XI Baltic Stratigraphical Conference

Abstracts and Field Guide

Edited by Olle Hints, Peep Männik and Ursula Toom

Geological Society of Estonia
Tallinn University of Technology, Department of Geology
University of Tartu, Department of Geology
Geological Survey of Estonia

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August 19-21, 2024
Tartu, Estonia

Tallinn 2024

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Post-conference Field Excursion (August 22–25, 2024)

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Preface

The Eleventh Baltic Stratigraphical Meeting will take place on August 19–21 in Tartu and Arbavere, Estonia, organised by the Estonian Commission on Stratigraphy and supported by the Geological Society of Estonia, Tallinn University of Technology, University of Tartu and the Geological Survey of Estonia.

The ten previous meetings under this title have been held in the Baltic countries, NW Russia and Poland:

1991 – Tallinn, Estonia
1993 – Vilnius, Lithuania
1996 – Tallinn, Estonia
1999 – Riga, Latvia
2002 – Vilnius, Lithuania
2005 – St. Petersburg, Russia
2008 – Tallinn, Estonia
2011 – Riga, Latvia
2014 – Vilnius, Lithuania
2017 – Chęciny, Poland

However, formalised collaboration in the field of stratigraphy in the Baltic region started already in 1969, when the Baltic Regional Commission on Stratigraphy was established, and various meetings, workshops and field trips were organised over the years. In 1990, this body transformed into a less formal Baltic Stratigraphical Association (BSA), whose primary task since then has been organising the Baltic stratigraphical conferences.

Following the usual 3-year periodicity, the eleventh meeting should have taken place in 2020, and St. Petersburg was agreed to be the location. However, the meeting was postponed due to the COVID-19 pandemic and then made impossible due to Russia's aggression war in Ukraine, which started in February 2022 and is continuing as of August 2024. Thus the turn was passed to the following country, Estonia.

The number of participants in the 2024 meeting is close to 40 (from 8 countries), which is less than in the previous meetings. There are several reasons for this. It is also true that the term "stratigraphical conference" does not appear particularly attractive to a broader audience of geologists, even though the need for stratigraphical service has not disappeared. On the other hand, the programmes of recent meetings have included many reports on palaeontology and bedrock geology and only a few strictly stratigraphical presentations, thus making the title somewhat misleading.

Perhaps it is now the right time to discuss the future of the Baltic stratigraphical conference series. It could involve into two alternative directions: firstly, a smaller and less formal (field) workshop, which aims at solving problems of regional stratigraphy and geology, and secondly, a regional conference on geology, open to a broad range of participants and topics. In 2024, we tried to combine these two paths having conventional scientific sessions in Tartu and then, after a field excursion day, discussions and core workshop in the Arbavere Core Repository and Research Center. We hope that the discussions to be held will provide the answers how the twelwth meeting should look like, and where and when it will be held.

We welcome the participants of the Eleventh Baltic Stratigraphical Meeting in Tartu and Arbavere and wish the readers of the conference volume useful information in the abstracts and field guide.

Olle Hints and Tõnu Meidla

Estonian Commission on Stratigraphy

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ABSTRACTS

XI Baltic Stratigraphical Conference

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Traces of predator attacks, post-mortem damages, and parasite activity in the vertebrate fossils from the Baltic Middle and Upper Devonian basin deposits

Valters Alksnitis

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The paleontological record of parasitic organisms is very incomplete, but parasite traces or parasite-induced pathologies can be found more often. However, due to difficulties in recognising and interpreting these, parasite traces as well as traces of predator attacks, diseases and post-mortem damage on vertebrate bones, are still insufficiently studied. These traces and pathologies can give an insight into predator-prey relationships and can give some information on the parasitic animals that do not have a mineralised skeleton and, for that reason, are extremely hard to study.

The Middle and Upper Devonian deposits in Latvia and Estonia are rich in vertebrate fossils that have been studied for more than 100 years. In the 1960s, the first damage traces – predator bite marks were spotted in the heterostracan armour plates and scales; however, not much attention was paid to the pathologies after that until the beginning of this century when previously described specimens together with new material were redescribed and reinterpreted in 2009 by Lebedev, Mark-Kurik, Lukševičs and Ivanov.

A thorough examination of the fossil vertebrate material from the Middle and Upper Devonian deposits of Estonia and Latvia that is stored at the University of Tartu and Tallinn University of Technology (where the previously published material is also stored) and the Museum of the University of Latvia was was carried out. New excavations in the Upper Devonian localities in Latvia from 2016 to 2023 have provided additional fossil vertebrate material that has also been studied.

Predator-caused pathologies – bite marks, deformations, fractures and torn-off plate or scale corners accompanied by regenerated tissue can be seen in the remains of almost all fishes, including predators – antiarchs, arthrodires, heterostracans and sarcopterygians, starting from the Givetian to the latest Famennian deposits. In placoderms, these are not always easy to distinguish. In some cases, there are no signs of healing due to a successful attack or scavenger activity.

The presumably parasite-induced pathologies include attachment pits that are usually found on the bones of sarcopterygians from Gauja to Ketleri Time. Traces of a migratory parasite or even a drilling scavenger - small boreholes sometimes accompanied by lesions of non-specific shape have been found in various species of *Asterolepis* from Burtnieki, Gauja and Amata Formation deposits, species of *Bothriolepis* and sarcopterygians from the Tērvete and Ketleri formations but are uncommon in other placoderms or heterostracans which generally do not display any other pathologies apart from bite marks. Swellings and pathological bone regrowth (bony lesions) without a clear cause have been identified in both Late Famennian placoderms and sarcopterygians, and post-mortem bone bioerosion of Frasnian and Famennian age have been documented.

Keywords: Baltic Devonian basin, vertebrates, pathologies, bite marks, parasite traces.

Brief history of lithostratigraphic work at the Geological Survey of Estonia

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The classification of stratigraphic units has been almost continuously revised since the 19th century in Estonia. Since the 1960s, the subdivision of the stratigraphic succession and boundaries of units used in the course of geological mapping carried out by the former state geological survey were defined by stratigraphic schemes that were subject to a two-step approval (local approval followed by the decision of the Interdepartmental Stratigraphic Commission in Moscow). The system of units was developing rapidly in the course of preparation of the published stratigraphic schemes, with major revisions in 1962, 1976 and 1984, with subsequent publications from 1965, 1978 and 1987, respectively. In the course of preparation of these schemes, differences and amendments to the subdivision were always extensively discussed with the academic institutions before they got accepted. During this period, the geological mapping was carried out in accordance with the Stratigraphic Code of the former USSR, which by definition linked chrono- and lithostratigraphic units (stages and formations) – a practice that was not in accordance with the International Stratigraphic Guide of today.

Further refinements were introduced after 1987, but there has also been less discussion, and the changes were not so well documented. During the 1990s and 2000s, there was a change of generations in the state geological organisation, and the number of people who had long-time and extensive experience in describing and identifying lithostratigraphic units decreased rapidly. The last overview on stratigraphic units in Estonian language was released in 1983, an emended version in English in 1997, but neither of them contains a thorough description of practices of distinguishing neighbouring units, addressing the problems related to transitionary lithological boundaries, etc. Both written sources are partially outdated today. The analysis of distribution and discrimination practices of the lithostratigraphic units within a special project funded by the Estonian Centre of Environmental Investments has demonstrated numerous mismatches in the practical application of these units within different mapping and exploration projects, eventually because of incomplete primary written documentation of rock units and their boundaries.

The Geological Survey of Estonia, in cooperation with the University of Tartu, has initiated a project to compile guiding materials for describing and discriminating lithostratigraphic units, starting with the Ordovician strata. This work is based on a large-scale comparative study of key core sections stored in the drillcore warehouse of the Arbavere Research Centre. The newly built drillcore storage in Arbavere has made this kind of study possible for the first time. Within this work, the historical perspective of the older mapping units will be taken into account in order to reduce the risks of possible misinterpretation of old primary core documentation. Unit descriptions will be analysed, revised and refined in order to unify the future discrimination practices. Preliminary results have already demonstrated problems with discrimination and description of several formations, e.g. Petseri, Zebre, Varangu, Leetse and Rokiškis. In parallel, the Geological Survey of Estonia is also working on updating the Ediacaran lithostratigraphic scheme based on the new and old drillcore data.

Keywords: correlations, revision, Ediacaran, Ordovician, historical data.

Sea grasses/meadows in the Ordovician and Silurian of Estonia

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Seagrass/seaweed meadows represent over-looked diversity hotspots. They are the key contributors to the production and accumulation of organic matter, and thus a significant factor in controlling biodiversity and sedimentation in the shelf areas. These underwater meadows are made up of "grass-like" flowering plants (mostly angiosperms), which grow on the sandy-mud substrates and less often on the rocks. Recent sea grasses are spread from the tropics to the temperate latitudes in shallow-water coastal areas. This biotope plays an important role as a nursery for invertebrates and fish, a nutrition source, a living substrate for diverse epibionts and a stabilisation of the sediment.

But even less is known about how similar ecosystems functioned in the distant geological past, such as the Palaeozoic, when other organisms, often in association with algae, functioned as a foundation for the underwater meadows instead of angiosperms. Commonly, their role and significance in the fossil record have not yet been fully understood. Since seagrasses/seaweeds are not well predisposed for fossilisation, the primary aim of this project is to use a set of indirect markers/proxies (a combination of palaeontology and organic geochemistry) to be able to identify them in the fossil record.

We have selected six sites in central and northern Estonia: Aru Quarry, a deposit of kukersite near Püssi, Madise Escarpment, Ristna, Sutlema Quarry, and Kalana Quarry, ranging from the Darriwilian to upper Katian (Ordovician) and Llandovery (Silurian). Field investigations were carried out at these sites in an attempt to assess the benthic and nektonic assemblages and to collect samples with organic remains (hydrocarbons) for a geochemical study utilising chromatographic analysis to identify their source and interpret the depositional conditions.

The identified compounds were mainly biomarkers for cyanobacteria and microalgae in all samples (localities), but with varying admixtures of other sources. The analysed samples also indicate that the localities differed in the sedimentary environment, but an increased salinity can be supposed in most of them.

Keywords: Baltica, biodiversity, fossil biomarkers, algae, hydrocarbons.

Wenlock brachiopods from boreholes in eastern Poland

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A brachiopod fauna was found in boreholes Tyniewicze IG-1, Proniewicze IG-1, Widowo IG-1, and Sobótka IG-1 situated in the Podlasie Depression (eastern Poland, vicinity of Bielsk Podlaski; Eastern European Platform), at depths ranging from approximately 400 to 700 m.

Thirty-four species can be identified in total, including four previously published inarticulates and thirty articulates (rhynchonelliformeans) dealt with here. Articulate brachiopods include strophomenides (4 species), productides (1), protorthides (1), orthides (7), pentamerides (3), rhynchonellides (1), atrypides (8), athyridides (3), and spiriferides (2). *Lissatrypa lithuanica* is the numerically dominant species, represented by several tens of specimens. Three specimens of *Gotatrypa* might belong to a new species, differing from *G. hedei* in the relative convexity of the valves. The athyridide *Dayia*, otherwise recorded from the Eltonian onwards, has probably its oldest species in the studied fauna, intermediate in characters with the presumably ancestral *Protozeuga*; the material is scarce (seven specimens), and the interpretation is tentative. *Ravozetina* sp. n. is likely present in both Poland and Estonia. Some widely distributed and well-known species are also present, like *Skenidioides acutus*, *Resserella canalis*, *Dicoelosia biloba*, and *Cyrtia trapezoidalis*.

Generally speaking, the brachiopod fauna represents mostly a deep-sea setting and is largely composed of species with wide biogeographical distribution. The Anglo-Welsh basin and Gotland show the greatest numbers of species in common with the fauna from eastern Poland.

Keywords: Silurian, Sheinwoodian, Homerian, Poland, rhynchonelliformeans, taxonomy.

The late Sandbian/Early Katian carbonate succession in the eastern St. Petersburg region: the stratigraphic record in the Krapivno 21 drill core

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This report treats the Krapivno 21 core section drilled ca. 160 km E to SE of St. Petersburg, in shallow water settings of the easternmost Baltoscandian Basin, and deals with strata of late Kukruse, Haljala, and late Keila ages (East Baltic Regional Stages; RS) up to the erosional contact between the Katian and Middle Devonian, thus spanning the Sandbian–Katian transition. We present a compilation of data on shelly faunas (brachiopods, trilobites), microfossils (conodonts, chitinozoans, prasinophytes), and the $\delta^{13}C$ record in this part of the basin.

The section is composed of sandy dolomitic mudstones and dolostones, with dispersed kukersite-rich layers. The graptolite *Nemagraptus* sp. and the chitinozoan *Eisenackitina rhenana* indicate a late Kukruse age for the strata below a discontinuity surface at 195.5 m. The overlaying supratidal sabkha dolostones of the Elizavetino Formation (Fm) are equivalents of the Keila RS in NW Russia. From the base of the latter Fm towards the early Katian (late Keila)/Middle Devonian boundary, five intervals are tentatively distinguished. The post-Kukruse strata in the interval 182–194 m are characterised by transitional species, including the FADs of the chitinozoan *Desmochitina holosphaerica*, the trilobites *Chasmops marginatus* and *Estoniops bekkeri,* and increased abundance of the brachiopod genera *Platystrophia* and *Clinambon*.

The Haljala/Keila boundary presumably falls in the complex of discontinuity surfaces between 179.0 and 181.8 m. The overlaying ~16-m-thick biodetrital dolostone unit is rich in shelly fossils characteristic of the latest Sandbian. This fauna of Keila age is characterised by the trilobites *Neoasaphus* sp., *Bolbochasmops bucculentus* and *Estoniops maennili*, the brachiopod genus *Clinambon*, and new species of the brachiopod genera *Hedstroemina* and *Geniculina*. The overlaying 15 m yields abundant organic-walled microphytoplankton (*Leiosphaeridia*, *Tasmanites*) and chitinozoans, but macrofossils are scarce. A 6 m thick interval of cavernous biodetrital dolostones above these strata presumably still correlates with the Keila RS. These rocks possibly show organic structures reminding of reefal carbonates. The variegated dolostones between 138 and 145 m contain chitinozoans which cannot be attributed to either the Keila or Oandu RS. With respect to their stratigraphic position, these strata can be compared to the so-called *Leperditia* beds in the Osmino 111 core drilled south of St. Petersburg. Descriptions and ecological interpretations of the *Leperditia* beds in this area do not differ from their analogues in Laurentia. In the East Baltic region, the siliciclastic *Tetrada* beds, named after an ostracod, follow stratigraphically directly above the GICE interval. Whether the *Leperditia* and *Tetrada* beds in the upper Keila RS are contemporaneous remains a matter of future studies.

The $\delta^{13}C$ record is similar to those described from the East Baltic. The low $\delta^{13}C$ values (-1–0‰) characterise the interval spanning the Haljala RS and the lower half of the Keila RS with its basal Keila fauna and kerogen-rich beds. The preserved part of the Guttenberg Isotopic Carbon Excursion (GICE) spans a ~15-m thick interval (144.0–159.5 m), the falling limb is cut off, and a late Keila age is assumed for the top of the Ordovician in the core. A comparison with Estonian records suggests that most of the time corresponding to the upper Elizavetino Fm is missing in N Estonia. The *Leperditia* beds fall into the peak interval of GICE, suggesting a possible correlation of this level to reef complexes in N Estonia and the lower Variku Fm (incl. *Tetrada* beds) further south.

Keywords: Ordovician, Baltica, St. Petersburg region, biostratigraphy, stable isotope chemostratigraphy, GICE.

Geoscience collections and data services in Estonia: current state and perspectives

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Collections of minerals, rocks and fossils constitute an integral part of geological research. If adequately documented and digitised, their value and usage are even greater as sources of new information and as physical evidence of research outcomes. In Estonia, the main geoscience collections are hosted by four academic and state institutions: Tallinn University of Technology (TalTech), Tartu University, Estonian Museum of Natural History and the Geological Survey of Estonia. Altogether, they host more than 0.8 million specimens of fossils, minerals, rocks, drill cores, material samples, preparations, etc. The scientific highlights of Estonian geocollections are related to Paleozoic rocks and fossils, primarily from the Baltic region, which have contributed to deciphering Earth's history worldwide. The Estonian microfossil collections are some of the largest for the Ordovician and Silurian periods; they have been used to create and correlate regional and global geological time scales and biozoanal schemes. The central repository of drill cores in Estonia is managed by the Geological Survey, but TalTech also holds hundreds of cores from Estonia and neighbouring regions.

In 2004, the geoscience collections of academic institutions formed a virtual consortium, "National Geological Collection", and since 2011, the National Research Infrastructure Roadmap project "Natural History Archives and Information Network" (NATARC, https://natarc.ut.ee) has allowed renewing collection storage facilities and creating database tools. During the last few years, the Geological Survey has also invested significantly in building a new core repository and study centre at Arbavere with modern equipment and working environment. These developments have ensured proper preservation and physical accessibility to geological collections in Estonia for the coming decades.

The first efforts in using an electronic database for cataloguing geoscience collections were made already 30 years ago, in 1994, at the University of Tartu. A few years later, the development of an in-house data management system "SARV" started at TalTech. By 2004, it had evolved into a client-server system that provided online access to data. It was soon adopted by the Estonian Museum of Natural History and the University of Tartu. As of 2024, SARV has become a multi-institutional geoscience data management platform with a complex data model and many web-based user interfaces. Importantly, all recent software developments of SARV are open source. Most of the data can be accessed through a standardised API, as well as the central "eGeology" web portal (https://geoloogia.info), the portal of fossils (https://fossiilid.info) and other services.

Extensive geological data are also managed by the Geological Survey and the Estonian Land Board. The largest state geological databases are "Geoloogiafond" (https://fond.egt.ee), a digital archive of geological reports, and the Survey's upcoming central database "GEA". In 2025, the geological expertise in these two institutions will be combined under the Geological Survey in order to create a stronger centre of geological competence.

The future perspectives on geoscience databases and e-services in Estonia are related to better interoperability between different platforms and applying the idea of "data spaces" or "data cubes". One such data space could be "a unified nature data space for Estonia". Another, not less important direction is the participation in the European Research Infrastructure Consortium "DiSSCo" (Distributed System for Scientific Collections; https://dissco.eu), which will be launched in coming years and hopefully help to ensure the application of common standards and improved accessibility of geological collections and data across Europe.

Keywords: geological collections, fossils, database, data management, e-services, stratigraphy.

Biogenic phosphate pollution inducing eutrophication as a catalyst for the decline of obolid-dominated brachiopod communities in the Early Tremadocian of East Baltica

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During the late Furongian - early Tremadocian (*Cordylodus andresi* to *Cordylodus angulatus* zones), the Baltoscandian epicratonic basin displayed environmental heterogeneity. The basin included a black shale depocentre (Alum Shale Formation), bordered in North Estonia by coastal plains and shoal complexes featuring extensive brachiopod shell accumulations (Kallavere Formation). Since the mid Cambrian to the Tremadocian, the costal planes and shoals of the inland Baltoscandian Basin were inhabited by low diversity benthic communities dominated by a single or few linguliform brachiopod species of the genera *Obolus*, *Oepikites*, *Schmidtites* and *Ungula*, characterised by organophosphatic shell mineralisation. Abundance of *Skolithos* trace fossils was also characteristic. These obolid dominant communities were adapted to the life on soft, mobile substrates affected by storms and tidal currents. Before expansion of bivalve and gastropod molluscs in the Ordovician, these habitats were marginal for almost all early Palaeozoic benthic animals. The gradual proliferation of these brachiopod dominant faunas through the Furongian reached its peak during in the latest Furongian (*Cordylodus andresi* and *Cordylodus proavus* zones), when bioclastic material produced by costal brachiopod communities invariably present in siliciclastic sediments deposited nearshore. It was a major source of biogenic phosphate accumulation in Furongian shoal complexes, which produced economically significant phosphorite ore deposits. The geological scale of bioaccumulation processes at that time can be illustrated by the fact that proven P_2O_5 reserves exceeding 27 million tons were reported just for the Toolse phosphorite ore deposit. These figures represent only a fraction of biogenic phosphates produced at the late Furongian time. The repetitive early Tremadocian (*Cordylodus lindstromi* and *Cordylodus angulatus* zones) marine transgressions coeval with the geographical expansion of the Alum Shale accumulation resulted in the collapse of shallow marine biota in the Baltoscandian basin. Due to extremely low net deposition rates, extensive Furongian obolid shelly substrates remained exposed to the redox environments in sediment/water interface. They were a major source of constant influx of phosphate nutrients into the water column resulting in widespread coastal eutrophication, which likely led to a significant seasonal enrichment of the water column with nutrients, linked to fluctuations in dissolved oxygen. The presence of substantial amounts of dissolved phosphate in the water during this period was evidenced by the deposition of concretions and crusts of chemogenic phosphorites outlining the periphery of the black shale depocentre. Simple shallow ecosystems with obolids on the top of a very short trophic chain and virtual lack of predation led to uncontrollable proliferation of the obolid-dominated nearshore communities and probably contributed to the extinction.

Keywords: late Furongian - early Tremadocian, East Baltica, phosphorites, brachiopods.

Ordovician trilobite fauna from erratic boulders from northern Poland

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The first regional studies related to the distribution of Scandinavian erratic sedimentary rocks and fossils in northern Poland began in the 19th century. These studies have focused on lithological classification of the erratic boulders and on trying to determine where they came from. At the same time, the first studies of trilobite fossils found in erratic boulders were published. This study compares the new preliminary results of the research with more recent studies.

New material comes from northern Poland, an area covered mainly by morainic till of the Pomeranian and Poznan phases of the Vistula glaciation. A total 53 erratic boulders with Ordovician trilobites were collected. The precise and correct way in which the fossils were prepared allowed the morphological features of the trilobites to be seen and led to the identification of 22 taxa.

The most common trilobites founds are the family Asaphidae. The next most numerous trilobite fauna is the family Pterygometopidae (subfamily Chasmopinae). The Early and Middle Ordovician trilobite fossils from the western part of Poland represent about 56% of all the Ordovician trilobite fossils collected. In contrast, no Early and Middle Ordovician trilobite fossils were collected in the northeastern part of Poland (only Late Ordovician trilobite fossils were collected).

Due to the comparatively limited collection of Ordovician trilobite fossils collected, these statistics will be verified by further research. The maintenance of a database of collected Paleozoic erratic boulders and fossils will allow for a comparison of the material with Western European rock and fossil collections. This study will also allow to explore the variation of the distribution of Palaeozoic sedimentary erratic boulders during the successive glaciations.

Keywords: Ordovician, trilobites, Vistula glaciation.

First aulaceratid stromatoporoid from Baltica

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During the Great Ordovician Biodiversification Event, stromatoporoids, especially labechiids, underwent a significant radiation. Various skeletal architectures in labechiids emerged since the late Darriwilian of the Middle Ordovician, peaking in the subsequent Late Ordovician. Among these, aulaceratid stromatoporoids stand out due to their tree-like growth morphologies, which can range from branching or unbranching columnar forms to dendroid or digitate structures. These distinctive stromatoporoids achieved worldwide distribution in the Late Ordovician but had not been previously discovered in Baltica. *Aulacera vohilaidia* Jeon & Toom sp. nov. from the Upper Ordovician Adila Formation (Pirgu Regional Stage; late Katian Stage) of Estonia is reported in this study, the first aulaceratid stromatoporoid reported from the Ordovician of Baltica. *A. vohilaidia* consists of three distinct zones - axial, lateral and outer - each characterised by distinct cyst plates of varying size and convexity. The axial zone is particularly narrow and has large horseshoe-shaped cyst plates arranged in a wavy imbricate pattern. The lateral zone consists of smaller cyst plates interspersed with sporadically developed pillars, while the outer zone consists of flat and parallel cyst plates. The outer zone also shows ridged structures with cusps formed by the parallel arrangement of cyst plates, and the growth surface shows a pustular reticulated structure with a polygonal morphology. The discovery of *A. vohilaidia* in Estonia extends the palaeogeographical range of aulaceratid stromatoporoids to Baltica, previously known only from peri-Gondwana, Laurentia and Siberia in the Ordovician. The appearance of aulaceratid stromatoporoids in Baltica coincides with the climatic warming of the palaeocontinent since the early Katian and the extensive expansion of this group during the Late Ordovician.

Keywords: Late Ordovician, Baltica, Estonia, Adila Formation, stromatoporoid, aulaceratid.

Depositional environments of the Šilalė Event (early Přidoli, Silurian) in Milaičiai 103 core section, Lithuania

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The Šilalė Event, first identified in the Milaičiai 103 core in southwestern Lithuania, is marked by a negative carbon isotope excursion in carbonate rocks known as the Šilalė Negative Carbon Isotope Event. The Šilalė Event resulted in a decline in conodont diversity and abundance, and a corresponding increase not just in the diversity of brachiopods but in their absolute abundance as well. After the event, conodont abundance surged during the interval of biotic recovery from the Šilalė mass rarity. In the presented contribution, the depositional environments during the Šilalė Event were studied using the geochemistry and lithology of the Milaičiai 103 core. Diagenetic overprint was estimated by CL (cathodoluminescence) technique. The grain size, carbonate/siliclastics ratio, redox etc were established from the major and minor element and REE data. Thin sections were used for detailed lithology and diagenetic studies. The studied interval shows a deep and relatively deep shelf sedimentary environments. In thin-sections, mainly micrite and allochems of different proportions are present. The shallowing of the basin could be suggested by the fact that the amount of allochems, mainly crinoids, increased. The composition of trace, REE and some ratios of the trace elements were used to investigate sedimentary environment peculiarities. Some of them – U, Th, V, Cr – are redox-sensitive elements and, along with Ce, were used for oxidation/reduction sedimentation environment identification. We used the Zr/Rb ratio as an indicator of grain size variation in the succession. The Th/U ratio was applied as a redox indicator, with high values typically of more oxic settings. Low values reflect less oxic to dysoxic and possibly anoxic depositional conditions. Because the Th/U, Zr/Rb and (Zr+Rb)/Sr ratios are all influenced by the chemical composition of the provenance area, a comparison of sediments from the same source is therefore important in order to rely on an environmental interpretation of the geochemical distribution. The (Zr+Rb)/Sr ratio was used as terrigenous (siliclastics) material vs carbonates indicator. Variations in redox conditions as well as differences in REE complexation and adsorption behavior, are reflected by changes in the oxidation state of cerium Ce (III) – Ce (IV). These changes may result in differences in Ce abundances. Ce-anomaly (Ce/Ce*) values we calculated by $Ce/Ce^* = Ce_{EUS}/(0.5*(La_{EUS} + Pr_{EUS}))$. The values less than 1.0, depletion in sediment Ce, suggest reductive dissolution of insoluble Ce (IV) to soluble Ce (III). It was observed that only Sr is negatively correlated with the rest of the elements. It suggests that two fractions – carbonate and terrigenous – could be responsible. The major source of Sr, as it could be seen from the thin sections, is detrital carbonate fauna – brachiopods, bivalves, crinoids etc. U/Th ratio >0.75 up to 1.25 indicates dysoxic environment – samples from 1104.5 and 1092 m are from Šilalė Bioevent interval. From the U/Th, Ce/Ce* data, the depositional conditions look slightly different. There are samples from all studied intervals which could be deposited under dysoxic conditions. U/Th vs V/Cr and U/Th vs Ce/Ce* data suggest that either the deposition took place close to the oxic – dysoxic boundary or some diagenetic alteration might have occurred, as could be seen in some thin-sections. (Zr+Rb)/Sr ratio approaching zero clearly indicates carbonate sedimentation or carbonate content increase. We could see that almost all Šilalė Event core interval is represented by carbonates, while after the event, the terrigenous material prevails. Zr and Rb ratio variation through the section has not revealed any noticeable changes even when carbonate depositional environment switched to terrigenous material dominated one and vice versa.

Keywords: Silurian, Šilalė Event, geochemistry, sedimentology.

Lithofacies-related changes of magnetic and radioactive rock characteristics along the Ordovician sequence in Lithuania

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The Ordovician succession of western Lithuania represents a rather continuous sedimentation, but still with recognised unconformities, in comparatively deeper shelf settings ascribed to the Livonian facies zone within the Baltoscandian palaeobasin. The Upper Ordovician sequence dominates over the Middle and Lower series. However, the Ordovician strata within the study area appear to be reduced in thickness towards the south, suggesting deposition on the slope of a topographic palaeohigh, the Lower Nemunas Elevation. This study aims to characterise trends in the magnetic and radioactive patterns of marine sedimentary facies spanning from the top of the Cambrian Deimena Series and Lower Ordovician to the lowermost part of the Silurian (Llandovery).

Along the studied profiles, magnetic susceptibility (MS) and spectral gamma-ray (GR) logs display similar shapes, i.e. both parameters increase within relatively more siliciclastic intervals (mudstones) and decrease in carbonate-rich intervals (limestones, carbonate concretions), pointing to common factors affecting the records. In general, the variability in MS and GR likely results from the introduction of siliciclastic detrital material to the basin, as well as locally associated authigenic and diagenetic fractions, which contain a higher portion of paramagnetic and/or ferromagnetic minerals and radioactive elements compared to the diamagnetic and low-radioactive 'pure' carbonates themselves. The siliciclastic component is well traced by spectral gamma Th and K contents, which serve as proxies for clastic material. In siliciclastic mudstone facies, carbonate minerals act as dilutants of bulk magnetic and radioactive signals. Although pyrite (paramagnetic) is abundant, it does not necessarily notably contribute to the MS record; instead, the MS signal in mudstones in the large portion may be controlled by paramagnetic Fe-chlorite content, implying the diagenetic origin of chlorite. Mudstones with a high content of organic matter (OM), marked by an elevated total GR due to authigenic U enrichment, often display decreased MS values, which could be linked to the diamagnetic nature of OM and its dilution effect resulting in suppressed bulk MS values. Very high total GR values are typical for the thin basal Lower Ordovician siliciclastic interval embracing *Obolus* sandstones (enriched in phosphatic shells of lingulate brachiopods) and overlying glauconite-rich sandstones.

In contrast to phosphate-bearing sandstone, characterised by low MS values and high GR mainly determined by uranium held in phosphatic constituent, glauconitic strata are marked by high values of MS due to the presence of paramagnetic glauconite mineral (evidenced by elevated K content). Beds of mudstone containing volcanic material or tephra show moderately elevated total GR due to higher K and Th contents. MS values are variable in those intervals, while tephra material itself appears to have low MS, thus this hints that the primary agent carrying the MS signal is siliciclastic detrital input. The reddish-brown colouration of beds in Middle and Upper Ordovician suggests the presence of hematite, possessing strong magnetic susceptibility properties. Despite this, the general trends of MS and GR remain similar along these 'red' sections, indicating detrital input as the primary controlling factor of MS signal, rather than diagenetic effects related to hematitisation, although its influence cannot be entirely neglected. Since there are evidences of dolomitisation throughout the Ordovician sequence, a local increase in MS could be linked to iron-bearing carbonates.

The strength of the MS and GR signals along the studied Ordovician succession, which represents the interaction of carbonate and siliciclastic environments, being diagenetically altered, can be mainly attributed to clastic terrigenous input to the basin, but with certain exceptions.

Keywords: magnetic susceptibility, spectral gamma-ray, Ordovician, sedimentary facies.

Early Silurian climate changes on Baltica and South China – a sedimentological, bio- and chemostratigraphic framework

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A series of glacial events during the early Silurian can be inferred from the sedimentological, bio- and chemostratigraphic records in Swedish and Estonian sedimentary successions, including the Siljan impact structure of Central Sweden, in successions of South China, including the Baizitian section in the Sichuan Province, from sections in Laurentia and high-latitude peri-Gondwana. Distinct $\delta^{18}O_{apatite}$ anomalies and subaerially exposed sequence boundaries with palaeokarst in these areas are interpreted as substantial climatic shifts and the development of ice-house conditions. In terms of $\delta^{18}O_{apatite}$, the re-evaluated and detailed record of the early Silurian in the Estonian Viki core serves as a standard section and provides a base for the evaluation of climate changes.

We present new Telychian to Sheinwoodian chemostratigraphic data, including several prominent excursions, such as the pronounced Manitowoc Carbon Isotope Excursion (Manitowoc CIE, 'Manitowoc Excursion'), spanning the upper *Pterospathodus eopennatus* Zone and the lower *Pterospathodus amorphognathoides amorphognathoides* Superzone in carbonates or a large part of the *Oktavites spiralis* Graptolite Zone in shaly successions. The Manitowoc CIE is well constrained by conodont biostratigraphy and an essential tie-point for a detailed correlation between the Baizitian succession in South China and the Telychian strata of Baltica and Laurentia. In the successions preserved in the Siljan impact crater, the corresponding early Silurian carbon isotope anomalies are measured on organic carbon of fine-grained siliciclastic strata (OCIEs in black shale and siltstone) and biostratigraphically constrained by graptolite biostratigraphy.

We focus on the early Silurian climate development, which includes the Telychian Valgu glaciation (more widely recognised than older glacials during the Aeronian), the Manitowoc Icehouse, including two short glacial events, the late Telychian Glaciation (LTG), and the Sheinwoodian glaciation, the latter reflected by the Sheinwoodian Oxygen Isotope Excursion (SOIE), which follows immediately after the $\delta^{13}C$ maximum of the widely known Early Sheinwoodian Carbon Isotope Excursion (ESCIE).

Keywords: Silurian, Baltica, South China, palaeoclimate, biostratigraphy, stable isotope chemostratigraphy.

COSC-2 and its well-preserved Lower Palaeozoic sedimentary succession – an unexpected treasure beneath the Caledonian nappes

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The COSC (Collisional Orogeny in the Scandinavian Caledonides) project focuses on processes related to the closure of the Iapetus Ocean causing the Ordovician-Silurian continent–continent collision between Baltica and Laurentia. The rock succession in the second drill core (COSC 2) from the Jämtland County, central Sweden, provides the base for a detailed sedimentological, stratigraphic, geophysical, geochemical, geothermal and structural studies. The basement, comprising a 1.66–1.65 Ga Transscandinavian Igneous Belt (TIB) porphyries intruded by 1.47 Ga and 1.27–1.26 Ga mafic dykes and sills, is heavily weathered towards the top. Here it grades into typical saprock and saprolite (including an immature soil reflecting the Sub-Cambrian peneplain). The overlying sedimentary sequence starts with basal conglomerates and heterogeneous sediments with shell fragments, indicating a Lower Cambrian rather than a Neoproterozoic age for a marine transgression in the area. The developing early Cambrian basin was rapidly filled, initially by mostly coarse-grained sediment gravity flows. These strata are covered by sandstone turbidites that show an upward transition into the Alum Shale Formation representing a tectonically more quiet period (Middle Cambrian/Maolingian through Lower Ordovician/Tremadocian). The upper part of the Alum Shale Formation is overlain by a late Early Ordovician turbidite succession. Local sources of sediments below the Alum Shale Formation and the extended time of deposition may indicate continuous sedimentation in a pull-apart basin preserved in a window beneath the Caledonian thrust sheets.

Keywords: Caledonian Orogeny in the Scandinavian Caledonides (COSC), ICDP, Baltica, Cambrian, Ordovician, Sweden.

Lower and Middle Ordovician bio- and chemostratigraphy of the Aizpute-41 drill core, Latvia

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The Ordovician Period was a crucial time interval in Earth's history characterised by the transition from a greenhouse world to an ice age, witnessing a rapid diversification of marine life, the start of terrestrialisation and the end-Ordovician mass extinction. Ordovician sea-surface temperature reconstructions are mainly based on oxygen isotope thermometry, notably deriving from conodont apatite ($\delta^{18}O_{cono}$). In Baltoscandia, which is known for its well-preserved geochemical archives, the $\delta^{18}O_{cono}$ record through the Ordovician Period is being established. However, the data from deeper shelf settings of the basin are still very scarce, and the trends within the basin are poorly constrained. Moreover, the bulk of paleontological data comes from shallow shelf sections, and less information is available from the distal part of the Baltoscandian basin. Here, we present the first results of our study on the Aizpute-41 drill core from western Latvia, which characterises the deep shelf settings in the eastern part of the Baltoscandian basin and was selected as a reference section for an ongoing research project. We studied biostratigraphy of four groups of microfossils (conodonts, chitinozoans, ostracods and scolecodonts) and carbon stable isotope chemostratigraphy ($\delta^{13}C_{carb}$) in the nearly 100-m-thick Lower and Middle Ordovician succession of the core, corresponding to the Hunneberg to Uhaku regional stages, and comprising the Zebre, Kriukai, Baldone, Segerstad and Taurupe formations.

The conodont fauna appeared abundant and diverse in all samples studied, often with several thousands of conodonts per kg of rock. The material allowed the establishment of a precise biostratigraphic framework, starting from the *Paroistodus proteus* Zone, and followed by zones and subzones recognised previously elsewhere in Baltoscandia, up to the *Pygodus anserinus* Zone.

A rich chitinozoan record starts in the Taurupe Fm, where *Laufeldochitina striata* Zone is established. The base of the Upper Ordovician can be identified by the *Laufeldochitina stentor* Zone and *Eisenackitina rhenana* Subzone. Additionally, the global index graptolite *Nemagraptus gracilis* has been identified in the Aizpute samples. Scolecodonts were rare in the section, showing that the deeper shelf settings were generally unfavourable for jaw-bearing polychaetes. They first appeared in the Taurupe Fm, where nine species were recorded. The ostracod record begins in the Zebre Fm, showing remarkable diversity and several distinct assemblages, partly older than previously recorded in Estonia and Latvia, and thus complementing the view on the development of the early ostracod faunas in the Baltic area.

The Early and Middle Ordovician $\delta^{13}C_{carb}$ record shows relatively invariable values in the Dapingian and early Darriwilian part of the Aizpute core, followed by the Mid-Darriwilian Excursion (MDICE) and then a declining trend towards the "Kukruse Low", being closely similar to previous records from other Baltoscandian sections.

Collectively, these data provide new insights into an integrated Baltic regional stratigraphy and form the basis for the next steps – including establishing a high-resolution SIMS-based $\delta^{18}O_{cono}$ record through the Early and Middle Ordovician for regional paleotemperature reconstruction and comparison across Baltoscandia and worldwide.

Keywords: Ordovician, Baltica, conodonts, chitinozoans, oxygen isotopes, stratigraphy.

The Upper Famennian Ketleri Formation of Latvia: fauna and flora from tide-dominated delta deposits in a seasonal climate

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The Upper Famennian in the Baltic Devonian basin consists of the Akmene, Spārnene, Piemare, Ketleri, and Šķervelis regional stages (RS). The Ketleri RS correspond to the Ketleri Formation (Fm) distributed in the southwestern Latvian and western Lithuania. The deposits of the Ketleri Fm are subdivided into three members (Mb), Nīgrande, Pavāri and Varkaļi, cropping out only in Kurzeme (SW Latvia). All three members are well known for their vertebrate fossil content, including one of the best-preserved Late Devonian tetrapod *Ventastega curonica* from the Pavāri and Varkaļi members. Combined sedimentological and palaeontological studies of the vertebrate fossil-bearing deposits of the Ketleri Fm provided new data on the sedimentary environment of the deposits, as well as taxonomical and taphonomical peculiarities of the fossil assemblage. Fluvial channels with strong tidal influence and tidal bars were identified, suggesting the tide-dominated delta environment during the formation of the Pavāri and Varkaļi members. The current energy changed from very high, when deposits with clay clasts and vertebrate debris accumulated, to moderate, when fine-grained cross-bedded and ripple-laminated sands sedimented, to low, represented by clayey and silty beds. Tidal features were found in almost all types of deposits, which allows us to suggest the tide-dominated settings. Data from the mathematical model of the Baltic Artesian Basin demonstrate that the sandy deposits of the Pavāri and Varkaļi members form a fan-shaped area resembling a wide delta developed in shallow marine settings, thus supporting the results of sedimentological study.

Until recently, the Late Famennian vertebrate, plant and trace fossils from the Ketleri Fm have been studied in detail in two localities: the Pavāri-1 locality at the left bank of the Ciecere River opposite the vanished farmhouse “Pavāri” (Pavāri Mb), and the Ketleri locality at the right bank of the Venta River close to the abandoned farmhouse “Ķetleri” (Varkaļi Mb). In 2019, a new fossil site named “Pavāri-2” (Pavāri Mb) was discovered on the left bank of the Ciecere River close to the mouth of the Paksīte River, at a distance of about 400 m from the Pavāri-1 site. Excavations during 2019-2023 field seasons provided a large number of vertebrate specimens, including taxa new for the Ketleri Fm, some skeletal elements previously not known from this formation, and well-preserved plant macroremains. Taphonomic studies testify the sedimentary concentrations of well-preserved vertebrate remains were formed under the influence of fluvial and strong tidal processes in the shallow water environment, most probably deltaic settings.

Abundant trace fossils were recognised in the Ketleri site; burrows of *Palaeophycus* isp. are interpreted as combined domichnia and fodinichnia produced by deposit-feeder or predatory worm-like organisms similar to acorn worms (enteropneusts), and traces of *Planolites* isp. are interpreted as fodinichnia produced by worm-like detritophagous animals. Possibly, the *Planolites*-producers dwelled in the *Palaeophycus*-burrows or around them using the remains of food of animals resembling the acorn worm. Both ichnogenera suggest brackish water or marine environment. The analysis of rhizocretes from the Varkaļi Mb allowed to suggest the strong influence of a seasonal climate.

Keywords: Devonian, Baltic basin, vertebrates, plants, sedimentology, palaeontology.

The Late Ordovician Hirnantian isotopic carbon excursion in the Baltic Basin: relationships between sedimentary facies and magnitude of isotopic excursion

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Palaeozoic carbonate $\delta^{13}C$ studies have predominantly focused on bulk rock analysis in the chemostratigraphic correlations and palaeoenvironmental interpretations. Most of the attention has been paid to positive $\delta^{13}C$ excursions that point to possible global or regional events that have perturbated the carbon cycle.

Correlating different drill core sections using lithology does not always match with accompanying chemostratigraphy, and many studies of modern and ancient carbonates have shown that bulk rock $\delta^{13}C$ values vary along onshore-offshore profiles. Such facies influenced $\delta^{13}C$ variations are also seen in the records of the Hirnantian Isotopic Carbon Excursion (HICE) from the Baltic Basin at the end of the Ordovician Period. These facies controlled differences in $\delta^{13}C$ values have prompted more detailed studies in carbonate rocks and highlighted the need to place the isotopic data into a depositional context.

Currently, work is being done on lithologically heterogeneous carbonate material with distinct components in the HICE recording intervals of Estonian drill cores. Preliminary results of component-specific $\delta^{13}C$ data derived from grainstones and packstones of the Porkuni Regional Stage show that $\delta^{13}C$ can vary up to 4‰ with some components having values up to 3‰ higher than bulk rock values. Such data can give more insight into carbon cycle dynamics and help to more accurately understand depositional settings.

Keywords: chemostratigraphy, carbon isotopes, component analysis, Hirnantian.

Silurian stratigraphy in Estonia: Recent developments and challenges

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The Silurian of Estonia has been studied for nearly 200 years. Its main stratigraphic features were broadly but adequately summarised by Roderick Murchison in 1845, and the succession was further subdivided by Alexander Schrenk and Friedrich Schmidt in the 1850s. A detailed stratigraphic subdivision into regional stages was proposed by Hendrik Bekker a century ago, in 1925. The correlation between the Silurian succession in Estonia and the global chronostratigraphic standard established in the 1980s has been considered reliable for many decades. However, new information on the distribution of microfossils, combined with chemostratigraphic markers and K-bentonites, has changed our understanding of the Silurian stratigraphy in the region, inferring the need to update the regional scheme. In this study, we discuss the new data and correlation possibilities. The most significant updates to the scheme are the following:

(1) the lower part of the Juuru Regional Stage (RS) is of Hirnantian age;

(2) the base of the Raikküla RS lies within the *Coronograptus cyphus* Graptolite Zone;

(3) the Aeronian–Telychian boundary in Estonian succession correlates with a level in the middle of the Rumba Formation, indicating that the lowermost Adavere RS is of the latest Aeronian age;

(4) the lower boundary of the Jaagarahu RS, as used up till now, is diachronous, and the best biostratigraphic approximation for the identification of this level is the FAD of conodont *Ozarkodina sagitta rhenana*;

(5) the Wenlock–Ludlow boundary in the Estonian succession correlates with a level in the upper Rootsiküla RS;

(6) the base of the Paadla RS corresponds to a level in the upper Gorstian, within the lower(?) *Phlebolepis ornata* Vertebrate Zone;

(7) the Sauvere and Himmiste beds of the Paadla Formation correlate with the upper Gorstian, the Uduvere Beds of the same formation with an interval in the lower Ludfordian, with part of the *Ancoradella ploeckensis* Conodont Zone;

(8) so far, there are no reliable criteria for recognising the Ludlow–Přidolí boundary in the Estonian succession.

It must be stressed that the proposed revised version of the regional Silurian stratigraphic scheme reflects the current understanding only, and there are still several challenges related to precise dating and correlation of strata, particularly considering the correlation of Estonian succession with the international standard and accurately identifying the global stage boundaries in the local sequence. Considering regional stratigraphy, one of the main problems that need to be addressed in future is the proper definition of the lower boundaries of the regional stages following the principles outlined in the International Stratigraphic Guide. So far, these boundaries are based primarily on lithological criteria being, in many cases, poorly constrained biostratigraphically and chemostratigraphically.

Keywords: regional stratigraphy, biostratigraphy, conodonts, correlation, Silurian, Estonia.

Microfossil response to the late Silurian Lau Event in the Bebirva-111 drill core, Lithuania

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The Silurian period was characterised by several environmental perturbations and biotic crises. The mid-Ludfordian time is known by one of the most significant carbon isotope excursions in the Phanerozoic (MLCIE), associated with changes in ocean circulation and chemistry. These environmental changes caused extinctions in many groups of marine organisms, although different fossil groups reacted somewhat differently, and thus the bioevent is known as the *kozlowskii* Event in graptolite successions and Lau Event when considering primarily conodonts and shelly faunas (below, we use the latter name to refer to this geo-bio event collectively). The Lau Event was initially defined based on the turnover in conodont faunas in Gotland, Sweden. In the East Baltic outcrop area of Ludfordian rocks on Saaremaa Island, western Estonia, the Lau Event interval is missing due to a gap in the succession but is well represented in the subsurface sections of Latvia and Lithuania. It is currently being studied for a better understanding of the spatial distribution of the carbon isotope event and associated geochemical signatures, as well as biotic responses.

Here, we report the preliminary results of an integrated paleontological study based on 32 samples collected from the Bebirva-111 drill core, Lithuania. The study interval (ca 1024 to 1135 m) corresponds to the Dubysa, Pagėgiai and Minija regional stages of Lithuania, and is represented by variable carbonate lithologies (marlstones, coarse-grained skeletal grainstones, nodular carbonate mudstones). The peak $\delta^{13}C$ values reach up to 7.5‰ in this interval.

