Ainsaar, L. and Meidla, T. Stop 11. Aluvere quarry. 139 pp. *In* Hints, O. and Ainsaar, L. (eds), *WOGOGOB-2004 8th Meeting on the Working Group on the Ordovician Geology of Baltoscandia May 13–18, 2004, Tallinn and Tartu, Estonia*. Tartu University Press.

Bauert H. and Kattai, V. 1997. Kukersite oil shale. 313–327. *In* Raukas, A. and Teedumäe, A. (eds), *Geology and Mineral Resources of Estonia*. Estonian Academy Publishers, Tallinn.

Bergström, S.M., Huff, W.D., Kolata, D.R. and Bauert, H. 1995. Nomenclature, stratigraphy, chemical fingerprinting, and areal distribution of some Middle Ordovician K-bentonites in Baltoscandia. *GFF* 117, 1–13.

Billings, E. 1865. Notice on some new genera and species of Palaeozoic fossils. *Canadian Naturalist and Geologist (new series)* 2, 425–432.

Buchwald, V.F. 1975. *Handbook of Iron Meteorites*. *University of California Press*. Berkley, Los Angeles. London, 704–707.

Calner, M. 1999. Stratigraphy, facies development, and depositional dynamics of the Late Wenlock Fröjel Formation, Gotland, Sweden. *GFF*, 121, 13–24.

Calner, M., and Säll, E. 1999. Transgressive oolites onlapping a Silurian rocky shoreline unconformity, Gotland, Sweden: *GFF*, 121, 91–100.

Chernyshev, B. B., 1937. Verkhnesilurijskie i devonskie tabulyata Novoj Zemli, Severnoj Zemli i Tajmyra [Tabulates from the Upper Silurian and Devonian of Novaya Zemlya and Tajmyr]. *Trudy Arkticheskogo Instituta 91*, 67–134. [In Russian.]

Cooper, R. A. and Sadler, P. M. 2004. The Ordovician Period. 165–187. *In* Gradstein, F. M., Ogg, J. G. and Smith, A. G. (eds), *A Geologic Time Scale 2004*. Cambridge University Press.

Copper, P. 1994. Ancient reef ecosystem expansion and collapse. *Coral reefs 13*, 3–12.

Copper, P. and Brunton, F. 1991. A global review of Silurian reefs. *Special Papers in Palaeontology*, (44), 225–259.

Dybowski, W. 1873/4. Monographie der Zoantharia sclerodermata rugosa aus der Silur-formation Estlands, Nord-Livlands und der Insel Gottland, nebst einer Synopsis aller palaeozoischen Gattungen dieser Abtheilung und einer Synonymik der dazu gehöringen, bereits bekannten Arten. *Archiv für die Naturkunde Liv- Ehst- und Kurlands*, Ser. 1, 5, 257–532.

Edwards, H. M. & Haime, J. 1854. A Monograph of the British Fossil Corals. Pt. 5. Corals from the Silurian formation. *Palaeontographical Society Monographs*, London. 245–299.

Eichwald, C. E., 1829. *Zooloogia Specialis*, 1, vi+314, (Vilnae).

Eichwald, E. 1843. Neuer Beiträg zur Geognosie Estlands und Finlands. *Beytrage zur topographischen Kenntniss des Russischen Reichs*, 8, 1–138.

Eichwald, E. 1854. Die Grauwackenschichten von Liv- und Estland. *Bulletin de la Société Impériale des Naturalistes de Moscou*, 27, 1, 1–111.

Eichwald, E. 1860. *Lethaea Rossica ou paleontologie de la Russie, décrite et figurée. 1*, Seconde Section de l'ancienne Période. Stuttgart, 1066–1188.

Einasto, R. E. 1986. Osnovnye stadii razvitiya i fatsial'nye modeli silurijskogo kraevogo basseijna Baltiki [Main stages of development and facies models of the East Baltic Silurian pericontinental basin]. 37–54. *In* D. Kaljo and E. Klaamann (eds), *Theory and practice of ecostratigraphy*. Academy of Sciences of Estonia, Institute of Geology. [In Russian with English summary].

Einasto, R. 1990a. Locality 6:2 Abula cliff. 165–166. *In* Kaljo, D. and Nestor, H. (eds), Field meeting, Estonia 1990. *An Excursion Guidebook*. Institute of Geology, Estonian Academy of Sciences, Tallinn.

Einasto, R. 1990b. Locality 6:3 Jaagarahu quarries. 166–167. *In* Kaljo, D. and Nestor, H. (eds), Field meeting, Estonia 1990. *An Excursion Guidebook*. Institute of Geology, Estonian Academy of Sciences, Tallinn.

Einasto, R. 1990c. Locality 6:7 Kogula quarry. 170–172. *In* Kaljo, D. and Nestor, H. (eds), Field meeting, Estonia 1990. *An Excursion Guidebook*. Institute of Geology, Estonian Academy of Sciences, Tallinn.

Einasto, R. 1990d. Locality 7:3 Kaugatuma cliff. 174–175. *In* Kaljo, D. and Nestor, H. (eds), Field meeting, Estonia 1990. *An Excursion Guidebook*. Institute of Geology, Estonian Academy of Sciences, Tallinn.

Einasto, R. 1995. "Liivi keele" omapärast Baltika arenguloos. 23–32. *In* Meidla, T., Jõeleht, A., Kalm, V. and Kirs, J. (ed.), *Liivimaa geoloogia*. Tartu Ülikooli Kirjastus, Tartu.

Goldfuss, G. A.,1829. *Petrefacta Germaniae*, I. Arnz and Co., Düsseldorf, 77–164.