The studied microfossils include conodonts, chitinozoans, scolecodonts, prasinophycean algae, melanoscleritoids, foraminiferans, graptolites, eurypterid fragments and vertebrate scales. A distinct decrease in abundance and diversity (including the disappearance of *Polygnathoides siluricus*) in the conodont succession (almost) coinciding with the base of the growing limb of MLCIE marks the beginning of the Lau Event in the section (at ca 1121m). The event is characterised by low-diversity conodont faunas strongly dominated (up to 95%) by *Panderodus equicostatus*. At its end (ca 1062 m), the conodont fauna starts to recover gradually, and new taxa appear. Graptolites found in the section are represented by fragments and occur below the Lau Event only. Melanoscleritoids show higher abundance in the upper part of the event, just above the maximum $\delta^{13}C$ values. The chitinozoan assemblage contains seven genera, including *Eisenackitina*, *Angochitina*, *Ramochitina* and *Alhajrichitina*. The last taxon is reported for the first time in the Baltic region. Due to the generally poor preservation of chitinozoans, their species-level identification needs further SEM studies. It is nevertheless apparent that the distribution of chitinozoans shows clear changes across the studied interval, suggesting a direct response to the Lau Event. The scolecodonts are well preserved and are represented by at least 30 species from 18 genera and nine families. Their distribution is somewhat uneven and possibly influenced by the Lau Event, but many species range through the event interval and show no signs of major extinction.

Collectively, these data provide new insights into the biotic effects of the Lau Event on several groups of organisms that were hitherto poorly documented in the Baltic region but also worldwide. It confirms the resilience of jawed polychaetes to environmental change that severely affected other elements of late Silurian marine ecosystems.

Keywords: Conodonts, chitinozoans, scolecodonts, biostratigraphy, Baltica, Ludfordian.

On the integrated regional Ordovician correlation charts of Estonia, Latvia and Lithuania

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The system of the Ordovician bio-, litho- and chronostratigraphic units is highly detailed in Estonia, Latvia and Lithuania. The regional stages of the Ordovician System were defined in Estonia and introduced for the western part of the East European Platform, including Latvia and Lithuania, in the 1960-1980s. Based on this chronostratigraphic standard, several versions of integrated regional Ordovician correlation charts were elaborated in a well-coordinated manner. These charts used a unified nomenclature of lithostratigraphic units, with different sets of formations for all major facies zones, and the distribution areas of most units crossed the national borders. The regional chronostratigraphic units, although not defined in full accordance with the International Stratigraphic Guide, are routinely applied in Estonia, Latvia and Lithuania also today, and their correlation to the global chronostratigraphic standard is mostly well-constrained.

Since the early 1990s, the developments in the Ordovician stratigraphy in different countries have been more independent and new attempts of compiling regional charts were not undertaken until 2023. This has led to increasing differences in the development of nomenclature and correlation of formations in different countries. The new, amended versions of the national Ordovician correlation charts reveal differences in nomenclature and ranks of several lithostratigraphic units, with remarkable differences in their boundaries and subunits in different countries, like in the case of the Drąseikiai, Daugavpils, Mežciems formations that are ranked as groups in the modern stratigraphic chart of Lithuania. In several instances, the correlation of the formations has been justified during the last decades, but there was usually no comprehensive analysis on how much this might influence the correlation of the formation in other national correlation charts; this is true, for example, for the Kallavere and Kõrgekallas formations in Estonia. There are numerous other discrepancies between the national correlation charts where we cannot be sure whether the differences are based on results of precise correlation or simply due to adherence to traditional views without further factual justification.

The Ordovician correlation chart compiled for the volume '*A Global Synthesis of the Ordovician System*' (part 1, 2023) emphasises these discrepancies. The differences between the national correlation charts clearly hamper cross-border cooperation between Estonia, Latvia and Lithuania in the field of regional geology and stratigraphy. The compilation of unified regional correlation charts has served as the main motivation for establishing the Baltic Stratigraphic Association in 1994. Today, there is an urgent need to reinvigorate cross-border cooperation in the preparation and development of stratigraphic charts to ensure their consistency in different countries, and the preparation of regional stratigraphic schemes will serve this purpose in the best possible manner. This is equally valid for the Ordovician System as well as other stratigraphic systems documented in the region.

Key words: regional stratigraphy, Ordovician, Estonia, Latvia, Lithuania, timescale, regional stage, formation.

Trace fossils from the Ordovician-Silurian boundary beds of Estonia (Baltica)

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The transition from the Ordovician to the Silurian Period marks a crucial time in Earth history. Associated with the Late Ordovician Mass Extinction (LOME), rocks of this age have been characterised by low diversity in body fossil assemblages. Until recently, studies associated with the Ordovician-Silurian boundary in Estonia were mostly restricted to drill cores. The exposure of this boundary in the Reinu Quarry has led to new research interests, one of which is ichnology, as the trace fossils of this stratigraphic interval have not been systematically studied before. The Reinu Quarry provides unique material for such research.

This study documents the trace fossils from the Ordovician-Silurian boundary beds in Estonia, specifically the Kamariku Member of the Ärina Formation (Porkuni Regional Stage) and the Koigi Member of the Varbola Formation (Juuru Regional Stage). Lithological characterisation of the samples collected from the section revealed two broad but distinct limestone facies: sandy limestone and carbonate mudstone facies, interpreted as the Kamariku and Koigi members, respectively. Nine ichnogenera, representing seven categories of architectural designs and five categories of ethological classification, are recognised from ichnological studies of the Ordovician-Silurian boundary beds. The Kamariku Member hosts ichnogenera, such as *Chondrites, Multina, Planolites,* and *Thalassinoides.* Horizontal components of *Thalassinoides* dominate the Kamariku Member. Bioerosional traces such as *Trypanites?* also occur in lithic substrates. Six ichnogenera are observed in the Koigi Member, including *Chondrites, Multina, Pilichnus, Planolites, Sinusichnus,* and *Treptichnus.* Overprinting is quite common in the Koigi Member, and there is repeated occurrence of *Chondrites* in association with *Planolites* burrows. Compared to the patchy occurrence of *Chondrites* in the Kamariku Member, the ichnogenus is relatively better preserved in the Koigi Member. This provides material on *Chondrites* in Palaeozoic carbonate sediments, which has been virtually lacking as the ichnogenus has been studied mostly in younger sediments.

The trace fossil assemblages in the Ordovician-Silurian boundary beds belong to the *Cruziana* ichnofacies. The assemblage and the dominance of horizontal traces reflect deposition in moderate to low-energy settings. The relatively high ichnodiversity suggests that organism-sediment interactions did not decrease despite the reduced biodiversity associated with the Hirnantian extinction. The dominance of traces that reflect feeding behaviour indicates that nutrient availability was likely a key environmental factor during the deposition of these beds. Other peculiar environmental factors also came into play. The Kamariku Member was likely deposited under relatively higher hydrodynamics than the Koigi Member. However, the hydrodynamics likely fluctuated. This is bolstered by the dominance of the horizontal component of *Thalassinoides* and the occurrence of substrate-controlled traces in the Kamariku Member, which suggests that colonisation occurred during periods of low-energy or non-deposition. The waters were also likely more oxygenated, considering the moderate abundance of shelly fossils and the low occurrence of *Chondrites* in the Kamariku Member.

On the other hand, the trace fossil assemblage in the Koigi Member reflects relatively quieter energy conditions. The dominance of *Chondrites* reflects stressful levels of oxygenation conditions. The trace makers likely inhabited dysoxic waters, where only opportunistic endo-benthos thrived. The moderate to intense bioturbation in the Koigi Member is likely due to low sedimentation rates.

Keywords: Ichnology, Ordovician-Silurian boundary, Baltica, Kamariku Member, Koigi Member.

Geology and geochronology of the Estonian Precambrian basement

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The Estonian Paleoproterozoic to Mesoproterozoic metamorphic and igneous rock basement can be considered a southern continuation of the Fennoscandian Shield within the East European Craton. The Estonian basement comprises two major units: amphibolite facies rocks in northern Estonia and mostly granulite facies rocks in southern Estonia, separated by the Paldiski-Pskov tectonic (shear) zone. These rock complexes are similar to the rocks found in southern Finland. Due to a sedimentary cover of 100–780 meters, geological information is primarily derived from drill core studies and geophysical investigations. Geophysical, petrological, and geochemical studies have delineated the Estonian basement six structural-petrological zones: Tallinn, Alutaguse, Jõhvi, West-Estonian, Tapa, and South-Estonian zones, each varying in rock composition, genesis, geophysical properties, and metamorphic degree.

Until the early 1980s, it was assumed that the granulite facies rocks in southern Estonia might be of Archaean origin. However, pioneering Sm-Nd analyses and U-Pb zircon age determinations in the early 1990s suggested a Palaeoproterozoic age for the granulites. The U-Pb zircon dating of metavolcanic rocks in northern Estonia reveals ages from 1889 Ma to 1844 Ma, while granulitic metavolcanics from the South-Estonian Zone show U-Pb zircon ages between 1840 Ma and 1802 Ma. Additionally, U-Pb monazite dating of orthopyroxene-garnet gneiss from the South-Estonian Zone yields an age of 1778 ± 2 Ma. Partial melting of granulitic rocks in the South-Estonian and Tapa zones indicates crystallization ages for tonalites and charnockites clustering around 1822–1833 Ma and 1761–1788 Ma, respectively. Zircons from the Jõhvi Zone in iron-rich gneisses show three distinct age groups: 1874 Ma, 1826 Ma, and 1789 Ma. Post-orogenic magmatism in Estonia is represented by small monzonite-type mafic to felsic plutons with shoshonitic geochemical affinity, originating from the enriched lithospheric mantle and emplaced within the Estonian crust between 1800 Ma and 1610 Ma.

Estonia, situated in the central part of the Fennoscandian Rapakivi province, hosts granitoids temporally similar to both Rapakivi subprovinces. The Neeme rapakivi yields a U-Pb zircon age of 1634 Ma, Taebla rocks date to 1648 Ma, and Ereda rocks exhibit two age groups at 1642 Ma and 1627 Ma (unpublished data by A. Soesoo). The Märjamaa rapakivi provides a U-Pb zircon age of 1626–1630 Ma. Notably, the Calymmian granitoids in Estonia are known only from the Riga batholith, with ages ranging from 1576 Ma to 1584 Ma.

Currently, the Geological Survey of Estonia is revising the crystalline basement map. Future goals include extending geological knowledge to marine areas, linking the Estonian parts of the Fennoscandian Shield to rock units of similar age in South Finland and Sweden, and integrating new information from deep boreholes and geophysical investigations to update the map.

Keywords: Paleoproterozoic, Mesoproterozoic, crystalline rocks, geochronology, composition, Estonia.

Sandbian-lower Katian conodont correlation of Baltoscandian Basin

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Conodonts are used as one of the main biostratigraphical correlational tools for the Ordovician strata in the Baltoscandian Palaeobasin. Established biozones have been fairly stable, with only a few changes implemented after the pioneering work in the last century. Conodont zones for Sandbian–lower Katian are based on the successive species of genera *Amorphognathus* and *Baltoniodus*, namely *A. inaequalis*, *A. tvaerensis* and *A. superbus*, and *B. variabilis*, *B. gerdae* and *B. alobatus*. Recently, it was discovered that *A. inaequalis* appears to be missing from Estonian and Swedish sections. With the *A. inaequalis* Conodont Subzone being part of regional biostratigraphic schemes, an additional study on the topic was advised. Additionally, an analysis of changes in the succession of *A. tvaerensis* revealed that elements in the upper part of its range differ morphologically quite distinctly from those in its lower part, and they were described as a new conodont species *A. viirae*. This raises a need to re-examine the *A. tvaerensis* Conodont Zone.

Validity of the use of *A. inaequalis* Conodont Subzone in the Baltoscandian region and revision of the *A. tvaerensis* Conodont Zone was based on the data from the Bliudziai-150 (Lithuanian) and Kovel-1 (Ukraine) drillcores. These two sections are currently the only ones in the Baltoscandian Palaeobasin where the *A. inaequalis* Conodont Subzone is still reported, and the presence of the *A. viirae* is not yet confirmed. The information we obtained enabled us to update the current Sandbian-lower Katian conodont zonation and correlation in Baltoscandia. The revision of the biozones enables the equalisation of all the zones to lineage interval zones. A few specifications for concurrent regional stages are also considered based on changes to current biozones.

An updated Sandbian–lower Katian conodont biostratigraphy in Baltoscandia allows us to evaluate the current correlations of sections based on $\delta^{13}C_{carb}$ data in the region. There are two distinct $\delta^{13}C_{carb}$ excursions known at that time interval: The Lower Sandbian Negative Isotopic Carbon Excursion (LSNICE; Upper Kukruse Low) and the Guttenberg Excursion (GICE). Reliable ties of conodont biozones and $\delta^{13}C_{carb}$ data would enhance regional and global correlations.

Keywords: Ordovician, conodont, biostratigraphy, carbon isotopes, chemostratigraphy.

The Lower Cambrian Trilobite Zonation of Estonia

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Trilobites, a group of the earliest arthropods, appeared in the fossil record in the lower Cambrian, marking the base of the Cambrian Series 2 on the global scale. They emerged on most major palaeoplates during the Age 3 or Age 4. Interestingly, they show little connection between the faunas palaeogeographically, and thus cannot be readily used for global correlations. Regionally, trilobites are more useful, albeit they are seldom preserved when they first appear. They diversified rapidly and became numerous and valuable in biostratigraphy over the Baltoscandian palaeobasin. Already in 1970s the regional correlation scheme of the East European Platform included the following zones based on trilobites: Pre-trilobite, *Schmidtiellus*, *Holmia*, *Protolenus* correlated to the Lontova, Dominopol, Vergale, Rausve ages accordingly in the former "Lower Cambrian". Later, the *Holmia* Zone was divided, *Protolenus* renamed and Ljuboml and Dominopol ages established. The most recent addition is the *Rusophycus* zone in the lower part of the Dominopol Stage, marking the level where trilobite remains have not been found or not preserved, but the traces have been recorded. In northern Estonia, only the first two zones and regional stages crop out, allowing a detailed study of these early arthropods that are in need of a fresh overview.

The old trilobite collections at the museums in Tallinn, Tartu, and St. Petersburg were restudied, and new material, including the trace fossils gathered together with the observations on the distribution of those mainly in three localities: Saviranna, Kakumäe and Kunda. The latest data allow upgrading the existing biostratigraphic zonation of trilobites, and the trace fossils — *Rusophycus* and *Cruziana* — most probably left behind by the trilobites.

The type material of *Schmidtiellus mickwitzi* originates from the Kunda River bank next to the old Cement Factory, and belongs to the Kakumäe Member of the Tiskre Formation, while *Schmidtiellus reetae* is described from the older beds — the upper part of the Lükati Formation. It is worth establishing a new biozone to recognise the age difference. The lower part of the Lükati Formation also reveals some fragmentary trilobites, which may represent a new species of *Schmidtiellus*?, but that needs well-preserved specimens to be proved. The ichnofossils *Rusophycus* and *Cruziana* occur in several levels through the Lükati and Tiskre formations, representing the suitable taphonomic conditions preserving them rather than the biostratigraphic marker bed. Nevertheless, they possibly do mark the level of trilobite existence and thus the Series 2; however, it is not advised to use as an independent zone below the *Schmidtiellus mickwitzi* Biozone as often used.

Keywords: Baltica, *Schmidtiellus*, *Rusophycus*, *Cruziana*, biostratigraphy.

Mid-Ludfordian carbon isotope records from open marine settings – deep-water clay-dominated and carbonate shelf (Lithuania)

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During the Lau/Kozlowskii biocrisis Silurian faunas underwent a decline in marine biodiversity on a global scale, which affected a various range of taxonomic groups, most notably conodonts and graptolites. This bioevent is linked to the largest positive carbon isotope excursion (Mid-Ludfordian CIE) recorded in the Phanerozoic which apparently coincided with a period of global cooling and eustatic sea level fall. These environmental changes are evidenced by corresponding changes in the sedimentary facies.

The studied Šilalė-5 core section from Western Lithuania represents relatively deep-water clay-dominated sedimentation on the shelf of the Baltica paleocontinent at low latitudes. This 18 meter-long section is dominated by argillaceous sediments with carbonate intercalations characteristic for mixed siliciclastic – carbonate depositional settings, which emerged due to the lateral coexistence of carbonate and siliciclastic depositional environments. The measurement of whole-rock carbon isotope ratios has revealed the presence of ~ 7 meter-thick positive excursion, with $\delta^{13}C_{carb}$ values reaching +5.69 ‰. This coincides with prominent lithofacies change, i.e. the occurance of fine-grained limestone interlayed with mudstone with a distinct 'varve-like' texture typical for Toliai Mb. positioned at the boundary of Dubysa and Pagėgiai Reg. Stages. The mid-Ludfordian age of the $\delta^{13}C_{carb}$ anomaly is evidenced by graptolite assamblage (*Pristiograptus* ex. gr. *dubius* (Suess), *Bohemograptus tenuis* (Bouček) and *Polonograptus* sp.) found in the lowermost core interval preciding the onset of $\delta^{13}C_{carb}$ anomaly and being characteristic of the pre-Kozlowski graptolite event interval.

The core section from the Lapgiriai-1 borehole in Middle Lithuania recorded a positive $\delta^{13}C_{carb}$ excursion at a comparable stratigraphic level. However, the anomaly is considerably more pronounced, reaching a maximum value of +7.51 ‰ and spanning approximately 60 meters in thickness. The onset of $\delta^{13}C_{carb}$ excursion coincides with deposition of a few meters-thick limestone, predominantly clayey organogenous-detrital, fine-grained and nodular, placed within a packet of marls. This limestone in the Lapgiriai area was found to be oil-saturated and maintained as possible hydrocarbon reservoir. The limestone has been considered as the upper part of the Nova Beds within the uppermost Dubysa Reg. Stage, and towards the east – a break in sedimentation appears at this stratigraphic level (Lapinskas, 2000: Structure and petroliferosity of the Silurian in Lithuania. Inst. Geol., Vilnius). The core section represents sedimentation within an open marine carbonate shelf. Lithofacies change is coupled with changing pattern of carbon isotope excursion. The growing limb of the positive $\delta^{13}C_{carb}$ anomaly is coeval with deposition of marls with detritus and limestone nodules/interlayers. Upward the section, marly facies pass into more calcareous packets of clayey, fine-grained and horizontally wavy-laminated organogenous finely to coarsly detrital limestones with stromatoporoids, crinoids and brachiopods and marl interlayers of Mituva Fm. (Pagėgiai Reg. St.) that correspond to the peak and falling limb of $\delta^{13}C_{carb}$ excursion. The uppermost several meters of the section is represented by clayey, fine-grained and detrital horizontally wavy-laminated limestone with marls of Ventspils Fm.

At present stage of the research we can conclude that the new data confirms the more suppressed pattern of carbon isotope excursion in the deep water section compared to the shallower section.

Keywords: Silurian, Baltica, graptolites, stable carbon isotopes.

Distribution of Silurian graptolites in the Kleczanów PIG - 1 well (Holy Cross Mountains, Poland): a preliminary report

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Two distinctive graptolite crises referred to as the Ireviken and Mulde events were recognised worldwide in the Wenlock of the Silurian period. These biological crises can be linked to early and later Wenlock glaciations and climate aridity.

New graptolite material comes from the Kleczanów PIG – 1 borehole (depth 233 – 178 m), and the drill core is composed of dark shales of the Prągowiec Beds. The samples were taken at intervals of approximately one metre. Kleczanów PIG – 1 borehole was drilled in the southern Holy Cross Mountains (Central Poland). According to the geological composition, the Holy Cross Mountains are divided into the Kielce Unit in the south and the Łysogóry Unit in the north. So, Kleczanów PIG – 1 borehole is in the Kielce Unit.

According to preliminary graptolite data, we can distinguish a graptolite biozone sequence from *Monograptus riccartonensis* (lower Wenlock, Sheinwoodian) *to Neodiversograptus nilssoni* (lower Ludlow, Gorstian). It is interesting to note that no *Retiolites* were found in the Kleczanów PIG - 1 borehole. The fossils of retiolitids were also not found in the Upper Homerian interval, where their diversity was very high. *Monograptus ambiguus* Jaeger from the uppermost *Cyrtograptus lundgreni* Biozone was identified for the first time in the Holy Cross Mountains. This species was previously known from Bohemia and Saxothuringia.

Keywords: Lower Silurian, Łysogóry Unit, graptolites, biostratigraphy.

A transient Baltic extinction pulse paused the start of the Ordovician radiations regionally

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The Great Ordovician Biodiversification Event (GOBE) is well-documented during the Middle Ordovician globally. This prolific burst of life occurred within multiple clades at the lowermost taxonomic levels, filling niches rapidly within just a few million years, mainly concentrated around the Darriwilian Age. Therefore, considerable research has been done to understand the conditions affecting the ambient environment at this time and there is thus now broad consensus that climatic cooling was a major facilitator driving the GOBE.

A new and complete-bed-by-bed appraisal of conodont species richness in the Hällekis quarry, Kinnekulle, southern Sweden, has been conducted. The biotic data is integrated with previously unpublished conodont oxygen isotope ($\delta^{18}O$) data, sampled at ~10cm increments, and whole rock carbon isotope ($\delta^{13}C$) data, at ~3cm increments, to provide detailed information about environmental conditions. The collective high-resolution data show a continuously rising conodont richness curve up through the *Lenodus antivariabilis* conodont zone before an overall richness peak is reached in the lowermost part of the succeeding *Lenodus variabilis* conodont zone. Hereafter a richness plateau is observed before a two-phased richness drop occurs in the upper half of the *L. variabilis* zone.

The oxygen isotope data from Hällekis corroborates a previously published microfacies-derived sea level curve from the same section and suggests most of the studied interval to be deposited during a relatively cold climate. The data further show that both the richness plateau and the subsequent extinction pulse occurred during colder climate when sea level was at its lowest level. As the richness data is range interpolated, any effects of facies change due to fluctuating sea levels should be minimal. This suggests that the extinction pulse is a true biotic signal.

The Hällekis quarry succession also tells the fascinating tale of an enhanced influx of micro-meteorites to Earth starting about 467 Ma. This extra-terrestrial dust has been associated with the breakup of the L-chondrite parent body (LCPB), and the contemporary stratigraphical level recording this event has been identified in the Hällekis succession. The LCPB event has been suggested to have had a fundamental influence on the GOBE, but this remains debated. As the inferred LCPB-related level occurs just after the conodont extinction pulse, within an overall cooling phase, we discuss potential connections between the influx of micro-meteorites and the regional conodont richness variations.

Keywords: Darriwilian, GOBE, Hällekis, conodonts, oxygen isotopes.

Analysing Mulde Event Dynamics with Ultra-High-Resolution Ostracod Paleocommunity Analysis

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The Silurian period witnessed significant global extinction occurrences, including the Mulde/lundgreni Event (late Wenlock), which led to intricate and sudden alterations in the Earth's biota. Due to the short span of these events, conducting paleontological studies requires a high sampling resolution, which is rarely achieved. Ostracods, abundant and small, are ideal subjects for high-resolution studies. By combining existing data with new samples from the Gėluva-118 core, we have achieved a resolution of approximately 10 Ka years in analysing ostracod paleocommunities during the Mulde/lundgreni Event.

Our approach involved a custom-made binary recursive segmentation algorithm for the hierarchical subdivision of stratigraphically contiguous segments. This algorithm was applied to ostracod taxonomic compositional time-series data from the Gėluva-118 core (Lithuania). The results revealed significant changes in ostracod community composition, enabling us to delineate the event's stages. We employed a Bayesian Age-Depth model to assess the timing of these changes. The median and 95% Highest Density Interval (HDI) durations for each stage, as well as for the entire event, are as follows: Collapse – 50 Ka (11 – 171 Ka), Maximal Stress – 120 Ka (31 – 601 Ka), Recovery – 80 Ka (21 – 576 Ka), and the entire Mulde/lundgreni Event – 260 Ka (100 – 1,136 Ka). Our analysis of bootstrapped sample averages of diversity indices revealed that the Maximal Stress stage, marked by a severe scarcity of ostracods, signified a distinct shift in community diversity state. Prior to this stage, ostracod communities were less diverse, yet exhibited higher increases in evenness with growing diversity, indicating distinct community assembly and community structure patterns. Ostracod communities from the Collapse and Recovery stages resembled those adjacent to the Mulde/lundgreni Event interval but showed significantly reduced abundances, lower inverse Simpson index, and higher evenness. Furthermore, our findings suggest a nonlinear recovery stage, punctuated by setbacks and stabilisation phases.

These insights demonstrate the potential of high-resolution paleontological studies in deciphering the chronology and pace of intermittent global events.

Keywords: Silurian, recursive segmentation algorithm, Bayesian model.

Cambrian Deimena Regional Stage sandstones – the oldest and most prospective geothermal reservoir in the Baltic Basin

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In the present study, the geological and geothermal data were collected from various sources from Estonia, Latvia, and Lithuania. As the major result, the geothermal and structural maps of the Cambrian reservoir were compiled. The common database incorporates porosity, gas permeability and heat-flow density, temperature (T), geothermal gradient, and thermal conductivity (TC) records collected from industrial and project reports. The most prospective areas for geothermal energy exploitation were defined and characterised. Estonia, Latvia, and Lithuania are in the eastern part of the Baltic Sedimentary Basin (BSB), a 700 km long and 500 km wide synclinal structure dipping to the southwest. The Ediacaran (formerly Vendian) comprises an important part of the underlying geothermal aquifer. These siliciclastic deposits overlie the Precambrian basement. The Ediacaran-earliest Cambrian hydrogeological complex is distributed in the eastern part of the Baltic region and is attributed to the western periphery of the Moscow sedimentary basin. The oldest Valdai Series is documented in SE Lithuania. The younger Valdai Series is distinguished in Lithuania, Latvia, and Estonia. The Ediacaran clastic sediments up to 120–130 m thick are distributed in Estonia and Latvia and reach 180 m in NE Lithuania. The thickness of the Cambrian terrigenous succession attains 150 m in W Lithuania. The top of the Cambrian succession of the periphery of the basin dips from +100 m (N Estonia) to -50 m (E Lithuania) to -2150 m) in W Lithuania. The Dominopol and Ljuboml RSs are composed of fine-grained sandstones and siltstones, reaching 110 m on Saaremaa Island. Due to the low reservoir properties, this aquifer is considered a low-quality geothermal aquifer. The first major maximum transgression in the BSB took place the Cambrian Age 4 and Wuliuan, which compose the major Deimena RS sandstone reservoir. The main part of the Cambrian Stage 4 consists of shales with subordinate sandstones and is classified as an aquitard. The rocks in the eastern part of Lithuania and Latvia are attributed to the Cirma and Lakajai Fms. The shallow marine sandstones are composed of fine-grained quartz arenites cemented by minor carbonate and clay cement in the shallow basin periphery. The quartz cementation controls the reservoir quality of deep-buried sandstone. The TC is measured at only 2.2 W/m K in shallow sandstones and exceeds 6.7 W/m K in strongly cemented sandstone. The porosity of the Cambrian sandstones is as high as 22–34 %, and permeability attains 500–2300 mD in the shallow part of the BSB and decreases to only 5–10 % and <1 to 100–200 mD in the W Lithuanian E periphery, the T of the Cambrian basin is measured 7–10 °C (Estonia, E Latvia, S Lithuania). The T of Latvian geothermal anomalies attain 55–62 °C (Liepaja and Jelgava anomalies) and reaches 80–95 °C in the W Lithuania anomaly.

The most prospective geothermal resources are defined in the Deimena RSt sandstones in Lithuania and Latvia and the Cambrian–Ediacaran aquifer in Estonia. The 40–60 m thick Cambrian reservoir sandstones with good reservoir properties (porosity 15–22 %, temperature 35–65 °C) have the highest prospects in the central Lithuania and central and westernmost Latvia. The W Lithuanian anomaly sandstones show poor reservoir properties related to a high temperature (up to 95 °C) controlled quartz cementation. The Cambrian–Ediacaran aquifer located at the shallow burial depth in Estonia shows low T, but good reservoir properties.

Keywords: Cambrian, Ediacaran, Wuliuan, porosity, permeability, temperature.

Geo3D strategy in the Estonian Land Board: national digital twin from a geological perspective

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According to the Geo3D strategy, the Estonian Land Board (ELB) will implement three-dimensional (3D) data production, maintenance, and delivery by 2026. The main aims for moving towards 3D are (1) improving user experience on web applications, (2) providing more versatile open geospatial data for advancing economic growth, (3) supporting decision-making in the public sector.

A digital twin is a multidimensional model composed for simulation and visualisation purposes. Geo3D business analysis (2023) concedes both the underground and aboveground datasets should be incorporated into the countrywide digital twin to be developed when implementing the Geo3D strategy. In many cases (e.g., spatial planning, construction sector, mining), these two realms are closely interlaced.

ELB published the first 3D web application prototype, 'Estonian Land Board 3D' in 2021, displaying buildings, LiDAR point clouds, trees, and other aboveground data layers. In 2024, a 'Geology 3D' prototype was released, where buildings, geotechnical study sites, boreholes (with probing and groundwater level information), and bedrock systems are visualised, along with various 2D data layers. Three digital elevation models are presented: (1) ground surface, (2) sedimentary bedrock relief, and (3) crystalline basement relief. While the ground surface is generated from the LiDAR point cloud, the other two are interpolated from borehole logging data. In fact, the thickness model of the Quaternary succession is shaped first, during multiple iterations. After subtracting the result from the ground elevation, sedimentary bedrock relief is obtained.

Further developments of the 'Geology 3D' web application depend greatly on user feedback. ELB is preparing the following data: geological successions (systems, formations, beds), objects from the Mineral Registry (deposits, mineral blocks, quarries, mines, survey sites), and abandoned mines. The farther one navigates from the direct measurements (e.g., boreholes), the higher the probability of an interpretational divergence. Hence, besides enriching data layers, uncertainty estimations and analytical tools need more attention. The two previously described prototypes will eventually be integrated into one coherent digital twin.

Future benefits of the subsurface domain within the Geo3D framework:

- upgraded functionality for validating borehole logging data,
- fast national model updates with regularly blended new logs and local models,
- automatic production of geological maps and other derivatives,
- creating synthetic boreholes and cross-sections, volume calculations,
- more sophisticated projecting of geological surveys, buildings, infrastructure,
- coastline changes presented in time sliding mode support marine spatial planning,
- preliminary stability predictions of slopes, abandoned mines,
- real-time monitoring of geological hazards,
- groundwater yield, flow, vulnerability estimations,
- new possibilities for subsurface visualisation enable to clarify the content for non-experts,
- geotourism promotion with augmented reality capabilities.

'Estonian Land Board 3D' web application prototype is available here: https://3d.maaamet.ee/

'Geology 3D' prototype is also accessible from the ELB's geoportal: https://geoportaal.maaamet.ee/eng/spatial-data/geological-data/geology-in-3d-p941.html

Keywords: 3D, web application, geotechnical, borehole, bedrock, crystalline basement.

Porosity characterisation of the Silurian succession in Middle Lithuania: A comparative analysis

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Porosity variation within the Silurian succession of Middle Lithuania, a key stratigraphic unit in the Baltic region was studied. Understanding porosity distribution is crucial for various geological applications, including hydrocarbon exploration and carbon storage. We employed two established porosity estimation methods: (1) laboratory measurements from core samples and (2) acoustic-derived porosities obtained from well log data using advanced petrophysical techniques. We focused on six wells distributed across two distinct regions: Bliūdžiai and Lapgiriai.

Depthwise comparisons were conducted to evaluate the trends and variations in porosity between the two measurement methods. In the Bliūdžiai region, a weak correlation (R-squared=0.09) was observed between acoustic-derived and laboratory porosity measurements for well Bliūdžiai 151. The Bliūdžiai 152 well exhibited a moderate correlation (R-squared=0.23), while data limitations precluded analysis for the Bliūdžiai 156 well. Similarly, the Lapgiriai region displayed weak correlations in wells Lapgiriai 122 (R-squared=0.06) and Lapgiriai 124 (R-squared=0.09). However, the Lapgiriai 123 well showed a moderate correlation with a value of 0.20. Overall, our findings suggest a trend where laboratory porosity values tend to be higher than acoustic-derived porosity values, with laboratory measurements exhibiting greater fluctuations throughout the wellbore. Conversely, acoustic-derived porosity values demonstrate relative stability across the analysed intervals.

This work contributes significantly to our understanding of the correlation between acoustic-derived and laboratory porosity measurements in the Silurian succession of the Baltic region. The observed discrepancies between the two methods highlight the importance of incorporating both techniques in porosity assessments. Laboratory measurements provide highly accurate, point-specific data, while acoustic logs offer continuous porosity profiles throughout the wellbore. By combining these approaches, geologists gain a more comprehensive understanding of porosity distribution within a geological formation, enabling them to make informed decisions in various applications.

Furthermore, the utilisation of data science and machine learning techniques in analysing the R-squared correlations enhances the rigor and depth of our findings, facilitating a more comprehensive understanding of the complex interplay between porosity estimation methodologies.

Keywords: acoustic-derived porosity, laboratory porosity, correlation, R-squared, porosity measurements, Silurian succession.

Evolution of a Katian tropical hardground

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A succession of shallow-marine carbonates characterises the Middle and Upper Ordovician of Estonia (Baltica). In northern Estonia, the boundary between the Nabala and Vormsi regional stages (and Saunja and Kõrgessaare formations) is marked by a prominent discontinuity surface, which has been interpreted as a paleo-karst horizon. The stable isotopic curve in the boundary beds shows the characteristic change for the Saunja Excursion and has been correlated with the Waynesville Excursion in North America.

Historically, the boundary has been exposed in several outcrops like Turvaste, Kohila, Saunja and Aulepa. Currently, in the new large Sutlema Quarry, tropical carbonates of the Saunja and Kõrgessaare formations (middle Katian) are exposed. For several years, it has been possible to collect samples and examine the flat, slightly wavy, hardground that marks the boundary between these formations.

The lithology of the uppermost part of the Saunja Formation and its fossil content is suggestive of restricted conditions, similar to a lagoonal depositional environment. It is characterised by higher salinity and the presence of microbial communities, which was also confirmed by the occurrence of specific biomarkers. Remnants of microbial mats were also observed in thin sections of the Saunja Formation, in the form of filamentous, carbonaceous structures. The hardground was thick and formed rapidly. Some borings from the surface demonstrate elevated openings, proving that the formation of the hard surface was rapid. The cementation process was enhanced by warm tropical water and microbial mats. The surface was partially cracked before its full lithification. These cracks are deep and filled with sediments. The hardground is heavily bored, and the bioerosional ichnofauna of the hardground is abundant, consisting of shallow *Trypanites sozialis*, elongated *Trypanites weisei*, winding and undulating *Trypanites* isp., algal bioerosional traces, and fine shallow grooves. Also occurring are large sub-surface U-shaped trace fossils with variable diameters, similar to *Balanoglossites triadicus*. The epizoans of the hardground include small-sized typical marine fauna like cornulitids, crinoids, bryozoans, brachiopods, and tabulate corals. Some hardground samples demonstrate shallow regular pits with smooth walls. These structures cannot be assigned as bioerosional trace fossils. They are most likely solution pits, which are surface features that form on horizontal surfaces under subaerial conditions.

Keywords: Ordovician, Estonia, hardground, bioerosion, microbial mats, solution pits.

Kalana *Lagerstätte*: expansion of stratigraphic ranges and palaeobiological data

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The Kalana *Lagerstätte* in Central Estonia opens a window into the shallow-water setting during the early Silurian (Llandovery, Aeronian, Raikküla Regional Stage) of the Baltic Palaeobasin. The biota is dominated by exceptionally preserved algae, with various uncalcified dasyclade species, such as *Palaeocymopolia silurica* Mastik et Tinn 2015, *Kalania pusilla* Tinn, Mastik, Ainsaar et Meidla, 2015 and several yet unnamed taxa, being particularly prevalent. Dasyclades are unicellular green algae with a specific siphonous radially symmetrical thallus, the length of which can reach up to 20 cm. Their stratigraphic record goes back to the Cambrian, but the bulk of their fossil record consists of highly mineralised taxa, unlike those found in Kalana. Today, the dasyclade flora includes only 11 species, all of which inhabit shallow, tropical marine waters. Due to their long fossil history and conservative morphological features, dasyclades are often regarded as „living fossils". One particular species from Kalana, *P. silurica*, being also closely similar to *P. nunavutensis* from the Silurian of Arctic Canada, is morphologically almost identical to a Recent species *Cymopolia barbata*.

What makes Kalana special is the preservation and details of organisms, which are rarely found in the fossil record. The fossils found here include a head shield of an agnathan vertebrate *Kalanaspis delectabilis* Tinn et Märss 2018. *K. delectabilis*, although atypically preserved as a carbonaceous microbial biofilm, shows a combination of characters that are common to osteostracans, along with a few features known also among other early vertebrates. *K. delectabilis,* being about 10 million years older than any previously described member of the class Osteostraci, has been referred to as a member of the stem group osteostracans.

Kalana has also yielded a considerable number of sponge fossils, a group that (apart from stromatoporoids) has been very poorly studied in Estonia. While statistically, according to the Estonian geological collections database (https://fossiilid.info) the Raikküla Stage shows the highest abundance and variety of sponges in Estonia, all of these are stromatoporoids. Our provisional studies have revealed a considerable taxonomic variety of non-stromatoporoid sponges in Kalana.

Estonian palaeontologists have always taken pride in their eurypterid fossils. Our geological collections hold more than 600 specimens identified as chelicerate arthropods. A large portion of these – either as nearly complete specimens or fragments with varying degrees of completeness – belong to the iconic species *Eurypterus tetragonophthalmus*, which comes from a locality on Saaremaa Island and dates to the Wenlock age (Rootsiküla Regional Stage). However, the oldest chelicerate fossils in Estonia have been collected from the Kalana *Lagerstätte*. This collection contains a diverse range of chelicerates, both in terms of taxonomy and preservation types.

Keywords: Silurian, Llandovery, Estonia, palaeontology, exceptional preservation.

Morphometric analysis of the Late Famennian *Holoptychius* (Sarcopterygii, Porolepiformes) from the Ketleri Formation, Latvia

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The Upper Devonian porolepiform sarcopterygian *Holoptychius* Agassiz, 1839 is one of the most widely distributed vertebrates in the Paleozoic fossil record. *Holoptychius* is thought to exhibit a more ubiquitous lifestyle and greater dispersal potential than any other sarcopterygian taxon, consistent with its almost cosmopolitan distribution and rich fossil material, represented mainly by scales. More than 20 species, mostly represented by isolated, difficult-to-diagnose scales, were described within the genus *Holoptychius*.

Nowadays, it is agreed that the morphology of holoptychiid scales depends more on the location on the individual's body and age than on the species. Therefore, only some species are treated as valid: type species *Holoptychius nobilissimus* Agassiz and *H. flemingi* Agassiz from the Famennian of Scotland, *H. jarviki* Cloutier et Schultze from the Frasnian of Quebec, Canada, and *H. bergmanni* Downs, Daeschler, Jenkins, Shubin from the Frasnian of Arctic Canada.

W. Gross, for the first time, described fossil remains of *Holoptychius* from the Ketleri Formation (Fm) of Latvia in 1933. Since then, these remains, mostly scales, were determined by various authors as belonging to *Holoptychius* cf. *nobilissimus*, *H*. cf. *flemingi*?, *H*. cf. *giganteus*, *H*. ex gr. *nobilissimus* or *Holoptychius* sp. nov. The material of this study was collected during the last ten years from the three localities: the Pavāri-1 locality at the left bank of the Ciecere River opposite the destroyed farmhouse "Pavāri", Pavāri-2 site about 400 m downstream of Pavāri-1, and the Ketleri locality at the right bank of the Venta River close to the abandoned farmhouse "Ķetleri". The material at the disposal of the authors contains 77 specimens (apart from scales), including disarticulated complete or fragmentary bones of the head, pectoral girdle and visceral skeleton, as well as partial jaws and separate jaw bones. Besides, several hundreds of scales of different sizes and shapes were collected, mostly from the Ketleri outcrops.

Linear and angle measurements of separate bones or skeletal elements such as the postparietal shield, as well as gular plates, cleithra and clavicles of *Holoptychius* from the Ketleri Fm were made, and the proportions were calculated. Two statistical methods, principal component analysis (PCA) and clustering, were used to perform the morphometric analysis of intraspecific variability and to compare the material with that of *H. nobilissimus*, *H. jarviki* and *H. bergmanni*. Scatter plots and cladograms were generated using the PAST programme. The comparison shows that the studied material of *Holoptychius* from the Ketleri Fm differs well from *H. nobilissimus* and *H. jarviki* by the maximal length, maximal width and two angles of the gular bone. It also differs significantly from *H. bergmanni* by the proportions of the occipital shield, as well as the proportions and shape of the cleithrum and clavicle.

The comparative morphological and morphometric analysis of the studied material and the material from some valid species of *Holoptychius* suggests that the material from the Ketleri Fm of Latvia could represent a new species.

Keywords: Upper Devonian, fossils, vertebrates, fishes, Holoptychiidae, morphology.

Formation and later changes of the Staicele and Gārsene Proterozoic iron ore deposits: evidence from structure, mineralogical and chemical composition

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Previous drillcore mineralogical and petrographic studies, as well as geophysical and geochemical research of the Proterozoic iron-bearing rocks of Latvia were mainly carried out in the 1980-1990s and stopped afterwards. By the data of V. Vetrennikov the ores of the Staicele and Gārsene deposits contain Fe, Mn, Ti, Zn, Co and other metals in relatively high quantities, but due to their depth (0,7-1 km) the ores were supposed to be non-prospective in the nearest future. However, the situation changes. The list of the critical raw materials of the European Union (2023) includes Mn and Co found in the ores, but modern analytic methods allow to determine the ore composition more precisely. That supports the renewed interest on the Proterozoic ore mineralogical and geochemical studies. S. Bogdanova and co-authors suggest that the iron and other metal ores are related mainly to the Palaeoproterozoic metavolcanites and metasedimentary rocks of the Latvian-East Lithuanian domain. The Proterozoic plate tectonic settings and history of the study area is described in several publications. Nevertheless, the iron accumulation and concentration processes are poorly known. Metamorphism and other alteration processes of the ores are also not well-understood.

For this study 17 ore samples were taken from the Staicele-1 drillcores (Staicele deposit) and 18 from the Subate-2A drillcores (Gārsene deposit). Polished specimens and thin-sections were made and studied in microscope. Powder XRD, SEM with EDX spectroscopy, energy-dispersive XRF, ICP-MS, and laser-induced breakdown spectroscopy (LIBS) analyses were done.

This study indicates that magnetite from the Staicele deposit contains an average of 3.1 w% MnO, which means the existence of magnetite-jacobsite series. Manganese content in magnetite varies in depth. Manganese content to 22.10 w% was identified in the garnet (mainly almandine-spessartine series with dominant spessartine component) in the Staicele iron ore deposits. Contents of many other metals, including REE, were also determined in ore, as well as in such separate minerals as magnetite, sulphides and several silicates.

The rhythmically laminated structure indicates that the ores of both deposits belong to the banded iron ore formations (BIF). The ores of the Gārsene deposit were highly altered by metamorphic processes, when magnetite and quartz grains formed larger aggregates and enriched the ores. Following successive processes are suggested to have occurred in the Staicele deposit: metamorphism, which resulted in the simultaneous formation of silicates and second-generation magnetite; later granitization, mainly represented by quartz and albite; the transformation of earlier minerals (mainly pyroxenes) to secondary minerals. The nature and sequence of hematite mineralization indicate that earlier metamorphic processes are also possible.

The contents of metals in definite oxide, silicate, and sulphide minerals, quantities of these minerals in definite ore types, and the distribution of the ores in drillcores will be studies in further research works.

This study was financially supported by means of the project of the Latvian Council of Science “Ore potential of metal-bearing crystalline basement rocks in central and eastern Latvia”, no. lzp-2023/1-0278.

Keywords: banded iron formations, magnetite, mineralogy, geochemistry, crystalline basement.

The correlation of the carbonate facies of the lower Silurian in Lithuania: carbon isotope and the cross-recurrence plot

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The facies of the lower Silurian deposits vary from shallow lagoon in east Lithuania to open deep shelf in the west. The fauna of eastern Lithuania is rare and correlations with deep facies are difficult. Sometimes, the solution to these problems is using stable carbon isotope chemostratigraphy.

The Ledai-179 borehole is located in the central part of Lithuania, and Wenlock geological section is composed of dolomitic marl of the Paprieniai Formation in the lower part, nodular limestone of the Birštonas Formation in the middle and dolostone of the Nevėžis Formation on the top. Two positive carbon isotope excursions were established in the investigated interval of the Ledai-179 borehole. The first one is identified as the Ireviken Carbon Isotope Excursion and linking to Paprieniai formation of the Jaani Regional Stage. The second one is the Mulde Carbon Isotope Excursion linking it to the Nevėžis Formation of the Gėluva Regional Stage. The Jočionys-299 well is located in the eastern part of Lithuania and contains sediments of a lagoonal environment. The geological succession consists of various conditions of dolomite with gypsum interbeds of the Paprieniai, Jočionys and Verknė formations. The Ireviken Carbon Isotope Excursion is identified in the Paprieniai and Jočionys formations (Jaani Regional Stage) in the Jočionys-299 borehole. The Mulde Excursion is absent there and is associated with a stratigraphic gap. So, the problem is how to correlate the geological section of the Jaagarahu Regional Stage.

For the purpose of this study, we employed stable carbon isotope data and the cross-recurrence plot (CRP) to compare two time series in a data-point-wise manner. The obtained 2D Heaviside-filtered binary matrix was then used as a field for searching for the most expensive continuous path from its starting to the finishing corner, i.e., the dynamic time warping (DTW) algorithm. The path obtained is referred to as a line of synchronisation (LOS), i.e., correlation. There are numerous paths with similar cost coming through laminar states, although many of them pass through narrow joints between laminar states where the confidence of the correlation is the highest.

The recurrence plot results indicate the presence of two stratigraphic gaps in the Jočionys-299 borehole. The first one was determined at the boundary of Paprieniai and Jočionys formations (stable zone of Ireviken CIE). This occurrence seems to be somewhat questionable, especially because the core interval related to the stable zone of Ireviken CIE in the Jočionys-299 well is missing.

The second stratigraphic gap was identified in the middle part of the Verknė Formation, indicating its probable occurrence. In conclusion, cross-recurrence plot analysis represents a valuable tool for correlating geological sections.

Keywords: Llandovery, Wenlock, Baltica, carbon isotopes, integrated stratigraphy.

FIELD GUIDE

XI Baltic Stratigraphical Conference

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Geology of Estonia: An introduction

Tõnu Meidla

The following text is based on Meidla (2023).

Estonia lies on the east coast of the Baltic Sea, south of the Finnish Gulf, comprising about 45 000 km2 area extending from 57°30’34” to 59°49’12”N and from 21°45’49” to 28°12’44”E.

The topography of this area is generally flat; the area is located about 50 m above sea level on average. Variety of landscapes comprises extensive forests and wetlands intersected by agricultural landscapes, wide depressions surrounding big lakes Peipsi and Võrtsjärv, about 1400 lakes, several thousands of kilometres long coastline and more than 2000 marine islands, most of them very small but more than ten of them being large enough to support the permanent population. The largest islands are Saaremaa, Hiiumaa, Muhu and Vormsi.

Geologically, the area of Estonia corresponds to the southern slope of the Fennoscandian Shield located in the central-western part of the East European Craton. Estonia is located in the area where the Earth’s crust is relatively thick (mostly 46–51 km but decreasing to 41–44 km in Saaremaa (Puura and Vaher 1997). The principal features of the crustal structure of the area formed during the Svecofennian orogeny dated about 2.0–1.75 Ga. Most of the crystalline basement belongs to the Palaeoproterozoic (1.8–1.9 Ga) Svecofennian orogenic complex that was also subjected to high-grade metamorphism. This complex is characterised by the gneisses of amphibolite facies in northern Estonia and represents an extension of the major structural units of southern Finland. In southern Estonia, the basement comprises gneisses of granulite facies belonging to the Belarussian–Baltic granulite subdomain.

The metamorphosed rocks of the Svecofennian orogenic complex is intersected by several generations of intrusive bodies, the most important of them being the rapakivi intrusions of the latest Palaeoproterozoic Vyborg Subprovince (the Naissaare, Neeme, Märjamaa and Ereda plutons, 1.62–1.67 Ga) and the huge Riga pluton of the Åland–Riga Subprovince. The Riga rapakivi pluton is of the earliest Mesoproterozoic age (1.54–1.58 Ga) and is associated with a few subvolcanic and volcanic rocks occurring on Saaremaa Island. The crystalline basement was subjected to long-lasting erosion (1.4–0.6 Ga) that resulted in the formation of a peneplane. (Puura et al. 1997). The sedimentary units and magmatic rocks from this period, although known in other parts of the Svecofennian region, are absent in Estonia. The crystalline rocks occasionally display evidence of weathering that

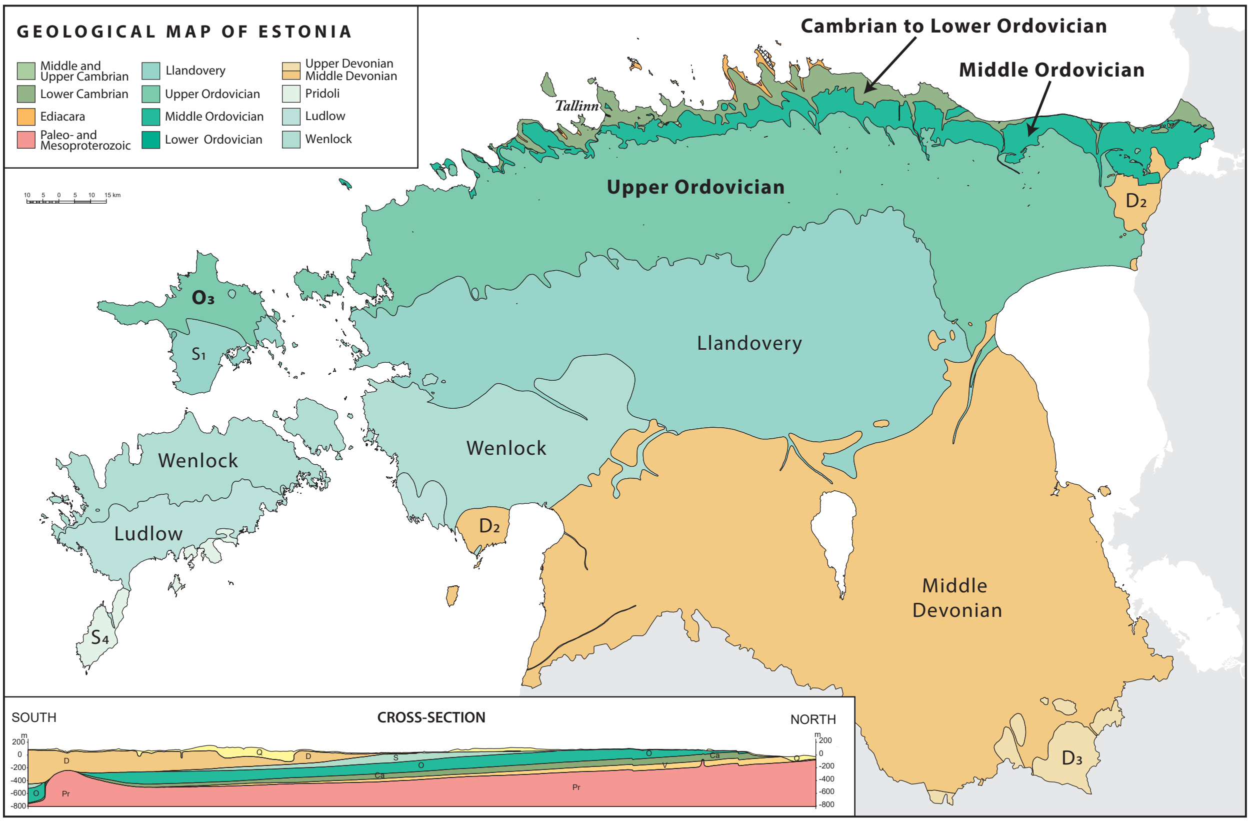

Fig. 1. Generalised bedrock geological map of Estonia with a cross-section, showing outcrop areas of lower and middle Palaeozoic rocks and a NS cross section shaped by the southward dip of the Proterozoic basement (modified from Puura 2008).

may reach up to a depth of 100 m into the basement (Puura 1997; Puura and Vaher 1997).

The top of the basement lies at a depth ranging from -120m (islands in the Finnish Gulf) up to -780m (the Island of Ruhnu, SW Estonia), dipping gently to the south within most of the territory but becoming slightly elevated again in SE Estonia forming the Mõniste Bedrock Uplift (altitude of the top at -232 m) (Tuuling and Vaher 2018). Because of this southward dipping, the thickness of the sedimentary cover is gradually increasing southwards. The northern border of the distribution area of sedimentary cover reaches the middle of the Gulf of Finland, dividing it into the shield and platform parts.

The sedimentary rocks Estonia are of latest Proterozoic to middle Palaeozoic age. Because of that, Estonia is sometimes called 'a Palaeozoic country'. The Ediacaran–Devonian sedimentary cover is overlain by the sediments of the mid to late Quaternary. The thickness of the pre-Quaternary sedimentary rocks reaches over 100 m in northernmost mainland Estonia and exceeds 800 m in southeastern Estonia (Puura and Vaher 1997), generally reflecting the southward dipping of the upper surface of the crystalline basement. In the outcrop sections, the bedding of the sedimentary bedrock usually looks nearly horizontal but may occasionally show minor local deformations. Because of the gentle dipping of strata, 8–15' (about 2–4.5 m/km) to the south, the outcrop belts of the series and stages display predominantly roughly west-east oriented pattern in the geological map (see Fig. 1).

The Ediacaran System (until the end of the 20th century referred to as the Vendian Complex or the Vendian System) comprises a subsurface unit distributed in northern, northeastern and eastern Estonia. These strata bear a signature of a cool climate as the Baltica Palaeocontinent was located in high latitudes in the late Ediacaran (Cocks and Torsvik 2005). The sandstones and clays prevailing in Estonia comprise a small segment of the latest Ediacaran (Meidla 2017), although a gap has been documented at the lower boundary of the Cambrian. The terrigenous sediments accumulated in a large water body located east of the Estonian area. Estonia comprised a part of its near-coastal zone, and the terrigenous sediments are coarser in the west. The total thickness of the Ediacaran reaches over 120 m, with the maximum in northeasternmost Estonia. Recent advances in the Ediacaran and Cambrian stratigraphy of Estonia are summarised by (Meidla 2017).

The overlying Cambrian is distributed nearly all over Estonia. The Cambrian rocks are predominantly sandstones and siltstones, with a limited supplement of clay, whilst coarser material is rare, occurring at some levels in West Estonia. An exception is the lowermost part of the succession that comprises the late Terreneuvian Blue Clay, a silty clay unit of a remarkable thickness (over 90 m – Meidla et al. 2017). Deposition of the Terreneuvian clays took place in an Ediacaran-like palaeogeographic setting in the course of a marine transgression advancing from the east, but the accumulation of younger Cambrian, Ordovician and Silurian strata was increasingly influenced by the developments along the southern slope of the Fennoscandian Shield. The Cambrian rocks, mostly sandstones, crop out in several coastal and riverside sections, whilst clays are mainly exposed in clay pits near the northern coast. The total thickness of the Cambrian strata is locally exceeding 120 m within the West Estonian archipelago.

The deposition of the Ordovician strata took place in a slowly subsiding marginal part of the East European Craton, initially of weak palaeobathymetric differentiation and slow deposition rate. The Lower Ordovician sandstones and thin clay-rich formations grade into the carbonates in the topmost Lower Ordovician, on the background of progressive depth differentiation due to the development of the Baltic Syneclise. The Middle and Upper Ordovician are represented by limestones that contain thin volcanic interbeds (K-bentonites) at several levels. Late diagenetic dolomitisation is unevenly distributed in limestones. Early Late Ordovician kukersite oil shale is a characteristic feature of northeastern Estonia, whilst Middle and Upper Ordovician red limestone packages and a few thin Upper Ordovician black shale units are known in the subsurface area. In many papers (e.g., Nestor and Einasto 1997) and references therein) the beginning of Katian (middle Upper Ordovician) is reported to mark a transition from cool-water to tropical carbonate sedimentation as the Baltica Palaeocontinent reached the southern tropical latitudes (Cocks and Torsvik 2005). Somewhat controversially, this seems to happen on the background of a gradual temperature decrease throughout the Late Ordovician (Männik et al. 2021). The Ordovician strata are exposed in coastal outcrops and escarpments, active pits and quarries of different ages, but the Upper Ordovician outcrops are mostly small and display only fragments of this unit that occasionally may reach about 100 m thickness. The topmost Ordovician is revealing evidence of the Hirnantian Glaciation, expressed as almost full faunal rearrangement (Nestor et al. 1986) and a major carbon and oxygen isotopic shift (Ainsaar et al. 2010; Männik et al. 2021). The latter feature is more clearly observable in the subsurface because of a gap in the outcrop area caused by the glacioeustatic sea level fall (Brenchley et al. 2003). Recent advances in Ordovician stratigraphy of Estonia and related areas are summarised in (Meidla et al. 2023).

The Silurian System has a more limited distribution, being absent in the northern and eastern parts of Estonia because of erosion. The Llandovery has the widest distribution, occurring both in the western islands and the mainland of Estonia. The distribution areas of the younger series are progressively smaller and gradually shifted to the southwest, to the Baltic Syneclise. The Přidoli Series occurs only in a very small area in southern Saaremaa Island and Ruhnu Island. The limestones and dolomites bear a signature of tropical sedimentation, and a number of K-bentonite beds (mainly lower Wenlock) is indicative of limited volcanic activity in the neighbouring areas. The rocks are locally exposed in the mainland, on Saaremaa Island and in smaller islands of West Estonia. The exposures, however, demonstrate only a minor part of the Silurian succession of over 400 m thickness. The most recent overview of the Silurian stratigraphy in Estonia is provided by (Männik 2014).

Distribution of the Devonian System is confined to southern, eastern and northeastern Estonia. The latter occurrence represents a small isolated area in northeastern Estonia where the Middle Devonian dolomitic marls and sandstones of rather limited thickness overlie the Upper Ordovician limestones containing the kukersite oil shale commercial deposit. The main distribution area in eastern and southern Estonia represents a transition from the Scandinavian orogenic belt to the Devonian Basin within eastern Laurussia. The Middle Devonian and basal Upper Devonian are mainly represented by sandstones and overlain by a thin succession of Upper Devonian carbonates (mainly dolomites) confined to marginal southeastern Estonia and extending to the south and southeast. The lower Devonian has been recorded in the subsurface only, being confined to a narrow belt near the southern border of Estonia. The Middle and Upper Devonian are often exposed in river valleys of South Estonia and in occasional sand pits. The present state of Devonian stratigraphy in Estonia is summarised in (Mark-Kurik and Põldvere 2012).

The initial thickness of the Ordovician, Silurian and Devonian sedimentary strata may have reached 500-1000 m in North Estonia, and the maximum sediment load was probably reached during the Late Devonian (Kirsimäe et al. 1999). The very long erosional period during Carboniferous-Neogene has created the present-day bedrock topography, shaping bedrock cores of the major uplands of modern topography and depressions of the lakes Peipsi and Võrtsjärv and the Gulf of Finland.

The Quaternary glaciation caused the last stage of erosion of the sedimentary bedrock. The glaciers removed up to 60 m layer from the bedrock surface (Tavast 1997), leaving almost no chance of discovering any strata that might be younger than the Devonian but older than the Quaternary in Estonia.

The accumulation of Quaternary sediments during the Pleistocene and Holocene resulted in the formation of a nearly continuous layer of glacial, glaciofluvial and glaciolacustrine sediments, covered with genetically variable Holocene deposits that are mostly of limited thickness and patchy distribution. The total thickness of Quaternary sediments is usually less than 5 m in North Estonia but generally over 10 m in South Estonia. Thicknesses over 100 m are relatively common in South Estonia (Haanja and Otepää heights) and the Gulf of Finland (Raukas and Kajak 1997), but locally it may exceed 200 m. The bedrock topography, uneven thickness of the Quaternary cover and postglacial land rise have shaped the modern topography of Estonia. Only 10% of the area has an elevation over 100 m a.s.l. The highest point in South Estonia is 318 m a. s. l. but its relative height is only about 60 m (Raukas 1997). A revised stratigraphic chart of the Quaternary sediments in Estonia was recently published by (Hang et al. 2019).

A remarkable feature in Estonian topography is the North Estonian Klint, a nearly continuous escarpment along the northern coast that forms the middle part of the Baltic Klint. It exposes the Cambrian to Middle Ordovician part of the sedimentary succession in numerous outcrops of the lower Palaeozoic strata forming a fairly continuous belt of actively abraded and passive inland escarpments.

Although Estonia is a small country, it still is relatively rich in mineral resources. The most important actively exploited resource is the unique kukersite oil shale that comprises the world's largest exploitable resource of its kind. The Cambrian – Ordovician shelly phosphorite deposit in North Estonia is one of the largest phosphorite deposits within the European Union. It was industrially used between 1924 and 1991 but excluded from the list of active reserves in the late 1990s, mainly because of the past devastating mining and industrial use history. Another potential resource is the Dictyonema argillite which is relatively rich in organic matter (up to 20%) and contains various microelements (Mo, V, etc.) in elevated concentrations. The groundwater in the sedimentary rocks and Quaternary deposits is used as the source of drinking water throughout the country. It formed about 70% of the drinking water consumed in Estonia in the mid-1990s (Vallner and Savitskaja 1997). The Middle–Upper Ordovician, Silurian and Upper Devonian carbonate rocks are widely exploited in numerous quarries. Sand, gravel and peat deposits are in active use. Other resources are less important.

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Ediacaran and Cambrian stratigraphy in Estonia

Tõnu Meidla

The principal features of stratigraphy of the Edacaran and Cambrian in Estonia were summarised in near-present shape by Mens & Pirrus (1997a, b; see also references therein). Refined correlation charts and the Ediacaran and Cambrian timescales are addressed by Meidla (2017).

As the term 'Ediacaran System' was formally adopted in 2004, the strata that were formerly termed 'the Vendian Complex' in Estonia, Latvia and Lithuania are attributed to the Ediacaran System today (Meidla 2017). The differences between the lower boundaries of the Ediacaran System and the Vendian complex are well known (see, e.g., Chumakov 2007; Meert et al. 2011) but do not complicate the use of the term 'Ediacara' in Estonia, where the system is represented by its uppermost part only. The Ediacaran strata in Estonia were likely formed within the last 7–10 My of the period (Meidla 2017; Fig. 2), based on the age constraints for the base of the Kotlin Stage in Belarus and Poland (between 551 and 548 Ma according to Grazhdankin et al. 2011).

The Cambrian System has been subdivided into three series in Estonia already by Öpik (1925) and this threefold subdivision was widely adopted for the Cambrian System here and in adjacent areas for almost a century. The four global series of the Cambrian System were introduced in the early 21st century. A comprehensive overview of the Cambrian System of Estonia in the context of the new subdivision was for the first time offered by Meidla (2017).

The lower boundary of the Cambrian System is marked by a regional conformity in Estonia that marks the appearance level of the first skeletal fossils and a rearrangement of the ichno- and phytofossil assemblages (Mens & Pirrus 1997b). These fossiliferous strata, the Lontova and Voosi formations, correspond to the upper half of the Terreneuvian Series, being overlain by the strata containing the first trilobites and attributed to the yet unnamed Series 2 (Fig. 3). Although the position of the boundary of this Series 2 is not yet fixed with a boundary stratotype, it is generally agreed that it will be

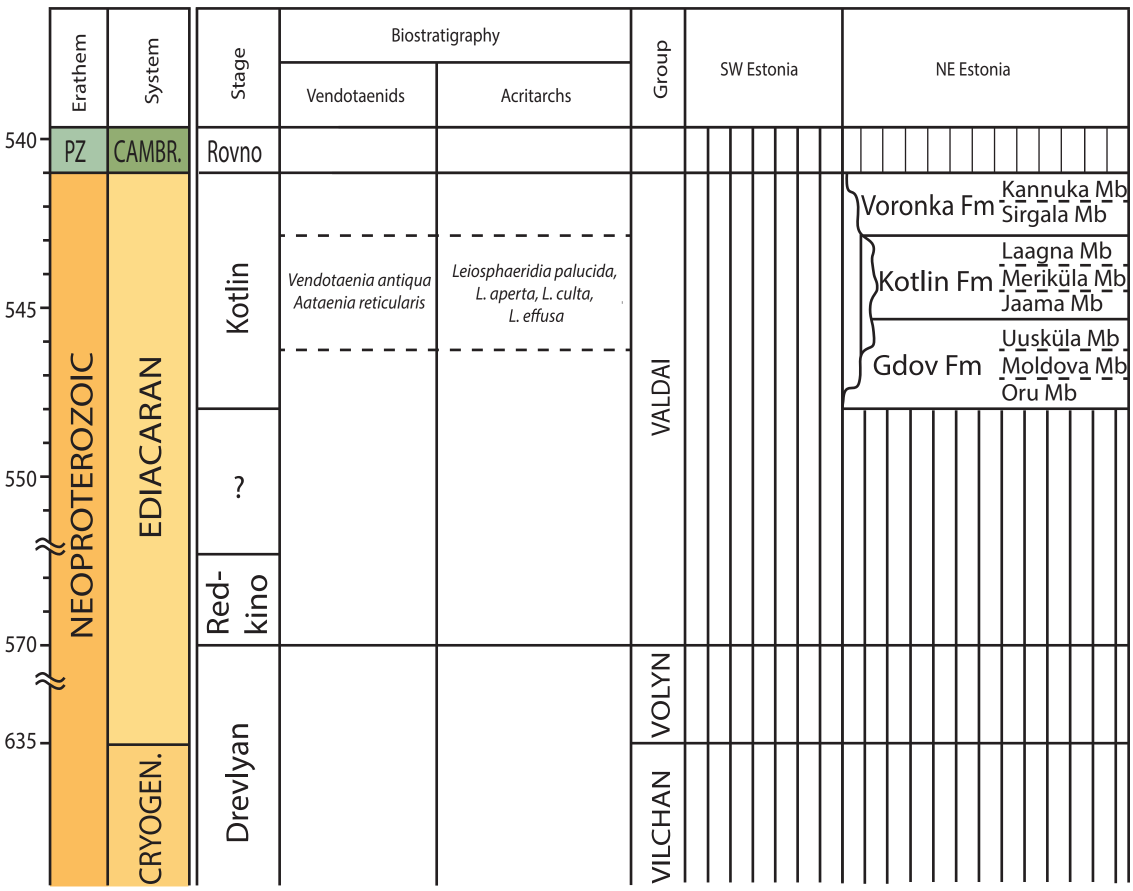

Fig. 2. Ediacaran chronology and stratigraphy in Estonia (Meidla 2020).

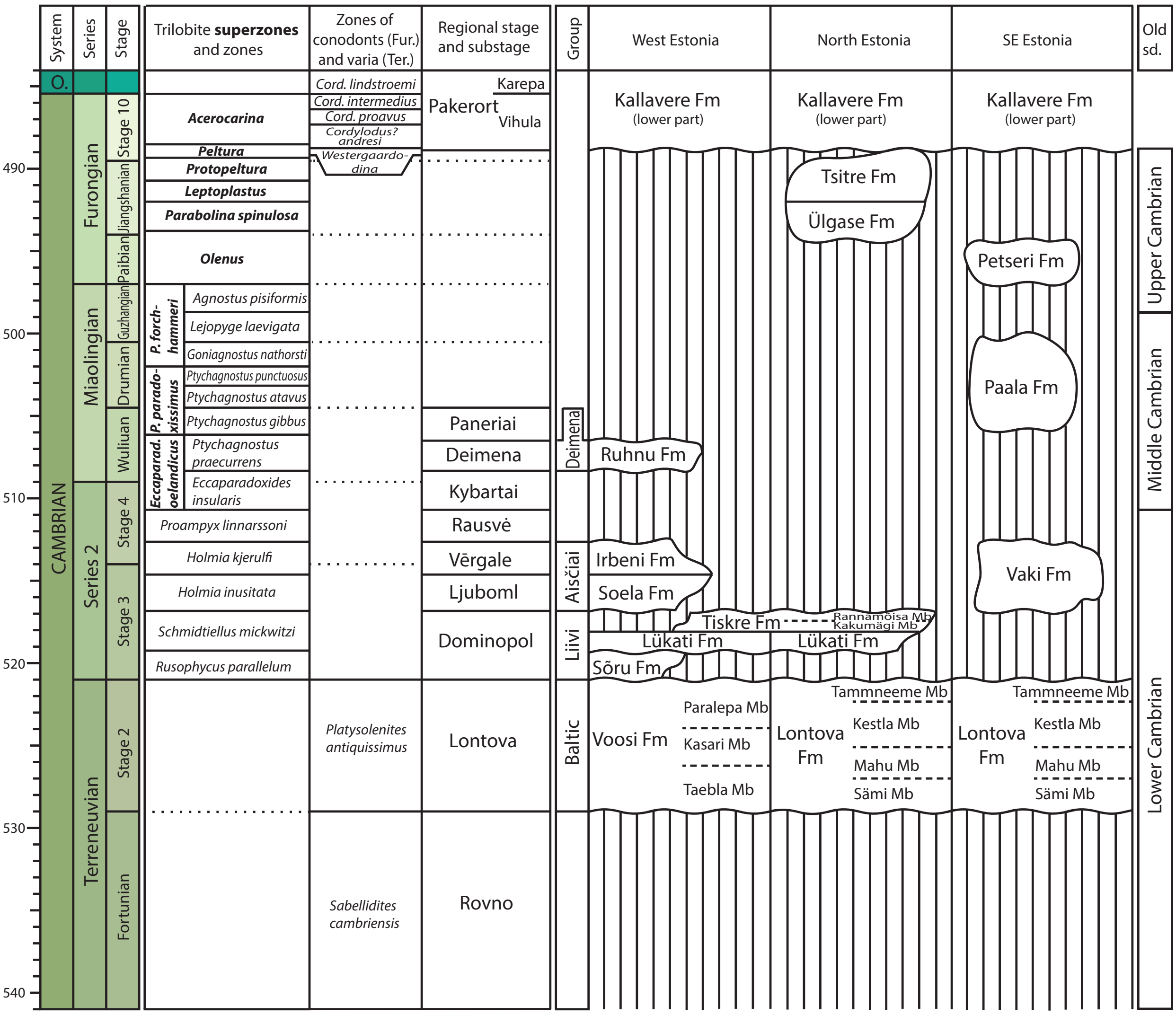

Fig. 3. Cambrian chronology and correlation of the formations in Estonia (modified from Meidla 2017).

tied to the appearance of the first trilobites. The first trilobite fragments are recorded in the basal part (0.2 m above the lower boundary) of the Lükati Formation in North Estonia (Mens & Pirrus 1977), i.e. higher than the appearance of trilobites in Scandinavia (in the *Rusophycus parallelum* Zone by Ahlberg et al. 1986). Based on the latter fact, the boundary of the second series of the Cambrian System is tentatively drawn at the base of the Sõru Formation, where agglutinated foraminiferans and the acritarch genus *Baltisphaeridium* make their first appearance (Mens et al. 1987).

The lower boundary of the Cambrian Stage 4, which will likely be drawn according to the first appearance of the trilobite genera *Olenellus* or *Redlichia* (Peng et al. 2012), could be within the *Holmia kjerulfi* Zone (Shergold & Geyer 2003) and can be tentatively positioned within the Irbeni and Vaki formations in Estonia (Mens et al. 1987; Fig. 3).

The lower boundary of the Miaolingian Series (tied to the first appearance of the trilobite *Oryctocephalus indicus*) is located within the *Eccaparadoxides insularis* Zone in Baltoscandia (Geyer, 2005). This level corresponds probably to a gap in the Estonian succession (see Fig. 3).

The stage boundaries within the Miaolingian Series are difficult to identify in Estonia because of poor biostratigraphic data (barren or missing strata). The lower boundary of the Drumian Stage, the *Ptychagnostus atavus* zonal boundary, was tentatively positioned by Mens & Pirrus (1997b) within the barren Paala Formation and the the base of Guzhangian (*Lejopyge laevigata* zonal boundary) tied to a gap between the Vaki and Petseri formations in Estonia.

The lower boundary of the Paibian Stage (marked by the appearance of trilobite *Glyptagnostus reticulatus*) is tentatively drawn at or below the base of the Petseri Formation (see Meidla 2017 for details). As the acritarch assemblage typical of the *Agnostus pisiformis* Zone has not been recorded in the Petseri Formation (Mens et al. 1993; Paalits 1992, Paalits *in* Põldvere and Paalits 1998), this formation is likely equivalent to the lower-middle parts of the *Olenus – Agnostus (Homagnostus)* Zone. The base of the Jiangshanian Stage (marked by the first appearance of agnostid trilobite *Agnostotes orientalis* and a polymerid trilobite *Irvingella angustilimbata*) is correlated by Shergold & Geyer (2003) with the upper part of the *Olenus* Zone in Baltica and drawn near the base of the Ülgase Formation in Estonia (Meidla 2017). The uppermost stage of the Furongian is formally undefined but could likely be drawn within the Tsitre Formation or at the base of the Kallavere Formation in Estonia (Meidla 2017).

Drawing the chart on a regular timescale is possible only based on the ages of boundaries of the series and stages, both defined or under definition. The timescale used in the Fig. 3 is based on Cohen et al. (2013).

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The Ordovician System in Estonia

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The following text is based on Meidla et al. (2023).

The area of continuous distribution of the Ordovician in the Baltic Sea area and east of it extends from the southern part of the Baltic Sea in the west to the vicinity of Moscow in the east and from the Gulf of Finland or northernmost Estonia in the north to Belarus and Poland in the south. In the northern part of this area, in the eastern coastal region of the Baltic Sea, beds are exposed in sections of the Baltic-Ladoga Klint, sometimes with more than 10 m of strata exposed, which attracted the attention of early investigators, together with other coastal and river bank sections, as well as old and new limestone quarries and open cast pits. Well-accessible successions with well-preserved fossils and sedimentary structures attracted the attention of investigators already in the early 19th century and were addressed in the papers by O. M. L. v. Engelhardt (1820), W. T. H. F. Strangways (1821), E. Eichwald (1825), and others. In particular, the characteristic succession of the Cambrian to Middle Ordovician with a number of distinctive rock units (the Cambrian Blue Clay, phosphatic brachiopod coquina, *Dictyonema* argillite, dark green glauconite sandstone and the succession of distinctive limestone units above) was of great interest.

The thorough monographic paper by F. Schmidt from 1858 brought to attention the main features of Ordovician stratigraphy in Estonia for the first time. The general pattern of his very old geologic map in the same volume is already well demonstrating the most characteristic feature of modern bedrock maps of Estonia —latitudinally orientated outcrop belts of the Ordovician and Silurian stages in northern Estonia. The feature is a result of the generally simple geologic structure of the area, with almost horizontal strata dipping southward only 2–5 m/km.

The Lower Ordovician thin succession of siliciclastics comprises sandstones, argillites and clays (Pakerort and Varangu RSs) overlain by the glauconitic sand- and siltstones (Hunneberg and Billingen RSs). Further up, the main part of the Ordovician succession in northern Estonia is heavily dominated by various kinds of limestones but also contains some intercalations of kukersite oil shale concentrated mainly in the Kukruse Regional Stage (RS). The transition from the terrigenous to carbonate rocks in the basal part of the Toila Formation (topmost Lower Ordovician to basal Middle Ordovician) is marked by the fairly sharp appearance of the first limestone/dolomite beds. The appearance of the first representatives of the numerous characteristic Middle Ordovician fossil groups is recorded in the same transition interval or in the overlying Volkhov Stage.

The Ordovician limestone succession in Estonia and adjacent areas begins with carbonates deposited in a sediment-starved shallow marine basin. Upward the sedimentation rates have increased in obvious correlation with the carbonate carbonate production. In the Upper Ordovician, corals make their first appearance, and the first carbonate buildups appear, emphasising a remarkable change in the overall character of the palaeobasin. Informer publications, change in the type of sedimentation and the character of biofacies is ascribed to a gradual climatic change resulting from the northward drift of the Baltica Palaeocontinent from the temperate climatic zone to the (sub)tropical realm (Nestor and Einasto, 1997). This interpretation, however, is not in full accordance with the results of a pilot study on conodont phosphate oxygen isotope palaeotemperature revealing a continuous cooling trend in the palaeobasin throughout the Middle and Later Ordovician (Männik et al. 2022). Independently of that, the Middle and Upper Ordovician changes resulted in an increase of carbonate production and sedimentation rate on the carbonate shelf where the deposition pattern was obviously controlled by accommodation space available.

The problems of the Ordovician geology in the subsurface area in central and southern Estonia were first revealed in the late1950s when the extensive drilling started in the area. Thanks to the high number of drill cores obtained during a comprehensive drilling programme in the 1950s–1980s, the main correlations problems between the stratigraphic successions in the outcrop area and in southern Estonia were mainly resolved. As a result of the comparison of the eastern Baltic and Scandinavian successions, the concepts of the structural-facies zones (by Männil 1966) or confacies belts (by Jaanusson 1976) were introduced for the Ordovician of Baltoscandia (see Fig. 1). As the term “confacies “is unique (being exclusively used for the Ordovician of Baltoscandia only), a different terminology has been introduced by Harris et al. 2004 (see explanation to the Fig. 1). The micropalaeontological and macrofaunal studies of the core sections also revealed the distinctive biogeographic differentiation pattern, characteristic of the Ordovician rocks (Männil 1966; Männil et al. 1968; Meidla 1996, etc.). Although the biofacies pattern is generally described for the eastern Baltic area, the facies zonation of the entire Baltoscandian area is still imperfectly known. The seismic investigations of the Baltic Sea area, performed in the last decades (Tuuling 1998 and references therein), but also detailed (micro)palaeontological investigations (e.g. Tinn 2002) might produce valuable new information in this field.

The total thickness of the Ordovician reaches up to 190 m, being maximal in central and eastern Estonia and considerably less in the outcrop area, as well as in the southwestern mainland of Estonia. Several correlation

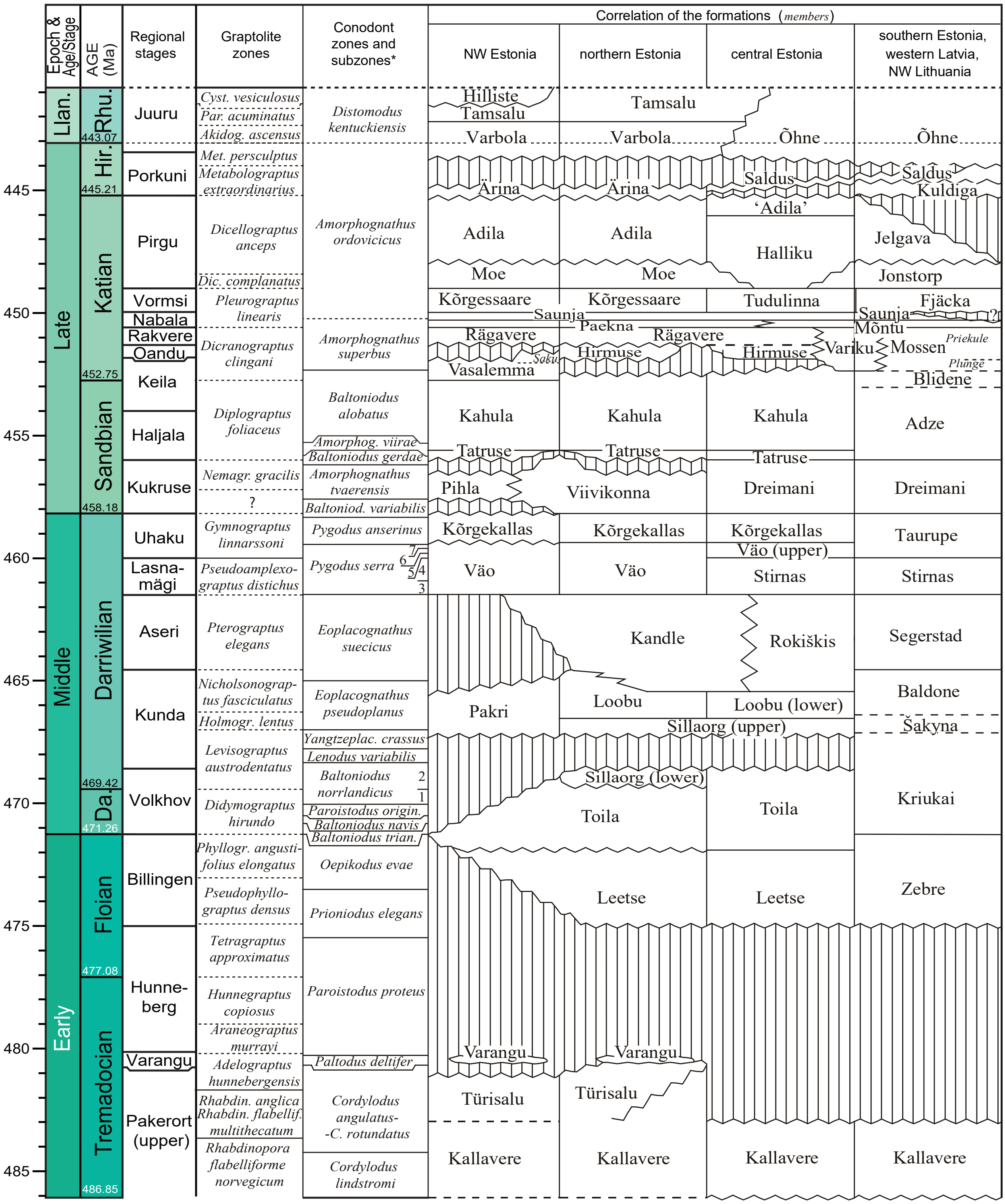

Fig. 4. Ordovician stratigraphy of Estonia. Graptolite zonation according to Kaljo & Vingissaar 1969; Kaljo et al. 1986; Männil 1976; Resheniya... 1987; Männil & Meidla 1994; Nõlvak et al. 2006; conodont zones according to Männik in Nõlvak et al. 2006; Paiste et al. 2020, 2022 and Meidla et al. 2023. Numbers in the column of the conodont zonation correspond to the conodont subzones as follows: subzones of the *Baltoniodus norrlandicus* Zone: 1 – *Trapezognathus quadrangulum* Subzone, 2 – *Lenodus antivariabilis* Subzone; subzones of the *Pygodus serra* Zone: 3 – *Eoplacognathus foliaceous* Subzone, 4 – *Eoplacognathus reclinatus* Subzone, 5 – *Eoplacognathus robustus* Subzone, 6 – *Eoplacognathus protoamosus* Subzone, 7 – *Eoplacognathus lindstroemi* Subzone. Abbreviations: Llan., Llandovery; Da., Darriwilian; Hir., Hirnantian; Rhu., Rhuddanian; *Cyst.*, *Cystograptus*; *Par.*, *Parakidograptus*; *Met.*, *Metabolograptus*; *Dic.*, *Dicellograptus*; Nemagr., *Nemagraptus*; *Holmogr.*, *Holmograptus*; *Phyllogr.*, *Phyllograptus*; *Rhabdin*, *Rhabdinopora*; *flabellif.*, *flabelliforme*; *Amorphog.*, *Amorphognathus*; *Baltoniod.*, *Baltoniodus*; *Yangtzeplac.*, *Yangtzeplacognathus*; *origin.*, *originalis*; *trian.*, *triangularis*.

problems still persist in the Ordovician of Estonia due to marked biofacies differences between northern and southern Estonia. In part, they are also discussed in a recent monographic overview of Estonian geology (see Heinsalu and Viira 1997, Meidla 1997; Hints 1997; Hints and Meidla 1997 in Raukas and Teedumäe, 1997). New prospects in this field have already been opened by stable isotope studies, as the stable carbon isotope curves have demonstrated a good correlation potential (Kaljo et al. 2004, 2007, and references therein; Ainsaar et al. 2004, 2007, 2010).

The development of the stratigraphic classification of the Ordovician strata in Estonia, from the "beds" (*Schichten*) by Schmidt (1858) to the stages in modern meaning, is documented in detail in Männil (1966), Rõõmusoks (1983) and Rõõmusoks et al. (1997). The term "Ordovician" was likely used to describe the Estonian succession for the first time by Bassler (1911) and became widely established in the geological literature of Estonia since Bekker (1921). A number of regional series and subseries for the Ordovician System in Estonia and neighbouring Russia were introduced by Schmidt (1881) and several subsequent authors. Raymond (1916) introduced the traditional American three-fold subdivision of the Ordovician System for this particular area, but this classification was subjected to repeated changes until 1987. Also, the terms "Oeland Series", "Viru Series" and "Harju Series" have been widely used as a basic three-fold classification for the Ordovician System of the area since the 1950s (introduced by Kaljo et al. 1958 and Jaanusson 1960 in a nearly recent meaning). The subseries have been introduced as well (see Männil and Meidla 1994 and Nõlvak et al. 2006 for a summary), but they lost their actuality and are rarely used today.

The modern three-fold classification of the Ordovician System (IUGS 2004) was first used for the Estonian succession by Webby (1998) and is presented here in detail (Fig. 4). In relation to the definition of the GSSP for the base of the Ordovician System in the Green Point section, Newfoundland (Remane, 2003), a revision of the traditional position of the Cambrian-Ordovician boundary at the base of the Pakerort RS in Estonia turned out to be necessary. According to conodont data, the system boundary in the northern Estonian sections lies some metres higher than previously suggested, i.e. in the middle of the Pakerort Stage, within the Kallavere Formation (Puura and Viira 1999). The upper boundary (the lower boundary of the Silurian System) has for a long time been correlated with the major hiatus between the Porkuni and Juuru RSs, corresponding to the maximum regression related to the Hirnantian glaciation, due to the fact that a major faunal overturn is recorded on this level. Recent chemostratigraphic correlations, however, suggest that the falling limb of HICE reaches into the basal part of the Juuru RS (Ainsaar et al. 2010, 2015; Bauert et al. 2014; Meidla et al. 2020, 2023) and the Ordovician–Silurian boundary is located within the beds formerly attributed to the basal Silurian.

The term "(Regional) Stage", first applied by Bekker (1921), has become the principal category in the chronostratigraphic classification of the Ordovician System in Estonia.

The main features of the chronostratigraphic classification of the Ordovician System were established already by Männil (1966). Only minor changes were introduced in the later decades: the Ceratopyge RS was renamed the Varangu RS (Männil, 1990), the Latorp RS was replaced by the Hunneberg and Billingen RSs (Hints et al., 1993) and a new unit, the Haljala RS, is used instead of the Idavere and Jõhvi RSs (following Jaanusson, 1995 and Nõlvak, 1997). Hints and Nõlvak (1999) brought the concept of boundary stratotypes ("golden spike") into the Estonian stratigraphy, proposing a stratotype — the Pääsküla outcrop — for the lower boundary of the Keila RS. However, as stratigraphic hiatuses on the stage boundaries are very common in northern Estonia (remarkable faunal changes are usually related to hiatuses), wide usage of this concept for the stage boundaries in this area looks rather complicated.

The lithostratigraphic classification of the Ordovician rocks was introduced by Orviku (1940) for the upper Middle Ordovician. This approach was widely accepted by subsequent authors and led to the compilation of a series of detailed correlation charts approved by the Interdepartmental Stratigraphic Committee of the former USSR (Resheniya... 1965, 1978, 1987 and a related paper by Männil and Rõõmusoks, 1984). The last version of such a formal correlation chart (the edition of 1987) was, in a slightly emended form, published also in English in the series of the IUGS publications (Männil and Meidla, 1994).

The correlation chart in Fig. 4 contains some recent improvements compared to this publication, the most recent ones being introduced by Ainsaar and Meidla (2001), Nõlvak et al. (2006), Meidla et al. (2020 and references therein) and Paiste et al. (2022, 2023). Some more versions of the Ordovician correlation charts for Estonia have also been published by Hints et al. (1993), Nõlvak (1997) and Meidla et al. (2014).

The composition and textures of the Ordovician carbonate rocks and the principal differences between the confacies belts were summarised by Põlma (1982 and references therein).

The monographic studies on Ordovician palaeontology started already in the 19th century. After the comprehensive review of the Ordovician and Silurian strata (in modern meaning) by Schmidt (1858 and several subsequent monographic papers), a number of important monographic papers were published by F. B. Rosen, W. Dybowski, A. Pahlen, G. Holm, A. Mickwitz, O. Jaeckel, J. H. Bonnema and R. F. Bassler. The tradition of palaeontological investigations on the Ordovician material of Estonia was continued by A. Öpik (1930, 1934 and others) and, later on, by the recent generation of palaeontologists. Monographs and extensive monographic papers were published on the Ordovician brachiopods, corals, stromatoporoids, chitinozoans, scolecodonts, ostracods, conodonts, etc. Summaries on the palaeontological investigations on virtually all fossil groups recorded from the Ordovician of Estonia are published in the recent monograph "Geology and mineral resources of Estonia" (Raukas and Teedumäe 1997).

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The Silurian System in Estonia

Peep Männik, Tõnu Meidla and Olle Hints

In Silurian, the territory of present-day Estonia was a part of the northern flank of a shallow cratonic sea in the western Baltica Palaeocontinent. The Silurian Palaeobasin was restricted to the Baltic Syneclise in the East Baltic area and North Poland (Nestor & Einasto 1997). In Silurian, the Baltica Palaeocontinent was located in equatorial latitudes and drifted gradually northwards (Melchin et al. 2004). From the Late Ordovician Katian Epoch until the end of the Silurian, the Baltic Palaeobasin was characterised by a wide range of tropical shelf environments with accumulation of various calcareous deposits and occurrence of rich and diverse biota (Nestor & Einasto 1997; Dronov & Rozhnov 2007).

The Silurian strata are exposed in western, central and eastern Estonia, south of the Haapsalu–Tamsalu–Mustvee line (Fig. 1). Further to the south of the Pärnu–Mustvee line, they are covered by Middle Devonian terrigenous rocks. Due to the gradual infilling of the sedimentary basin from north to south and east to west, the oldest Silurian rocks are found in the eastern and northern parts of the outcrop area; to the south and southwest, successively younger strata become exposed. The Silurian strata can be studied in a number of small old and several larger modern quarries. The most spectacular natural outcrops are located on the northern and western coasts of the Saaremaa.

Based on the distinctly expressed lateral facies changes of the Silurian rocks, the Middle Estonian and South Estonian facies belts have been distinguished (Kaljo 1977). Various limestones and late diagenetic dolostones, originally rich in shelly faunas, dominate the central Estonian facies zone. These rocks are distributed in the islands of the West Estonian Archipelago and in the western and central parts of mainland Estonia. As a rule, these strata are well exposed. In mainland Estonia, the Silurian succession is less complete, and its upper part has undergone extensive dolomitisation. The South Estonian Facies Belt is mostly characterised by argillaceous carbonate rocks (marl- and mudstones) with deeper-water shelly fauna and occasional graptolites in some intervals. These rocks are covered by the Middle Devonian strata and can be studied in core sections only.

The study of the rocks of the Silurian age in Estonia started in the early 19th century (Engelhardt & Ulprecht, 1830). Their first stratigraphic classification was proposed by Schmidt (1858, 1881, 1892), and several of his units (called 'Schicht' in the German language and interpreted as regional stages today) and their notation system (G, H, J, etc.) are still in use. Bekker (1922, 1925) and Luha (1930, 1933, 1946) established the present nomenclature of the Silurian regional stages, adopting contemporary geographic names to the units.

Before 1940s, geological studies in Estonia were mainly based on natural outcrops and on number of small quarries located in the outcrop area. A new stage of studies began after the Second World War. Since the late 1940s and until the collapse of the Soviet Union, extensive drilling projects were carried out in Estonia by the predecessors of the Geological Survey of Estonia, and a particularly active period of the studies on the Silurian in Estonia started in the late 1950s to early 1960s. During the following decades, various aspects of the Silurian succession were studied based on the very rich core material and the results were summarised in several monographs (e.g., Jürgenson 1966; Kaljo 1970, 1977; Kaljo & Klaamann 1986; several papers in Raukas & Teedumäe 1997; etc.).

During the long history of the Silurian studies in Estonia, the regional stratigraphical scheme has been revised and updated many times. The majority of the lithostratigraphic units (formations, members, beds) that are used today were defined and described in the monograph "The Silurian of Estonia" (Kaljo 1970). Further amendments to the stratigraphical nomenclature and correlation with the successions in the adjacent areas have been published in the unified regional stratigraphical schemes (Resheniya… 1978; Resheniya… 1987) and in several other papers (e.g., Aaloe et al. 1976; Nestor & Nestor 1991; Perens 1992, 1995; Jeppsson et al. 1994; Nestor 1995, 1997; Nestor & Nestor 2002; Nestor et al. 2003; Viira & Einasto 2003; Hints 2008; Männik 2014; Kaljo et al. 2015). The supposed correlation between the succession of Silurian regional stages in Estonia and the global chronostratigraphic standard has been considered reliable for a long period of time and has remained almost unchanged. Studies of the last decades, however, have revealed several correlation problems, and the need to restudy and revise some parts of the scheme has become evident.

The Silurian succession in Estonia consists of ten regional stages (RSs) (Nestor 1997; Fig. 5). However, due to sporadic distribution of macrofauna and poor information about microfossils the RSs were defined by a combination of palaeontological and sedimentological data, and their boundaries were based on sedimentological criteria (see Kaljo 1970, and references therein). The RSs were distinguished based on their characteristic lithology and faunas, and, as a rule, no boundary stratotypes were defined. The stage boundaries are still biostratigraphically poorly constrained.