Eichwald, C. E.,1854. Die Grauwackenschichten von Liev- und Esthland. *Bulletin de la Société Impériale des Naturalistes de Moscou,* 28 (4), 1–111.

Hints, L. 1990. Locality 2:2 Vasalemma quarry. 131–133. *In* Kaljo, D. and Nestor, H. (eds), *Field Meeting Estonia 1990. An Excursion Guidebook*. Estonian Academy of Sciences, Tallinn.

Hints, L., Männik, P. and Pärnaste, H. 2004. Stop 3. Vasalemma quarry. 121–124. *In* Hints, O. and Ainsaar, L. (eds), *WOGOGOB-2004 8th Meeting on the Working Group on the Ordovician Geology of Baltoscandia May 13–18, 2004, Tallinn and Tartu, Estonia*. Tartu University Press.

Hints, L., Oraspõld, A. 2004. Stop 6. Porkuni quarry. 127–128. *In* Hints, O. and Ainsaar, L. (eds), *WOGOGOB-2004 8th Meeting on the Working Group on the Ordovician Geology of Baltoscandia May 13–18, 2004, Tallinn and Tartu, Estonia*. Tartu University Press.

Hints, L., Oraspõld, A. and Kaljo, D. 2000. Stratoptype of the Porkuni Stage with comments on the Röa Member (Uppermost Ordovician, Estonia). *Proceedings of the Estonian Academy of Sciences. Geology* 49, 177–199.

Fischer-Benzon, R. von, 1871. Mikroskopische Untersuchungen über die Struktur der *Halysites*-Arten und einiger silurischer Gesteine aus der russischen Ostsee-Provinzen. *Abhandlungen aus dem Gebiete der Naturwissenschaften herausgegeben von dem naturwissenschaftlichen Verein in Hamburg* 2, 1-31.

Hofman, E. 1837. *Geognostische Beobachtungen auf einer Reise von Dorpat bis Abo*. Dorpat, 1–52.

Jaanusson, V. 1973. Aspects of carbonate sedimentation in the Ordovician of Baltoscandia. *Lethaia*, 6, 1, 11–34.

Jeppsson, L. 1998. Silurian Oceanic Events: Summary of General Characteristics. 239–257. *In* E. Landing and M. E. Johnson (eds), Silurian Cycles. Linkages of dynamic stratigraphy with atmospheric, oceanic, and tectonic changes. *New York*

State Museum Bulletin, 491.

Johnson, M. E. 1996. Stable cratonic sequences and a standard for Silurian eustasy. 203–211. *In* B. J. Witzke, G. A. Ludvigson and J. E. Day (eds), Paleozoic Sequence Stratigraphy: Views from the North American Craton. *Geological Society of America, Special Paper*, 306.

Johnson, M. E., Rong, J.-Y., Kershaw, S. 1998. Calibrating Silurian eustasy against the erosion and burian of coastal topography. 3–13. *In* E. Landing and M. E. Johnson (eds). Silurian Cycles - Linkages of dynamic stratigraphy with atmospheric, oceanic, and tectonic changes. *New York State Museum Bulletin*, 491.

Kaljo, D. L. 1956. Novye rody *Primitophyllum* gen. nov. i *Leolasma* gen. nov. [New genera *Primitophyllum* gen. nov. and *Leolasma* gen. nov. 35–37. *In Materialy po paleontologii. Novye semejstva i rody* [*Materials in palaeontology. New families and genera*]. Gosgeoltekhizdat. Moskva. [In Russian]

Kaljo, D. L. 1956. O streptelasmidnykh rugosakh Pribaltiiskogo ordovika. *Eesti NSV Teaduste Akadeemia Uurimused*, 1. 68–73. [In Russian].

Kaljo, D. L. 1958. Nekatorye novye i maloizvestnye rugozy Pribaltiki [Some new and little-known Baltic tetracorals]. *Eesti NSV Teaduste Akadeemia Uurimused*, 3. 101–123. [In Russian with English summary].

Kaljo, D. L. 1970. Rugozy. [Rugose corals], 101–123. *In* D. Kaljo (ed.), *Silur Estonii* [*The Silurian of Estonia*], Tallinn, “Valgus”, 343 pp. [In Russian with English summary].

Kaljo, D. (ed.). 1987. *Resheniya mezhvedomstvennogo stratigraficheskogo soveshchaniya po ordoviku i siluru vostochno-evropejskoj platformy 1984 s regional’nymi stratigraficheskimi skhemami.* [*Conclusion of the meeting of the Ordovician and Silurian stratigraphy in East European platform with the regional strtigraphical scemes*]. VSEGEI, Leningrad, 112 pp. [In Russian].

Kaljo, D. 1990. An introduction to the geology of Estonia. 6–10. *In* Kaljo, D. and Nestor, H. (eds), *Field Meeting Estonia 1990. An Excursion Guidebook*. Estonian Academy of Sciences, Tallinn.

Kaljo, D. 1996. Diachronous recovery patterns in Early Silurian corals, graptolites and acritarchs. *Journal of the Geological Society, London, Special Publications*, 102, 127–133.

Kaljo, D. 1997. Rugose corals. 223–224. *In* Raukas, A. and Teedumäe, A. (eds) *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn.

Kaljo, D. and Einasto, R. 1990. Locality 8:1 Päri outcrop. 179–180. *In* Kaljo, D. and Nestor, H. (eds), Field meeting, Estonia 1990. *An Excursion Guidebook*. Institute of Geology, Estonian Academy of Sciences, Tallinn.