Based on the lithological composition of strata, the stages were subdivided into formations (Fm). Several sets of Fms have been established within different facies belts. In accordance with the rules of the Stratigraphical Code of the former Soviet Union (Stratigraphic… 1977)

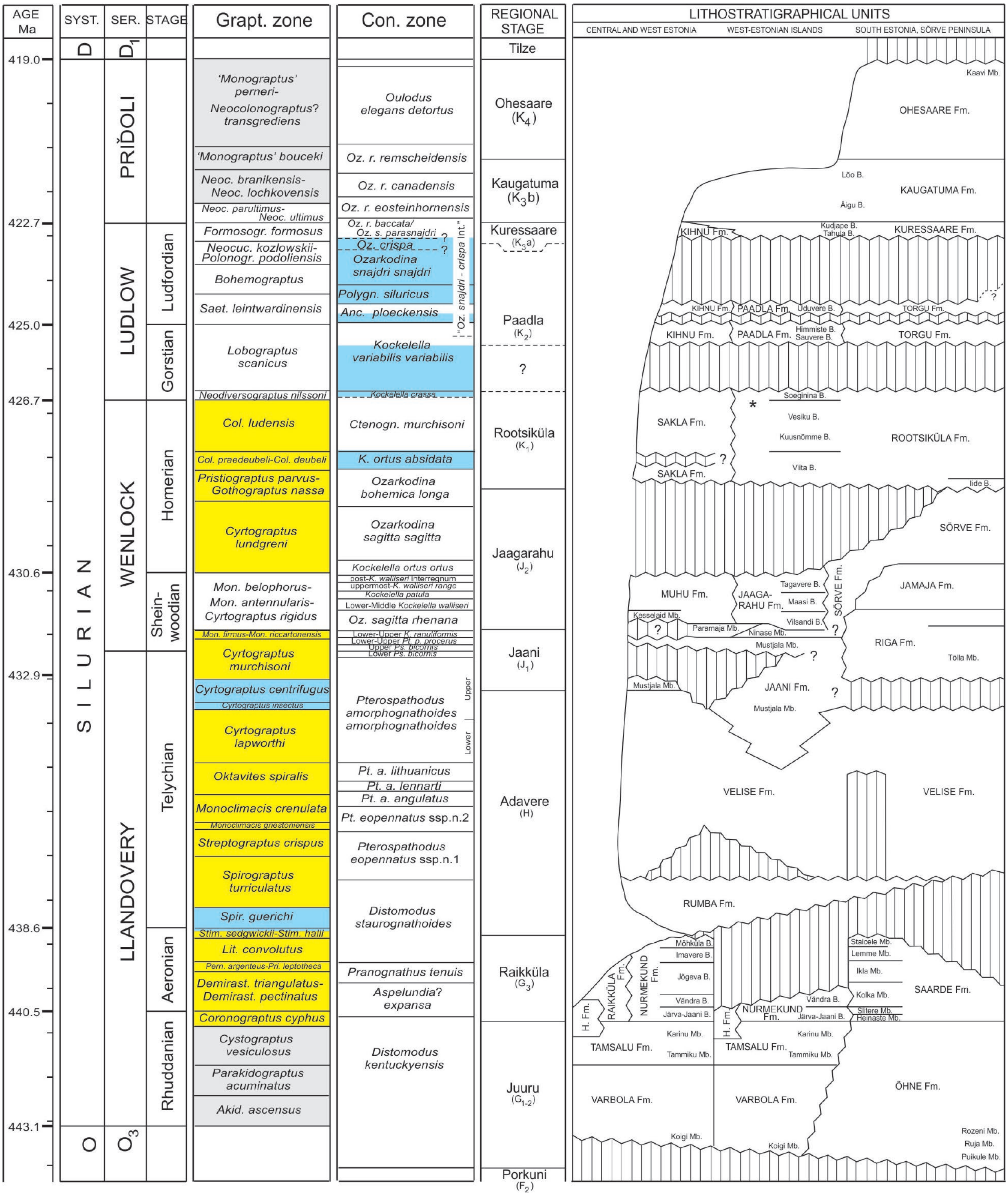

Fig. 5. Updated Silurian stratigraphical scheme of Estonia. The global Silurian time scale according to Melchin et al. (2020) with proposed by these authors ages of stage boundaries indicated. 432.9 marks the base of the *Cyrtograptus murchisoni* GZ which was considered as the base of Wenlock (Melchin et al. 2020) but, in reality, is older than the Llandovery–Wenlock boundary at Leasows, in the type section of this boundary (Männik, 2014). Graptolite zonation modified from Cramer et al. (2011). Colours in the column of grptolite zones: yellow – zones reliably correlated with Estonian succession (based on co-occurrences of graptolites, conodonts and chitinozoans: Loydell et al., 1998, 2003, 2010); white – some indirect correlation available; grey – no information. Graptolite and conodont zones marked with blue colour mark more or less well proved and dated gaps in Estonian succession. The Llandovery–Wenlock part of the conodont zonation is based on Jeppsson (1997), Jeppsson & Calner (2003), and Männik (2007a and b). The zonation in the Ludlow interval (excluding the upper Ludfordian) is modified from Cramer et al. (2011), and the uppermost Ludfordian–Přidoli zonation from Viira (1999). "*Oz. snajdri–crispa* Interval" marks the total range interval of closely related, often co-occurring and, in several cases difficult to distinguish *Oz. s. snajdri*, *Oz. crispa* and *Oz. s. parasnajdri*. Due to common identification problems, all representatives of these taxa are identified as *Oz. snajdri* s.l. in Märss & Männik (2013). In parentheses below the names of RSs in the column of regional stages are indicated traditional notations of these units by F. Schmidt. * – proposed position of the Anikaitse Beds (after Viira & Einasto, 2003).

Fig. 5 (cont). Abbreviations: Syst. – System, Ser. – Series, Grapt. – Graptolite, Con. – Conodont, Int. – Interval, Mb. – Member, Fm. – Formation, B. – Beds. H. Fm. – Hilleste Fm.; graptolites: *Akid*. – *Akidograptus*, *Col*. – *Colonograptus*, *Demirast*. – *Demirastrites*, *Lit*. – *Lituigraptus*, *Mon*. – *Monograptus*, *Neoc*. – *Neocolonograptus*, *Neocuc*. – *Neocucullograptus*, *Neodiv*. – *Neodiversogrptus*, *Pri*. – *Pribylograptus*, *Saet*. – *Saetograptus*, *Spir*. – *Spirograptus*, *Stim*. – *Stimulograptus*; conodonts: *Anc*. – *Ancoradella*, *Ctenogn*. – *Ctenognathodus*, *K*. – *Kockelella*, *Oz. r*. – *Ozarkodina remscheidensis*, *Oz. s*. – *Ozarkodina snajdri*, *Polygn*. – *Polygnathoides*, *Pt. a*. – *Pterospathodus amorphognathoides*, *Pt. p*. – *Pteropspathodus pennatus*, *Ps*. – *Pseudooneotodus*.

that was used as a standard before the 1990s, a formation has been dealt with as a topostratigraphic unit: it was defined mainly by its specific lithological composition whilst positions of their boundaries were adjusted based on biostratigraphical data and considered to be isochronous – a feature that is evident in the earlier stratigraphical schemes from the ‘box-like’ appearance of the formations. Also, according to the Stratigraphic… (1977), a formation was a subdivision of regional stage, and its distribution interval was mandatorily limited to one stage only (e.g. the stratigraphic scheme in Nestor 1997). These rules have caused some confusion and resulted in repeated revisions of several Fm boundaries from publication to publication, in accordance with the newly obtained biostratigraphical data (e.g. the lower boundary of the Jaani Fm in the Viki core section in the successive publications by H. Nestor (1990), V. Nestor (1994) and A. Põldvere (2010)).

Based on the specific lithological characteristics, several Fm-s were further subdivided into members (Mb). Additionally, as many intervals of the Silurian succession reveal clear cyclicity, particularly within the more shallow-water Middle Estonian Facies Belt, cyclostratigraphical units consisting of alternating types of rocks reflect certain (mostly regressive) trend of sea level change and, as a rule, are bounded by gaps were distinguished. These cyclicity-based units were called ‘beds’ and treated as subdivisions of Fms but sometimes as substages. General lithological and palaeontological characteristics of the units presented in the Silurian stratigraphical scheme of Estonia are available in Nestor H. (1997, and references therein).

Modern high-resolution biostratigraphy in the region, dating of sections, and regional and interregional correlations, are based mainly on conodonts (Viira 1999; Männik 2007a, b, c) and chitinozoans (Nestor 2012, and references therein). However, the use of chitinozoan zonation in dating and correlation of sections, particularly representing shallow-water environments, is limited. This is mainly due to the inconsistency of chitinozoan biostratigraphy as applied in different sections caused by sporadic occurrences of chitinozoans. In the upper part of the succession (Wenlock and above), vertebrates provided additional useful information (Märss 1986; Märss & Männik 2013). Due to the rare occurrence of graptolites in the Silurian strata in Estonia, the correlation of several RSs with the standard graptolite succession has been, and still is, problematic. In the last decades, detailed palaeontological and biostratigraphical studies of several core sections from SW Estonia and western Latvia where graptolites, conodonts and chitinozoans co-occur, but also co-occurrences of graptolites and conodonts from Gotland, improved the situation in some intervals considerably (Loydell et al. 1998, 2003, 2010; Jeppsson & Calner 2003). Now, most of the mid-upper Llandovery and Wenlock graptolite biozones (marked with yellow colour in Fig. 5) can be traced reliably into the sections formed in shallow water environments in Estonia and not yielding graptolites. However, dating of other intervals (particularly in Rhuddanian and Přidolí, grey intervals in Fig. 5) is still problematic but combined biostratigraphical and chemostratigraphical ($\delta^{13}C$, K-bentonites) studies allowed reasonable although indirect dating of some intervals (white in Fig. 5) from where co-occurrence data of aforementioned groups are fragmentary or missing (Ainsaar et al. 2011, 2015; Kiipli et al. 2012; Märss & Männik 2013; Männik 2014; Kaljo et al. 2015; Meidla et al. 2020; Gul et al. 2021; Kaljo et al. 2022).

New information gathered during the last decades, particularly new data about the distribution of microfossils, changed our understanding of the Silurian stratigraphy in the region and required some updating of the stratigraphical scheme (Männik 2014). The scheme presented here represents a revised version of the latter. The main changes in the scheme resulting from the analysis of recent palaeontological, biostratigraphical and geochemical ($\delta^{13}C$, K-bentonites) information include:

(1) the lower part of the Juuru RS is of Late Ordovician (Hirnantian) age;

(2) the base of the Raikküla RS lies within the *C. cyphus* GZ;

(3) the Aeronian–Telychian boundary in Estonia should be looked for not higher in the succession than the middle of Rumba Fm, but in the main part of the region, the boundary strata are missing due to a gap;

(4) the lower boundary of the Adavere RS correlates with a level in the uppermost Aeronian;

(5) the former Riksu Fm is dealt with as the proximal, older part of the Sõrve Fm;

(6) the lower boundary of the Jaagarahu Fm, but also the Jaagarahu RS as used up till now, is diachronous and, considering data from the stratotype region of these units in NW Saaremaa, the best biostratigraphic approximation for identification of the base of this RS is the FAD of *Ozarkodina sagitta rhenana*;

(7) the Wenlock–Ludlow boundary in Estonian succession correlates with a level in the upper Rootsiküla RS (is tentatively correlated with the boundary between the Vesiku and Soeginina Beds);

(8) the Sauvere and Himmiste Beds of the Paadla Fm correlate with the upper Gorstian;

(9) the Uduvere Beds correlate with an interval in the lower Ludfordian, below the Lau $\delta^{13}C$ excursion, and are tentatively correlated with the upper *Ancoradella ploeckensis* CZ;

(10) the base of the Paadla RS corresponds to a level in the upper Gorstian, to a level in the lower(?) *Phlebolepis ornata* Vertebrate Zone, and is separated from the underlying Rootsiküla RS by a gap corresponding to the main (middle) part of the Gorstian;

(11) in Estonia, only the lower and upper parts of the Ludfordian are represented by deposits;

(12) so far, there are no reliable biostratigraphic criteria for recognising the Ludlow–Přidolí boundary in the Estonian succession. Additionally, the duration and distribution of several gaps in the succession were updated.

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The Devonian System in Estonia

Anne Põldvere

The following text is from Põldvere (2014).

The Devonian forms the youngest part of Estonian bedrock (Fig. 6). They are mainly spread to the south of the imaginable line between the towns of Pärnu and Mustvee and in a small area in NE Estonia (Fig. 1), unconformably overlying the Ordovician and Silurian sedimentary rocks. Containing mainly quartz sand- and siltstones with dolostones, dolomitic marl or clay interbeds, the Devonian rocks may attain a thickness of 450 m in southeastern Estonia. Biostratigraphy of these deposits is mainly based on fish fossils and miospores.

The Lower Devonian is known from some drill cores in South Estonia. The incomplete succession of the Lochkovian, Pragian and Emsian stages (respectively the Tilžė, Ķemeri and Rēzekne regional stages) comprises light grey, weakly to strongly cemented quartz sandstones with siltstone and clay, rarely dolomitic marl and dolomite interbeds. The horizontally and cross-bedded complex has a maximum thickness of 60 m.

The Early Devonian non-deposition period on the Estonian territory was followed by a rise of sea level when the sea flooded a great part of the East European Platform up to the Moscow Syneclise (Kuršs 1992; Plink-Björklund & Björklund 1999). In the area occupied by Scandinavian rivers, sediments derived from the erosion of mountains were transported across a coastal plain to the shallow sea. Poorly sorted and angular, mainly finegained sands deposited in the shallow marine basin in southeastern Estonia in the Tilžė, Ķemeri and Rēzekne ages (Kleesment 1997). Carbonate deposits with an admixture of terrigenous material accumulated at the end of the epoch.

The Middle Devonian (Eifelian, Givetian) is exposed across a broad outcrop area in southern Estonia and separately in the northeastern part of the country. Numerous outcrops (stratotypes) occur on the banks of rivers and lakes and in the operating and abandoned quarries. Many places, particularly caves, are linked to folk beliefs about devils and religious ceremonies. The total thickness of the Middle Devonian rocks is 400 m in Estonia.

The Eifelian Stage in the northern part of the outcrop area is represented by multicoloured cross-bedded sandstones (Pärnu Regional Stage) and horizontally bedded grey dolomitic marl with dolomite, clay, siltand sandstone interbeds, covered by reddish-brown horizontally bedded or lens-shaped silty sandstone (Narva Regional Stage).

The lower part of the Givetian (Aruküla Regional Stage) is characterized by reddish-brown, horizontally and cross-bedded sand- and siltstones with rare dolomitic marl interbeds. These rocks are rich in fossil fishes: heterostracans (psammosteids) and placoderms. Famous sources of fossil fish specimens are the Kalmistu outcrop and the Aruküla caves in the NW part of Tartu. The middle part of the Givetian (Burtnieki and Gauja regional stages) is mainly represented by white and yellowish-grey cross-bedded sandstones with siltstone and clay interbeds. Weakly cemented sandstones contain locally layers rich in Fe-hydroxides and ball clay (up to 20 cm across). The upper part of the Givetian (Amata Regional Stage) is represented by mottled wavy-bedded siltstone and light grey to white or yellowish-grey crossbedded sandstone with reddish-brown clay interbeds or balls.

The Middle Devonian marine transgression flooded a wide area of the East European Platform and reached its maximum in the Narva Age when carbonate muds accumulated (Kleesment 1997). A delta front with fluvial sediments was formed in the Aruküla Age. The slow retreat of the marine basin was repeatedly interrupted by temporary transgressions. Delta plane formations accumulated periodically in subaquatic (Plink-Björklund & Björklund 1999) and subaerial conditions. The main influx of terrigenous material during the epoch was from the Scandinavian massif.

The Upper Devonian (Frasnian) carbonate rocks are spread in the southeasternmost part of Estonia. A few outcrops are found on river banks and on the walls of operating and abandoned quarries. Light grey horizontally bedded dolomites and limestones with dolomitic marl, clay, gypsum and anhydrite interbeds are in some places highly fractured and contain vugs and karst caves. The layers are often rich in stromatoporoids and contain moulds of brachiopods and gastropods. Fish fragments and claycemented bioherms are found in some places. The total thickness of these rocks is 47 m in Estonia.

A new marine transgression occurred in the entire East European Platform in the Frasnian Age. In the Estonian part of the basin, with a rich assemblage of fauna, a periodic influx of fresh water and terrigenous material continued from the north (Kleesment 1997).

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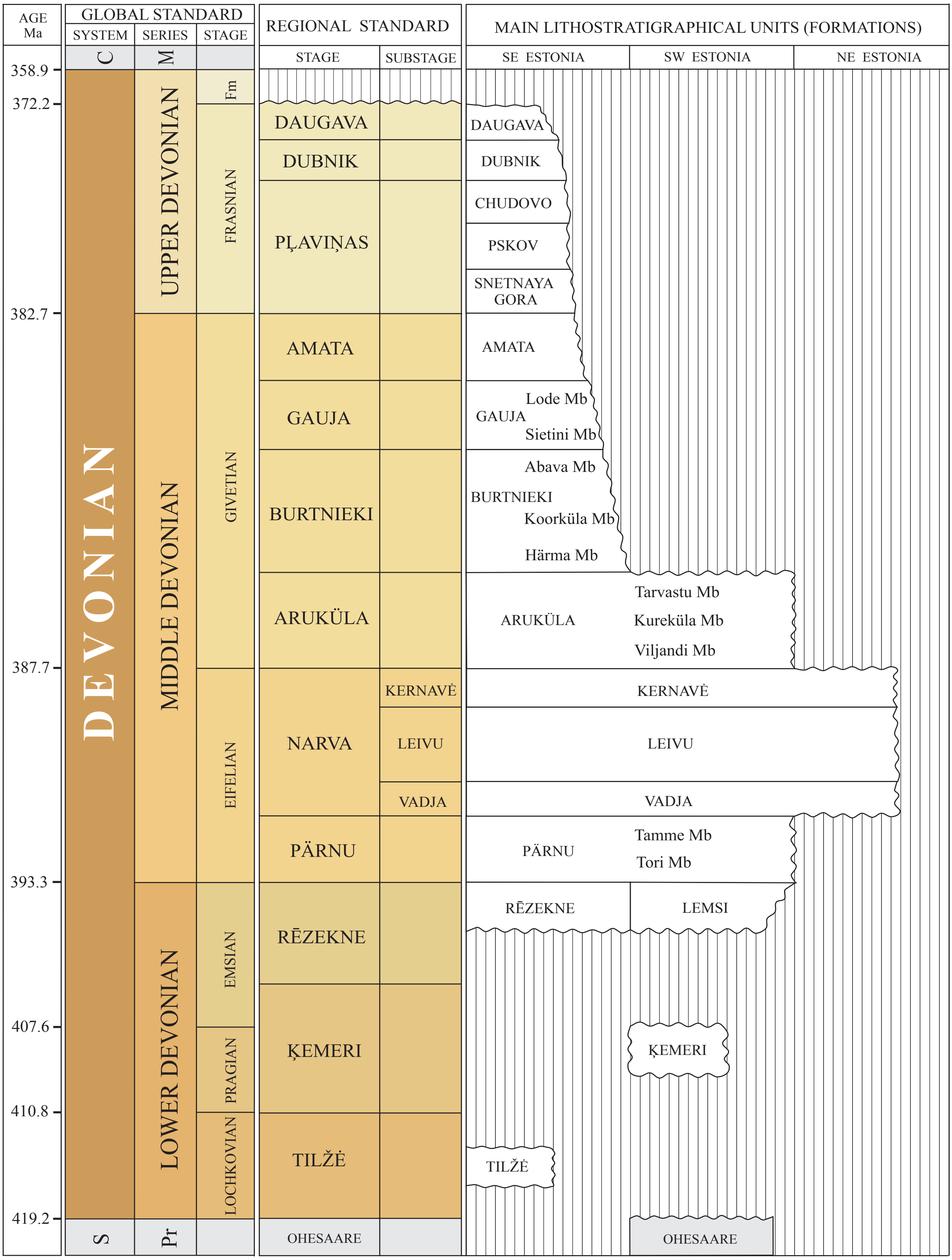

Fig. 6. Devonian stratigraphy of Estonia (from Põldvere 2014, after Mark-Kurik & Põldvere 2012).

Plink-Björklund, P., Björklund, L., 1999. Sedimentary response in the Baltic Devonian Basin to postcollisional events in the Scandinavian Caledonides. *GFF*, **121**, 79–80.

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Mid-conference Excursion

August 20, 2024

XI Baltic Stratigraphical Conference

August 19-21, 2024
Tartu, Estonia

Stop 1: Tartu cemetery outcrop

Tõnu Meidla and Peep Männik

Location: Latitude 58°23´42.1˝N, longitude 26°42´41.3˝E; Tartu, Estonia.
Stratigraphy: Middle Devonian, Givetian, Aruküla RS.
Status: The outcrop is under nature protection; no hammering, but loose material may be collected.
More information: https://geoloogia.info/en/locality/13574

The outcrop of the Aruküla Regional Stage (Fig. 1.1) is situated on the left slope of the Emajõgi River valley, just below the Uus-Jaani and Vana-Peetri cemeteries, near the end of the Ujula Street. The outcrop (cliff) is about 250 m long and up to 5.5 m high, with the maximum height in its southeastern part. It comprises a part of the composite stratotype of Aruküla RS. Here, the Viljandi Beds of the lower part of the Aruküla Formation are exposed.

Fig. 1.1. Southeastern part of the Tartu cemetery outcrop. Photo: Gennadi Baranov, 2015.

Description of the section (from the top to the base, based on Kleesment 1991):

0.5–2.0 m – Quaternary cover (argillaceous till);

3.0 m – interval is dominated by red to yellowish-brown cross-bedded sandstone. Its upper part, up to 0.7 m thick, is represented by platy, brownish-grey, reddish-brown and grey siltstone with dolomitic cement, yielding thin interbeds of reddish-brown clay and yellowish-grey dolomitic marlstone with cubic caverns;

0.2 m – brownish-red sandy siltstone;

2.0+ m – pinkish- to yellowish-brown cross-bedded fine-grained moderately cemented sandstone with lenses of whitish-grey mica-rich sandstone and occasional small clay pebbles. These lenses yield fragments of fossil fishes.

The accumulation of sands took place in a subaqueous tide-dominated delta environment (Tänavsuu-Milkevičiene & Plink-Björklund, 2009).

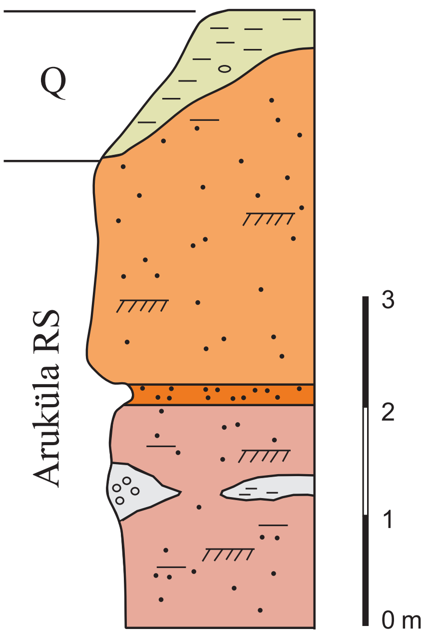

Fig. 1.2. A composite section of the outcrop, modified from Kleesment (1991). For details see the description.

Fossils

The succession (Fig. 1.1) is nearly equivalent to the stratigraphic interval exposed in the walls of Aruküla Caves, the famous fossil vertebrate locality comprising the other part of the composite stratotype of the Aruküla RS. The fossil-rich conglomeratic layer that was formerly exposed in the caves has not been documented in the cemetery section located about 1 km south of the caves. Several vertebrate taxa have still been recorded in the lower part of the outcrop, like *Heterostius ingens* Asmuss, *Pycnosteus palaeformis* Preobrazhensky, *Homostius* sp. and fragments of Crossopterygii (eMaapõu, 2024). A rich assemblage of vertebrate microremains, most abundantly represented by acanthodians, is known from the cemetery outcrop (Niit et al. 2005). Examples of fossils from the outcrop are shown in Fig. 1.3.

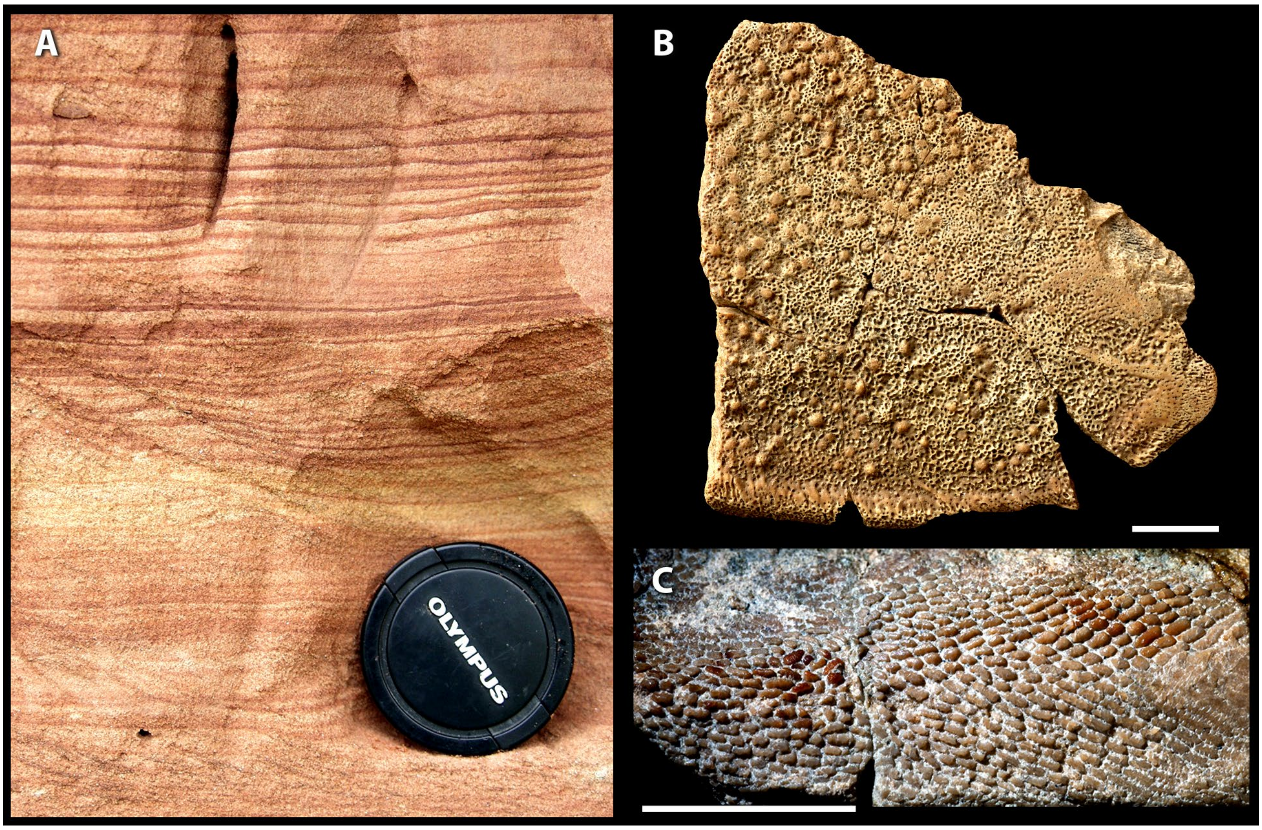

Fig. 1.3. Lithology and selected fossils from the Tartu Cemetery outcrop, Aruküla Regional Stage. **A** – close-up photo of the section, red cross-bedded sandstone. Photo: Kairi Põldsaar. **B** – placoderm *Homostius* sp., a fragment of left inferognathal plate, GIT 99-48. **C** – psammosteid *Pycnosteus palaeformis* Preobrazhensky, close-up from the surface of squama fastigiata, GIT 116-115. Scale bars B, C – 1 cm.

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Stop 2: Kalana quarry

Oive Tinn, Kalle Kirsimäe, Leho Ainsaar and Peep Männik

Location: Latitude 58°43´15.8˝N, longitude 26°01´53˝E; Jõgeva County, Estonia.
Stratigraphy: Aeronian, Raikküla Fm, Jõgeva and Imavere beds, Raikküla RS.
Status: Active quarry; please follow safety instructions. Sampling and fossil collecting are welcome.
More information: https://geoloogia.info/en/locality/15417

The new Kalana quarry (officially known as the Otisaare limestone quarry) is located about 8 km to NNE from the small town of Põltsamaa and approximately 1 km west of Kalana village. It has an area of 16.34 ha and is operated by AS Kaltsiit, producing crushed stone. The smaller old Kalana quarry is located 1–1.5 km southeast of the new quarry.

Fig. 2.1. The western wall of the Kalana quarry (height about 15 m). Beds 1–5, Jõgeva Beds. **1** – fine-grained limestone (packstone, grainstone) with marl intercalations, 2.4+ m; **2** – massive grainstone ("Kalana Marble"), 0.8–1.2 m; **3** – grainstone with marl intercalations, 1–2 m; **4** – massive grainstone ("Kalana Marble"), with a bed of thin laminated grainstone-marl at the base, 0.5–1.0 m; **5** – grainstone intercalating with argillaceous limestone (wackestone, packstone) and marl, 3 m. Bed **6**, Imavere Beds – argillaceous limestone and marl (wackestone, mudstone), 3.5+ m.

General information

In Central Estonia, in the surroundings of Põltsamaa, the cover of Quaternary sediments is thin and Silurian limestones and dolostones lie close to the surface. This is why local people have used these rocks for building and lime burning for centuries (Perens 2006). The region is dotted with numerous small old quarries, which are mostly out of use and hardly distinguishable in the modern landscape. However, several large quarries, such as Rõstla, Kalana and Sopimetsa, are actively operating and producing crushed stone for various uses.

The Kalana quarry has caught the attention of geologists for several reasons. First, it is one of the few localities in a confined area where a distinctive type of grainstone, known as Kalana marble, can be observed. Second, in

2006, Tõnu Pani, then the curator of geological collections at the Natural History Museum of the University of Tartu, discovered the first exceptionally preserved algal fossils. Over time, it became clear that the number, preservation, and quality of these fossils is truly remarkable, and has led to the description of the biota as the Kalana *Lagerstätte* (Tinn *et al.* 2009). Finally, certain levels and parts of the quarry reveal an uncommon amount of mineralisation, mostly barite, various sulfides and variable degrees of silicification.

Lithology and stratigraphy

In the Kalana quarry (Fig. 2.1), an interval of the shallow shelf carbonates of the Raikküla Regional Stage is exposed. The succession includes a series of shallowing-upward sedimentary cycles of the Aeronian age. In general, the cycles consist of open shelf argillaceous carbonates in their lower parts and of shoal and restricted shelf carbonates with interbeds of cross-bedded bioclastic grainstone and micritic limestone in their upper parts (Tinn *et al.* 2009). In micritic intervals, tempestites and organic-rich laminae are common. Five major sedimentary cycles, the Järva-Jaani, Vändra, Jõgeva, Imavere and Mõhküla beds, are described in the Raikküla Stage (Perens 1992). The upper part of the Jõgeva Beds and the basal Imavere Beds are exposed in the Kalana quarry. The strata are slightly deformed and dipping westwards; therefore, the oldest part of the interval is exposed on the eastern side of the quarry.

Mining in the Kalana quarry has been intensive, and the fossil-rich strata of the Jõgeva Beds (Ainsaar *et al*. 2014;

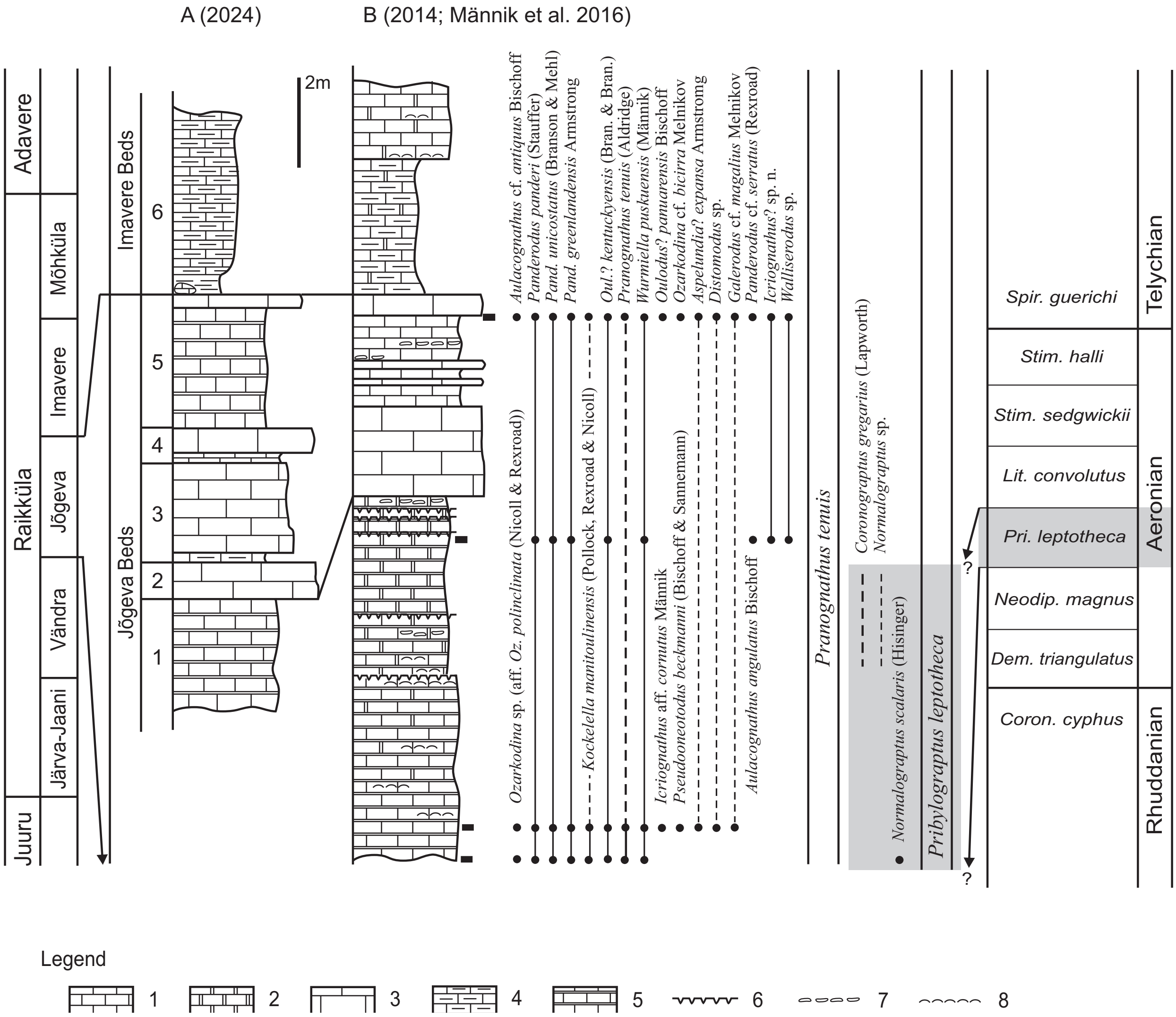

Fig. 2.2. Section of the Kalana quarry in 2024 (A) and 2014 (Ainsaar *et al*. 2014) with conodont distribution and biostratigraphy after Männik et al. (2016). From left to right: regional stages; beds in the Nurmekund Formation; beds of the 2024 quarry wall description (Fig. 2.1); lithology; section published in Männik *et al*. (2016); distribution of conodonts; conodont biozone recognised; distribution of graptolites; graptolite biozone recognised; Aeronian graptolite biozonation. Grey interval marks the identified graptolite biozone. Legend: 1, limestone (wackestone and packstone); 2, dolomitised wackestone and packstone; 3, limestone (grainstone); 4, argillaceous limestone (wackestone); 5, intercalation of different limestones and dolomitised limestones (mainly wackestone and packstone) with kerogenous laminae and thin interbeds; 6, pyritised discontinuity surfaces; 7, lithoclastic tempestites; 8, coquinal interbeds. Abbreviations: *Coron*., *Coronograptus*; *Dem*., *Demirastrites*; *Lit*., *Lituigraptus*; *Neodip*., *Neodiplograptus*; *Pri*., *Pribylograptus*; *Spir*., *Spirograptus*; *Stim*., *Stimulograptus*; Bran. & Bran., Branson & Branson.

Tinn *et al*. 2009) are not exposed any more, lying below the quarry floor (Fig. 2.2). These beds are described as dolomitic limestone, which originally might have been wackestone and/or packstone. This interval contains numerous 1–20 mm thick lenses and irregular interbeds of light to dark brown organic-rich, microlaminated, dolomitised limestone, which contains abundant non-calcified algae. Fauna in these kerogenous interbeds is represented by monograptid and diplograptid graptolites, scolecodonts, bryozoans, sponges and crinoids. The succession also contains lithoclastic and bioclastic tempestites, the latter yielding abundant gastropods, ostracods and brachiopods (Tinn *et al*. 2009). Small rugose corals are also common, and cephalopods can be found.

The top of the Jõgeva Beds is well exposed, and it is represented by a series of beds of pure hard light grey cross-bedded fine-grained grainstone in a thickness of 1–4 m. This rock is known as a good building limestone and, historically, is called the "Kalana Marble". Interbeds of micritic limestone in grainstone often contain lithoclastic tempestites, formed from lithified pebbles of the same micritic limestone. The Imavere Beds are represented by partly dolomitised greenish-grey argillaceous micritic limestone. The exposed thickness of these beds increases westwards, where an increase in carbonate content is visible upwards in the succession (Ainsaar *et al*. 2014).

Stratigraphically, the section with the highest concentration of exceptionally preserved fossils is of mid-Aeronian age and corresponds to the *Pribylograptus leptotheca* graptolite Biozone that is not exposed in the new (2024) section. In terms of conodont biostratigraphy, the strata correlate with the middle of the *Pranognathus tenuis* conodont Biozone (Männik *et al*. 2016).

The Jõgeva and Imavere beds have been considered to be of early and middle Aeronian age, respectively (Nestor 1997). All samples processed for conodonts from the Kalana quarry come from the Jõgeva Beds, and three of them yielded specimens of *Pranognathus tenuis* (Aldridge), indicating the *P. tenuis* conodont Zone for this interval (Männik *et al*. 2016). *P. tenuis* occurs in the Jõgeva Beds also in several other sections in Estonia (Nestor *et al.* 2003). Based on co-occurrences of conodonts and chitinozoans in these sections, and chitinozoans and graptolites in others (e.g., Loydell *et al.* 2003), the level of its appearance in the region has been dated as early Aeronian. However, this does not agree with data from elsewhere where *P. tenuis* seems to occur in the upper Aeronian, in the *Lituigraptus convolutes* graptolite Zone (Cramer *et al.* 2011). The sample from the middle part of the Jõgeva Beds in the Kalana section shows the appearance of *Aulacognathus angulatus* Bischoff and the sample from its uppermost part of *A.* cf. *antiguus* Bischoff both of which were stated to occur in the uppermost Aeronian *Stimulograptus sedgwickii* graptolite Zone in Australia (Bischoff 1986), although this has not been proved by the finds of graptolites. Hence, when comparing with data from elsewhere, both samples indicate a younger age for the Jõgeva Beds than the data from the northern Baltic area. The explanation for this discrepancy might be that, as *P. tenuis* and *A. angulatus* are both known from very few regions, their specimens are rare in the sections and occur sporadically, the real FADs and distribution intervals of these taxa have been poorly known, and they appeared earlier than suggested before. However, problems in regional stratigraphy cannot be excluded as well.

Fossils

The studies have revealed a high abundance and remarkable diversity of noncalcareous algal fossils of exceptional preservation in the Kalana section. About a dozen morphological groups of algal fossils that have been distinguished represent either distinct species or different growth stages. The most abundant in this flora is *Leveilleites hartnageli* Foerste (Fig. 2.3: A), a species that is morphologically indistinguishable from the specimens described from the Hirnantian strata of Canada. From the palaeoecological perspective, this indicates a wide distribution of the species in two palaeobasins, its long temporal range in the Iapetus Ocean, and survival of the Late Ordovician Mass Extinction (Mastik & Tinn 2017). Based on the distinctive architecture of its thallus and the position of the reproductive structures, *L. hartnageli* has been assigned to the Division Rhodophyta.

Many of the algal fossils in Kalana can be assigned to the Order Dasycladales (Division Chlorophyta), which is an extant group of large unicells generally dominated by calcareous forms and having a long and highly diverse geological history (Berger & Kaever 1992). The dasyclade flora in Kalana includes *Paleocymopolia silurica* (Mastik & Tinn 2015) (Fig. 2.3: B, C), a species with serially segmented dichotomously branching non-calcified thallus, *Kalania pusilla* (Tinn *et al*. 2015) (Fig. 2.3: D), and several yet undescribed species.

Crinoid fossils often occur as disintegrated fragments or short columnals. However, the section has also yielded well-preserved, almost complete specimens of stalked crinoids with fine pinnules attached to slender brachials on calyces. Two species, *Kalanacrinus mastikae* (Fig. 2.3F) and *Tartucrinus kalanaensis* (Fig. 2.3E), have been described from Kalana (Ausich *et al*. 2019).

In addition to common normal marine Silurian skeletal fossils like rhynchonelliformean brachiopods and gastropods, which often occur in well-sorted lenses (lithoclastic and bioclastic tempestites), occasional rugose and tabulate corals, nautiloid cephalopods, bryozoans, sponges and trilobites can be found. Certain levels show thin lamination with abundant leperditiid crustaceans and infrequent eurypterid remains, suggesting short periods of shallow lagoonal environments (Mastik 2019).

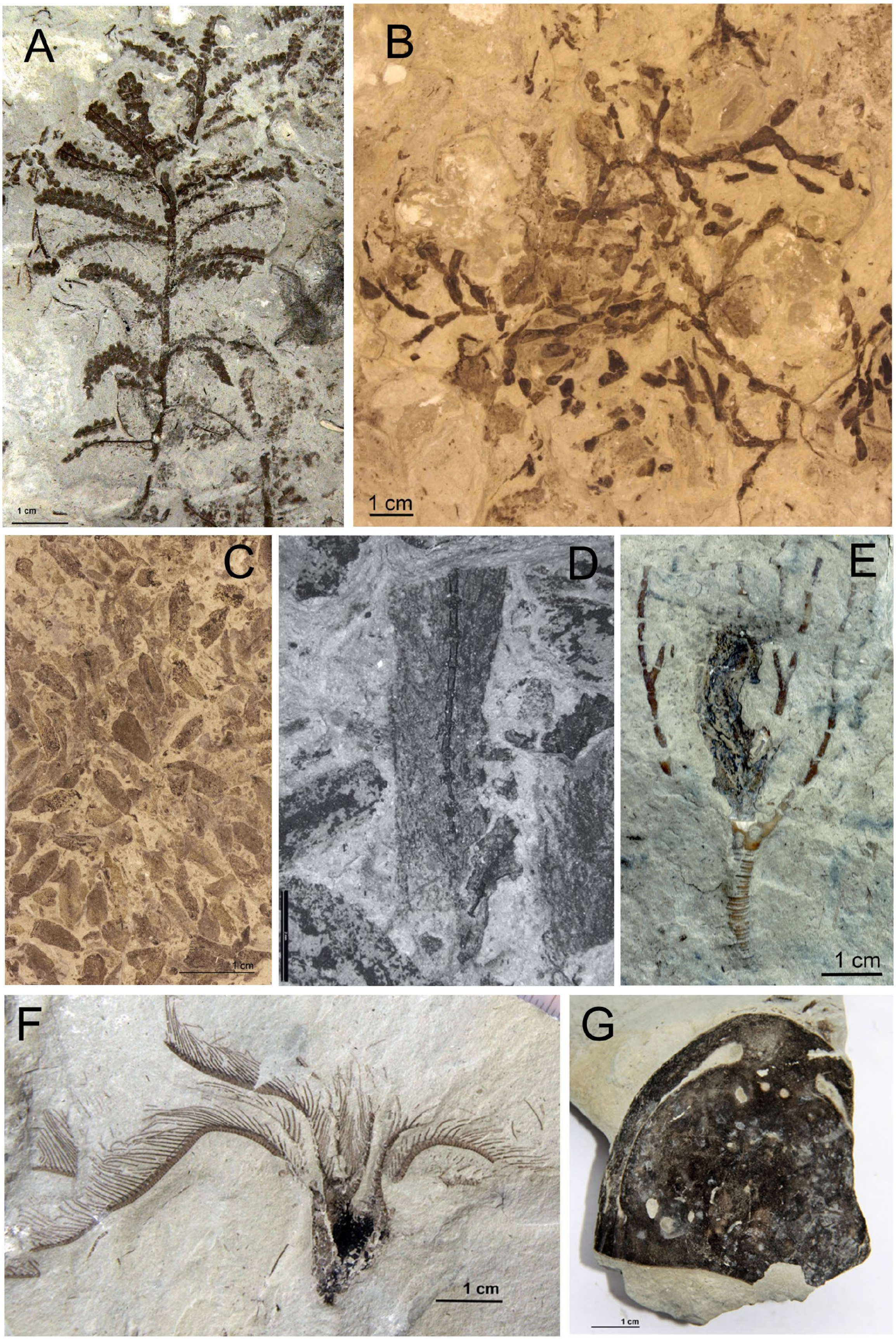

Fig. 2.3. Selected fossils of exceptionally preserved algae, crinoids and an agnathan from the eastern part of the Kalana quarry (now covered). **A** – Rhodophyte alga *Leveilleites hartnageli* Foerste, TUG 1269-1; **B** – dasyclad alga *Palaeocymopolia silurica* Mastik & Tinn, TUG 1269-9; **C** – disintegrated fragments of dasyclad alga *P. silurica* Mastik & Tinn, TUG 1269-12, on the rock surface; **D** – fragment of a dasyclad alga *Kalania pusilla* Tinn, Mastik, Ainsaar & Meidla, TUG 1269-247 demonstrating well-preserved central axis and gametophores; **E** – crinoid *Tartucrinus kalanaensis* Ausich, Wilson & Tinn, TUG 1376-2; **F** – *Kalanacrinus mastikae* Ausich, Wilson & Tinn, TUG 1736-6 with open arms; **G** – head shield of an agnathan *Kalanaspis delectabilis* Tinn & Märss, TUG 1708-1-1.

A single osteostracan fossil *Kalanaspis delectabilis* proved that the ecosystem also comprised vertebrates (Tinn & Märss 2018). However, its anomalous type of preservation – carbonaceous instead of phosphatic – could be the key to the complex taphonomic history of the whole Kalana *Lagerstätte*. According to the current hypothesis (Tinn *et al*. 2021), microbial activity has played a major role in the extraordinary preservation of the Kalana fossils.

Mineralisation

The low-temperature hydrothermal fluid-driven mineralisation in a fracture-controlled cave and vein systems in Kalana quarry carbonate succession is characterised by sphalerite, barite, pyrite, and ^{13}C-depleted speleothem calcite (Eensaar *et al*. 2017a). The earliest calcite-sphalerite veins contain two generations of sphalerite, whose primary fluid inclusions suggest formation in a $NaCl$-$CaCl_2$-H_2O composition fluid with 24–28 wt% $CaCl_2$eq salinity at temperatures 192–220 °C and 60–120 °C for the first and second sphalerite generation, respectively.

The cave-like structures at the quarry floor exploit pre-existing fractures and are filled with botryoidal calcite, barite, and pyrite aggregates. The calcite from speleothem-like aggregates is depleted in ^{13}C, with $\delta^{13}C$ PDB values as low as −56‰, indicating anaerobic methane oxidation providing the DIC. The $\delta^{18}O$ PDB values range from −10 to −12‰, suggesting precipitation at elevated temperatures, while variations in $\delta^{13}C$ PDB and $\delta^{18}O$ PDB values imply a shift from biogenic methane to thermogenic methane or hydrocarbons as carbon sources in the hydrothermal fluid with the time (Eensaar *et al*. 2017b). The cave structures also contain barite aggregates with individual barite crystala reaching 5-10 cm that likely formed at the mixing front of sulphate-rich seawater/groundwater and methane-bearing hydrothermal fluids in a hypogenic-hydrothermal karst system, facilitating abundant barite and pyrite precipitation under varying redox conditions (Gaškov *et al*. 2017). The timing of the mineralisation is unclear but could be tied to the continental-scale fluid flow induced by the buildup of the Scandinavian Caledonian Orogen in late Silurian–early Devonian.

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Stop 3: Porkuni quarry

Linda Hints and Peep Männik

Location: 59°11'13.47"N, longitude 26°11'12.78"E; Lääne-Viru County, NE Estonia.
Stratigraphy: Hirnantian, Ärina Fm of the Porkuni RS.
Status: The outcrop is under protection; no hammering, but loose material may be collected.
More information: https://geoloogia.info/en/locality/10186

The following text is based on Hints & Männik (2014).

The Porkuni quarry (historical name – Borkholm), the type locality of the uppermost Ordovician Porkuni Regional Stage, is located in Porkuni village, NE Estonia, about 20 km SW of the town of Rakvere. Eichwald (1854) was the first to mention the Borkholm dolostone as a specific type of rock. A few years later, Schmidt (1858) established the Borkholm'sche Schicht, comprising four different lithologies, which, according to the modern nomenclature, correspond to the Röa, Vohilaid, Siuge and Tõrevere members of the Ärina Formation, Porkuni RS. The uppermost part of the formation, the sandy limestone of the Kamariku Member, is not exposed in the Porkuni quarry. This member is traceable mainly in drill core sections and is preserved in some regions only (Oraspõld 1975). One exception is the Neitla quarry, located about 26 km to SWW from the Porkuni quarry, where dolomitised limestone rich in quartz sand is up to 1.38 m thick (Kaljo *et al.* 2008b; Männik & Nõlvak 2023).

Fig. 3.1. Porkuni quarry after cleaning from vegetation in 2017 during the summer gathering of the Geological Society of Estonia. Photo: Olle Hints, 2017.

The Kamariku Member is probably present also in the Reinu quarry (previously, these strata were assigned to the Koigi Member; Hints et al. 2023).

The Ärina Formation in the Porkuni quarry consists of shallowing-upward lithologies: crinoidal dolostone (Röa Member) in the lowermost part of the section, followed upwards by skeletal grainstone (Vohilaid Member), kerogenous wack- and packstone (Siuge Member) and coral-stromatoporoid-bryozoan reefs (Tõrevere Member) (Figs 3.1, 3.2). However, the thickness and succession of these units are highly variable (Hints *et al.* 2000), evidently due to the sea bottom relief, including channels (Kröger 2007). Nodules and layers of chert at the bottom of channel fills in the Siuge Member comprise small well-preserved fossils, including cephalopods (Kröger 2007).

Based on the occurrence of *Hirnantia* brachiopod fauna (Rong & Harper 1988) in the Porkuni RS in South Estonia and central East Baltic (Brenchley *et al.* 1994; Hints *et al.* 2010), it is correlated with the global Hirnantian Stage. Until the studies of microfossils and carbon isotopes were initiated, the correlation of the shallow-water Ärina Formation (Central Estonia) with the deeper-water Kuldiga and Saldus formations (South Estonia) was highly problematic. The early Hirnantian age of the main part of the Ärina Formation was proved by the occurrence of *Spinachitina taugourdeaui* in this interval (Kaljo *et al.* 2001, 2004, 2008a). Recent studies of carbon isotopes in the East Baltic (Kaljo *et al.* 2001; Ainsaar *et al.* 2010; Hints *et al.* 2014), but also in other regions (Bergström *et al.* 2006; Schmitz & Bergström 2007; Bergström *et al.* 2009), improved the correlation of the latest Ordo-

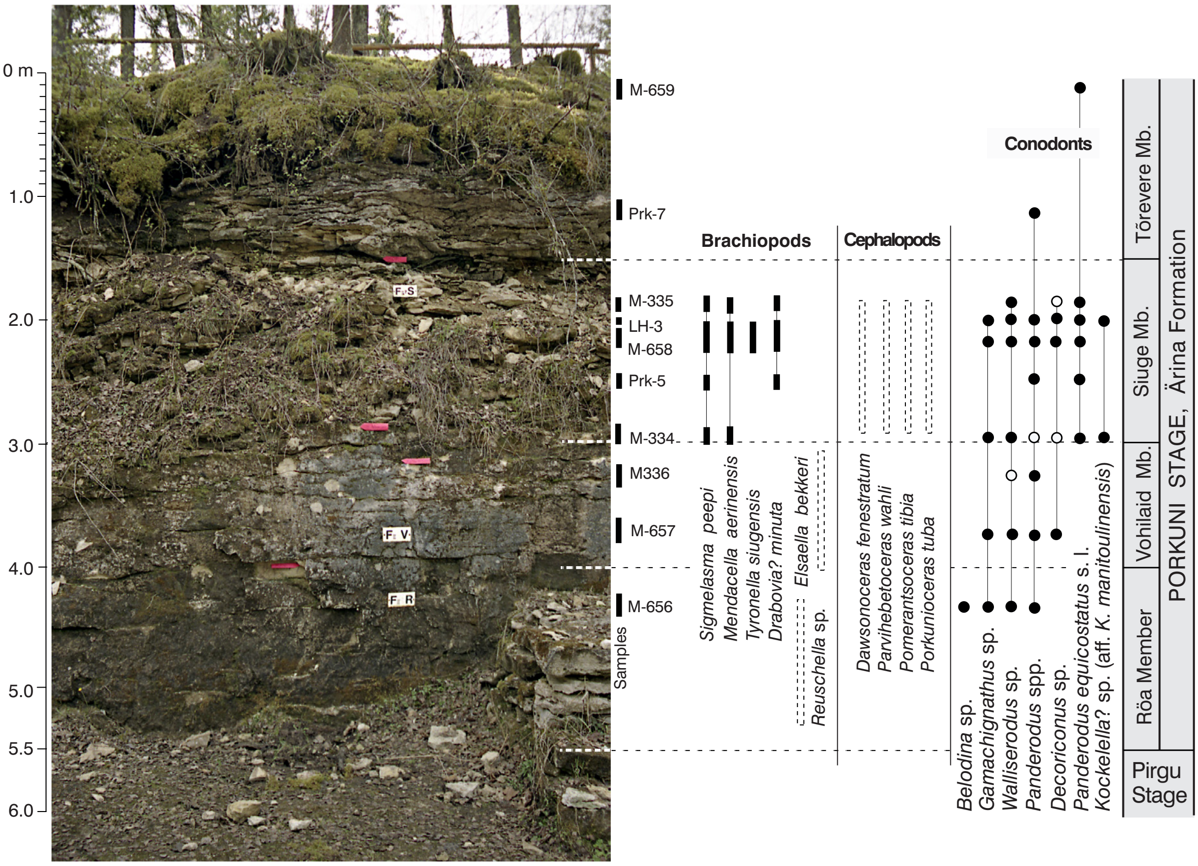

Fig. 3.2. Section of the Porkuni Regional Stage in the type section of the Porkuni quarry (Hints et al. 2000). Red lines mark the boundary levels between the Röa (R) and Vohilaid (V) members (see Fig. 3.3), transitional interval between the Vohilaid and Siuge (S) members and the boundary between the Siuge and Tõrevere (T) members. Distribution of macrofossils by Hints 2012 and Kröger 2007. Figure from Hints & Männik (2014).

vician sections. The results of carbon isotope studies also clearly demonstrate variable completeness of the uppermost Ordovician succession in different parts of the Baltic region. The Porkuni section corresponds to the rising limb of the Hirnantian carbon isotope excursion (HICE) (Fig. 3.2). In the most complete sections in western Latvia, this interval correlates roughly with the strata characterised by the *Hindella–Cliftonia* and *Dalmanella testudinaria* associations and also yielding the trilobite *Mucronaspis mucronata* (Hints *et al*. 2010). The late Hirnantian deposits are missing in the stratotype area of the Porkuni Stage, evidently due to the glacioeustatic sea-level drop. The stratigraphically incomplete sections also occur in the area transitional to the offshore environments (for example, in the Kaugatuma core section: Kaljo *et al.* 2001; Hints *et al.* 2014).

In general, the Ärina Formation in northern Estonia has been correlated with the Kuldiga Formation in southern Estonia. The Saldus Formation in the latter region is considered to correspond to a gap in northern Estonia. However, in some regions, the proximal and distal lithologies may overlap: e.g. in the Viki core section, bioclastic limestones of the probable Röa Member are overlain by oolitic limestones of the Saldus Formation (Põldvere 2010). The age of the Kamariku Member is problematic. It has been considered to be genetically related to the Ärina Formation and correlated with the upper part of the Kuldiga Formation (Fig. 3.1; Kaljo *et al.* 2001). Alternatively, Ainsaar *et al.* (2011) suggest that the Kamariku Member might be of late Porkuni age, is separated from the main part of the Ärina Formation below by a gap of considerable duration and correlates with the Saldus Formation in southern Estonia.

Description

Description of the Porkuni section is available in guidebooks of previous geological excursions (Hints & Oraspõld 2004; Kaljo *et al.* 2008b). Results of a detailed study of the section were published by Hints *et al.* (2000). Additional data about the section and faunas can be found in Oraspõld (1975), Kaljo et *al.* (2001), and Kröger (2007). In the section are exposed (from the top):

1. Tõrevere Member. 1.5+ m. Micro- to fine-crystalline light grey coral limestone, with partly silicified tabulate [*Eocatenipora parallela* (Schmidt), *Mesofavosites nikitini* Sokolov, *Rhabdotetradium frutex* Klaamann, *Porkunites amalloides* (Dybowski)] and rugose corals [*Tryplasma tubulus* (Dybowski), *Strombodes middendorffii* (Dybowski)], and stromatoporoids (*Clathrodictyon gregale* Nestor, *Ecclimadictyon koigiense* Nestor). Brachiopods

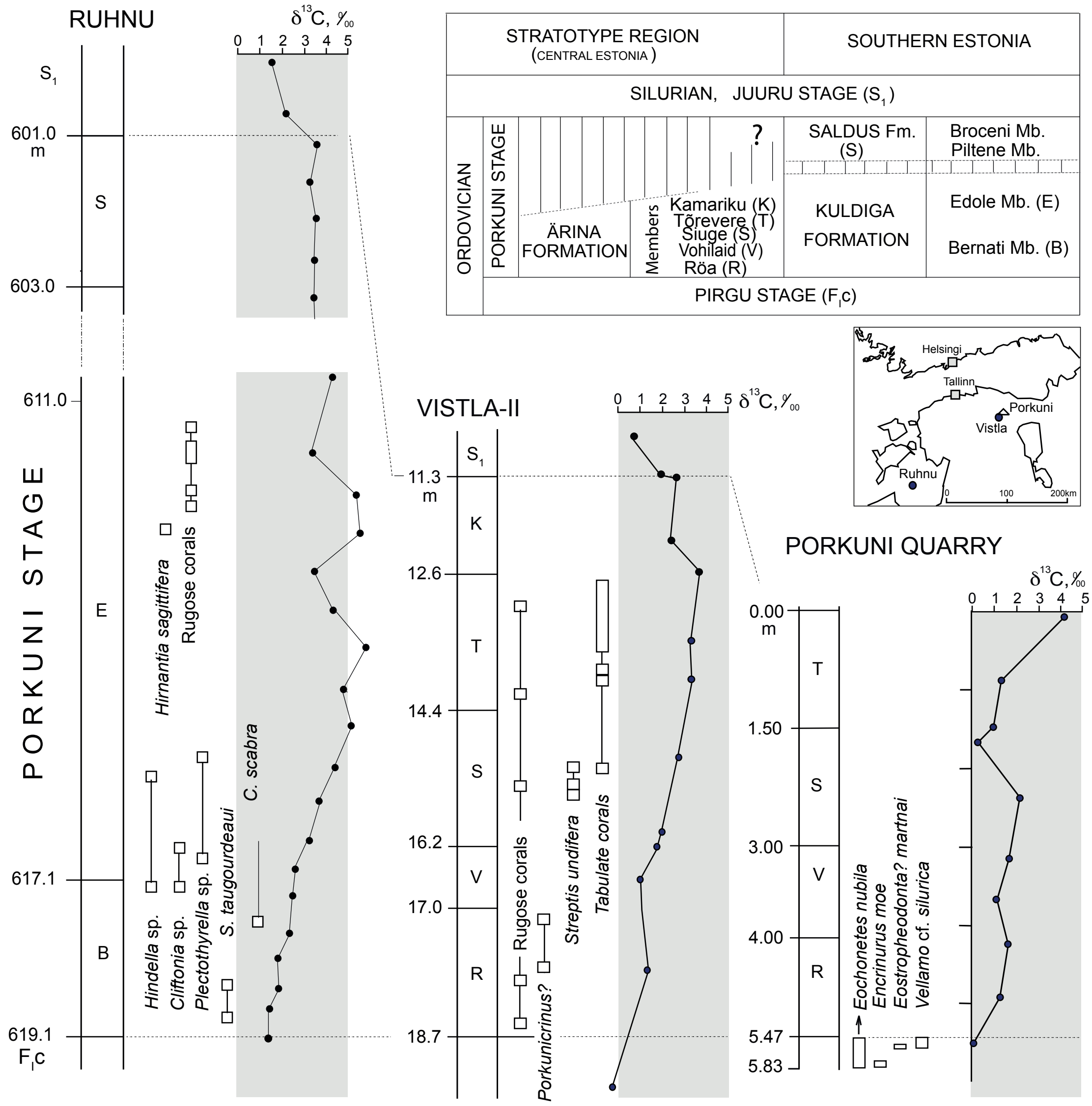

Fig. 3.3. The carbon isotope curves and distribution of some fossils in the Ruhnu and Vistla-II drill cores, and in the Porkuni quarry (from Hints & Männik, 2014; after Hints et al. 2000).

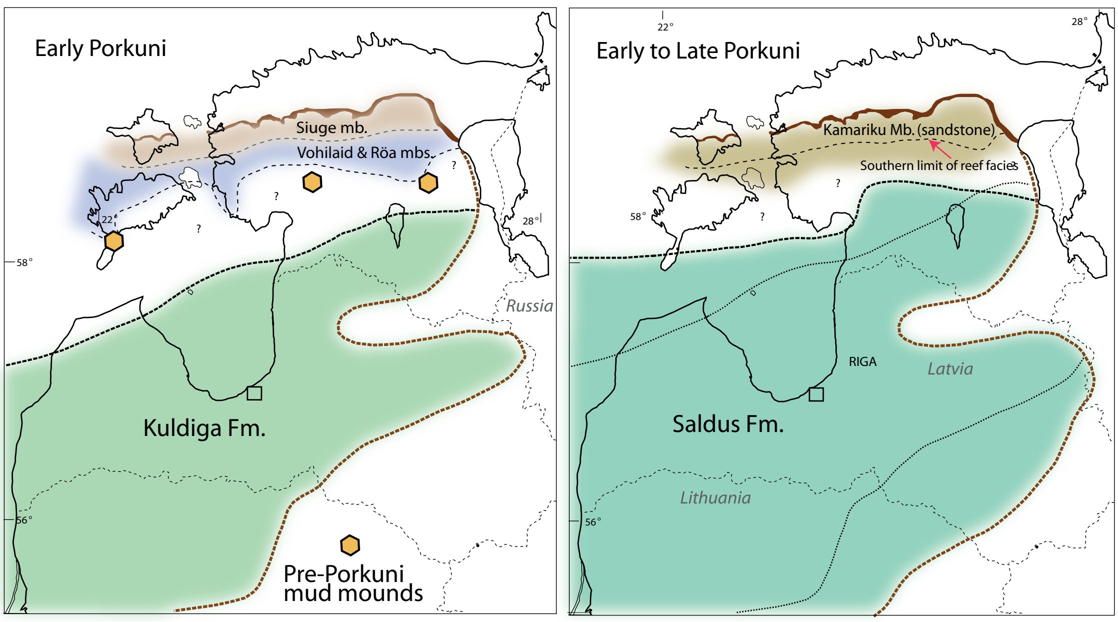

Fig. 3.4. Distribution of the formations and members of the Porkuni Regional Stage (from Hints & Männik, 2014; modified from Oraspõld 1975).

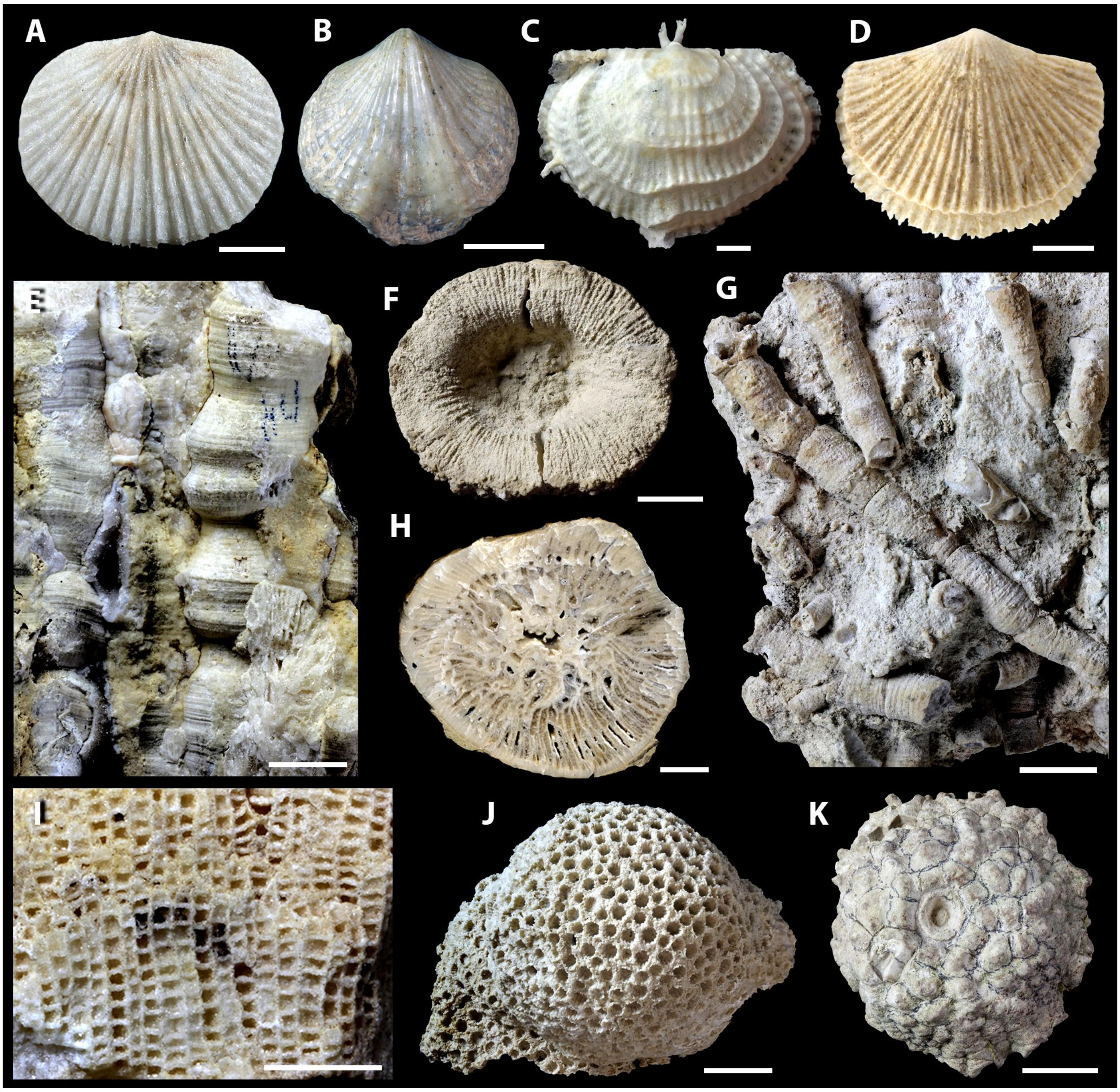

Figure 3.5. Selected fossils from the Porkuni quarry, Porkuni Regional Stage (Hirnantian). Scale bars E–H, J, K – 1 cm; B, I – 5 mm; A, C, G – 1 mm. **A**–**D** brachiopods; **A** – *Mendacella aerinensis* Hints, GIT 626-37; **B** – *Eospirigerina porkuniana* Rubel, GIT 574-273; **C** – *Streptis undifera* (Schmidt), GIT 626-64; **D** – *Sigmelasma peepi* Hints, 626-26. **E** – **H** rugose corals; **E** – *Donacophyllum middendorffii* Dybowski, GIT 81-15; **F** – *Kodonophyllum rhizobolon* (Dybowski), GIT 79-8; **G** – *Porkunites amalloides* (Dybowski), GIT 406-584; **H** – *Kaljolasma giganteum* (Kaljo); GIT 406-580. **I, J** tabulate corals; **I** – *Mesofavosites dualis* Sokolov, GIT 740-134; **J** – *Propora conferta* Milne-Edwards & Haime, GIT 740-75. **K** – crinoid *Tallinnicrinus toomae* Cole, Ausich & Wilson, TUG 1709-2.

are relatively rare. Skeletal fragments of echinoderms and bryozoans form an essential part of fine-grained skeletal debris (up to 30%).

2. Siuge Member. 1.5 m. Micro- to fine-crystalline brownish-grey to brown kerogenous wackestone–packstone with irregular argillaceous interbeds. Silt-size quartz is common: in the uppermost part of the unit, its content reaches 30%. Fragments of echinoderms, bryozoans, ostracods and brachiopods form up to 25% of the rock in some beds. Due to silicification, fossils are often well preserved, especially small (juvenile) specimens. Together with taxa characteristic of the section in general [*e.g. Porkunites amalloides* (Dybowski), *Sclerophyllum sokolovi* Reiman, *Streptis undifera* (Schmidt), *Leptaena (L.) acuteplicata* (Schmidt)], several fossils known only from the Siuge Member have been reported, e.g., brachiopods *Sigmelasma peepi* Hints and *Tyronella siugensis* Hints, and several species of juvenile and small cephalopods (Kröger 2007).

3. Vohilaid Member. 1 m. Light grey to grey, weakly dolomitised bioclastic grainstone consisting mainly of echinoderm, bryozoan, coral and brachiopod fragments. Matrix is fine- to coarse-crystalline calcite. The rock yields some siliciclastic matter whose content reaches 6% in some intervals. The boundary between the Vohilaid and Siuge members is transitional. In the uppermost 0.3 m of the Vohilaid Member, the content of bioclastic material decreases, and that of siliciclastic material increases

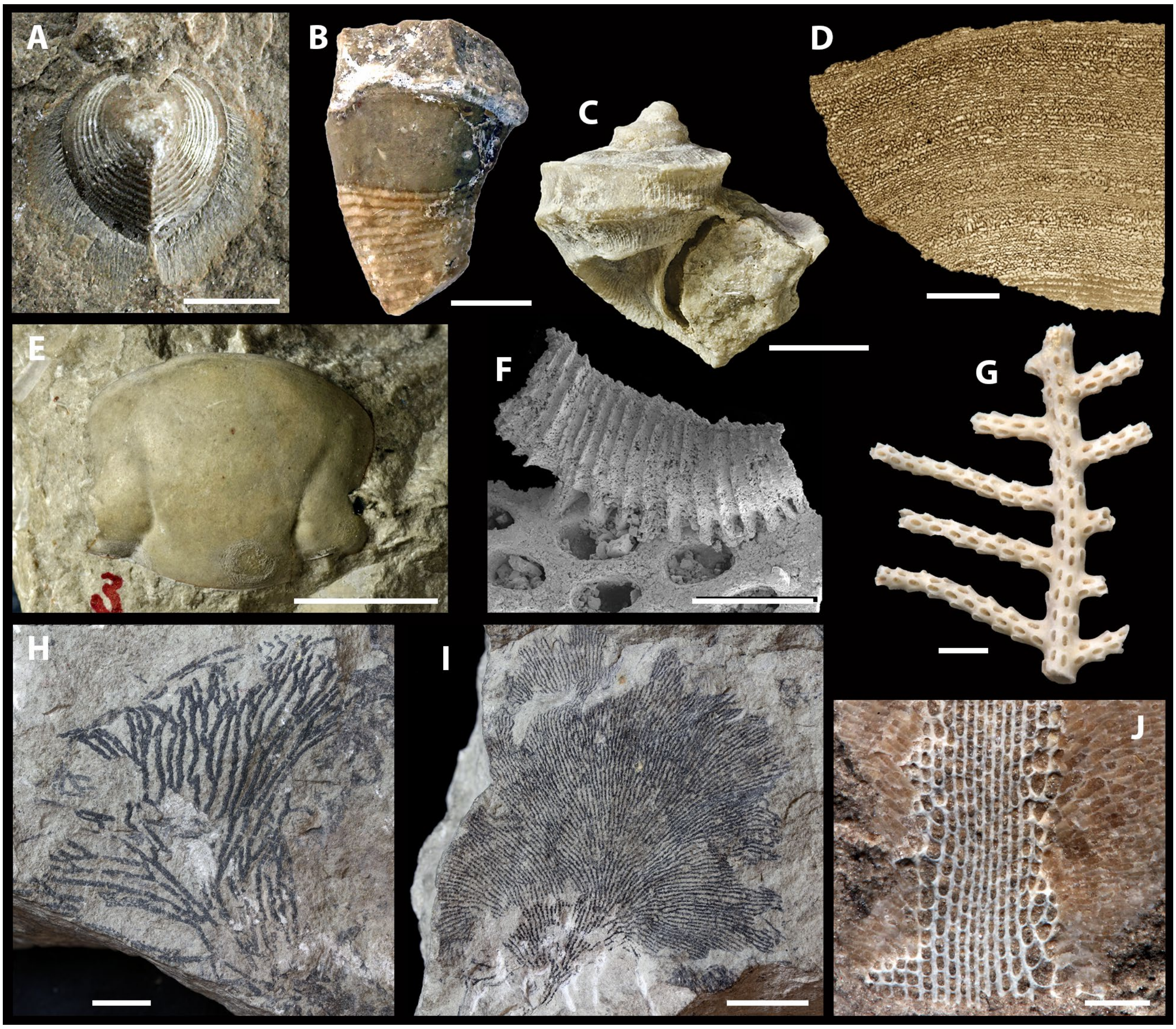

Fig. 3.6. Selected fossils from the Porkuni quarry, Porkuni Regional Stage (Hirnantian). Scale bars E, H, I – 1 cm; A–D – 5 mm; G, J – 1 mm; **F** – 500 µm. **A** – rostroconch *Hippocardia* sp., TUG 2-149. **B** – cephalopod *Strandoceras orvikui* Kröger, TUG 1227-27. **C** – gastropod *Trochonema panderi* Koken, GIT 404-360. **D** – strmatoporoid *Clathrodictyon zonatum* Nestor, GIT 113-38. **E** –trilobite *Parillaenus depressa* (Holm), GIT 437-3-1. **F–G, I** – bryozoans; **F** – silicified cornulitid *Conchicolites sutlemaensis* Vinn, Madison, Wilson & Toom encrusting bryozoan *Trigonodictya cyclostomoides* (Eichwald), GIT 421-206. **G** – silicified bryozoan *Arcanopora plumula* (Wiman), GIT 873-14. **J** –bryozoan *Eichwaldictya flabellata* (Eichwald), GIT 537-2396. **H, I** graptolites**;** **H** – *Callograptus kaljoi* Obut & Rytzk, GIT 119-15-2; **I** – *Dictyonema delicatulum* Lapworth, GIT 119-15-1.

gradually. The Vohilaid Member comprises a diverse association of rugose and tabulate corals, bryozoans and brachiopods. The oldest reefs in the Porkuni section, built by corals and stromatoporoids, appear close to the lower boundary of the member. A large colony of tabulate coral *Mesofavosites dualis* Sokolov is exposed in the southern wall of the quarry.

4. Röa Member. 1.5 m. Yellowish- to brownish-grey, thick-bedded fine- to medium-crystalline dolostone. The content of siliciclastic matter varies from 4% to 10%. The most common fossils are stem fragments of crinoids, often concentrated in thin lenses and/or irregular interbeds. Brachiopods of the genera *Eochonetes* (=*Thaerodonta* in earlier interpretation), *Elsaella*, *Pirgumena* (= ?*Eostropheodonta*), together with rare rugose corals and trilobites, can be found on bedding planes. As a rule, fossils are preserved as internal and/or external moulds.

5. Pirgu Stage, Adila Formation. 0.3+ m. Yellowish-grey to yellow micro- to fine-crystalline argillaceous dolostone, probably with several discontinuity surfaces. The brachiopod *Eochonetes nubila* (Rõõmusoks) and trilobite *Encrinurus moe* Männil have been found. The Adila Formation, and the contact between the Pirgu and Porkuni stages, is not exposed in the section at present. However, it lies just below the quarry floor and was accessible after some digging in 2000.

The Porkuni quarry section has been sampled for conodonts, and samples of up to 20 kg have been processed. As elsewhere in Central Estonia, the uppermost Ordovician conodonts are very rare and poorly preserved also in the Porkuni section, and, as a rule, species are difficult to identify. The faunas are mostly characterised by *Gamachignathus* sp., *Walliserodus* sp. and *Panderodus* spp. (Fig. 3.2). In the Röa Member, rare specimens of

Belodina sp. are found. Conodonts are most abundant in the Siuge Member. From this interval *Panderodus* ex gr. *equicostatus* (Rhodes) (probably occurring also in the lower part of the section), *Decoriconus* sp. and a few specimens similar to *Kockelella* [identified as *Kockelella*? sp. aff. *K. manitoulinensis* (Pollock, Rexroad & Nicoll)] have been identified. The residues of the conodont samples are rich in silicified fossils: tiny bryozoans, different echinoderm fragments, brachiopods and dwarf cornulitids, part of which were recently described in three papers (Hints 2012; Hints *et al.* 2013; Vinn et al. 2024). Examples of Porkuni fossils are presented in Figs 3.5, 3.6.

Massive homogenous dolostone of the Röa Member has been used as a building and carving stone for a long time. Its earliest known use dates back to the 15th century. The Porkuni castle was built mainly from this rock, and it has been used in many old buildings (churches, farm buildings, etc.) in the region. In Porkuni, only the gate tower of the medieval castle is preserved. Now, a small museum of carbonate rocks (Porkuni Paemuuseum) is open in that tower. The term “paas” in Estonian means both limestone and dolostone, which are used widely as building materials and industrial minerals. “Paas” is the national stone of Estonia since 1992.

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Stop 4: Põhja-Kiviõli II open-pit mine

Heikki Bauert and Olle Hints

Location: 59.365394°N, 26.842046°E; Ida-Viru County, NE Estonia.
Stratigraphy: Sandbian, Kukruse Regional Stage, Viivikonna Formation.
Status: Active open-pit mine; please follow safety regulations; sampling and fossil collecting are welcome.
More information: https://geoloogia.info/en/locality/23669

The following text is based on Bauert and Nõlvak (2014) and Bauert & Hints (2023).

Kukersite oil shale has been Estonia's most important mineral resource for over a century, with the first test mining site opened in NE Estonia in 1916. Oil shale has been used primarily for energy production in power plants and producing shale oil and other chemicals. Oil shale production peaked in the 1970-1980s, with over 30 million metric tonnes excavated in Estonia annually. As of 2022, the annual production slightly exceeded 10 million tonnes. However, due to the high environmental impact of oil shale mining and utilisation, the production is expected to decrease gradually, even though carbon capture, utilisation, and storage technologies (CCUS) could make its impact on climate much smaller.

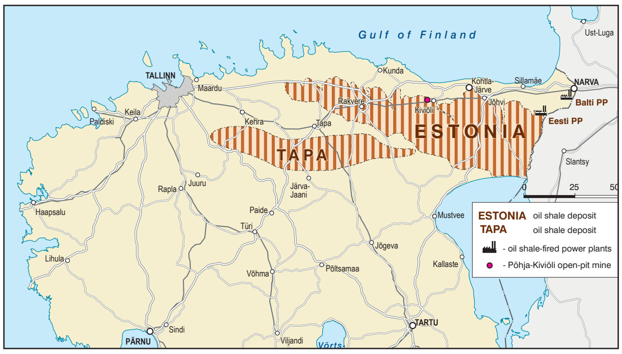

Fig. 4.1. Locality map showing the oil shale deposits in Estonia (from Bauert & Nõlvak 2014).

The Põhja-Kiviõli II open-pit mine (Figs 4.2, 4.4) is owned and operated by Kiviõli Keemiatööstus (KKT, https://www.keemiatoostus.ee/en). It is located in NE Estonia, along the northern edge of the central part of the main oil shale deposit (Fig. 4.1).

Characteristics of the kukersite oil shale

Oil shale is commonly defined as a fine-grained sedimentary rock containing organic matter (OM) that yields substantial amounts of oil and combustible gas upon destructive distillation. The kukersite OM deposited in argillaceous marine limestones and as many as 50 beds of kukersite and kerogen-rich limestone, alternating with biomicritic limestones (wackestones), have formed during the main phase of kukersite OM deposition in northeastern Estonia during the latest Mid to earliest Late Ordovician time span (Fig. 4.7).

The kukersite oil shale beds (seams) form an up to 20–30 m thick succession. However, individual kukersite beds of chocolate-brownish colour are commonly 10–40 cm thick and may reach as much as 2.4 m (bed III in the Kerguta-565 drill core; Põldvere 2006) in thickness. The beds designated from "A" to "F2" are feasible for mining and are currently mined in three open-pit mines (Narva, Põhja-Kiviõli, Ubja) and two underground mines (Estonia, Ojamaa).

Fig. 4.2. Oil shale succession in the Põhja-Kiviõli II open-pit mine. Photo: Gennadi Baranov, 2019.

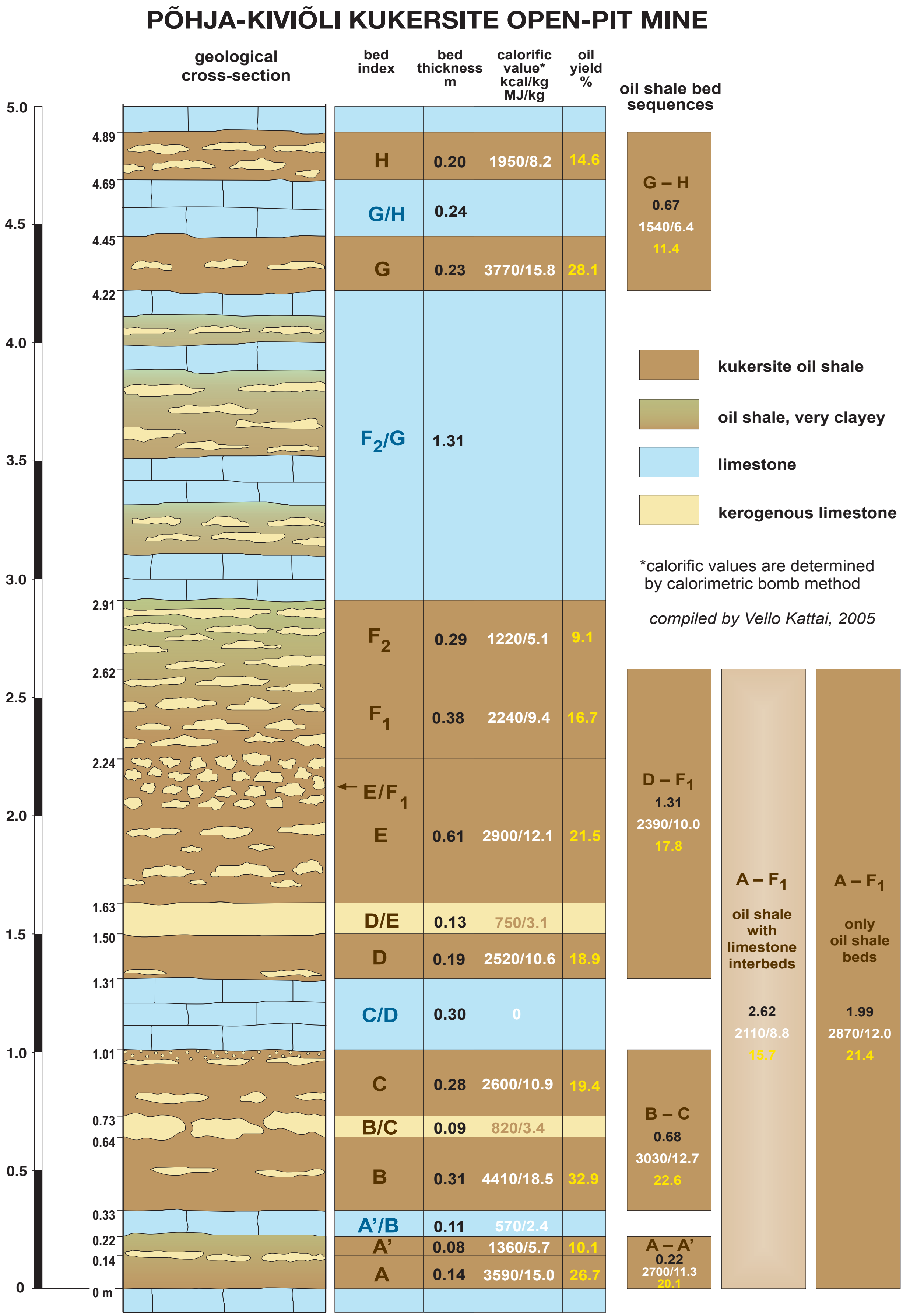

Fig. 4.3. Succession and properties of the oil shale seams in the Põhja-Kiviõli opencast mine (from Bauert & Nõlvak 2014).

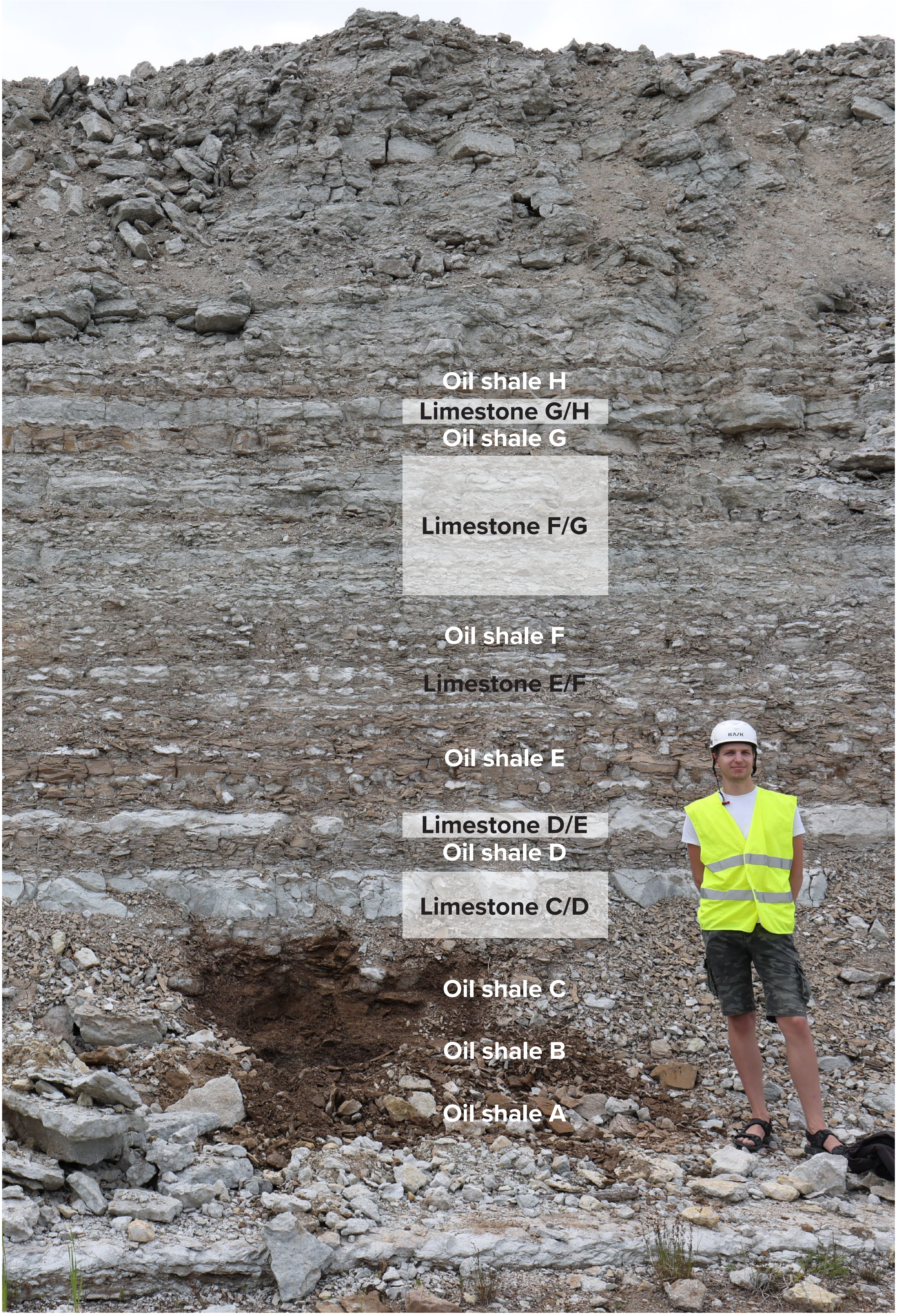

Fig. 4.4. Succession of the oil shale seams in the Põhja-Kiviõli II opencast mine. The lowermost beds are covered by debris, their appriximate position is indicated. The subdivition of beds E to F is complicated on weathered walls. Photo: Olle Hints, 2023.

The main characteristics of individual kukersite beds in the Põhja-Kiviõli mine are shown in Fig. 4.3. The OM content of kukersite oil shale beds varies considerably, reaching as high as 50% TOC in beds B and E in the central area of the Estonia deposit (Foster et al. 1989). Rock-Eval pyrolysis analyses (Dyni et al. 1989; Foster et al. 1989) indicate that kukersite oil shales have a significant hydrocarbon potential [S1 & S2 = 300–350; S1 – kg of hydrocarbons (extractable) per tonne rock; S2 – kg of hydrocarbons kerogen pyrolysate) per tonne rock] and are characterised by a high hydrogen index [HI = 675–960; mg hydrocarbons (S2) per gram of total organic carbon]. These data suggest the prevalence of Type I kerogen in kukersite OM. The elemental composition of kukersite kerogen is as follows: C – 67%, H – 8.3%, O – 12.8%, N – 2.2%, S – 3.5%, H/C – 1.48, O/C – 0.14, S/C – 0.02 (Derenne et al. 1989).

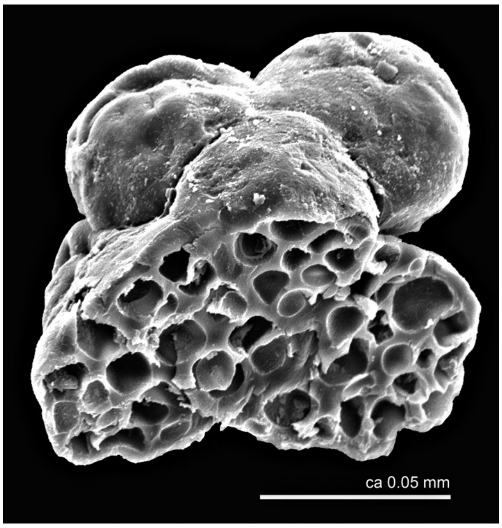

Fig. 4.5. *Gloeocapsomorpha* prisca SEM image (photo: Jaak Nõlvak).

The matrix minerals in Estonian kukersite oil shale beds and interbedded more or less argillaceous limestones (Bauert & Kattai 1997) include mainly low-Mg calcite (usually >50%, but less in kukersite beds), dolomite (generally less than 15%) and siliciclastic minerals. The XRD analyses and thin section studies have revealed that the siliciclastic component mainly comprises silt-sized quartz and illite, while feldspars and chlorite occur in subordinate amounts. Besides, kukersite oil shale contains authigenic pyrite.

The origin of kukersite

Major kukersite-type OM accumulations have been recorded in the late Uhaku to Kukruse age rocks (Kõrgekallas and Viivikonna formations). However, a few thin kukersite beds or kukersite OM-enriched marlstone beds are known to occur at several other stratigraphic levels in the Ordovician succession (Kõrts 1992): in the Kunda Stage (lower Darriwilian) as well as in the Keila and Nabala stages (uppermost Sandbian to Katian). Based on the dominant OM type, the kukersite is classified as a *Gloeocapsomorpha*-related telalginite (Cook & Sherwood 1991; telalginite refers to the presence of lensoidal, flattened spheroidal or fan-shaped algal remains in OM).

The algal structure of the kukersite was recognised by a Russian botanist M. Zalessky in 1916. He described oval bodies in kukersite kerogen and interpreted them as the remains of an extinct microorganism. Due to morphological similarity with the extant cyanobacterium *Gloeocapsa quaternata* Kützing, he named the colonial cellular bodies in kukersite *Gloeocapsomorpha prisca*. Viewed under the light microscope, the microfossils are bright yellow. The individual colonies are spherical to oval in outline and range in size from 10 to 40 µm (Fig. 4.5). The external surface is smooth and unbroken, with no pitting (Burns 1982). A thorough revision of *Gloeocapsomorpha prisca* by Foster et al. (1989) showed that based on morphological and biochemical characteristics, *G. prisca* has a close similarity with the extant, mat-forming and stromatolite-forming marine cyanobacterium *Entophysalis major*.

Depositional environment of kukersite

The depositional environment of the kukersite is still vaguely known. The few points so far established are as follows:

1. A major kukersite deposition occurred during a regression of the Kukruse sea southwards. The re-

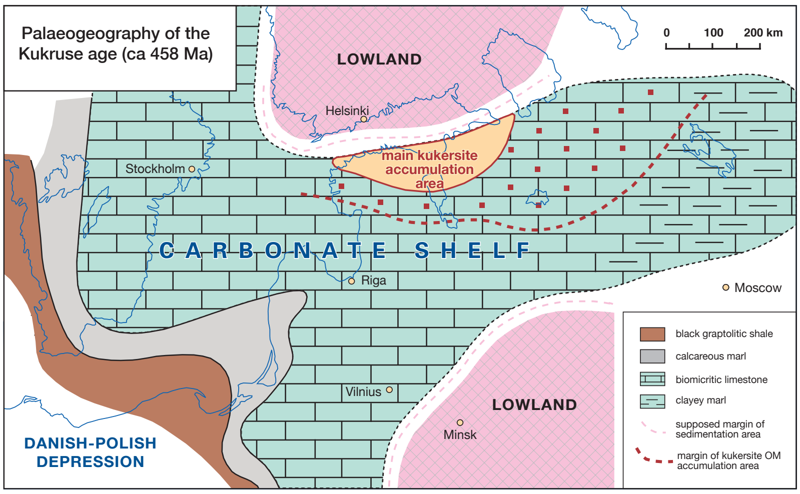

Fig. 4.6. Palaeogeograpy of the Baltoscandian basin during the Kukruse time, earliest Late Ordovician, when the majority of kukersite oil shale accumulated. Scheme from Bauert & Nõlvak (2014).

gression is suggested by detailed bed-by-bed lithostratigraphic studies, which have revealed a hiatus in sedimentation for beds of the Peetri Member of the Viivikonna Formation in northern Estonia and the appearance of younger kukersite beds (beds III – IX) on a north-south transect in a distance of 80 km. At the same time, most kukersite beds are traceable for over 250 km in the west-east direction (Bauert & Kattai 1997).