Kaljo, D., Hints, L., Martma, T. and Nõlvak, J. 2001. Carbon isotope stratigraphy in the latest Ordovician of Estonia. *Chemical Geology* 175, 49–59.

Kaljo, D., Kiipli, T. and Martma, T. 1998. Correlation of carbon isotope events and environmental cyclicity in the East Baltic Silurian. 297–312. *In* E. Landing and M. E. Johnson (eds), Silurian Cycles - Linkages of dynamic stratigraphy with atmospheric, oceanic, and tectonic changes. *New York State Museum Bulletin*, 491.

Kaljo, D., Nestor, H. and Põlma, L. 1988. East Baltic Region. *Bulletin of the British Museum* (*Natural History*), *Geology Series*, 43, 85–91.

Klaamann, E. 1959. O faune tabulyat yuuruskogo i tamsaluskogo gorizontov [On the Tabulata fauna in Juuru and Tamsalu Stages]. *Eesti NSV Teaduste Akadeemia toimetised*, 8, 256–270. [In Russian with English summary].

Klaamann, E. 1961. Tabulyaty i geliolitidy venloka Estonii [Tabulates and heliolitids from Wenlock of Estonia]. *Eesti NSV Teaduste Akadeemia, Geoloogia Instituudi Uurimused* 6, 69–112. [In Russian with English summary].

Klaamann, E. 1962a. Tabulyaty verkhnego silura Estonii [Upper Silurian Tabulata of Estonia]. *Eesti NSV Teaduste Akadeemia, Geoloogia Instituudi Uurimused*, 9, 25–74. [In Russian with English summary].

Klaamann, E. 1962b. Rasprostranenie ordovikskikh i silurikskikh tabulyat Estonii (s opisaniem nekotorykh novykh vidov) [Distribution of Tabulata in the Ordovician and Silurian of Estonia (with a description of some new species)]. *Eesti NSV Teaduste Akadeemia, Geoloogia Instituudi Uurimused*, 10, 149–172. [In Russian with English summary].

Klaamann, E. 1964. *Pozdneordovikskie i rannesilurijskie Favositida Estonii* [*Late Ordovician and early Silurian Favositida from Estonia*]. Eesti NSV Teaduste Akadeemia Geoloogia Instituut, 118 pp. [In Russian with English summary].

Klaamann, E. 1966. *Inkommunikatnye tabulyaty Estonii* [*The incommunicate Tabulata of Estonia*]. Eesti NSV Teaduste Akadeemia Geoloogia Instituut, 96 pp. [In Russian with English summary.]

Klaamann, E. 1970. Tabulyata. [Tabulata]. 114–125. *In* D. Kaljo (ed.), *Silur Estonii* [*The Silurian of Estonia*], Tallinn, “Valgus”. [In Russian with English summary].

Klaamann, E. 1986. Soobshchestva i biozonal’nost’ tabulyatomorfnykh korallov silura Pribaltiki [The tabulate communities and biozones of the East Baltic Silurian]. 80–98. *In* Kaljo, D. and Klaamann, E. (eds), *Theory and practice of ecostratigraphy*. Academy of Sciences of Estonia, Institute of Geology. [In Russian with English summary].

Klaamann, E., Einasto, R., Viira, V., Männil, R., Nestor, V., Rubel, M. and Sarv, L. 1980. Fatsial’nye zakonomernosti raspredeleniya fauny v verkhnem llandoveri i venloke severnoj Pribaltiki [Facies conrol in the distribution of fauna in the Llandovery and Wenlock of northern Baltic]. 38–47. *In* Stepanov, D. L. and Hozatski, L. I. (eds), *Ekostratigrafiya i ekologicheskie sistemy geologicheskogo proshlogo* [*Ecostratigraphy and systems of ecology of geological past*]. Trudy XXII sessii vsesoyuznogo paleontologicheskogo obshchestva, Leningrad. [In Russian with English summary].

Klaamann, E. and Einasto R. 1982. Coral reefs of Baltic Silurian (structure, facies relations). 35–41. *In* Kaljo, D. and Klaamann, E. (eds), *Ecostratigraphy of the East Baltic Silurian*. Academy of Sciences of the Estonian Institute of Geology, Tallinn, Valgus.

Kraus, E., Meyer, R. and Wegener, A. 1928. Untersuchungen uber den Krater von Sall auf Osel. *Gerlands Beitriige zur Geophysik*, 20, 3/4, 312–378.

Kutorga, S. 1837. *Zweiter Beitrag zur Geognosie und Paläontologie Dorpat’s und seiner nächsten Umgebung*. St. Petersburg, 1–51.

Kõrts, A. and Einasto, R. 1990. Localities 4:1 Kohtla and Maidla quarries. 145–148. *In* Kaljo, D. and Nestor, H. (eds), Field meeting, Estonia 1990. *An Excursion Guidebook*. Institute of Geology, Estonian Academy of Sciences, Tallinn.

Lamarck, J. B. P. A. de M. de, 1816. Histoire naturelle des animaux sans vertèbres; vol. 2., Paris, 568 p.

Laufeld, S. and Martinsson, A. 1981. *Reefs and ultrashallow envioronments. Guidbook to the field excursions in the Silurian of Gotland, Project Ecostratigraphy Plenary Meeting 22nd-28th August, 1981*. Project Ecostrtigraphy. 24 p.

Lindström, G. 1896. Beschreibung einiger obersilurischer Korallen aus der Insel Gotland. *Bih. Kongl. Svenska Vetenskaps-Akademiens Handligar*, vol. 21, 1–50

Linnaeus, C., 1767. *Systema Naturae. Edition* 12, 1, 533–1327 +

(37). Laurentius Salvius, Holmiae.
Linstow, O. 1919. Der Krater von Sall auf Ösel. ZBl. *Miner. Geol., Abt.* A, 21/22, 326–329.
Lonsdale, W. 1839. Corals. 675–694. *In* Murchison, R. I. (ed.), *The Silurian System* 2. London.
Luce, J. W. L. 1827. *Wahrheit und Mutmassung. Beitrag zur ältesten Geschichte du Insel Oesel*. Pernau, 1–164.
Lõugas 1978 Archaeological research at Kaali meteorite crater. *ENSV TA Toimetised. Ühiskonnateadused*, 27, 1, 64–66.
Lõugas, V. 1980. Archaeological excavations in the Kaali crater area. *ENSV TA Toimetised. Ühiskonnateadused*, 29, 4, 357–360.
M'Coy, F. 1850. On some new genera and species of Silurian Radiata in the Collection in the University of Cambridge. *Annals and Magazine of Natural History*, London (2) 6, 270-290.
Melchin, M. J., Cooper, R. A. and Sadler, P. M. 2004. The Silurian Period. 188–201. *In* Gradstein, F. M., Ogg, J. G. and Smith, A. G. (eds), *A Geologic Time Scale 2004*. Cambridge University Press.
Meri, L. 1976. *Hõbevalge*. Tallinn, 1–486.
Meri, L. 1983. *Hõbevalgem*. Tallinn, 1–215.
Milne-Edwards, H. and Haime, J., 1851. Monographie des Polypiers fossiles des terrains paléozoiques.*Archives du Muséum D'Histoire Naturelle* 5, 1–502.
Mõtus, M.-A. 2005. Silurian (Llandovery-Wenlock) tabulate corals of Baltoscandia: taxonomy, palaeoecology, distribution. *Dissertationes Geologicae Universitatis Tartuensis*, 17, Tartu University Press, 167 pp.
Mõtus, M.-A. 2006. Intraspecific variation in Wenlock tabulate corals from Saaremaa (Estonia) and its taxonomic implications. *Proceedings of the Estonian Academy of Sciences*, *Geology*, 55, 1, 24–42
Mõtus, M. A. and Sandström, O. 2005. *Cystihalysites* sp. and its significance to biostratigraphy and event stratigraphy in the Ludlow (Late Silurian) of Gotland, Sweden. *GFF* 127, 269–272.
Männil, R. M. 1966. *Istoriya razvitiya Baltijskogo bassejna v Ordovike* [*Evolution of the Baltic basin during the Ordovician*]. Tallinn, "Valgus", 200 p. [In Russian with English summary].
Männil, R., Bauert, H. and Puura, V. 1986: Pecularities of kukersite accumulation. 48–54. *In* Puura, V. (ed.), *Geology of the Kukersite-Bearing Beds of the Baltic Oil Shale Basin*. Valgus, Tallinn. [in Russian with English summary].
Nestor, H. 1960. *Plumatalinia* – novyi rod otryada stromatoporoidea iz verkhnego ordovika Estonskoi SSR [*Plumatalinia* – a new genus of Stromatoporoidea from the Upper Ordovician of the Estonian S.S.R.]. *ENSV Teaduste Akadeemia toimetised. Füüsikalis-matemaatiliste ja tehniliste teaduste seeria*, 9, 225–228.
Nestor, H. 1964. *Stromatoporoidei ordovika i llandoveri Estonii* [*Ordovician and Llandoverian Stromatoporoidea of Estonia*]. Tallinn, "Valgus", 112 p. [In Russian with English summary].
Nestor, H. 1966. *Stromatoporoidei venloka i ludlova Estonii* [*Wenlockian and Ludlovian Stromatoporoidea of Estonia*]. Tallinn, "Valgus", 87 p. [In Russian with English summary].
Nestor, H. 1990a. Some aspects of lithology of the Ordovician and Silurian rocks. 27–32. *In* Kaljo, D. and Nestor, H. (eds) *Field Meeting Estonia 1990. An Excursion Guidebook*. Estonian Academy of Sciences, Tallinn.
Nestor, H. 1990b. Basin development and facies models. 33–36. *In* Kaljo, D. and Nestor, H. (eds), *Field Meeting Estonia 1990. An Excursion Guidebook*. Estonian Academy of Sciences, Tallinn.
Nestor, H. 1990c. Biogeography of Silurian stromatoporoids. 215–221. *In* McKerrow, W. S. and Scotese, C. (eds), Palaeozoic palaeogeography and biogeography. *Geological Society Memoir*, 12.
Nestor, H. 1990d. Stromatoporoids. 46–51. *In* Kaljo, D. and Nestor, H. (eds) *Field Meeting Estonia 1990. An Excursion Guidebook*. Estonian Academy of Sciences, Tallinn.
Nestor, H. 1990e. Locality 5:1 Koguva quarry. 157–158. *In* Kaljo, D. and Nestor, H. (eds), Field meeting, Estonia 1990. *An Excursion Guidebook*. Institute of Geology, Estonian Academy of Sciences, Tallinn.
Nestor, H. 1990f. Locality 7:4 Ohesaare cliff. 175–178. *In* Kaljo, D. and Nestor, H. (eds), Field meeting, Estonia 1990. *An Excursion Guidebook*. Institute of Geology, Estonian Academy of Sciences, Tallinn.
Nestor, H. 1990g. Locality 8:2 Laukna (Pakamägi cliff). 181 pp. *In* Kaljo, D. and Nestor, H. (eds), Field meeting, Estonia 1990. *An Excursion Guidebook*. Institute of Geology, Estonian Academy of Sciences, Tallinn.
Nestor, H. 1994. Main trends in stromatoporoid evolution during the Silurian. *Courier Forschungsinstitut Senckenberg*, 172, 329–339.
Nestor, H. 1995. Ordovician and Silurian reefs in the Baltic area. 39–47. *In* Lathuiliere, B. and Geiser, J. (eds), Coral reefs in the past, present and future. *Publications du Service géologique du Luxembourg*, 29.
Nestor, H. 1997a. Sedimentary cover, Silurian. 89–106. *In* Raukas, A. and Teedumäe, A. (eds) *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn.
Nestor, H. 1997b. Stromatoporoids. 215–219. *In* Raukas, A. and Teedumäe, A. (eds) *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn.
Nestor, H. and Einasto, R. 1977. Fatsial'no-sedimentologicheskaya model' silurijskogo paleobaltijskogo perikontinental'nogo bassejna [Facies sedimentary model of the Silurian Paleobaltic pericontinental basin]. 89–121. *In* D. Kaljo (ed.), *Fatsii i fauna silura pribaltiki* [*Facies and fauna of the Baltic Silurian*]. Tallinn, AN ESSR. [In Russian with English summary].
Nestor, H. and Einasto, R. 1997. Ordovician and Silurian carbonate sedimentation basin. 192–204. *In* A. Raukas and A. Teedumäe (eds), *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 436 pp.
Nestor, V. and Nestor, H. 1991. Dating of the Wenlock carbonate sequences in Estonia and stratigraphic breaks. *Proceedings of the Estonian Academy of Sciences*, *Geology*, 40, 2, 50–60.
Neuman, B. 1969. Upper Ordovician streptelasmatid corals from Scandinavia. *Bulletin of the Geological Institution of the University of Uppsala*, n. s., 1, 1–73.
Neuman, B. 1986. Rugose corals from the Upper Ordovician erratic boulders of Öland. *GFF*, 108, 349–365.
Nicholson, H. A. 1886a. On some new or imperfectly described species of stromatoporoids, 1-2. *Annals and Magazine of Natural History*, ser. 5, vol. 17-18.
Nicholson, H. A. 1886-1891. A monograph of the British stromatoporoids. *Palaeontographical Society of London*, 1886b, vol. 39; 1889, vol. 42; 1891, vol. 44; 1892, vol. 46.
Nõlvak, J. and Grahn, Y. 1993. Ordovician chitinozoan zones from Baltoscandia. *Review of Paleobotany and Palynology 79*, 245–269.
Nõlvak, J; Hints, O.; Männik, P.; Pärnaste, H. 2007. Ordovician time scale in Estonia. Beijing, China. *Acta Palaeontologica Sinica* 46(Suppl.), 351–356.
Pander, C. H. 1856. *Monographie der fossilen Fische des silurischen Systems der Russisch-Baltischen Gouvernements*. St. Petersburg, 1–91.