2. The kukersite OM deposited along the northern margin of the shallow carbonate shelf, bordering the Finnish lowland in the north (Fig. 4.6).

3. Many hardgrounds, either with thin pyritic impregnation veneer or without impregnation, have been recorded in the Uhaku – Kukruse succession. Most represent synsedimentarily lithified carbonate seafloors (Wilson & Palmer 1992), but a few resemble modern coastal microkarst forms. The surfaces attributed to microkarst have developed narrow, subvertical cavities with highly irregular walls that may extend down to 25 cm from the hardground level (Bauert 1989). One such surface is observed on top of kukersite bed III and is traceable over several hundred square kilometres.

4. Based on the premise that *G. prisca* was an intertidal mat-forming cyanobacterium (similar, but not identical to extant *E. major*), Foster et al. (1990; Fig. 4.6) proposed a model that *G. prisca* grew on broad intertidal mats that may have been subaerially exposed. Tidal movements and offshore winds were suggested as agents for transporting algal mat fragments to deeper-water accumulation areas. Another plausible alternative for kukersite deposition could be a sink-down of relatively inert cyanobacterial OM directly from algal blooms.

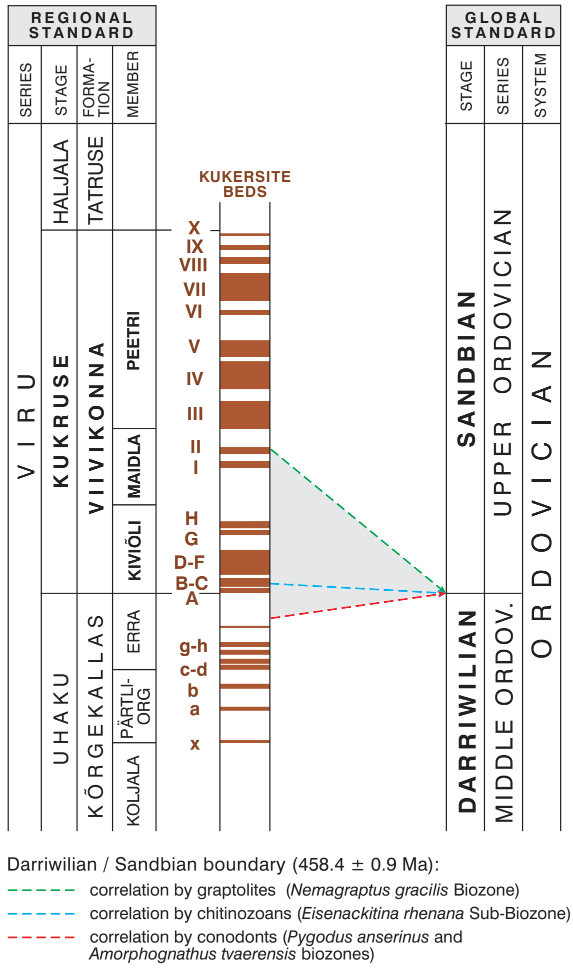

Fig. 4.7. Stratigraphic chart of the Kukruse Stage, showing levels of main indexed kukersite seams and possible correlation between global and regional time scales (redrawn from Hints et al. 2007).

Faunas of the Kukruse Stage

Abundant marine fossils, with more than 250 species listed (Bekker 1921; Rõõmusoks 1970), have been collected from both argillaceous limestones and kukersite oil shale beds during the past two centuries (Figs. 4.8 to 4.10). The most common fossils encountered are trilobites, brachiopods and bryozoans, whereas, in some kukersite beds, even delicate feathery structures of bryozoans may be well preserved (Fig. 4.9). It should be pointed out that contrary to most other organic-rich rocks, no anoxia is recorded during the accumulation of kukersite, as indicated by flourishing bottom life, the abundance of trace fossils and the relative scarcity of authigenic pyrite.

Kukruse Regional Stage and the base of the Upper Ordovician

The Fågelsång section in Scania, southern Sweden, has been chosen as the GSSP for the global Upper Ordovician Series as it represents the level of the first appearance of *Nemagraptus gracilis* Hall (Bergström et al. 2000). An overview of the present knowledge for correlating the base of the global Sandbian Stage with Baltoscandian stages by means of graptoloids, chitinozoans and conodonts was given by Hints et al. 2007).

Graptoloids are rare and only occasionally found in shallow-shelf carbonate succession. The first reliable finds of *N. gracilis* come from the middle part of the Kukruse Stage in some central Estonian sections (Nõlvak & Goldman 2007). No *N. gracilis* has been recorded from the outcrop area of the Kukruse Regional Stage in northern Estonia.

A study on conodonts from the Kiviõli Member of the Kukruse Stage in the Kohtla section (ca 15 km east of the Põhja-Kiviõli open-pit mine) was conducted by V. Viira and co-authors in 2006. They recorded the FAD of *Amorphognathus tvaerensis* within the limestone interbed A/B, just above the base of the Kukruse Stage. It should be noted that in the Fågelsång section in Scania, *A. tvaerensis* was recorded above the *N. gracilis* find (Bergström et al. 2000), which means that in Estonian sections, the base of the Upper Ordovician lies either at the boundary of the Uhaku/Kukruse stages or somewhat lower.

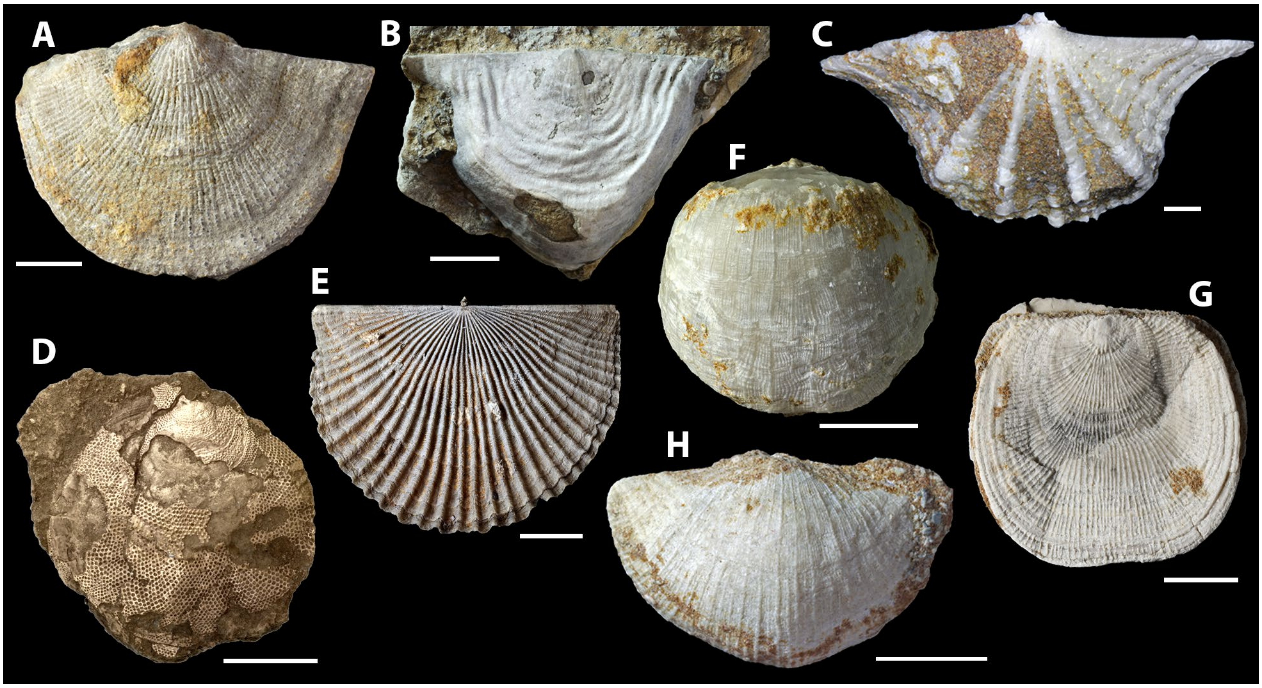

Fig. 4.8. Selected brachiopods from the Viivikonna Formation, Kukruse Stage (Sandbian). Scale bars: B, C, D – 1 cm; A, E–H – 5 mm. **A** – *Estlandia marginata*, Humala, GIT 543-1305. **B** – *Kiaeromena* (*Kiaeromena*) *estonensis,* Küttejõu, GIT 677-4. **C** – *Kullervo lacunata*, Kiviõli, GIT 543-433. **D** – *Foveola ivari*, Küttejõu, TUG 1003-307. **E** – *Cyrtonotella kuckersiana kuckersiana*, Kukruse, GIT 400-124. **F** – *Bekkerina dorsata*, Kohtla, GIT 251-179. **G** – *Orthisocrania planissima*, Küttejõu, GIT 772-125. **H** – *Sowerbyella* (*Sowerbyella*) *liliifera,* Kohtla-Järve, GIT 675-590.

Some chitinozoan species, particularly *Eisenackitina rhenana* and *Conochitina savalaensis* (Nõlvak & Bauert 2015), have proven to be reliable indicators for correlating the base of the Kukruse Stage throughout Estonia. Both chitinozoans appear close to the kukersite bed A in the Viru underground mine and Savala drill core sections. Estonian researchers have found these chitinozoans also in Latvia, Lithuania and NE Poland; T. Vandenbroucke (2004) identified *E. rhenana* in the Fågelsång section.

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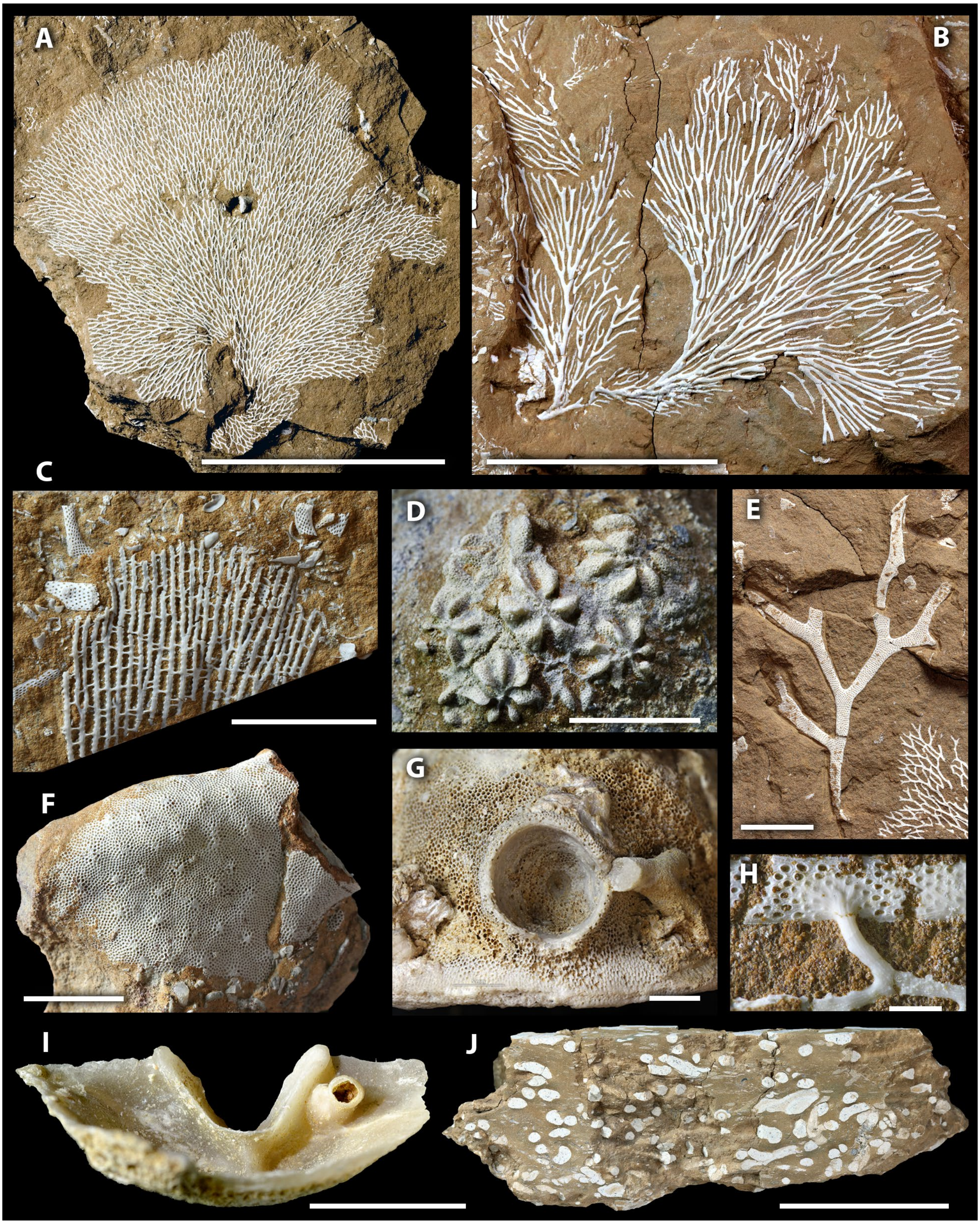

Fig. 4.9. Selected fossils from the Viivikonna Formation, Kukruse Stage (Sandbian). Scale bars: A, B, J – 5 cm; C–F – 1 cm, G, I – 5 mm; H – 1 mm. **A**–**F**, **H** – bryozoans; **A** – *Chasmatopora furcata*, North Estonia, GIT 398-995; **B** – *Pseudohornera bifida*, North Estonia, GIT 369-315; **C** – *Esthonioporina quadrata*, Küttejõu, GIT 537-2501; **D** – *Revalopora revalensis*, Põhja-Kiviõli, GIT 343-168; **E** – *Pachydictya kuckersensis*, Kohtla, GIT 537-1602; **F** – *Hemiphragma panderi*, Kohtla-Järve, GIT 537-3664; **H** – *Graptodictya bonnemai,* Kohtla, GIT 537-1606-2. **G**, **I**, **J** – trace fossils; **G** – *Kuckerichnus kirsimae* in *Diplotrypa*, Kohtla-Järve, TUG 72-826-2; **I** – *Burrinjuckia clitambonitofilia* in the ventral valve of *Clitambonites squamatus*, North Estonia, GIT 343-236-1; **J** – *Tisoa siphonalis*, North Estonia, GIT 362-612.

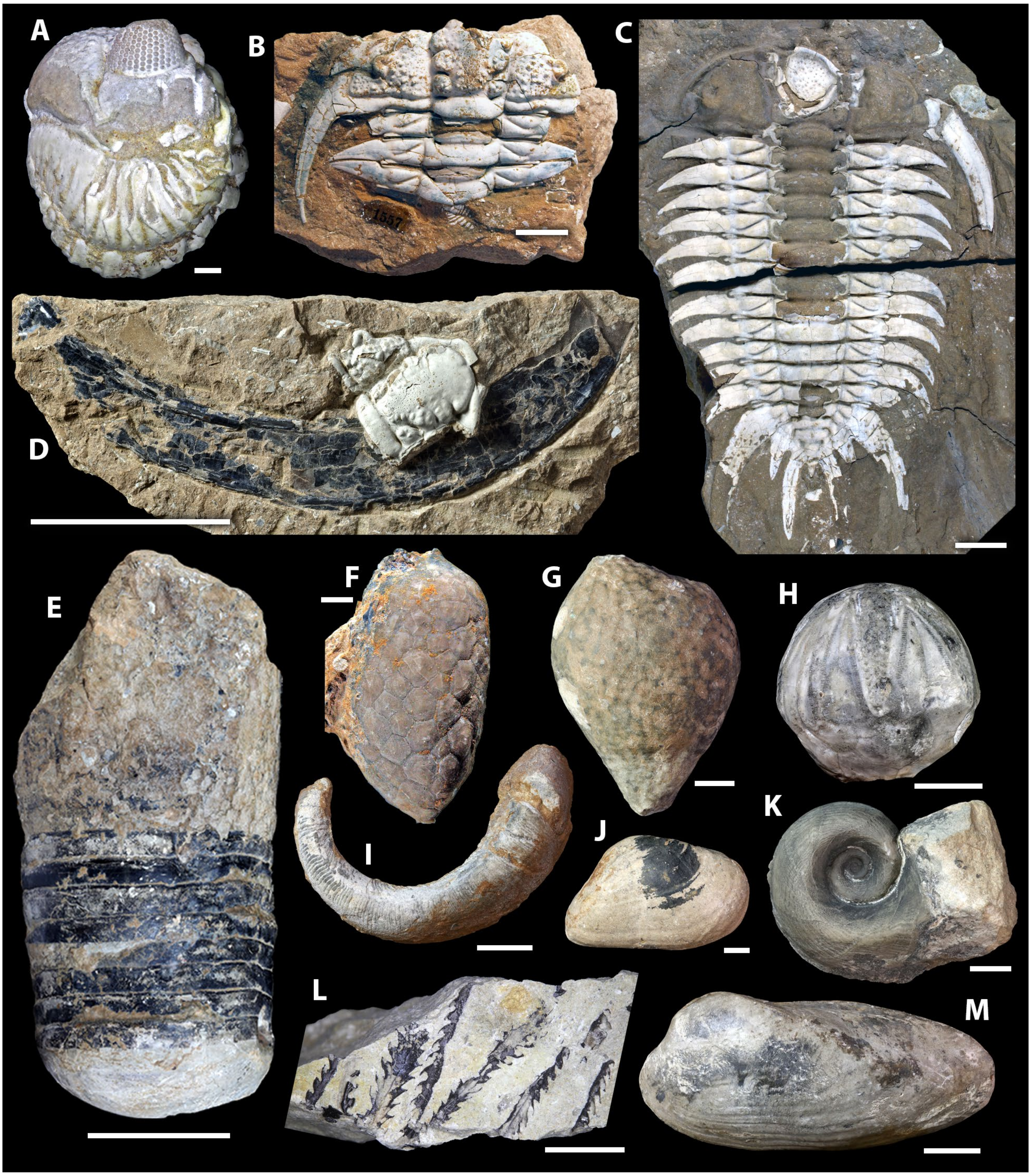

Fig. 4.10. Selected fossils from the Viivikonna Formation, Kukruse Stage (Sandbian). Scale bars: D, E – 5 cm; B–C, G - I, M – 1 cm; F, J, I – 5 mm; A – 1 mm. **A**–**C** – trilobites; **A** – *Estoniops exilis*, Kohtla, GIT 459-165; **B**, **C** – *Paraceraurus aculeatus*, **B** – Kukruse, TUG 1085-79, **C** – Kohtla-Järve, TUG 1672-52. **D** – cnidarian *Sphenothallus kukersianus* (together with a trilobite fragment), Kohtla, TUG 1087-32-1. **E** – cephalopod *Ormoceras*, North Estonia, GIT 695-51. **F** – eocrinoid *Heckerocrinus laevis*, Ubja, TUG 1589-137. **G**, **H** – blastozoans; G – *Echinosphaerites pirum*, Kiviõli, GIT 631-81; **H** – *Cystoblastus kokeni*, Kohtla-Järve, TUG 1727-548. **I**, **K** – gastropods; **I** – *Ecculiomphalus*, Küttejõu, GIT 343-89; **K** – *Bucania czekanowskii,* Küttejõu, TUG 666-37. **J**, **M** – bivalves; **J** – *Dystactella aedilis*, North Estonia, GIT 398-200; **M** – *Goniophora*, North Estonia, GIT 398-207. **L** – graptolite *Oepikograptus bekkeri*, Kohtla, GIT 343-613-1.

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Post-conference Excursion

August 22–25, 2024

XI Baltic Stratigraphical Conference

August 19-21, 2024
Tartu, Estonia

Stop 5: Pakerort cliff, Pakri Peninsula

Olle Hints

Location: Latitude 59.37747°N, longitude 24.03648°E; Harju County, NW Estonia.
Stratigraphy: From Cambrian Series 2 to Darriwilian, Pakerort to Uhaku regional stages.
Status: Cliff is under nature protection; no hammering, but loose material may be collected.
More information: https://geoloogia.info/en/locality/13546

The following text is after Hints (2023).

Coastal cliffs on the Pakri Peninsula, ca 50 km west of Tallinn, provide the best exposures of Cambrian to Middle Ordovician rocks in NW Estonia. These cliffs are part of the Baltic Klint – a nearly 1200 km long escarpment that runs from Öland (Sweden) through the Baltic Sea and North Estonia to NW Russia. The sections on the Pakri Peninsula and the nearby Pakri islands have been well-known since the 1840s, nowadays regularly visited by geology students and geological field excursions (Hints 2014). The up-to-24-m-high Pakerort cliff is also an important geotourism site in Estonia.

The western coast of the Pakri Peninsula constitutes a nearly continuous outcrop subdivided into the Paldiski, Uuga and Pakerort cliffs (Fig. 5.1). This is one of the few places in Estonia where the gentle southward dip of bedrocks (ca 3–4 m per km) can be directly observed. The Pakerort cliff in the north is the etymon for the Pakerort Regional Stage and provides an opportunity to study the lower Cambrian (Series 2) to Tremadocian strata. The Floian to Darriwilian succession is best accessed at the Uuga cliff, close to the Paldiski Northern Port (see Stop 2 below).

The composite section on the Pakri Peninsula (Fig. 5.2, 5.3) is characterised below, based on the descriptions and data by Mens et al. (1996, 1999), Nemliher and Puura (1996), Hints et al. (2014), Löfgren et al. (2005),

Fig. 5.1. Locality map of cliff sections on Pakri Peninsula, NW Estonia (from Hints 2014). The Pakerort Regional Stage is named after Cape Pakerort.

Fig. 5.2. Tremadocian to Darriwilian succession of the 24-m-high Pakerort Cliff, Cape Pakri in distance. Photo: Olle Hints, 2015.

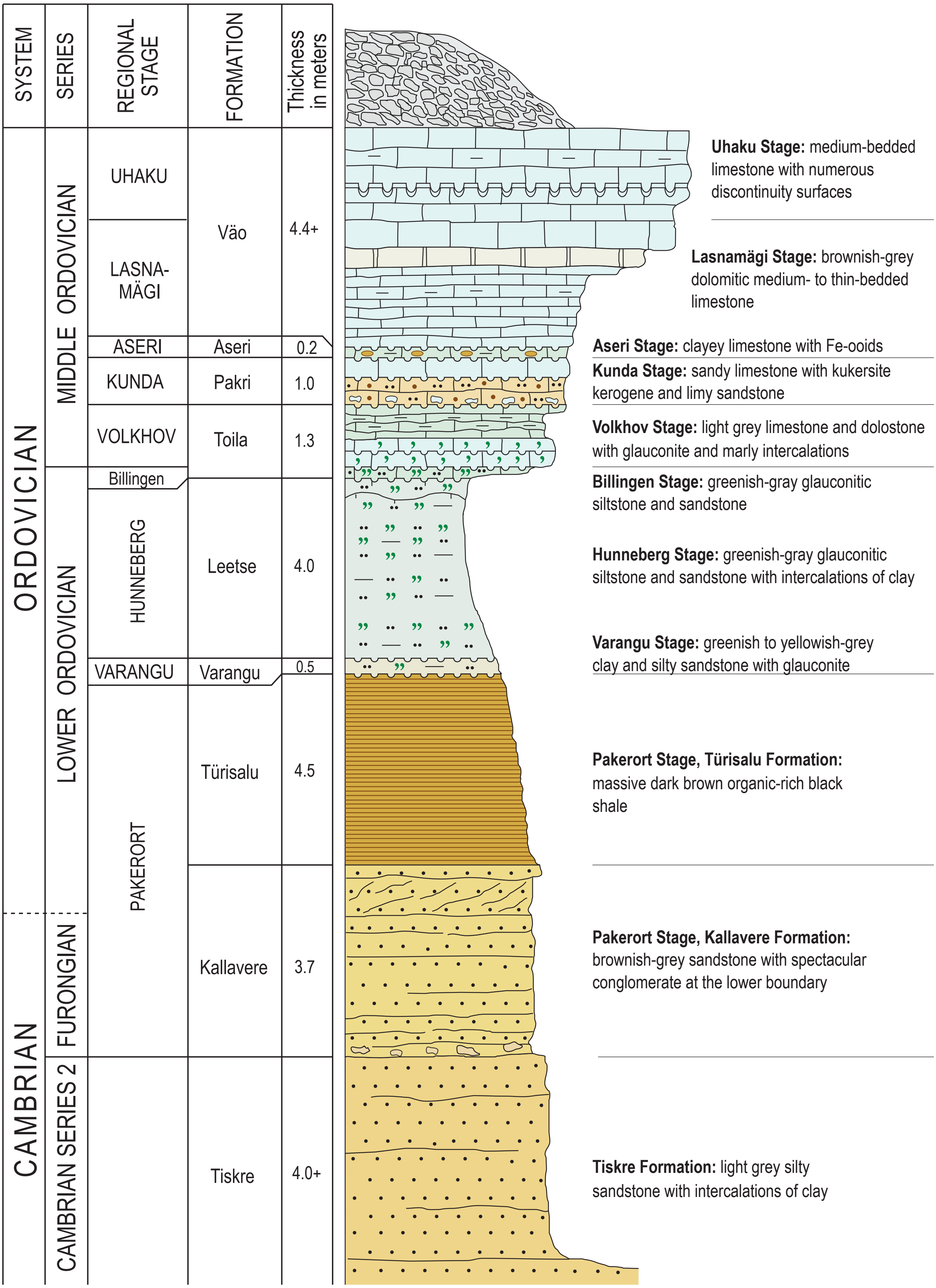

Fig. 5.3. Composite section of the cliffs on Pakri Peninsula, NW Estonia. After Mens and Puura (1996).

Fig. 5.4. Basal conglomerate on the boundary of the Cambrian Series 2 Tiskre Formation and the Furongian-Lower Ordovician Kallavere Formation. Photo: Olle Hints, 2020.

Fig. 5.5. The Cambrian-Ordovician boundary on Pakri Peninsula can be approximated with the base of the Suurjõgi Member within the Kallavere Formation indicated by the right hand of the student. Photo: Olle Hints, 2019.

Fig. 5.6. The topmost part of the Kallavere Formation just below the black shale is strongly pyritised ("Pyrite layer") and sometimes preserves ripple marks. Photo: Rutt Hints, 2015.

Põldsaar and Ainsaar (2014), Tammekänd et al. (2010), Einasto and Rähni (2005), Mens and Puura (1996), Orviku (1940).

(1) The **Tiskre Formation** (4+ m, lower Cambrian) is composed of light grey sandy siltstones with interbeds of shaly siltstones and clays. Based on drill core data, the entire thickness of the formation reaches ca 18 m. Ripple marks are common in the upper part of the formation (Mens et al. 1996).

(2) The **Kallavere Formation** (ca 3.7 m, Furongian to Tremadocian) is represented by yellowish fine- to medium-grained sandstones with interbeds of dark brown kerogenous shale in the lower part. The contact with the underlying Tiskre Formation is sharp, marked by a conspicuous basal conglomerate (Fig. 5.4). This conglomerate comprises (1) loose cobbles and boulders of the Tiskre Formation, up to ca 40 cm in diameter and (2) dark-coloured flat pebbles and cobbles cemented with pyrite, apatite and carbonates (Nemliher and Puura 1996). The upper part of the Kallavere Formation (Suurjõgi Member) is represented by cross-bedded sandstones and a strongly pyritised sandstone layer on the top, sometimes with ripple marks (Fig. 5.6). The formation contains scattered debris of lingulate brachiopods, mostly belonging to the genus *Ungula* (Nemliher and Puura 1996).

Conodont and acritarch evidence suggest that the basal conglomerate formed slightly before or during the *Cordylodus proavus* time (Mens et al. 1996, 1999). Thus, the base of the Pakerort Stage, drawn at the appearance of *Cordylodus andresi* in Estonia (see Puura and Viira 1999), coincides with the base of the Kallavere Formation in the Pakerort section. The base of the Ordovician System cannot be precisely correlated on the Pakri Peninsula, but unpublished finds of conodonts and the age of the Suurjõgi Member elsewhere in Estonia allow us to approximate it with the base of the cross-bedded sandstones of the Suurjõgi Member (Fig. 5.5).

(3) The **Türisalu Formation** (4.5 m, Pakerort Regional Stage, Tremadocian) consists of homogenous dark brown kerogenous shale (commonly referred to as graptolite argillite, previously known as the "Dictyonema Shale") containing graptolites *Rhabdinopora flabelliformis flabelliformis* and *Rhabdinopora flabelliformis* cf. *norvegica* in Pakri sections (Mens et al. 1996). The formation is characterised by a high content of organic matter (10–20%), authigenic K-feldspar, pyrite and redox-sensitive trace elements, such as V, U and Mo. Based on microfabrics studies (Hints et al. 2014 and references therein), it has been suggested that dynamic sedimentation events, rather than slow net sedimentation, may have

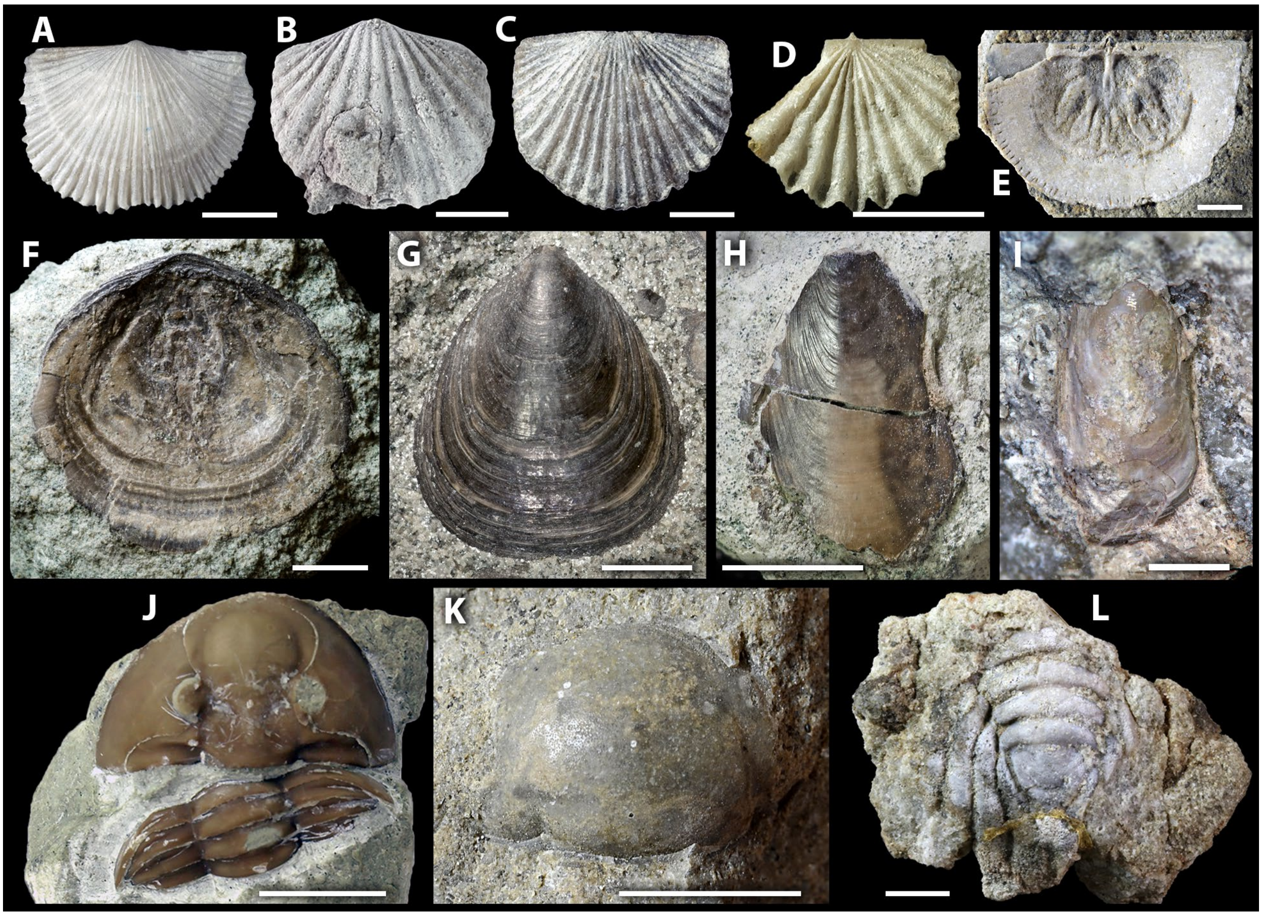

Fig. 5.7. Selected fossils from the Pakri Peninsula and Pakri islands. Scale bars: J – 1 cm; A–H, K, L – 5 mm; I – 1 mm. **A**–**I** – brachiopods; **A** – *Panderina pakriensis*, Väike-Pakri Cliff, Toila Formation (Dapingian), GIT 125-47; **B** – *Rogorthis pakriensis*, Väike-Pakri Cliff, Pakri Formation (Darriwilian), GIT 125-102; **C** – *Orthambonites fundata*, Paldiski, Pakri Formation (Darriwilian), GIT 125-89; **D** – *Nicolella pterygoidea*, Pakri, Pakri Formation (Darriwilian), GIT 125-174; **E** – *Ingria pakriana*, Väike-Pakri Cliff, Pakri Formation (Darriwilian), GIT 675-29; **F** – *Thysanotos siluricus*, Paldiski, Leetse Formation; GIT 275-86; **G** – *Leptembolon lingulaeformis*, Leetse, Leetse Formation; GIT 275-63; **H** – “*Lingulella*” *nitida*, Paldiski, Leetse Formation; GIT 275-70; **I** – lingulid *Rowellella* inside *Trypanites sozialis* boring, Uuga Cliff, Väo Formation (Darriwilian); TUG 1393-186. **J**–**L** – trilobites; **J** – *Paraptychopyge pahleni,* Väike-Pakri Cliff, Toila Formation (Dapingian), TUG 1355-410; **K** – *Panderia,* Väike-Pakri Cliff, Pakri Formation (Darriwilian), GIT 437-417; **L** – *Pliomera fisheri*, Väike-Pakri Cliff, Pakri Formation (Darriwilian), GIT 435-23.

been the dominant mechanism behind the accumulation of these beds. Storm-related near-bottom flows and the bed-load transport of mud particles were likely common distribution agents of organic-rich mud, which can be viewed as a near-shore tongue of the Scandinavian Alum Shale complex.

(4) The **Varangu Formation** (0.5 m, Varangu Regional Stage, Tremadocian) is represented by greenish-grey to beige clay and silty sandstone with glauconite. It contains the zonal conodont *Paltodus deltifer deltifer* (Löfgren et al. 2005).

(5) The **Leetse Formation** (ca 3.9 m, Hunneberg and Billingen regional stages, Tremadocian to Floian) is composed of greenish-grey weakly lithified glauconitic sandstone (20–40% glauconite grains). The type locality of the formation is the Leetse cliff on the eastern coast of the Pakri Peninsula. The Leetse Formation corresponds to the *Paroistodus proteus* conodont Zone, and the base of the Floian Global Stage is identified within the lower third of this unit on the Pakri Peninsula (Löfgren et al. 2005). The upper ca 20 cm of the formation is distinguished as the Mäeküla Member, which becomes calcareous and corresponds to the *Oepikodus evae* conodont Zone. The *Prioniodus elegans* Zone seems to fall into a gap in this area (Löfgren et al. 2005). The transition to the overlying Toila Formation is gradual, characterised by increasing carbonate content.

(6) The **Toila Formation** (ca 1.3 m, Billingen and Volkhov regional stages, Floian to Dapingian) is represented by grey glauconitic limestones (packstones and wackestones). The lower ca 10 cm of the formation (Päite Member) corresponds to the *Oepikodus evae* conodont Zone (Löfgren et al. 2005) and is overlain by a distinct and geographically widespread discontinuity surface (hardground), informally known as the “Püstakkiht” in Estonia (Fig. 6.2). This surface indicates a regional hiatus. It is taken as the base of the Volkhov Regional Stage in northern Estonia and correlated with the base of the Dapingian. Conodonts of the Volkhov Regional Stage are insufficiently known on the Pakri Peninsula, but the top of the formation seems to fall into the *Paroistodus originalis* Zone (Hints et al. 2012). This suggests that the upper part of the Volkov Stage corresponds to a gap in NW Estonia.

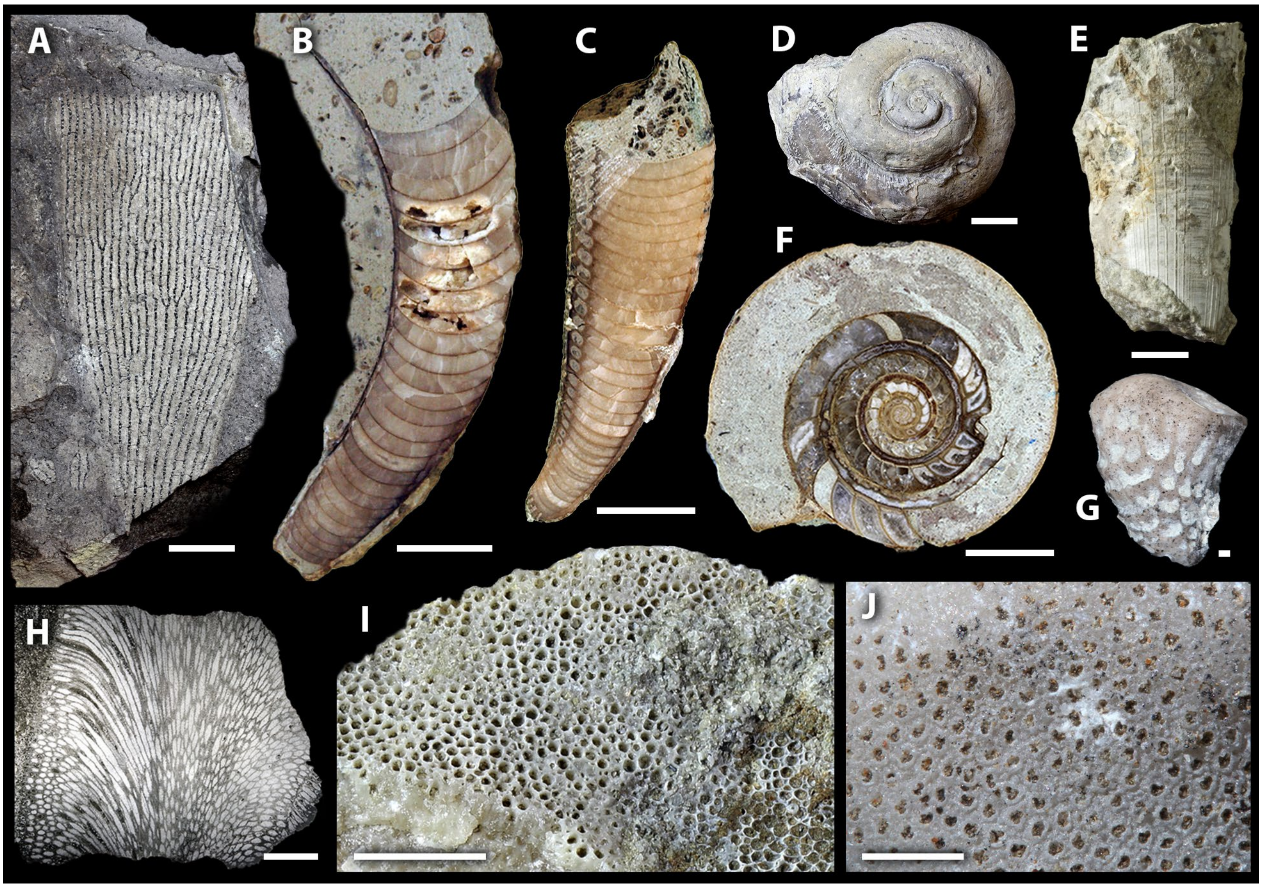

Fig. 5.8. Selected fossils from the Pakri Peninsula and Pakri islands. Scale bars: A, F–D – 1 cm; B–E, H, I – 5 mm; G, J – 1 mm. **A** – graptolite *Rhabdinopora flabelliformis flabelliformis*, Pakri, Türisalu Formation (Tremadocian), GIT 398-1034. **B**, **C**, **F** – cephalopods; ***B*** – *Richardsonoceras goldmanni,* Uuga Cliff, Kandle Formation (Darriwilian), TUG 1285-51; ***C*** – *Paldoceras paldiskense*, Uuga Cliff, Kandle Formation (Darriwilian), TUG 1285-10; **F** – *Trocholites depressus*, Väike-Pakri Cliff, Väo Formation (Darriwilian), GIT 145-1. **D** – gastropod *Proturritella cingulata*, Paldiski, Pakri Formation (Darriwilian), GIT 404-400. **E** – hyolith *Hyolithes gerhardi*, Paldiski, Väo-Kõrgekallas formations (Darriwilian), GIT 387-2. **G** – eocrinoid *Bolboporite*s (*Bolboporites*) *uncinatus*, Pakri, Pakri Formation (Darriwilian), GIT 468-76. **H**–**J** – bryozoans; **H**–**I** – *Dianulites pakriensis*, Väike-Pakri Cliff, Pakri Formation (Darriwilian), GIT 537-1294; **J** – *Pakripora cavernosa***,** Väike-Pakri Cliff, Pakri Formation (Darriwilian), GIT 537-1227-1.

(7) The **Pakri Formation** (ca 1.0 m, Kunda Regional Stage, Darriwilian) is composed of sandy limestone to limy sandstone (up to ca 80% quartzose sand according to Põldsaar and Ainsaar 2014). These sediments are spread in a limited area in NW Estonia, probably representing one of the few remains of a near-shore facies in the Ordovician Baltoscandian Basin. The unit contains numerous soft-sediment deformation structures (such as load casts, flame structures, ball-and-pillow morphologies, sedimentary dykes, autoclastic breccias, and sand volcanoes) that indicate large-scale liquefaction and fluidisation of the unconsolidated and water-saturated sediments, probably by a large earthquake (Põldsaar and Ainsaar 2014). The coincidence of a deformation event and the Middle Ordovician meteoritic bombardment period, and the occurrence of shock metamorphic features and extraterrestrial chromite in the Pakri Formation suggest that a meteorite impact might have caused such an earthquake (Alwmark et al. 2010). The basal part of the Kunda Stage corresponds to a gap in NW Estonia, and thus, the base of the Darriwilian coincides with the Volkhov–Kunda stage boundary on the Pakri Peninsula. The upper part of the formation corresponds to the *Eoplacognathus pseudoplanus* conodont Zone and the *Cyathochitina regnelli* chitinozoan Zone. The Pakri Formation also contains several strong pyritic discontinuity surfaces, the oldest kukersite kerogen in the region and is rich in shelly faunas.

(8) The **Kandle Formation** (ca 0.1 m, =Aseri Formation in some previous publications; Aseri/Lasnamägi regional stages, Darriwilian) is composed of argillaceous limestone with brown or white ooids. In the Uuga cliff, this unit contains the zonal conodont *Yangtzeplacognathus foliaceus*, which is considered to indicate the lower Lasnamägi age. If true, the Aseri Regional Stage may be missing in some parts of the Pakri Peninsula and other places in NW Estonia (Hints et al. 2012).

(9) The **Väo Formation** (ca 5.1 m, Lasnamägi and Uhaku regional stages, Darriwilian) is represented by grey thin- to medium-bedded limestones (wacke- to packstones), a discrete layer of dolostone (Pae Member) and numerous phosphatic and pyritic discontinuity surfaces. The dolomitic Pae Member is characterised by a positive magnetic susceptibility anomaly likely because of fluid migration, which produced secondary iron input and/or rearrangement of existing iron and precipitation of ferroan dolomite crystals (Plado et al. 2016). The age of the

Väo Formation and individual members are well-constrained by conodont and chitinozoan biostratigraphy, the most useful being subzones of the *Pygodus serra* conodont Zone. The base of the Uhaku Regional Stage is drawn at the appearance of *Gymnograptus linnarssoni*, but as only a single find of this species comes from the Uuga cliff, the appearance of the conodont *Baltoplacognathus robustus* provides a more helpful level (Hints et al. 2012). The upper part of the Väo Formation, starting from the Pae Member, constitutes the so-called Building Limestone, which is widely quarried and utilised all over northern Estonia. Many of the individual layers are named explicitly by local quarrymen, and some can be recognised over hundreds of kilometres (Einasto and Rähni 2005).

(10) The **Kõrgekallas Formation** (1.0+ m, Uhaku Regional Stage, Darriwilian) is composed of grey limestones, which are relatively more argillaceous than the underlying Väo Formation. The boundary between the formations is marked by six distinct successive discontinuity surfaces.

Younger rocks belonging to the Kukurse and Haljala regional stages, basal Sandbian, are distributed (but not well exposed) in the central part of the Pakri Peninsula.

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Stop 6: Uuga cliff, Pakri Peninsula

Olle Hints

Location: Latitude 59.36138°N, longitude 24.03941°E; Harju County, NW Estonia.
Stratigraphy: From Tremadocian-Floian to Darriwilian, Hunneberg to Uhaku regional stages.
Status: Cliff is under nature protection, no hammering.
More information: https://geoloogia.info/en/locality/13545

The Uuga cliff is located close to the Paldiski Northern Port, where the cliff gradually emerges and gains height toward the north. It is possible to walk along the coast to the Pakerort cliff (Stop 5) and observe the gentle southwards dip of the layers (due to that, successively older rocks get exposed northwards). At the Uuga cliff, the upper part of the Leetse Formation and the oldest carbonate rocks of the Toila, Pakri, Kandle, Väo and Kõrgekallas formations are accessible. These are characterised in detail above (Stop 5).

The Uuga cliff succession has been analysed for microfossils (Fig. 6.4; Tammekänd et al. 2010; Hints et al. 2012), geochemistry, magnetic properties, as well as sedimentology (Põldsaar and Ainsaar 2014). A prominent hardground at the base of the Volkhov Regional Stage, coinciding with the base of the Dapingian, can be observed within the glauconite-rich limestones of the Toila Formation (Fig. 6.2).

The Pakri Formation, Kunda Regional Stage, lower Darriwilian, is characterised by sandy limestones to calcareous sandstones with soft-sediment deformations (Fig. 6.3).

Fig. 6.1. Succession of Tremadocian-Floian glauconitic sandstone (Leetse Formation) and Dapingian-Darriwilian carbonate rocks at the Uuga cliff near the Northern Port of Paldiski. Photo: Olle Hints, 2020.

Fig. 6.2. A characteristic hardground ("Püstakkiht") at the base of the Volkhov Regional Stage (coinciding with the base of the Dapingian). The same surface with *Gastrochaenolites* borings can be traced from NW Russia to Öland Island, Sweden. Left – outcrop photo, right – polished slab GIT 362-538.

Fig. 6.3. Soft-sediment deformations (load casts and flame structures, Põldsaar & Ainsaar 2014) in the Pakri Formation, Kunda Regional Stage. Photo: Gennadi Baranov, 2011.