Puura, I., 2006. Introduction to geology of Estonia, *In* A.Grigelis and K. Bork (eds), *History of Quaternary geology and geomorphology, Fieldtrip Guidebook.* Vilnius, Lithuanian Academy of Sciences, 87–90.

Puura, V., and Vaher, R., 1997. Cover structure. 167–177. *In* A. Raukas and E. Teedumäe (eds), *Geology and Mineral Resources of Estonia,* Tallinn, Estonian Academy Publishers.

Raukas, A., Pirrus, R., Rajamäe, R. and Tiirmaa, R. 1995. On the age of the meteorite craters at Kaali (Saaremaa Island, Estonia). *Proceedings of the Estonian Academy of Sciences*, *Geology*, 44, 3, 178–183.

Raukas, A., and Teedumäe, E. (eds). 1997. *Geology and Mineral Resources of Estonia,* Tallinn, Estonian Academy Publishers, 436 pp.

Reiman, V. M. 1956. Novyj rod *Sclerophyllum* nov.gen. [New genus *Sclerophyllum* gen. nov.]. *In Materialy po paleontologii. Novye semejstva i rody* [*Materials in palaeontology New families and genera*]. Gosgeoltekhizdat. Moskva. 37–39. [In Russian]

Reiman, V. M. 1958. Novye rugozy iz verkhneordovikskikh i llandoverijskikh otlozhenij Pribaltiki. [Neue Tetrakorallen des baltischen Oberordoviziums und des Llandovery]. *Eesti NSV Teaduste Akadeemia Uurimused*, 2. 33–48. [In Russian with German abstract].

Riabinin, V. N. 1951. Stromatoporoidei Estonskoi SSR (silur i verkhi ordovika) [Stromatoporoids of Estonian SSR (Silurian and Upper Ordovician)]. *Trudy VNIGRI,* 43. Leningrad, 1–58. [In Russian].

Rosen, F. B. 1867. Über die Natur der Stromatoporen und über die Erhaltung der Hornfasern der Spongien im fossilen Zustande. *Verhandlungen der Russisch-Kaiserlichen Mineralogischen Gesellschaft zu St. Petersburg, Ser.* 2, 4, 1–98.

Rubel, M. and Einasto, R. 1990. Locality 6:1 Panga cliff. 163–165. *In* Kaljo, D. and Nestor, H. (eds), Field meeting, Estonia 1990. *An Excursion Guidebook*. Institute of Geology, Estonian Academy of Sciences, Tallinn.

Rukhin, L. B., 1937. *Verkhnesilurijskie Tabulata Turkestanskogo Khrebta i Khan-tengri* [*Upper Silurian Tabulata from the Turkestan mountain range and Khan-tengri*]. Dissertatsiya na soiskanie uchenoj stepeni kandidata geologicheskikh nauk, 99 p. Leningradskii gosudarstvennyi Universitet, Leningrad.

Rõõmusoks, A. 1970. *Stratigraphy of the Viruan Series (Middle Ordovician) in northern Estonia.* Valgus, Tallinn. 346 pp. [in Russian with English summary]

Saadre, T. 2004. Stop 9. Kohtla quarry and Estonian oil shale. 135–136. *In* Hints, O. and Ainsaar, L. (eds), *WOGOGOB-2004 8th Meeting on the Working Group on the Ordovician Geology of Baltoscandia May 13–18, 2004, Tallinn and Tartu, Estonia*. Tartu University Press.

Saarse, L., Rajamäe, R., Heinsalu, A. and Vassiljev, J. 1992. The biostratigraphy of sediments deposited in the Lake Kaali meteorite impact structure, Saaremaa Island, Estonia. *Bulletin of the Geological Society of Finland*, 63, 2, 129–139.

Saarse, L., Rajamäe, R. and Vassiljev, J. 1990. Formation of the meteor crater of Lake Kaali (Island Saaremaa, Estonia). *In* Pesonen, L. J. and Niemisvaara, I. H. (eds), *Symposium on Fennoscandian impact structures. Programme and Abstracts*. Espoo, 55 p.

Samtleben, C., Munnecke, A., Bickert, T. and Pätzold, J. 1996. The Silurian of Gotland (Sweden): facies interpretation based on stable isotopes in brachiopod shells. *Geologische Rundschau*, 85, 278– 292.

Schlotheim, E.F. von, 1820. *Die Petrefactenkunde auf ihrem jetzigen Standpunkte durch die* Beschriebung seine Sammlung versteinerten und fossiler Überreste des Their- und *Pflanzenreiches der Vorwelt erläutert*. Becker, Gotha, 437 pp.

Schmidt, F. 1858. Untersuchungen über die silurische Formation von Estland, Nord-Livland und Öesel. *Archiv für die Naturkunde Liv- Ehst- und Kurlands*, Ser. I, 1–248.

Schmidt, F. 1881. Revision der ostbaltischen silurischen Trilobiten nebst geognostischer Übersicht des ostbaltischen Silurgebiets. Abt. I. Phacopiden, Cheiruriden und Encrinuriden. *Mémoires de l`Academie Impériale des Sciences de St.-Petersbourg*, VII sér., t. XXX, nº 1, 238 pp.

Scotese, C. R. and McKerrow, W. S. 1990. Revised World maps and introduction. 1–21. *In* McKerrow, W. S. and Scotese, C. R. (eds), Palaeozoic Palaeogeography and Biogeograpgy. *Geological Society Memoir*, 12.

Scrutton, C. T. 1988. Amural arachnophyllid corals from the Silurian of the North Atlantic area. *Palaeontology*, 32, 1, 1–53.

Shymanovich, S., Kolosova, T., Raukas, A. and Tiirmaa, R. 1993. Extraterrestrial spherules in the surroundings of Kaali meteorite craters (Saaremaa Island, Estonia). *Proceedings of the Estonian Academy of Sciences*, *Geology*, 42, 3, 127–133.

Sokolov, B. S. 1951. Tabulyaty paleozoya Evropejskoj chasti SSSR. Silur Pribaltiki, II (favositidy llandoverskogo yarusa) [Tabulates from paleozoic of European part of SSSR. Silurian of Baltic, II (favositids from Llandovery Series)]. *Trudy VNIGRI,* 52, 1–124. [In Russian].

Sokolov, B. S. 1952. Tabulyaty paleozoya Evropejskoj chasti SSSR. Silur Pribaltiki, III (favositidy venlokskogo i ludlovskogo yarusov) [Tabulates from paleozoic of European part of SSSR. Silurian of Baltic, III (favositids from Wenlock and Ludlow Series)]. *Trudy VNIGRI*, 58, 85 pp. [In Russian].

Sokolov, B. S. 1955. Tabulyaty paleozoya Evropejskoj chasti SSSR. Vvedenie (Obshchie voprosy sistematiki i istorii razvitiya tabulyat) [Tabulates from paleozoic of European part of SSSR. Introduction (General aspects of systematics and evolution of tabulates)]. *Trudy VNIGRI*, 85, 527 pp. [In Russian].

Spencer, L. J. 1938. The Kaalijärv meteorite from the Estonian craters. *Mineralogical Magazine*, 25, 161, 75–80.

Teichert, C. 1927. Einige Bemerkungen zum "Krater von Sall" auf der Insel Ösel. *Zeitschrift fuer Geomorphologie*, 3, 2, 99–103.

Tinn, O. 2004. Stop 10. Valaste waterfall. 137 pp. *In* Hints, O. and Ainsaar, L. (eds), *WOGOGOB-2004 8th Meeting on the Working Group on the Ordovician Geology of Baltoscandia May 13–18, 2004, Tallinn and Tartu, Estonia*. Tartu University Press.

Tiirmaa, R. 1997. Meteorite craters. 378-383. *In* Raukas, A. and Teedumäe, A. (eds), *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn.

Torsvik, T. H., Smethurst, M. A., van der Voo, R., Trench, A., Abrahamsen, N. and Halvorsen, E. 1992. Baltica. A synopsis of Vendian–Permian palaeomagnetic data and their palaeotectonic implications. *Earth-Science Reviews*, 33, 133–152.

Vaher, R., Winterhalter, B., Mägi, S., and Põlma, L., 1992, Sedimentary cover. 30-37. *In* A. Raukas and H. Hyvärinen (eds), *Geology of the Gulf of Finland,* Tallinn. [In Russian].