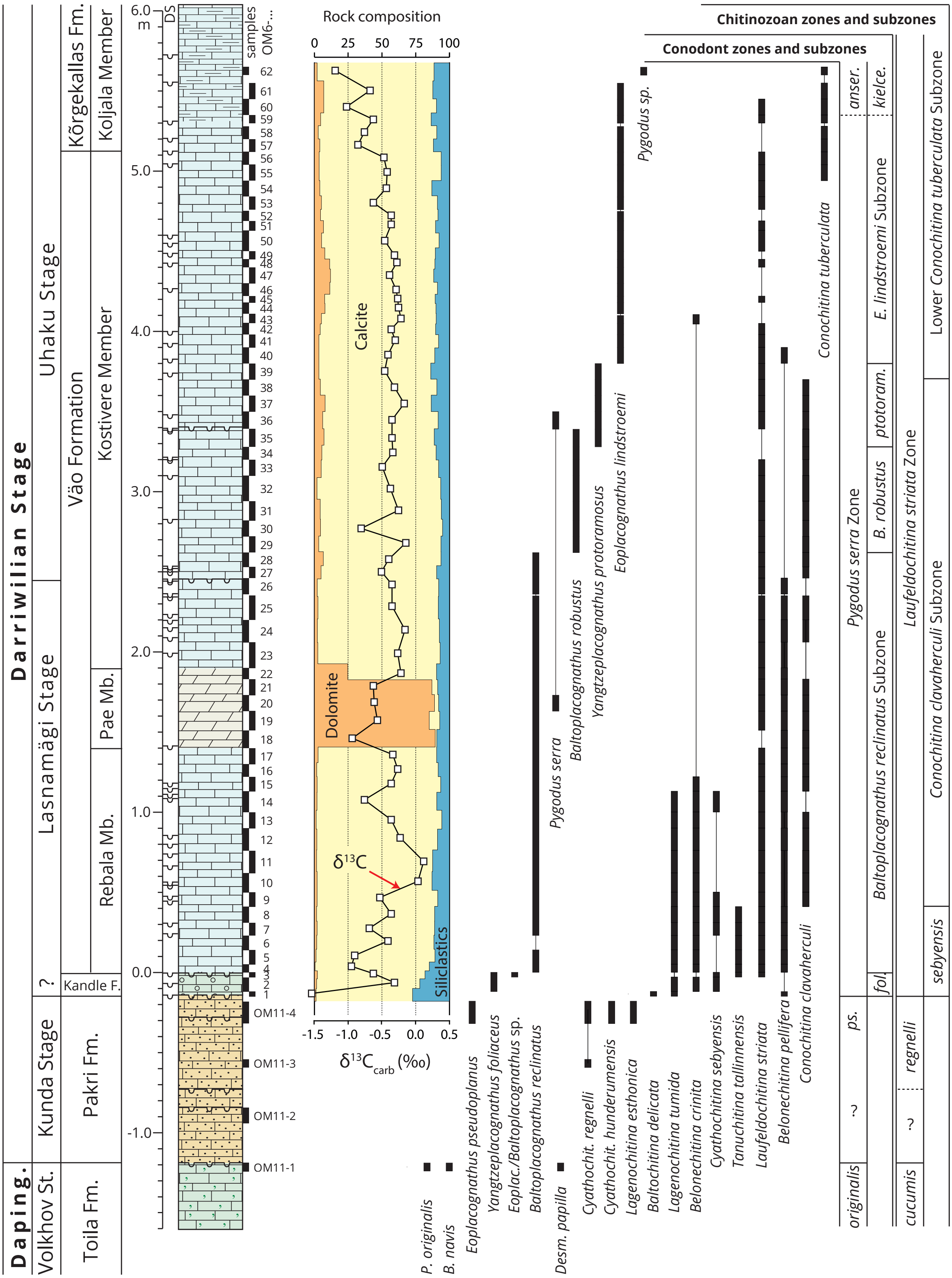

Fig. 6.4. Distribution of key conodonts and chitinozoans in the Uuga cliff (from Hints et al. 2012).

Stop 7: Rummu quarry

Björn Kröger, Ursula Toom, Peep Männik and Andrej Ernst

Location: Latitude 59°13´42,8˝N, longitude 24°13´49,5˝E; Harju County, Estonia.
Stratigraphy: Latest Sandbian, Keila Regional Stage, Vasalemma Formation.
Status: Abandoned quarry. Sampling and fossil collecting are welcome.
More information: https://geoloogia.info/en/locality/10177

The following text is updated and slightly modified from Kröger & Toom (2023).

The Rummu quarry is an abandoned quarry located c. 30 km south-west of Tallinn, near Keila, Harju County. The large quarry is largely filled with water. On the eastern and northern margins parts of the former quarry wall expose upper-most sections of the Vasalemma Formation with partly beautifully weathered patch reefs.

History

The echinoderm limestone of the Vasalemma Formation has been quarried for centuries and is known in the region as the "Vasalemma Marble". The limestone was described and named in a stratigraphical context by Eichwald (1854) and Schmidt (1881). The names "Hemicosmitenkalk" (Eichwald 1854) and "cystoid limestone" (Männil 1960) refer to the rock-building abundance of echinoderm intraclasts (mainly of the genus *Hemicosmites*, Rhombifera). Within the massive echinoderm limestone beds, echinoderm-bryozoan-receptaculitid reefs are abundant (Fig. 7.1). Together, the echinoderm grainstone and the reefs form the "Wasalemm'sche Schicht" of Schmidt (1881), which is synonymous with the Vasalemma Formation of subsequent authors (e.g., Männil & Rõõmusoks 1984; Hints & Miidel 2008). In Schmidt's system, the Vasalemma Formation was designated as D3, the topmost layer of sequence D, and thus formed the stage above the "Kegel'sche Schicht" (Keila Regional Stage, D2). In a series of field guides, Linda Hints, and her colleagues (Hints 1990, 1996; Hints *et al*. 2004; Kröger *et al*. 2014b) published several drill core sections and outcrop details. A comprehensive review and reappraisal of the stratigraphy and sedimentology of the formation was published by Kröger and co-authors (Kröger *et al*. 2014b, 2014c). Today, the Vasalemma Formation is stratigraphically placed within the Keila Regional Stage, being of late Sandbian age (Meidla *et al*. 2023).

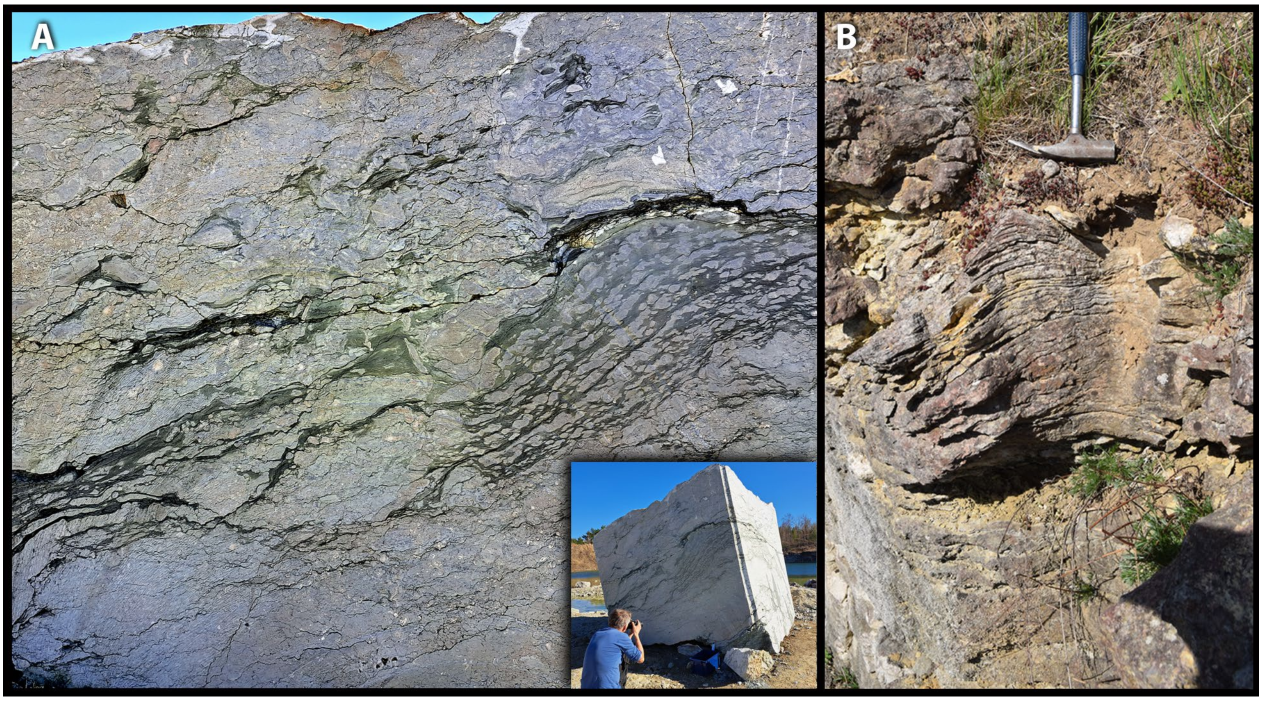

Fig. 7.1. Rummu quarry, Vasalemma Formation (Katian), **A** – block of limestone with reef's body. Photo: Ursula Toom; **B** – large crust of stromatoporoid. Photo: Björn Kröger.

The Rummu quarry was opened in the late 1930s to excavate limestone , including "Vasalemma marble". The latter is a specific kind of limestone with its structure and texture resembling that of marble. During the Soviet era, until the 1990s, excavation was performed as hard labour by Murru and Rummu prisoners, who excavated and processed limestone from the water-drained quarry. When the pumping of water ceased, the quarry quickly filled with groundwater, forming a lake, and immersing some of the utility buildings and machinery. With the closure of the Rummu quarry, the area became a featured location for nature photography, hiking, rafting, scuba diving, as a summer spot, musical and sports events, and as a filming location for its unique layout (https://en.wikipedia.org/wiki/Rummu_quarry).

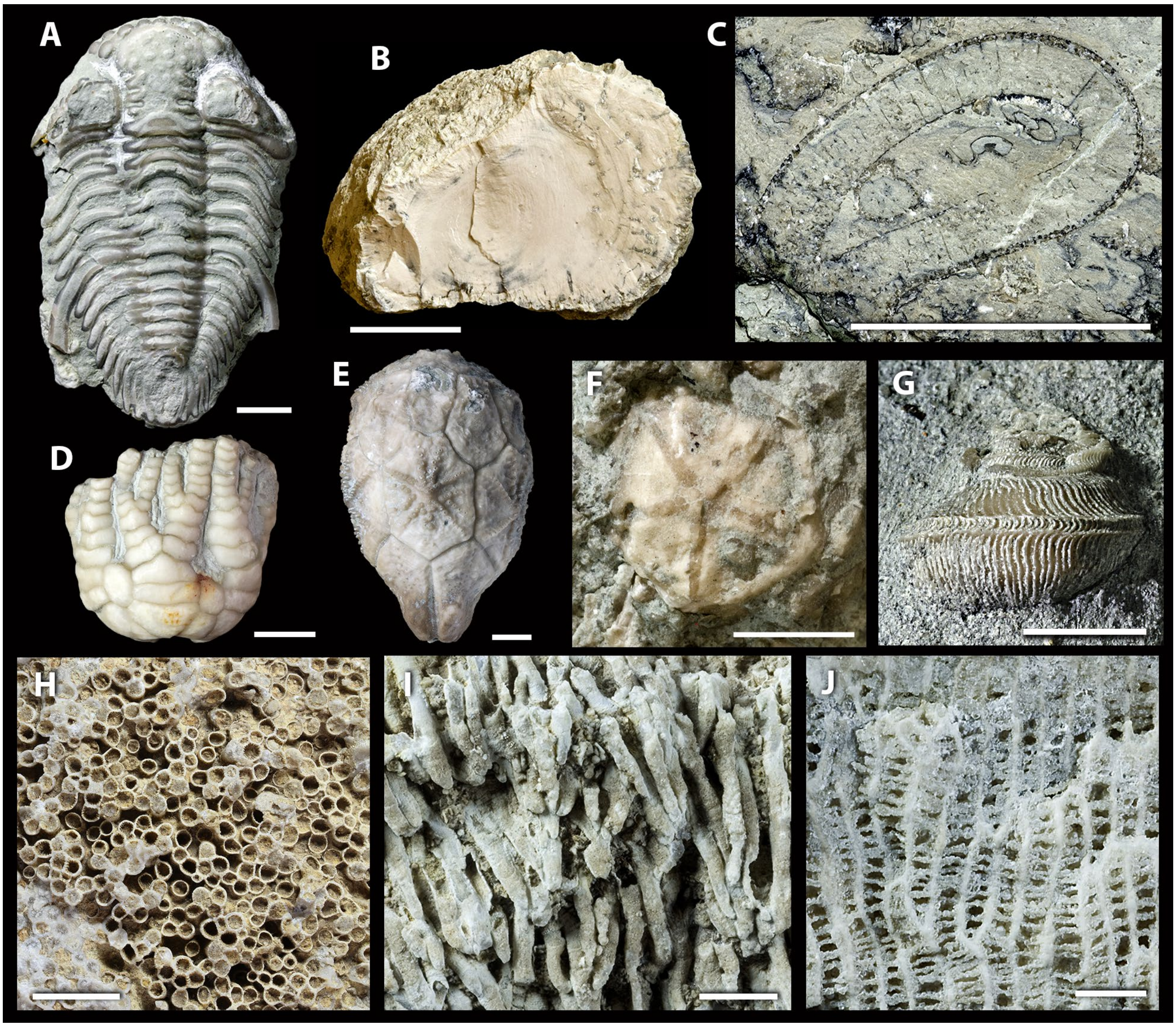

Fig. 7.2. Selected fossils from the Vasalemma Formation (Katian), Vasalemma quarry. Scale bars: H, I – 1 cm; A– G, J – 5 mm. **A** – trilobite *Atractopyge kutorgae* (Schmidt), TUG 1393-1. **B** – *Solenopora* sp., GIT 339-1043. **C** – retceptaculitid Receptaculites poelmi Miagkova, GIT 413-166. **D** – crinoid *Tintinnabulicrinus estoniensis* Wright & Toom, GIT 653-3. **E** – blastozoans *Hemicosmites extraneus* Eichwald, GIT 633-206. **F** – edrioasteroid *Cyathocystis rhizopora* Schmidt, GIT 643-11-1. **G** – gastropod *Brachytomaria baltica* (Verneuil), GIT 222-114. H, I, J – tabulate corals; **H, I** – *Eoflecheria orvikui* (Sokolov), H –GIT 94-10, I – GIT 180-94; **J** – *Saffordophyllum tulaensis* (Sokolov), GIT 94-10.

Stratigraphy

The Vasalemma Formation is a partly discontinuity-bounded unit. The lower and the upper boundaries are diachronous. From the combined drill core and outcrop data, it is known that in the southern part of the Vasalemma quarry, 5 km north-east of the Rummu quarry (see e.g. Kröger & Toom 2023), the base is marked by a prominent hardground on top of the Pääsküla Member, Kahula Formation (Kröger et al. 2014b, 2014c). In other places, the base is less than a few meters above this hardground, within the overlying Saue Member of the Kahula Formation (Kröger *et al*. 2014a). Laterally the echinoderm limestone of the Vasalemma Formation grades into the skeletal wacke- to packstone lithologies of the Saue and Lehtmetsa members of the Kahula Formation. This gradual lateral change is exposed along a kilometre-long quarry wall of the Vasalemma quarry.

The top of the formation is formed by a distinct hardground surface on top of the reefs, which locally

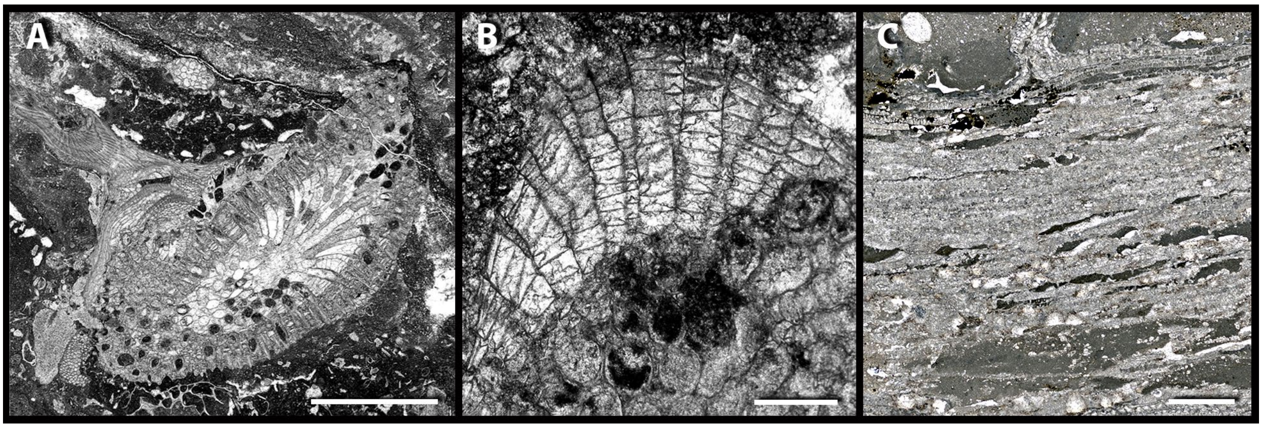

Fig. 7.3. Selected thin sections of bryozoa and stromatoporoid, Vasalemma Formation (Katian), Rummu quarry. Scale bars A – 0.5 mm, B, C – 5mm. **A** – *Orbignyella germana* Bassler; **B** – *Dittopora colliculata* (Eichwald); **C** – *Cystistroma sakuense* Nestor.

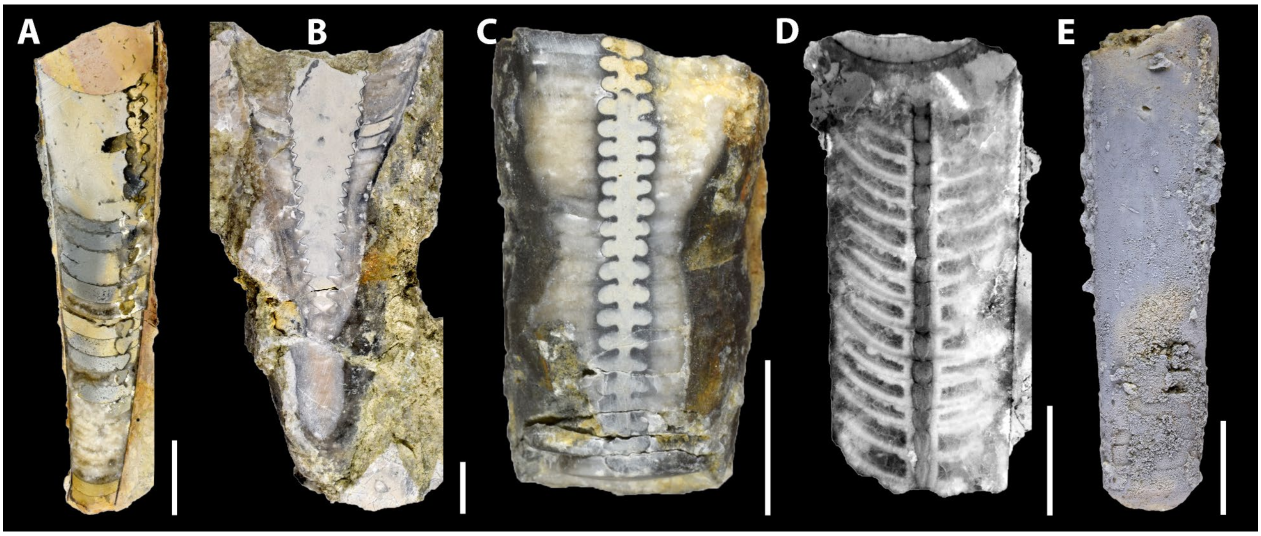

Fig. 7.4. New cephalopods taxa from the Rummu quarry described by Kröger & Aubrechtová (2018), Vasalemma Formation (Katian). All scale bars 1 cm. **A** – *Hoeloceras muroni*, TUG 1709-6; **B** – *Rummoceras rummuensis*, TUG 1709-31; **C** – *Hemibeloitoceras arduum*, TUG 1612-13; **D** – *Isorthoceras cavi*, TUG 1585-41; **E** – *Isorthoceras padisense*, TUG 1585-18b.

also represents a (partially subaerial) erosional surface, which cuts into the reefs and the echinoderm limestone. This upper surface is overlain by the argillaceous sediments of the Hirmuse Formation, Oandu Regional Stage, or locally by yellowish micritic limestone of the Rägavere Formation (Kröger *et al*. 2014a, 2014c).

The conodont zonation in the Upper Ordovician is mainly based on the evolutionary lineage of *Amorphognathus*. However, only a few unidentifiable fragments of *Amorphognathus* were found in the Vasalemma Formation. Previous studies have shown that there is an interval corresponding to the upper Haljala and Keila, but probably also to the lowermost Oandu regional stages in Estonia, where *Amorphognathus* is extremely rare or missing. Tentatively, this interval was assigned to the *Amorphognathus tvaerensis* conodont zone (Männik 2017) or, based on the recently revised conodont zonation, to the (upper part) of the *Baltoniodus alobatus* conodont zone (Paiste et al. 2023). $\delta^{13}C_{carb}$ data from drill cores of the Vasalemma Formation record the rising limb of the upper Sandbian Guttenberg Isotopic Carbon Excursion (GICE; see e.g., Meidla *et al*. 2023) and a sharp drop of values at its upper discontinuity, indicating that the main interval of the GICE is younger than the formation (Fig. 6.2; Kröger *et al*. 2014a, 2014c).

Geological setting and sedimentology

The Vasalemma Formation occurs along a c. 20 km E–W stretched belt with an N–S extension of c. 5 km. Toward the north, it is partly limited by an erosional front. The formation has a thickness of up to 15 m and consists mainly of a massive echinoderm grainstone with, in its central areas, concentrations of patch reefs. The echinoderm limestone is a massively bedded grainstone, almost completely composed of *Hemicosmites* ossicles held together by syntaxial cement. Ripple waves and crossbedding are widespread features within the echinoderm limestone. The reefs are up to c. 10 m thick and up to 50 m wide, and their cores are formed by a matrix-rich boundstone (50–80% matrix), with abundant echinoderms, bryozoans, and receptaculitids as main skeletal components and abundant fenestral fabric (Kröger *et al*. 2014a) (Fig. 7.1). The reefs of the Rummu quarry are comparatively strongly dominated by bryozoans and edrioasteroids (Kröger *et al*. 2023a). Associated with the reef cores are commonly pockets, preserving locally restricted siliciclastic (marl, silt) and microbial limestone facies. In the north-eastern part of the Vasalemma quarry, the base of the formation forms the top hardground of the Pääskula Member, which here exposes a rippled surface and which is partly highly bioeroded with borings of *Trypanites sozialis*. The ripple-marks have a mean wavelength of c. 0.4 m and an NE/SW direction (Hints & Miidel 2008). In the Vasalemma quarry, the top of the Vasalemma Formation is formed by an iron (pyrite) impregnated and bioeroded hardground and erosional surface, which is locally covered by a conglomerate with highly rounded, pyrite-impregnated clasts from the Vasalemma Formation. In the eastern part of the Rummu quarry herringbone cross-bedding and gravitational cements in the uppermost sections of the echinoderm limestone indicate a very shallow, intertidal depositional environment, and subaerial exposure (Kröger *at al*. 2014a).

Sea level and paleoclimate

The top Vasalemma discontinuity reflects a major regional sea level drop (corresponding to the base of the depositional sequence VIII of Dronov *et al*. 2011, the Lower Wesenberg Sequence of Dronov 2017, and the Frognerkilen Lowstand Event of Nielsen 2011). This discontinuity and its associated facies and faunal change mark a massive change in the regional sedimentation regime and faunal composition during the late Keila to Rakvere time that has been termed Mid-Caradoc Event (Meidla *et al*. 1999) or Middle Caradoc Facies and Faunal Turnover (Ainsaar *et al*. 2004). The interval has been interpreted as related to climate change and associated changes in ocean circulation (Ainsaar *et al*. 2004). Oxygen isotope data suggest that the Mid-Caradoc Event (late Haljala-Keila stage) was an interval of global cooling that climaxed during the Frognerkilen Lowstand Event (Männik *et al*. 2021).

Fauna and flora

The Vasalemma Formation contains extraordinarily rich and abundant fauna. Dozens of species of bryozoans were described from the Vasalemma Formation by Bassler (1911), Männil (1959), Modzalevskaya (1953), Pushkin (1990) and Gorjunova & Lavrentjeva (1993). A thorough revision of the bryozoan fauna is still needed. Hemispherical and massive species of bryozoans are less abundant in the reefs of the Rummu quarry compared with that of the Vasalemma quarry (Kröger *et al.* 2023a). Results from a statistical analysis of the bryozoan fauna indicate that the extraordinarily high bryozoan richness reflects high small-scale (within reef) heterogeneities in lithology and original bryozoan habitat (Kröger *et al*. 2023a). The echinoderm fauna is strongly dominated by *Hemicosmites*, but locally edrioasteroids (*Cyathocystis*, Rozhnov 2004), rare solutans (Rozhnov & Jeffries 1996), asteroids (Blake & Rozhnov 2007) and crinoids (Ausich *et al*. 2015; Rozhnov 1990, 2012; Wright & Toom 2019) are worth mentioning. The reefs of the Vasalemma Formation contain rugose corals, such as *Lambelasma carinatum* which are among the oldest of the region. Retseptaculitids are common; *Receptaculites poelmi* from the Vasalemma Formation has been described by Miagkova (1981). The chaetetid sponge *Solenopora* is locally common within the reefs. Bryozoans, echinoderms, receptaculitids and *Solenopora* form complex, partly densely intergrown assemblages (Vinn *et al*. 2018). Locally, the uppermost sections of the reefs contain large colonies of tabulate corals *Eofletcheria orvikui*, *Saffordophyllum tualensis* and *S. grande* (Klaamann 1975); also crusts of stromatoporoids such as *Cystistroma sakuense* occur (Fig. 7.3). The reefs contain rich macrofauna with monoplacophorans (*Pilinia* sp.) and gastropods (*Brachytomaria baltica* and *Cyclonema lineatum*). The trilobites of the Vasalemma Formation have not been systematically studied, but the most common representatives include *Asaphus*, *Chasmops*, *Stenopareia* and *Toxochasmops*. Kröger & Aubrechtová (2018) described a rich cephalopod fauna from the Vasalemma Formation that included five new taxa from the Rummu quarry (*Hemibeloitoceras arduum, Isorthoceras padisense, I. vexilli, Orthonybyoceras isakari, Rummoceras rummuensis*; Fig. 7.4). Cephalopods, trilobites and echinoderms occur frequently as concentrations in pockets associated with the reefs. Dense cornulitid infestations of the reef and echinoderm-limestone on the capping hardground surface are remarkable (Vinn & Toom 2015). Brachiopods *Estlandia pyron silicificata*, *Bassettella alata*, Saukrodictya, *Horderleyella kegelensis*, and *Apatorthis* sp. occur mainly in the argillaceous interlayers of the lower half of the Vasalemma Formation. Three taxa of well-preserved noncalcified dasyclad algae have been discovered from an algal-Lagerstätte within dolomitic mudstone layers associated with the reefs (Kröger et al. 2023b).

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Stop 8: Päri quarry

Olle Hints

Location: Latitude 58.84046°N, longitude 24.04279°E; Harju County, Estonia.
Stratigraphy: Telychian, Adavere Regional Stage, Rumba Formation.
Status: Abandoned quarry. Sampling and fossil collecting are welcome.
More information: https://geoloogia.info/en/locality/10230

Fig. 8.1. Overview of the Päri quarry. Photo: Olle Hints.

The following text is based on the compilation of Hints (2014).

A shallow disused Päri quarry is located on a flat limestone hillock, ca 5.5 km SW from the Kullamaa village, 1 km W from the Tallinn-Virtsu road (Fig. 8.1). In this outcrop argillaceous nodular limestones of the upper part of the Rumba Formation, Adavere Regional Stage, early Telychian, are exposed in a maximum thickness of ca 3.9 m.

The Päri locality has been known for more than 150 years, referred to as Kattentack in the old literature (after Kattentack/Päri manor). The outcrop is a neostratotype for both the Rumba Formation and the Adavere Regional Stage (Nestor 1993). It is moreover the type locality for several fossil species, in particular corals and stromatoporoids, and the only outcrop of the Osmundsberg bentonite in the East Baltic region.

According to Kaljo & Einasto (1990) the succession of the deepest part of the quarry is described as follows (from the top; see Figs 8.2, 8.3; note that starting from the middle part of bed 5 the section is commonly filled with debris; as of 2024, this part of the succession, including the Osmundsberg K-bentonite, is not accessible):

(1) 1.30 m – irregularly nodular, argillaceous limestone (skeletal packstone) with lens-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.

(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.

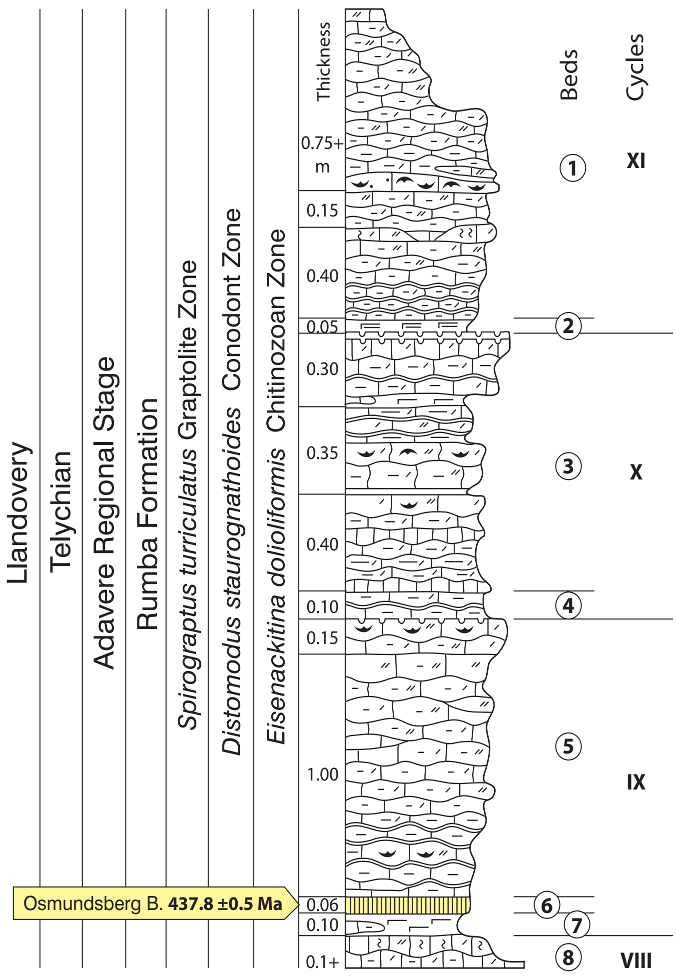

Fig. 8.2. Succession of argillaceous limestones in the Päri quarry. Lithology from Kaljo & Einasto (1990), age of the Osmundsberg bentonite according to Bergström et al. (2008), stratigraphy combined from different sources.

Fig. 8.3. Deepest part of the quarry; the lower part of the section is covered by debris and thus the 6-cm thick the Osmundsberg bentonite is currently inaccessible. Photo: Olle Hints, 2024.

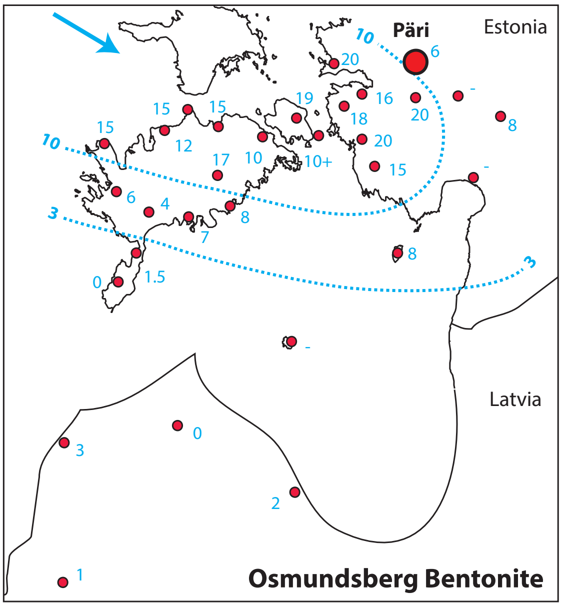

Fig. 8.4. Thickness distribution of the Osmundsberg bentonite in the eastern Baltic area after Kiipli et al. (2006).

(5) 1.15 m – greenish-grey, irregularly nodular, argillaceous skeletal limestone (packstone) with lenses of skeletal grainstone (*Pentamerus*-coquinas). The upper 15 cm contains purer limestone with a pyritic discontinuity surface on the top.

(6) 0.06 m – bioturbated bentonite bed (Osmundsberg bentonite).

(7) 0.1 m – grey calcitic marl with grainstone nodules.

(8) 0.1 m – brownish grey microcrystalline irregularly nodular limestone (packstone).

In drill cores, the Rumba formation is up to 19 m thick, consisting of 12 low-grade depositional cycles (Einasto et al. 1972). Four of these cycles have been identified in the Päri Quarry (Fig. 8.2). Usually, a cycle begins with a thin marlstone layer, upwards the clay content decreases, and grainstone or coquinoid rudstone lenses appear; each cycle ends with a distinct discontinuity surface (Kaljo & Einasto 1990).

In the lower part of the Päri section, a 6 cm thick bioturbated K-feldspar-rich bentonite layer occurs. This is the thickest Silurian volcanogenic layer in Estonia, previously referred to as the "O"-bentonite (Kiipli et al. 2006 and references therein), and now known to correlate with the Osmundsberg bentonite in Scandinavia (Bergström et al. 1998). In its type locality at Osmundsberget, Central Sweden, the bed is 1.1 m thick. In Estonian drill cores, it reaches 20 cm (Kiipli et al. 2006; Fig. 8.4); the thickness map suggests the source area in the direction of Trondheim, Norway. Within-bed mineralogical and geochemical variations suggest that the eruption occurred in two stages. In the Päri section, two cycles within the Osmundsberg bentonite are expressed by the variation of carbonate content of burrows within the bed (Kiipli 2008). U-Pb dating of the Osmundsberg bentonite from the type locality in Sweden provided radiometric age of 437.8 ±0.5 Ma (Bergström et al. 2008).

Fig. 8.5. Erosional surface with cut shells of *Pentamerus oblongus* in the Päri quarry. Photo: Olle Hints.

The Päri quarry is rich in shelly faunas, which is generally typical of the Rumba Formation. Characteristic of the Rumba formation, and the Päri section, is the abundant occurrence of *Pentamerus oblongus* (Fig. 8.5). Other brachiopods, tabulate corals (*Paleofavosites*, *Catenipora*, *Aulopora*, *Placocoenites*, *Subalveolites*, *Propora*) and stromatoporoids (*Clathrodictyon*) are common, and rugosans (*Calostylis*), gastropods (*Hormotoma*), cephalopods, echinoderms

Fig. 8.6. Selected fossils of the Päri quarry Adavere Regional Stage. Scale bars A, E, I – 1 cm. B–D, F–H, J–M – 5 mm. **A**–**C** brachiopods; **A** – *Pentamerus oblongus* (Sowerby), GIT 362-85; **B** – *Stegerhynchus borealis* (von Buch), GIT 173-28; **C** – *Hesperorthis davidsoni* (Verneuil), GIT 126-13. **D** – rugose coral *Prodarwinia speciosa* (Dybowski), GIT 397-675. **E**–**M** tabulate corals; **E** – *Aulopora assueta* Klaamann, GIT 94-49; **F** – *Placocoenites pellicula* Klaamann, GIT 398-899, **G** – *Catenipora elegans* (Fischer-Benzon), GIT 180-83; **H** – *Catenipora exilis* Klaamann, GIT 94-39; **I** – *Adaverina acclinis* (Klaamann), GIT 94-61; **J** – *Sinopora callosa* Klaamann, GIT 94-63; **K** – *Heliolites* sp., GIT 393-4; **L** – *Subalveolitella majuscula* Klaamann, GIT 91-17; **M** – *Paleofavosites jaaniensis* Sokolov, GIT 180-36.

and trilobites (*Calymene*, *Encrinurus*) may also be found (Fig. 8.6).

However, chitinozoans, conodonts (*Panderodus* spp., *Ozarkodina* sp.) and thelodonts (*Thelodus* sp.) are virtually absent or very rare (Kaljo & Einasto 1990). Therefore, the biostratigraphic age of the section can only be inferred indirectly, based on the tracing of the Osmundsberg bentonite in biostratigraphically well-dated sections (like Osmundsberg North, central Sweden, and the Viki drill core, western Estonia). According to these correlations, the section in the Päri quarry corresponds to the *Spirograptus turriculatus* Graptolite Zone (Bergström et al. 2008), *Eisenackitina dolioliformis* Chitinozoan Zone and *Aspelundia*? *expansa* Conodont Zone (and possibly *Pterospathodus eopennatus* ssp. n. 1 Conodont Zone).

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Stop 9: Salevere Salumägi

Peep Männik

Location: Latitude 58°41´27˝N, longitude 23°35´23˝E; Pärnu County, Estonia.
Stratigraphy: Sheinwoodian, Jaani Fm (Mustjala(?) Mb) and Muhu Fm (Kesselaid Mb), Jaani and Jaagarahu RSs.
Status: Cliff is under nature protection; no hammering, but loose material may be collected.
More information: https://geoloogia.info/en/locality/14272

The following text is updated and slightly modified from Einasto & Männik (1991).

The Salevere Salumägi (Salevere grove mountain) is located in western Estonia, about 15 km west of the Lihula settlement. It is a remnant reef rock that has been more resistant to erosion and survived denudation by glaciers during the last ice age and later by the wave activity of

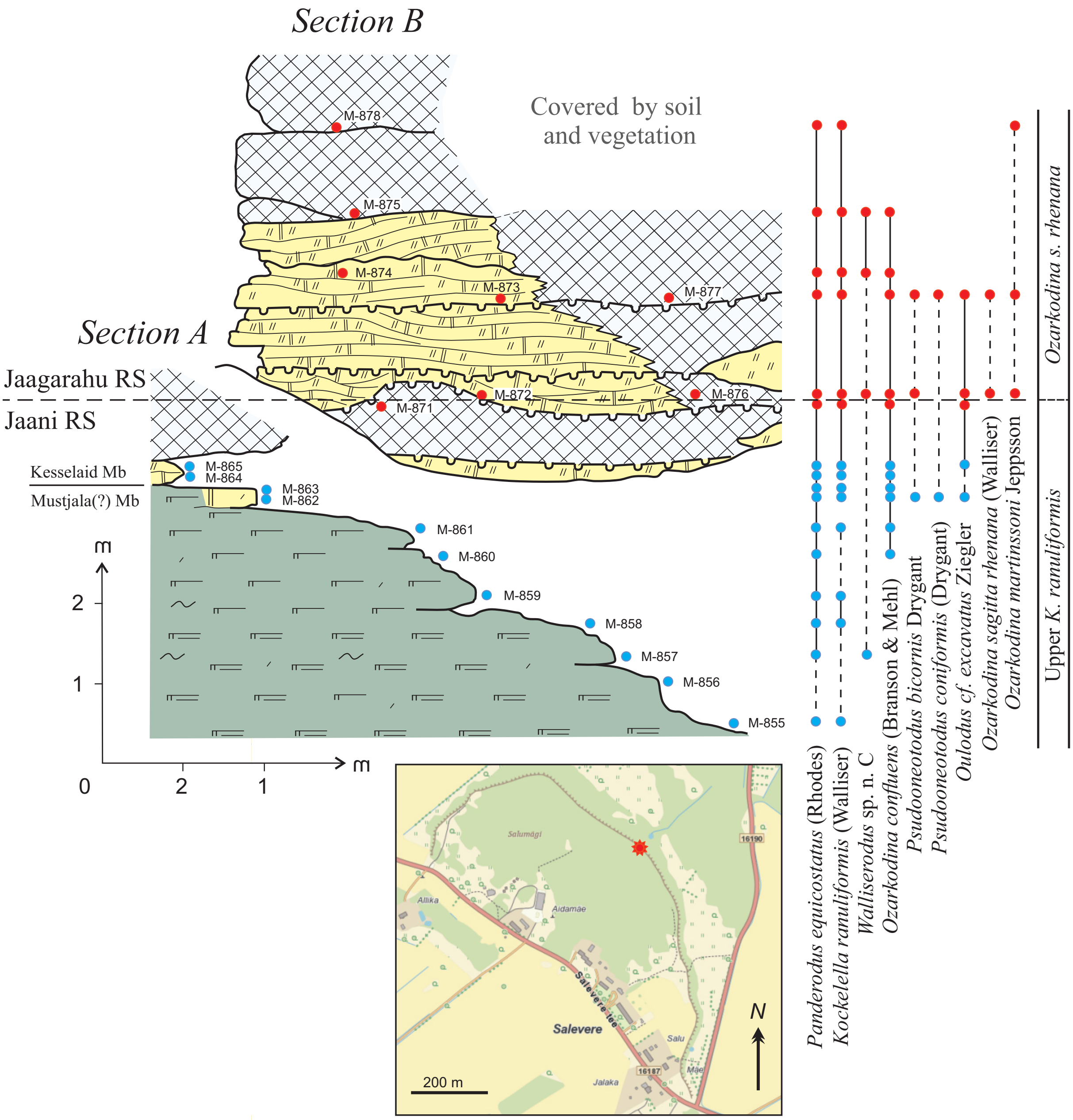

Fig. 9.1. Studied sections (red star in the map marks their location). From left to right: regional stratigraphy, lithology; location of micropalaeontological samples (blue and red dots with sample numbers); distribution of conodonts; conodont zones. Abbreviations: RS – Regional Stage; Mb – Member.

the Baltic Sea (about 4000-6000 years ago). As a result of the latter process, a coastal cliff formed on the northern side of the reef body. Nowadays, the cliff is partly covered and only separated outcrops, some of them up to 5–7 m high, can be observed along the northern edge of the Salevere Salumägi in an interval up to 1 km long. The cliffs consist of dolomitised bioherms surrounded by coarse-grained and often cross-bedded grainstone. The only exposure of dolomitic marlstones underlying the cliff-forming reefs is located near the spring (Section A in Fig. 9.1). Here, the section characterised below was studied and described. Section B is located a few meters to the West of Section A.

Description of the sections

Section A

Mustjala(?) Member, Jaani Stage

3.3+ m – dark grey, on weathered surface yellowish, dolomitized argillaceous marlstone, which becomes more calcareous in the upper part of the interval. Rare pyritized brachiopod, ostracod, and trilobite fragments occur, and bioturbation can be observed. In the upper part of the interval, nodules and interbeds of argillaceous dolostone appear. The upper boundary of this interval is marked by a distinct denudation surface.

Section B

Kesselaid Member, Jaagarahu Stage

6.6 m – reef complex in which three intervals of different composition were recognized:

(1) 0.8–1.0 m – strongly dolomitized massive bioherm with up to 0.2 m thick basal bed of dolomitic coarse grainstone. Few poorly preserved tabulate corals and stromatoporoids were recognized. The upper boundary is marked by a wavy denudation surface.

(2) 1.8–2.1 m – dolomitized grainstone, relatively well sorted in the lower and less in the upper part. Gain size increases, and the rock becomes cross-bedded in the upper part of the interval. To the west, these grainstones are replaced by bioherm. Two distinct denudation surfaces, both observable in grainstone as well as in bioherm, cut the interval. The upper surface of the complex is wavy, resembling large ripples.

(3) 3.1–3.2 m – relatively homogenous massive, cavernous biohermal dolostone. In the lower part of this interval, some rugose corals and brachiopods were observed. The interval is cut by a wavy denudation surface in its middle part.

Stratigraphy

Dating of the section is based on conodonts (Fig. 9.1). Dolomitic marlstone in the lower part of the succession, probably representing the Mustjala Mb (Jaani Fm), and the basal part of the reef complex of the Kesselaid Mb (Muhu Fm) above yield conodonts characteristic of the Upper *Kockelella ranuliformis* Zone. The appearance of *Ozarkodina sagitta rhenana* in the lower Kesselaid Mb correlates the strata above with the *Oz. s. rhenana* Zone, indicating that the boundary between the Jaani and Jaagarahu RS-s in this section lies in the basal part of the reef complex, about 1 m above the contact between the Jaani and Muhu Fm-s.

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Stop 10: Pulli cliff

Peep Männik

Location: Latitude 58°36´52˝N, longitude 22°57´20˝E; Saare County, Estonia.
Stratigraphy: Sheinwoodian, Paramaja Mb of the Jaani RS and the Kesselaid Mb of the Jaagarahu RS.
Status: Cliff is under protection; no hammering, but loose material may be collected.
More information: https://geoloogia.info/en/locality/10237

The following text is modified from Männik & Nestor (2014).

The Pulli (=Oiu) cliff (Figs 10.1, 10.2) is located in the northeastern corner of Saaremaa, about 10 km northwest of the Orissaare settlement. The outcrop was first described by Schmidt (1858) as the Ojo cliff. Based mainly on sedimentological reconstructions, Jürgenson & Nestor (1990) suggested that the boundary between the Jaani and Jaagarahu regional stages is exposed in this section. In the Pulli section, dolomitic marlstones of the Mustjala(?) Member (Jaani Formation) and stratified vuggy and massive reefal (mudmound) dolostone of the Kesselaid Member (Muhu Formation) are exposed. These two lithologies (members) are separated by a distinct, strongly wavy contact.

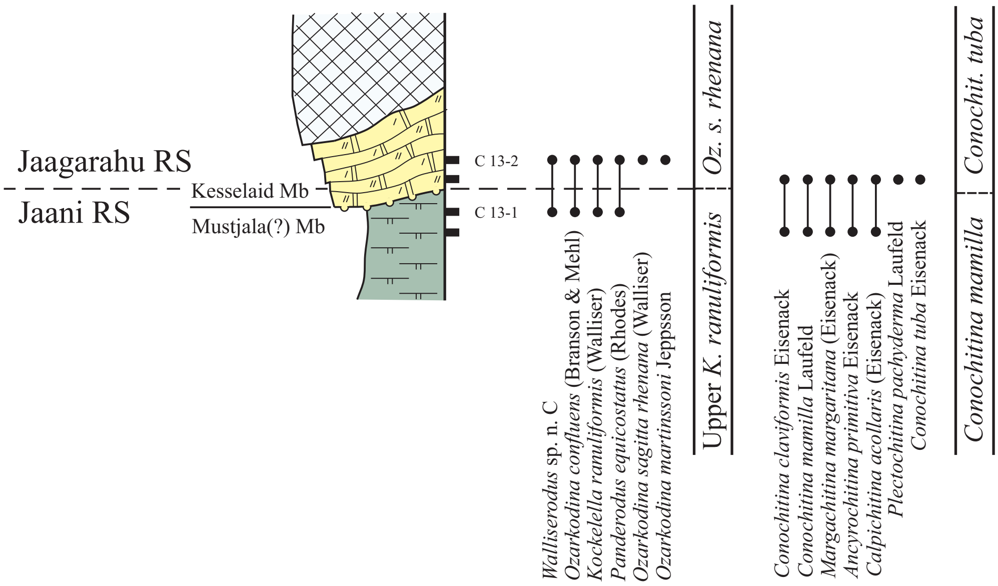

Fig. 10.1. The Pulli Cliff section. From left to right: regional stratigraphy, lithology; location of micropalaeontological samples; sample numbers; distribution of conodonts; conodont zones; distribution of chitinozoans; chitinozoan zones.