Wahlenberg, Göran, 1821. Petrificata telluris Svecanae, *Nova acta Regiae societatis scientiarum Upsaliensis*, 8, 1–116.

Webby, B. 1980. Biogeography of Ordovician stromatoporoids. *Palaeogeography*, *Palaeoclimatology*, *Palaeoecology*, 32, 1, 1–19.

Wedekind, R. 1927. Die Zoantharia Rugosa von Gotland (bes. Nordgotland). Sveriges Geologiska Undersökning, Ser. Ca, No 19, 1-95. Stockholm.

Weissermel (1894), Weissermel, W. 1894. Die Korallen der Silurgeschiebe Ostpreussens und des Östlichen Westpreussens. *Zeitschrift der Deutschen geologischen Gesellschaft*, 46, 580–686.

Weyer, D. 1973. Über den Ursprung der Calostylidae Zittel 1879 (Anthozoa, Rugosa, Ordoviz–Silur). *Freiberger Forschungshefte*, C 282, 23–87.

Weyer, D. 1982. Das Rugosa-genus Neo tryplasma Kaljo (1957) aus dem Ordoviz der europäischen UdSSR. *Freiberger Forschungshefte*, C 366, 89–95.

Weyer, D. 1983. Lambelasma-Arten (Anthozoa, Rugosa) aus dem baltoscandischen Mittelordoviz. *Freiberger Forschungshefte*, C 384, 7–19.

Weyer, D. 1993. *Lambelasma carinatum*, eine neue Rugose Koralle aus dem Mittel-Ordoviz von Estland. *Abhandlungen und Berichte für Naturkunde, Magdeburg*, 16, 70–77.

Yavorsky, V. I. 1929. Silurijskie Stromatoporoidea [Silurian stromatoporoids]. *Izvestiya Geologicheskogo Komiteta*, 48, 110 p.

LIST OF PARTICIPANTS

Dr. Natsuko Adachi
Department of Geosciences, Graduate School of Science, Osaka City University
Sugimoto 3-3-138,
Sumiyoshi-ku, Osaka 558-8585
E-mail: natsuko@sci.osaka-cu.ac.jp

Dr. Boo-Young Bae
103-102, Taewang Apt (2nd), Maeho-Dong, Susung-Gu, Daegu, 706-140, Korea.
E-mails: ybbybb@dreamwiz.com, ybbybb@hanmail.net

Prof. Robert Elias
University of Manitoba, Department of Geological Sciences
125 Dysart Road, Winnipeg, Mantinoba, Canada R3T 2N2
E-mail: eliasrj@ms.umanitoba.ca

Mr. Keiichiro Higa
Department of Physics & Earth Sciences,
Faculty of Science University of the Ryukyus
1 Senbaru, Nishihara, 903-0213
E-mail: hippie_keich@yahoo.co.jp

Dr. Steve Kershaw
Department of Geography and Earth Sciences and Institute for the Environment
Halsbury Building Brunel University Uxbridge Middlesex UB8 3PH U.K.
E-mails: kershaw@onetel.com; stephen.kershaw@brunel.ac.uk

Dr. Erika Kido
Department of Earth System Science, Faculty of Science, Fukuoka University, 3-20-38 Maebaru Chuo, Maebaru City, Fukuoka, Japan 819-116,
E-mail: erikakido07@yahoo.co.jp

Prof. Dong-Jin Lee
Department of Earth & Environmental Sciences, Andong National University
388 Songchon-Dong, Andong 760-749, Seoul, Korea, E-mail: djlee@andong.ac.kr

Dr. Ross McLean
Canadian Natural Resources
Ltd, 2500, 855 2nd St SW, Calgary AB, T2P 4J8 Canada
E-mail: Ross.McLean@cnrl.com

Dr. Koichi Nagai
Department of Physics & Earth Sciences
Faculty of Science University of the Ryukyus
1 Senbaru, Nishihara, 903-0213
E-mail: k-nagai@sci.u-ryukyu.ac.jp

Dr. John W Pickett
Londonderry Geoscience Centre
943-957 Londonderry Road, Londonderry, NSW 2753
E-mail: picketj@bigpond.net.au

Prof. Edouard Poty
University of Liège
Bât. B18, Allée du 6 Août, Sart Tilman, Liège, Belgium 4000
E-mail: E.Poty@ulg.ac.be

Prof. James Sorauf
Binghamton University, University of South Florida
986 Spinnaker Court, Tarpon Springs, Florida, U.S.A. 34689
E-mails: jsorauf@tampabay.rr.com, jsorauf@binghamton.edu

Ms. Lori Stewart
University of Manitoba, Department of Geological Sciences
125 Dysart Road Winnipeg, Mantinoba, Canada R3T 2N2
E-mail: shell_bell46@hotmail.com

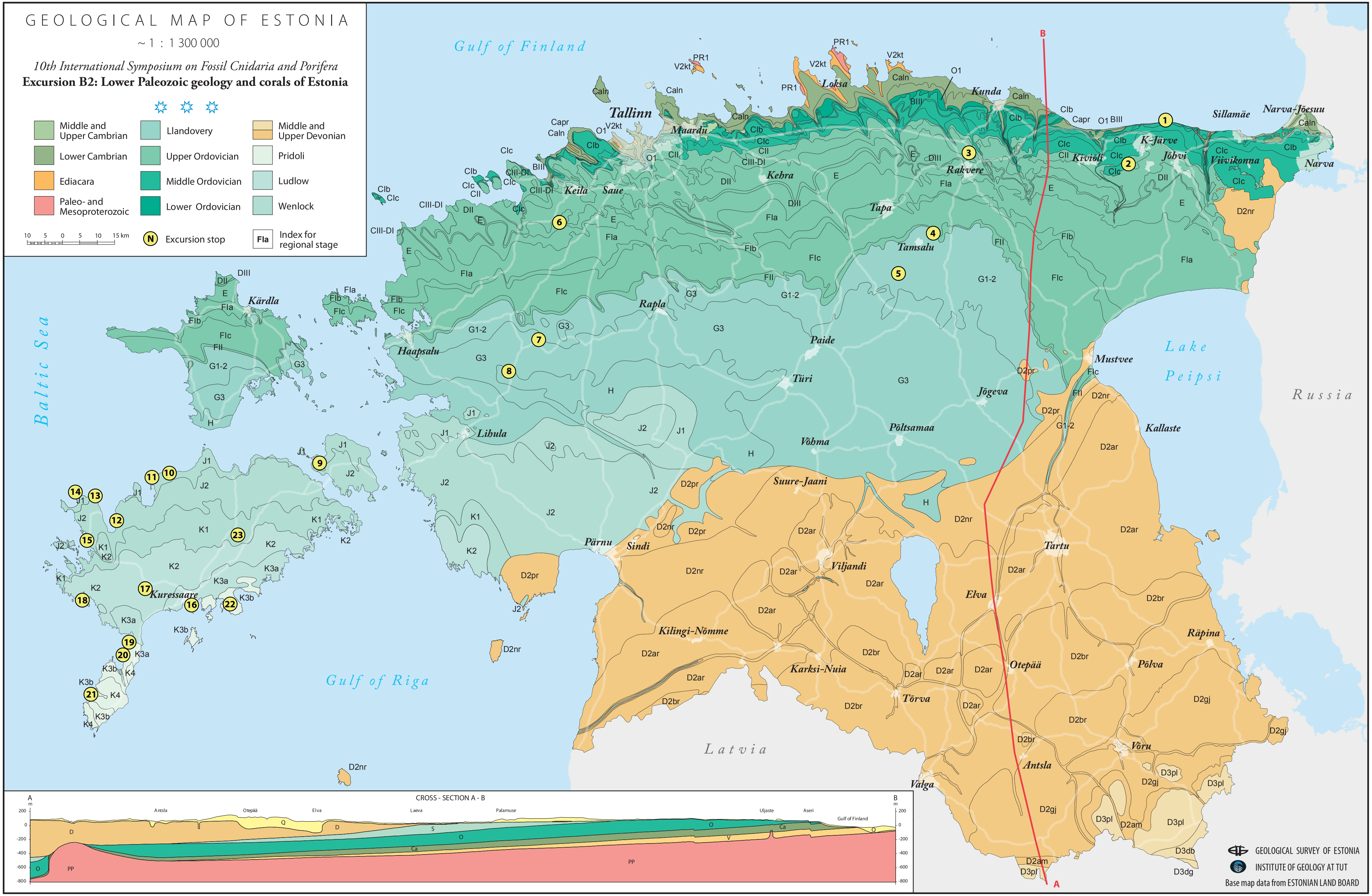
Mrs. Kyoko Sugiyama
2-10-24 Tani, Chuo-ku, Fukuoka, Japan 810-0031,
E-mail: kyokosg@jcom.home.ne.jp

Dr. Tetsuo Sugiyama
Department of Earth System Science, Faculty of Science, Fukuoka University
8-19-1 Nanakuma, Jonan-ku, Fukuoka 814-0180,
E-mail: sugiyama@fukuoka-u.ac.jp

Mr. Yuki Tokuda
Department of Geosciences, Graduate School of Science
Osaka City University, 3-3-138 Sugimoto,
Sumiyoshi-ku, Osaka, Japan 558-8585
E-mail: Tokuda@sci.osaka-cu.ac.jp

Dr. Graham Young
The Manitoba Museum
190 Rupert Avenue Winnipeg, MB, Canada R3B 0N2, E-mail: gyoung@manitobamuseum.ca

NOTES


GEOLOGICAL MAP OF ESTONIA
~ 1 : 1 300 000
10th International Symposium on Fossil Cnidaria and Porifera
Excursion B2: Lower Paleozoic geology and corals of Estonia
Middle and Upper Cambrian
Lower Cambrian
Ediacara
Paleo- and Mesoproterozoic
Llandovery
Upper Ordovician
Middle Ordovician
Lower Ordovician
Middle and Upper Devonian
Pridoli
Ludlow
Wenlock
Excursion stop
Index for regional stage
Gulf of Finland
Baltic Sea
Gulf of Riga
Lake Peipsi
Russia
Latvia
Tallinn
Maardu
Keila
Saue
Loksa
Kunda
Rakvere
Kehra
Tapa
Tamsalu
Sillamäe
Narva-Jõesuu
Narva
K-Järve
Jõhvi
Kiviõli
Viivikonna
Rapla
Paide
Türi
Haapsalu
Kärdla
Jõgeva
Põltsamaa
Võhma
Mustvee
Kallaste
Libula
Pärnu
Sindi
Suure-Jaani
Viljandi
Tartu
Elva
Otepää
Kilingi-Nõmme
Karksi-Nuia
Tõrva
Valga
Antsla
Võru
Põlva
Räpina
Kuressaare
CROSS - SECTION A - B
GEOLOGICAL SURVEY OF ESTONIA
INSTITUTE OF GEOLOGY AT TUT
Base map data from ESTONIAN LAND BOARD