Description of the section

From the top:

Kesselaid Member, Jaagarahu Stage

The upper part of the section (up to 2 m) includes upward-expanding dolomitized mudmounds. They consist of fine- to microcrystalline vuggy dolostone with irregular structure and contain small irregular pockets of greenish argillaceous marlstone and brownish-grey dolostone. Mudmounds are underlain and laterally replaced by bluish- to greenish-grey medium-bedded fine-crystalline dolostone (thickness up to 1 m) with the relict texture of coarse-grained bioclastic grainstone, thin discontinuous argillaceous partings and abundant vugs of various sizes. The vugs were formed by the dissolution of calcitic shells of brachiopods, rugose corals, pelmatozoans and bryozoans. At the base of the Kesselaid dolostone, there is an intensely impregnated rusty discontinuity surface.

Mustjala(?) Member, Jaani Stage

1.05+ m – bluish-grey, in weathered state yellowish, argillaceous dolostone and dolomitic marlstone with rare pyritized fossil fragments (mainly brachiopods and trilobites), pyritic concretions and burrows.

Stratigraphy

Trilobites *Encrinurus punctatus* (Wahlenberg) and *Calymene blumenbachii* Brongniart have been identified from the marlstones of the Mustjala(?) Member. Two samples were processed for conodonts, one from the topmost Mustjala(?) Member and the other from the lowermost Kesselaid Member yielded similar faunas strongly dominated by *Panderodus equicostatus* (Rhodes). The appearance of *Ozarkodina sagitta rhenana* (Walliser) in the lowermost Kesselaid Member and its lack in the sample below indicates that the boundary between the Upper *Kockelella ranuliformis* (Walliser) and *O. s. rhenana* conodont zones, but also between the Jaani and Jaagarahu regional stages, lies close to the contact between the Mustjala(?) and Kesselaid members (Männik et al. 2024; Fig. 10.1). Similarly, the appearance of *Conochitina tuba* Eisenack in the lowermost Kesselaid Member suggests that the lower boundary of the *C. tuba* Chitinozoan Zone lies close to the same level.

Fig. 10.2. Pulli cliff. Photo: Gennadi Baranov, 2024.

References

Jürgenson, E., Nestor, H., 1990. Locality 5:2. Pulli cliff. In: *Field Meeting, Estonia 1990. An Excursion Guidebook* (Kaljo, D. & Nestor, E. eds). Estonian Academy of Sciences, Tallinn, Estonia, p. 159–160.

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Stop 11: Panga cliff

Peep Männik

Location: Coordinates of the terminal points: west: 58°33´09˝N, 22°17´10˝E; east: 58º34'12'' N, 22º17'49''E; Saare County, Estonia.

Stratigraphy: Telychian (underwater escarpment) and Sheinwoodian, Adavere, Jaani and Jaagarahu RSs.

Status: Cliff is under protection; no hammering, but loose material may be collected.

More information: https://geoloogia.info/en/locality/10235

The Panga cliff is located east of the Küdema Bay, close to the Võhma village in northern Saaremaa (coordinates of its eastern end). It is the highest cliff in Western Estonia, in the Silurian outcrop area (Fig. 11.1). The Silurian cliff is an extensive escarpment. It starts on Gotland in Sweden, continues below the Baltic Sea, and rises again above the sea level on the western coast of Saaremaa. The Panga cliff has two main escarpments, one below and the other above sea level. These escarpments are separated by a shallow-water plateau several hundred meters wide. A surf zone marks the edge of the plateau (Fig. 11.2). The underwater part of the cliff is up to 12 m high. The maximum height of the cliff above sea level is 21.3 m. The cliff ranges arch-shapely along the western coast of the Panga Peninsula, about 3 km from north to south.

The escarpment below sea level consists of dolomitized marlstone and dolomitic argillaceous limestone of Telychian age (upper Adavere and lower Jaani stages). In the cliff above sea level, dolomitised marlstone and argillaceous dolomitic limestone of the Jaani Formation (Jaani Stage) and porous dolostone of the Vilsandi Beds (Jaagarahu Stage) containing small bioherms are exposed. For a detailed description, see Männik & Nestor (2014).

As a prominent landform and scientifically important natural object, the Panga cliff (also known as the Mustjala cliff) is protected by the state. It is also one of the main tourist attractions in Saaremaa.

Fig. 11.1. The main escarpment of the Panga cliff. Photo: Peep Männik.

Fig. 11.2. A surf zone is marking the edge of the lower escarpment at the Panga cliff. Photo: Peep Männik.

References

Männik, P., Nestor, V., 2014. Stop B5: Panga cliff. In *4th Annual Meeting of IGCP 591, Estonia, 10-19 June 2014. Abstracts and Field Guide.* (Bauert, H., Hints, O., Meidla, T., Männik, P. eds), University of Tartu, Tartu. p. 185–187.

Stop 12: Suuriku cliff

Tõnu Meidla and Oive Tinn

Location: Coordinates of the terminal points: west: 58°30´32.65˝N, 21°59´24.14˝E; east: 58°30´22.61˝N and 22°0´15.91˝E; Saare County, Estonia.

Stratigraphy: Sheinwoodian, Jaani Fm (Mustjala and Ninase Mbs), Jaani and Jaagarahu RSs.

Status: Cliff is under protection; no hammering, but loose material may be collected.

More information: https://geoloogia.info/en/locality/12227

The following text is modified from Meidla & Tinn (2015).

The Suuriku cliff (Fig. 12.1), the second highest on Saaremaa Island, is located in north-western Saaremaa. It comprises about 950 m long escarpment along the northern coast of the Tagamõisa Peninsula. The maximum height of the Suuriku cliff reaches 8 m. It is actively abraded and rather unstable, with heaps of limestone debris and blocks below the escarpment pointing at recent collapses.

The description of the section is largely based on the section at the coordinates 58°30´28.48˝N and 22°0´1.76˝E (Fig. 12.2). Six subunits are distinguished in the succession. The thicknesses of the subunits vary in different parts of the cliff (see Fig. 12.3).

Description (from the top):

1) 0.4–1.3 m – grainstone beds (5–12 cm) intercalating with calcareous marl (up to 3 cm);

2) 1.7–3.0 m – thick-bedded oncoidal grainstone, grading into argillaceous wackestone to packstone rich in brachiopods;

3) 0.5–2.2 m – crinoidal grainstone, slowly grading into argillaceous wackestone rich in isolated valves and complete shells of brachiopods; the lower boundary of the unit represents a distinct, slightly undulating surface;

4) 0.2–0.3 m – calcareous marl with limestone pebbles, with crinoidal grainstone lenses (up to 2 cm in thickness) in the lower part and bioclastic packstone lenses and nodules in the upper part;

5) 0.4–0.7 m – cross-bedded crinoidal(?) grainstone, with frequent bryozoans; stromatoporoids and (in some places) oncoids are found in the upper part;

Fig. 12.1. View of the Suuriku Cliff. Photo: Tõnu Meidla.

6) 0.6–1.5 m – calcareous marl with interbeds and nodules of argillaceous limestone, unsorted bioclastic material; stromatoporoids and tabulate corals are common in some intervals;

The lowermost unit (6) represents the Mustjala Member that is overlain by the Ninase Member (units 1-5).

Lens-like bryozoan reefs could be observed near the eastern end of the cliff, in the upper part of the escarpment.

Stratigraphy

In terms of conodont zonation, the Mustjala Member and the lower part of the Ninase Member (intervals 3-6) correspond to the Upper *Kockelella ranuliformis* Condont Zone and the upper part of the Ninase Member (intervals 1-2) comprises the *Ozarkodina sagitta rhenana* Conodont Zone (Männik in Meidla et al. 2014). According to the revised stratigraphy, the appearance of *O. s. rhenana* marks the boundary between the Jaani and Jaagarahu RSs (Männik et al. 2024).

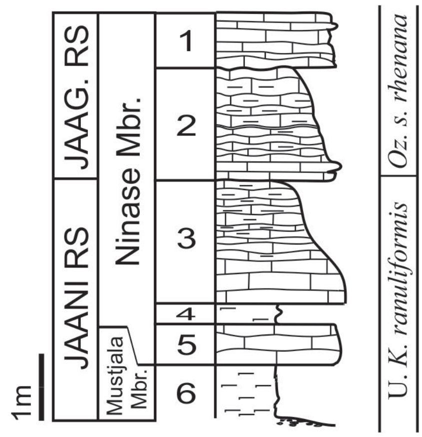

Fig. 12.2. Composite section of the Suuriku Cliff (modified from Meidla et al. 2014). Jaag. RS – Jaagarahu RS.

Environments

The transition from the open shelf mudstones (the Mustjala Member) to shoal fore reef grainstones (the Ninase Member) marks a remarkable shallowing event in the palaeobasin (Nestor and Einasto 1997). The same interval is also exposed in several other sections along the northern coast of Saaremaa. This shallowing marks a distinct stage in the long-term sea level fall throughout the latest Llandovery and Wenlock, culminating near the Wenlock-Ludlow boundary. During this period, the open shelf clay-rich sediments are continuously shifted towards the subsurface area whilst cyclically but progressively shallowing up limestone and dolostone succession is characteristic of the outcrop belt.

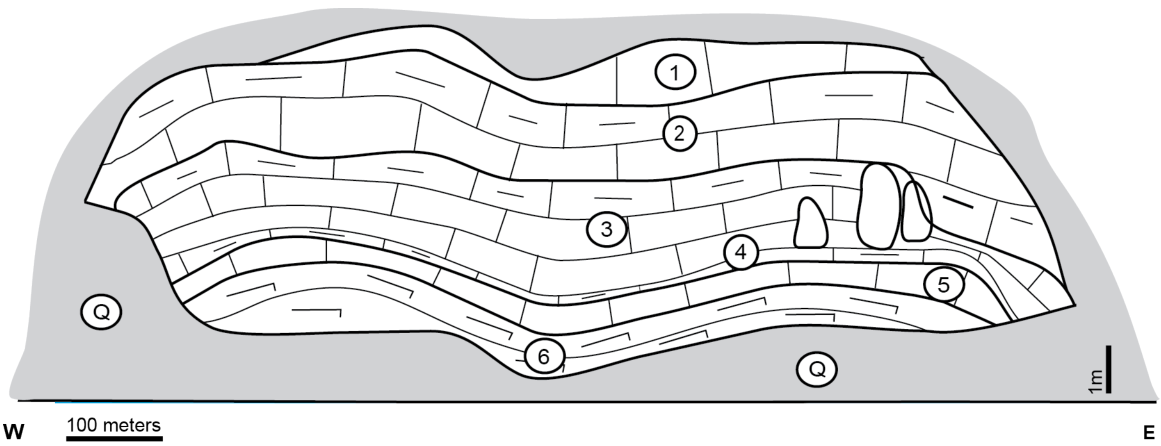

Fig. 12.3. Profile of the Suuriku cliff (Meidla et al. 2014). The principal units distinguished in the succession are shown in the Fig. 12.2 and described in the text.

Fauna

Conodonts. The Upper *Kockelella ranuliformis* and *Ozarkodina sagitta rhenana* conodont zones are recognised in the Suuriku section. Samples from the Upper *K. ranuliformis* Zone are dominated by *Panderodus equicostatus* (Rhodes) and *Wurmiella excavata* (Branson & Mehl), whilst *Ozarkodina sagitta rhenana* (Walliser) is strongly dominated in the upper part of the section (Meidla et al. 2014).

Trilobites. *Encrinurus punctatus* (Wahlenberg) has been recorded (Männil 1978).

Brachiopods. 34 species of brachiopods are identified in this section (Rubel et al. 1991). *Eoplectodonta (Eoplectodonta) duvalii* (Davidson) and *Visbyella visbyensis* (Lindström) are common in the lowermost part of the section (the marls of Mustjala Member), whilst *Rhynchotreta cuneata* (Dalman) and unidentified species of the genera *Whitfieldella, Craniops, Isorthis* and *Dolerorthis* range also into the lower Ninase Member (intervals 2-4), being accompanied by *Atrypa reticularis* (Linnaeus) that makes its first appearance in this interval. The diversity of brachiopods decreases upwards in the section. *Dolerorthis*

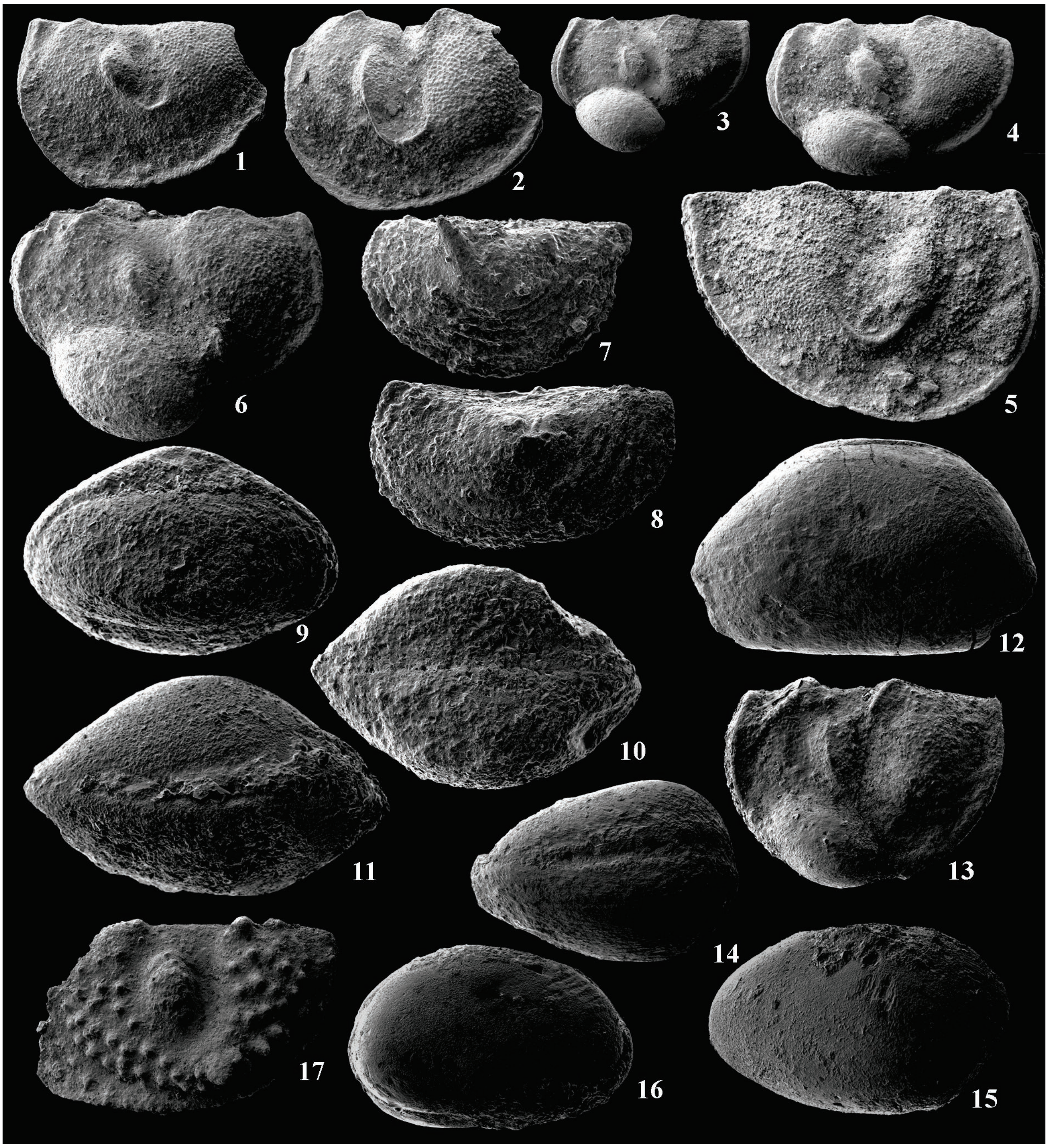

Fig. 12.4. Selected ostracod species from the Suuriku Cliff section. **1** – *Craspedobolbina (Craspedobolbina) ornulata* (Martinsson), incomplete left tecnomorphic valve, x30; **2** – *Craspedobolbina (Craspedobolbina) mucronulata* Martinsson, incomplete left tecnomorphic valve, x31; **3** – *Craspedobolbina (Craspedobolbina) mucronulata* Martinsson, left heteromorphic valve, x21; **4** – *Craspodobolbina (Mitrobeyrichia) unculifera* Martinsson, slightly incomplete left heteromorphic valve, x21; **5** – *Craspodobolbina (Mitrobeyrichia) unculifera* Martinsson, right tecnomorphic valve, x31; **6** – *Craspedobolbina (Craspedobolbina) ornulata* (Martinsson), left heteromorphic valve, x31; **7** – *Schaefericoncha theatri* Schallreuter, right valve, x63; **8** – *Schaefericoncha theatri* Schallreuter, left valve, x53; **9** – *Daleiella ianica* Neckaja, carapace, right view, x62; **10** – *Daleiella ianica* Neckaja, carapace, ventral view, 52; **11** – *Daleiella ianica* Neckaja, juvenile carapace, dorsal view, x101; **12** – *Silenis* aff. *subtriangulatus* Neckaja, slightly incomplete carapace, left view, x42; **13** – *Craspodobolbina (Mitrobeyrichia) unculifera* Martinsson, left tecnomorphic valve, x31; **14** – *Microcheilinella variolaris*? (Neckaja), carapace, dorsal view, x41; **15** – *Microcheilinella variolaris*? (Neckaja), juvenile carapace, left view, x54; **16** – *Microcheilinella variolaris*? Neckaja, carapace, right view, x44; **17** – *Beyrichia (Beyrichia) suurikuensis* Sarv, left, slightly incomplete tecnomorphic valve, x31.

rustica (J. de C. Sowerby), *Microsphaeridiorhynchus nucula* (J. de. C. Sowerby) and *Whitfieldella nitida* (Hall) are the most common species in the upper part of the section, above the reefs (beds 5-6).

Corals. Eight tabulate species of the genera *Palaeofavosites*, *Mesofavosites*, *Syringolites*, *Thamnapora*?, *Subalveolites*, *Halysites, Heliolites* and *Propora* are identified in this section by Klaamann (1961).

Stromatoporoids. Stromatoporoids are common in this section. Nestor (1966) has identified five species: *Clathrodictyon affabile* Nestor, *Densastroma pexisum* (Yavorsky), *Eostromatopora impexa* (Nestor), *Petridio-*

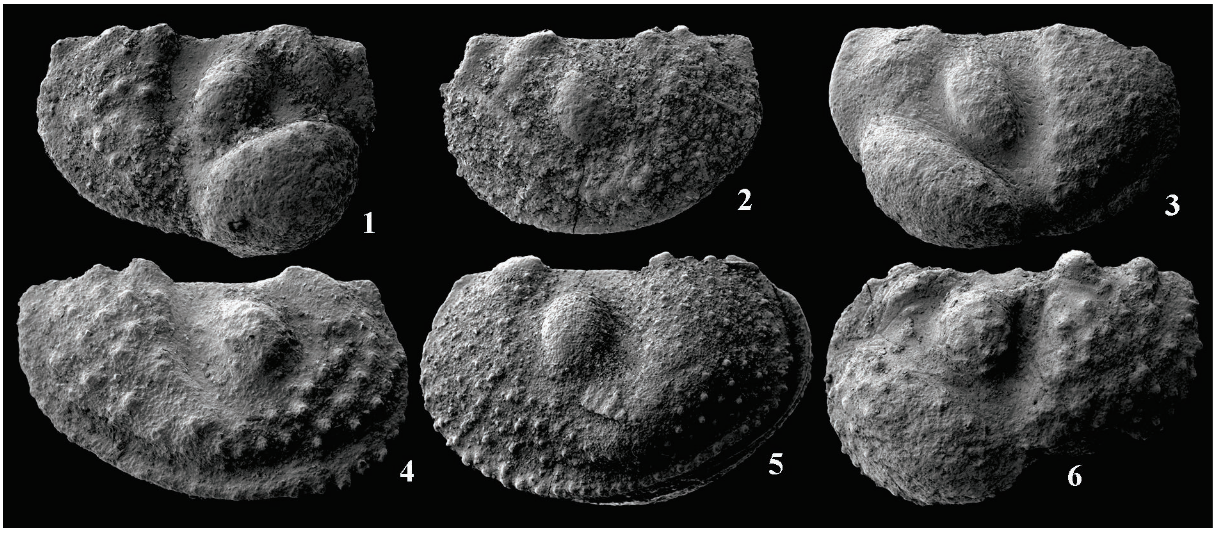

Fig. 12.5. Selected beyrichiids from the Suuriku Cliff section. **1** – *Beyrichia (Beyrichia) bicuspis* (Kiesow), right heteromorphic valve, x26; **2** – *Beyrichia (Beyrichia) bicuspis* (Kiesow), left tecnomorphic valve, x26; **3** – *Beyrichia (Beyrichia) suurikuensis* Sarv, left, slightly incomplete heteromorphic valve, x27; **4** – *Beyrichia (Beyrichia) suurikuensis* Sarv, right tecnomorphic valve, x30; **5** – *Beyrichia (Beyrichia) halliana* Martinsson, tecnomorphic carapace, left view, x21; **6** – *Beyrichia (Beyrichia) halliana Martinsson,* left heteromorphic valve, x21.

stroma simplex (Nestor) and *Simplxodictyon simplex* Nestor.

Ostracods. A detailed ostracod log has never been compiled for this section. The main part of this section comprises the grainstones of the Ninase Member with a very poor ostracod yield. This is likely due to several reasons: sorting of the coarse-grained sediment, destruction of the fragile shells in the coarse carbonate sand and preparation difficulties. Most of the ostracod data comes from the Mustjala Member, which is the lowermost part of the section. The documentation of ostracods in the Ninase Member in this section is mostly based on the clay-lenses related to the bryozoan reefs.

The ostracod assemblage at Suuriku (Figs 12.4 and 12.5) represents the second successive ostracod fauna in the Silurian of Estonia. The assemblage of beyrichiid ostracods is dominated by *Beyrichia (B.) halliana* Martinsson (Fig. 12.5:5-6), *Beyrichia (B.) suurikuensis* Sarv (Fig. 12.4:17, Fig. 12.5:3-4), *Craspedobolbina (Mitrobeyrichia) unculifera* Martinsson (Fig. 12.4:4-5) and *Clavofabella juvenca* Sarv. *Beyrichia (Beyrichia) bicuspis* Kiesow (Fig. 12.5:1-2) makes its first appearance in the Ninase Formation, as well as *Craspedobolbina (Craspedobolbina) ornulata* Martinsson (Fig. 12.4:1, 12.4:6). *Apatobolbina gutnica* Martinsson and *Craspedobolbina (Craspedobolbina) mucronulata* Martinsson (Fig. 12.4:2-3) are also referred to by Sarv (1968, 1970).

The Mustjala Member was, for a long time, thought to be the appearance level of the first Silurian primitiopsids. There is a considerable gap between the Ordovician *Baltocyamus primarius* Meidla (Anisocyaminae; Oandu Regional Stage of Estonia, lower Katian; Meidla 1995, 1996) and the first Silurian primitiopsids in the lower Wenlock. *Venzavella germana* Sarv is one of the oldest representatives of this family in the Silurian.

The record of Metacopina is incomplete, being limited to *Eoprimitia*? *versipella* Neckaja (Thlipsuridae), *Daleiella ianica* (Neckaja) (Fig. 12.4:9-11), *Microcheilinella variolaris* (Neckaja) (Fig. 12.4:14-16) and *Microcheilinella acutafinis* (Neckaja), all listed species being so far recorded in this section from the Mustjala Member only.

Pseudoaparchites gregarius (Neckaja) (Cytherelliformes, Platycopina) has also been recorded in this section, but the level could not be specified.

Other fauna. Lens-like bryozoan reefs near the eastern end of the cliff, in the upper part of the escarpment, are mainly built by the bryozoans *Ceramopora* and *Lioclema,* but branching tabulates, stromatoporoids, echinoderms and, less commonly, ostracods and brachiopods are present in the clay lenses between the bryozoan encrustations (Aaloe & Einasto 1970; Rubel et al. 1991). Ausich et al. (2012, 2015) have identified three genera of crinoids from the marlstone interlayers of the Ninase Member: *Enallocrinus, Eucalyptocrinites* and *Protaxocrinus*.

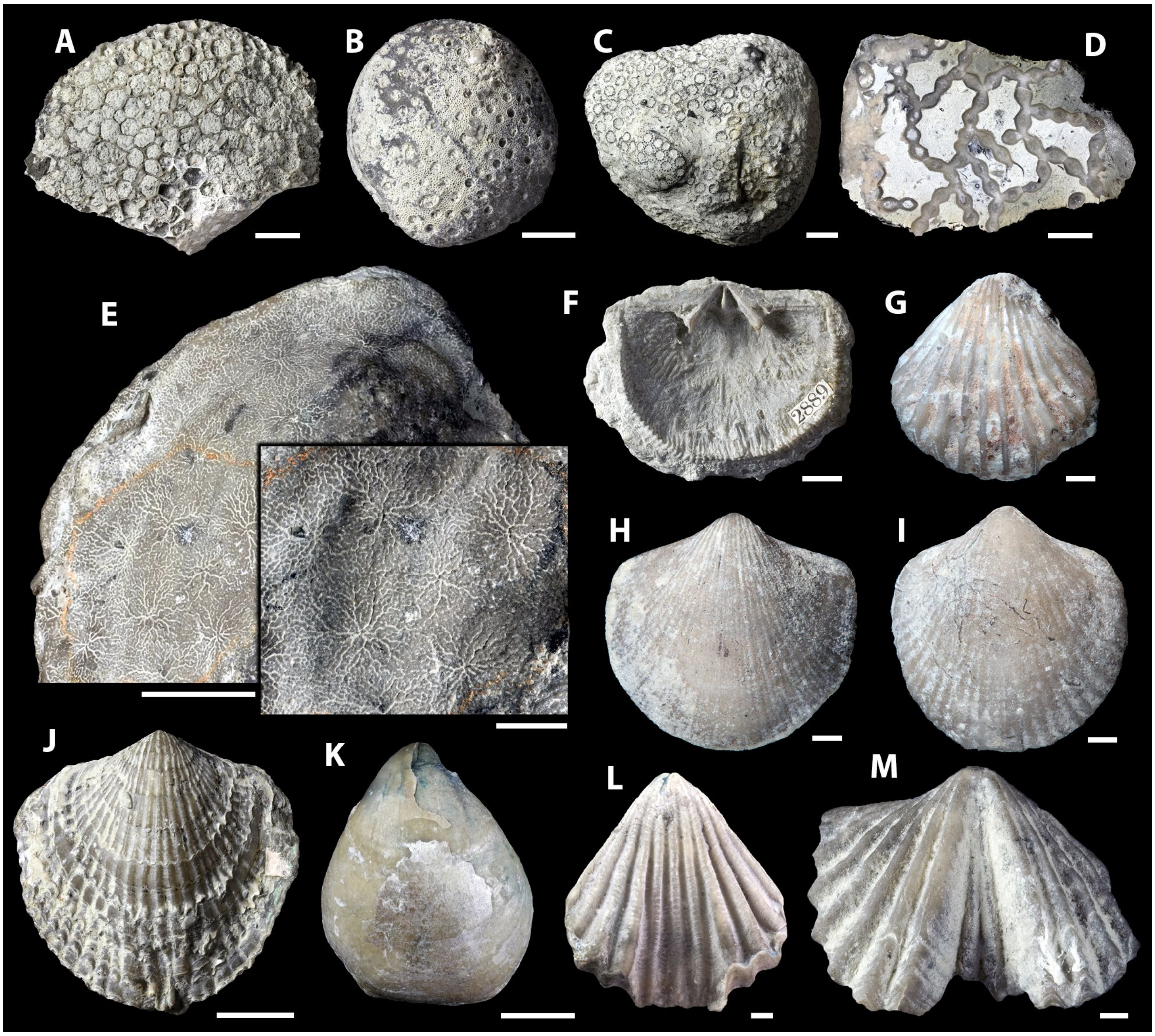

Fig. 12.6. Selected macrofossils of the Suuriku cliff, Jaani Regional Stage. Scale bars E – 1 cm, A–D, E close-up, F, J, K – 5 mm; G–I, L, M –1 mm. **A**–**D** tabulate corals; **A** – *Favosites serratus* Sokolov, GIT 180-715; **B** – *Heliolites interstinctus* (Linnaeus), GIT 529-151; **C** – *Propora* sp., GIT 529-149; **D** – *Halysites senior* Klaamann, GIT 180-367. **E** – stromatoporoid *Stromatopora impexa* Nestor and close-up from the upper surface with astrorhizae, GIT 435-44. **F–M** brachiopods**;** **F** – *Dolerorthis rustica* (J. de C. Sowerby), GIT 128-36; **G** – *Microsphaeridiorhynchus nucula* (J. de C. Sowerby), GIT 853-28; **H** – *Visbyella visbyensis* (Lindström), GIT 128-130; **I** – *Resserella canalis* (J. de C. Sowerby), GIT 128-149; **J** – *Atrypa* (*Atrypa*) *reticularis* (Linnaeus), GIT 130-129; **K** – *Whitfieldella nitida* (Hall), GIT 130-188; **L** – *Rhynchotreta cuneata* (Dalman), GIT 173-13; **M** – *Neoplatystrophia jaaniensis* (Rubel), GIT 128-112.

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Stop 13: Soeginina cliff

Tõnu Meidla, Oive Tinn and Peep Männik

Location: Coordinates of the terminal points of the cliff: north-east - 58°17’20.22“ N, 21°50’30.05“ E; south-west - 58°55.96“ N and 21°49´54.73“ E; Saare County, Estonia.

Stratigraphy: Homerian–Gorstian, Rootsiküla Fm, Rootsiküla RS.

Status: Cliff is under nature protection; no hammering, but loose material may be collected.

More information: https://geoloogia.info/en/locality/12650

The following text is modified from Meidla et al. (2014).

The Soeginina cliff (Figs 13.1–13.3) is located in western Saaremaa, in the south part of the Vilsandi National Park. In this section upper Vesiku, Anikaitse and Soeginina Beds of the Rootsiküla Formation are exposed.

The Soeginina cliff is about 1000 m long escarpment along the western coast of Saaremaa. Its maximum height reaches almost 4 m. It is actively abraded by the sea and, from time to time, some collapses may occur.

Description of the section

Description of the section (58°17’5.68“ N, 21°50’18.06“ E; from base; Fig. 13.1) is modified from Viira & Einasto (2003):

Vesiku Beds

I (0.8 m) – laminated argillaceous dolomitic mudstone with large (over 1 m in diameter) *Stratifera*-type stromatolites and fragments of eurypterids, cephalopods and leperditiid arthropods. The upper boundary is marked by a distinct pyritized discontinuity surface.

II (up to 1.8 m) – yellowish-brown mottled bioturbated argillaceous *Eurypterus* dolostone with spots of fine dispersed pyrite. Lamination is preserved locally only. The upper boundary is a distinct pyritized discontinuity surface.

Anikaitse and Soeginina beds

IIIa (up to 0.2 m) – brownish-grey dolomitic bioturbated bioclastic wackestone with relatively large irregular oncoids, and stromatolitic encrustations on bedding planes. Viira and Einasto (2003) described this interval as the Anikaitse Beds (in Fig. 13.1, beds IIIa and IIIb are merged together), according to Nestor (1997), this interval corresponds to the basal part of the Soeginina Beds.

IIIb (up to 0.3 m) – light brown dolomitic unsorted bioclastic packstone to grainstone with oncoids, leperditiid arthropods, gastropods, nautiloids, bivalves, bryozoans and calcareous algae (*Solenopora*). A lens-like interbed of flat-pebble conglomerate occurs at the base of the bed.

IV (0.2–0.5 m) – light grey massive unfossiliferous(?) dolomitic mudstone;

V (0.3–1.0 m) – light brownish-grey vuggy thin-bedded fine-grained bioclastic-pelletal dolomitic grainstone with occasional accumulations of leperditiid arthropods and gastropods. The upper boundary is a distinct discontinuity surface.

VI (up to 1.2 m) – dark brown vuggy varygrained pelletal-bioclastic dolomitic floatstone with oolites, small pebbles of light grey dolomitic mudstone and (moulds of) bivalves, gastropods and leperditiid arthropods, intercalated with light grey dolomitic mudstone. Vugs are occasionally filled with sparry calcite. On three levels, 0.3–0.4 m high *Stratifera*-type stromatolites are present.

The uppermost Vesiku Beds exposed in this section represent one of the shallowest water/lagoonal facies in the Silurian succession of Estonia; the overlying Anikaitse and lower Soeginina Beds correspond to the lower, transgressive part of the uppermost cycle in the Rootsiküla Formation.

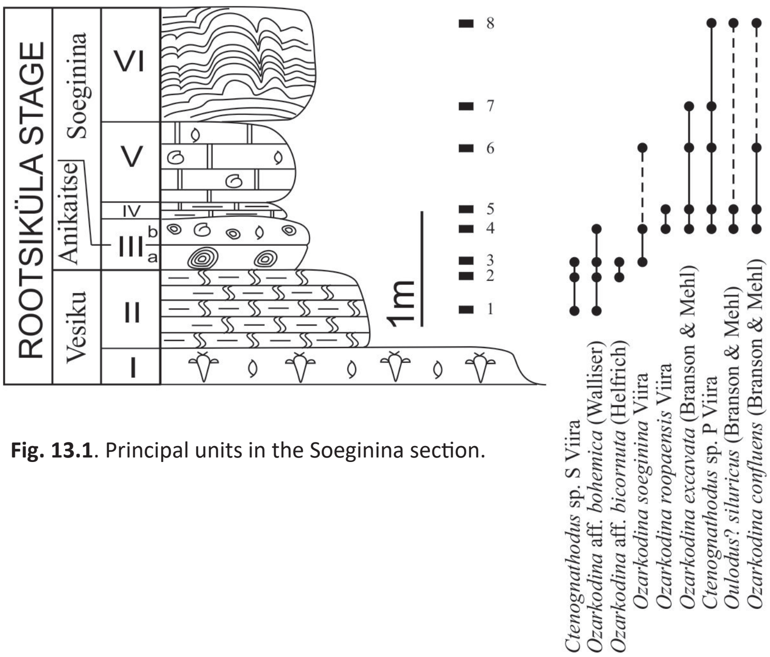

Fig. 13.1. Principal units in the Soeginina section.

Fig. 13.2. Soeginina Cliff. Photo: Peep Männik.

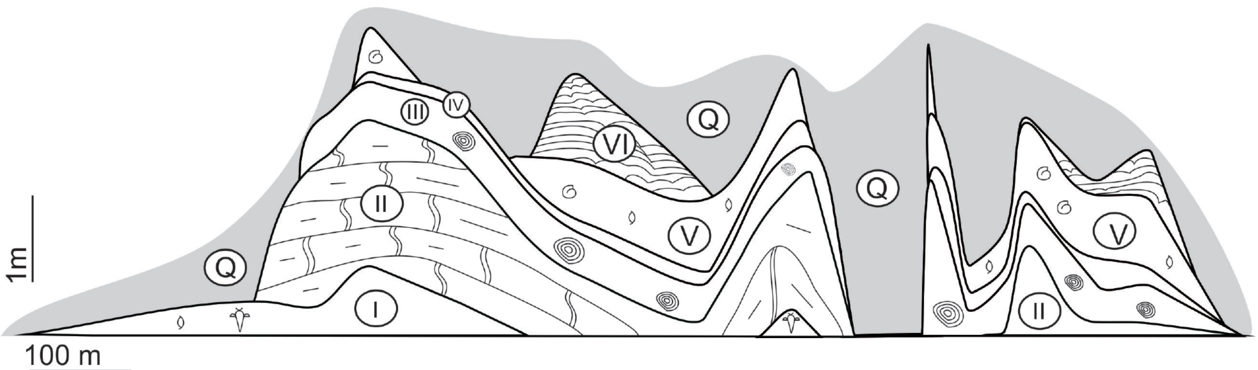

Fig. 13.3. Profile of the Soeginina Cliff. The principal units distinguished in the succession are shown in Fig. 13.1 and described in the text.

Stratigraphy

Due to rare occurrences of age-diagnostic fauna in the Rootsiküla Stage, its age has been debated for a long time, and its correlation with the global stratigraphical scheme has been repeatedly revised. Tentatively, Kaljo et al. (1970) attributed the stage to Ludlow. H. Nestor (1997) correlated the Rootsiküla Stage with the upper Wenlock. V. Nestor (2007) identified the *Sphaerochitina lycoperdoides* Chitinozoan Zone, the global topmost Wenlock zone, in the Viita Beds in the Ohesaare drill core and, based on analysis of chitinozoan distribution in several sections in Estonia and western Latvia, concluded that the Soeginina Beds might be of Ludlow in age and probably should be attributed to the Paadla Regional Stage. According to Märss & Männik (2013), the Soeginina Beds yield the *Paralogania martinssoni* Vertebrate Zone fauna and might correlate with the (lowermost part of) early Ludlow *Kockelella crassa* Conodont Zone.

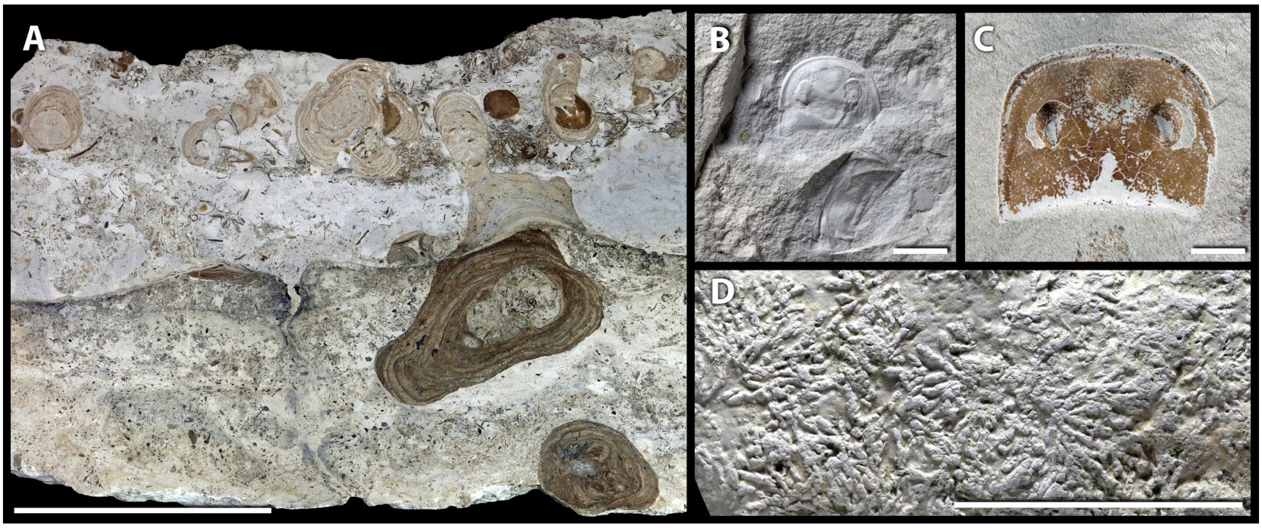

Fig. 13.4. Selected fossils from the Soeginina cliff, Rootsiküla Regional Stage. Scale bars A, D – 5 cm; B – 1 cm; C –5 mm. **A** – dolomitic limestone with oncoids, boundary between Anikaitse and Soeginina Beds; GIT 378-243. **B, C** – *Eurypterus tetragonophthalmus* Fischer, Vesiku Beds; **B** – GIT 200-128, **C** – TUG 1763-4. **D** – trace fossil *Chondrites* isp., Vesiku Beds; GIT 362-696.

Fossils

The Soeginina section is palaeontologically poorly characterised. The lower part of the succession contains fragments of *Eurypterus remipes tetragonophthalmus* Fischer. Complete specimens are extremely rare. Oncoids in the middle part of succession are often formed around coralline alga *Solenopora* sp. and contain cyanobacterial fragments (genus *Bevocastria* according to Kõrts 1991). Moulds of bivalves and gastropods, common in the upper part of the succession, are too poorly preserved to be identified. The leperditiid arthropods recorded in this section are tentatively attributed to *Herrmannina* (Viira & Einasto 2003). Märss (1986) identified *Thelodus laevis* (Pander 1856) and *Paralogania martinssoni* (Gross 1967) in this section. According to Viira & Einasto (2003) conodonts in the Vesiku and Anikaitse Beds are dominated by *Ctenognathodus* sp. S Viira (occurs in this interval only), also *Ozarkodina* aff. *bohemica* (Walliser) is quite common. In the lowermost Soeginina Beds, in the unit IIIb (Fig. 13.1), several new taxa (*Ctenognathodus* sp. P Viira, *Oulodus*? *siluricus* (Branson & Mehl), *Ozarkodina confluens* (Branson & Mehl), *Wurmiella excavata* (Branson & Mehl), etc.) appear. No taxon in these faunas is age-diagnostic, but the appearance of *O. confluens* and *W. excavata* in the lowermost Soeginina Beds suggests some improvement in environmental conditions.

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Stop 14: Kaarma quarry

Leho Ainsaar and Imre Andreas Martin

Location: Latitude 58°20´17˝N, longitude 22°28´30˝E; Saare County, Estonia.
Stratigraphy: Gorstian, Paadla RS, Sauvere and Himmiste beds.
Status: Active quarry; please follow safety instructions. Sampling and fossil collecting are welcome.
More information: https://geoloogia.info/en/locality/12672

The Kaarma quarry is located 12 km north of the town of Kuressaare, next to the Uduvere-Saia road. An interval of lagoonal microlaminated argillaceous dolostones of the Paadla Formation (Paadla RS, Ludlow) is exposed in this quarry.

Description of the section

According to Einasto (1990), the exposed section can be divided into three parts with eight distinctive beds. The upper part (Fig. 14.1, bed 1) is yellowish-grey vuggy massive secondary dolostone containing imprints of gastropods, bivalves, leperditiid arthropods (*Hermannina*), bryozoans, calcareous algae (*Solenopora*), brachiopods, small tabulate corals and encrusted stromatoporoids. In the southeastern part of the quarry, this bed is only partly dolomitized and contains up to 0.15 m thick lenses and wedging-out interbeds of skeletal grainstone with several wavy discontinuity surfaces.

The middle part of the section (beds 2–7) comprises the typical wavy microlaminated argillaceous "Kaarma dolo-

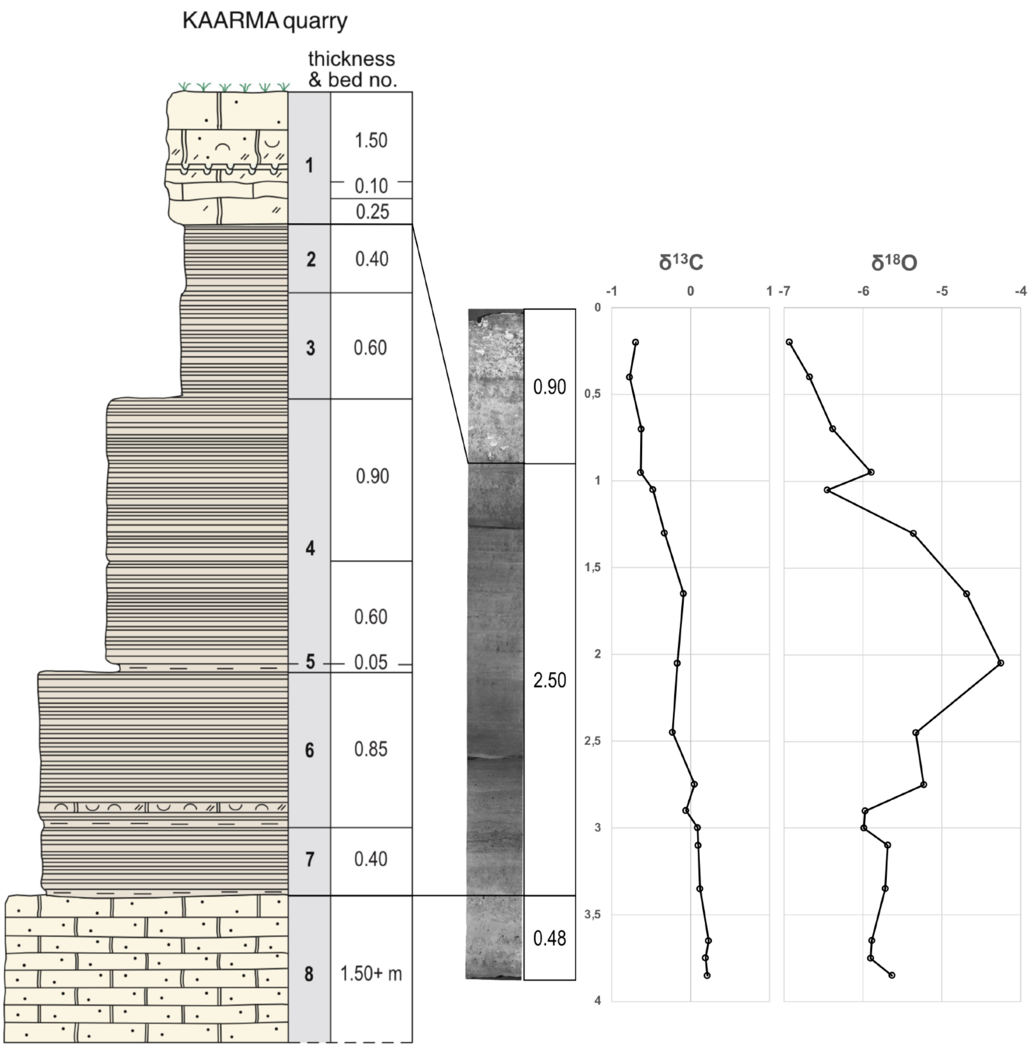

Fig. 14.1. Kaarma quarry section with new isotopic data. Lithological column by Rein Einasto (1990), photo column by Tiia Tuuling (1987).

Fig. 14.2. Extraction of dimension stone in the Kaarma quarry. Photo: Olle Hints, 2021.

mite" with distinct irregular lamination and microcycles. The total thickness of the Kaarma lagoonal dolostone is up to 3.8 m in the Kaarma quarry. A bed of argillaceous dolostone (bed 5) is subdividing the lower massive blocks of this rock. The Kaarma dolostone is very poor in fossils. Moulds of gastropods, bivalves and leperditiids are found at only some levels. The microlaminated structure of dolostone is disturbed by distinct bioturbation, showing limited life activity in this saline lagoonal environment. Rare thin intervals with dissolved traces of shelly fossils might have been formed by occasional storm events. The dolostone contains about 5–22% insoluble residue, mainly siliciclastic clay and silt, with authigenic pyrite admixture (Einasto 1962; Tuuling 1987). The basal part of the section (bed 8) is represented by brownish-grey medium-bedded dolostone, which originally might have been pelletal limestone (Einasto 1990).

Biostratigraphy

According to Einasto (1990), the Kaarma lagoonal dolostone represents the upper part of a mesocyclite, tentatively attributed to the junction of the Sauvere and Himmiste beds of the Paadla RS. The Paadla RS is including the interval of the global Mid-Ludfordian Lau carbon isotope excursion and the Lau/Kozlowskii extinction event (Männik 2014). The prominent Lau isotope excursion marks a global cooling or glacial event. It has been described within the *Ozarkodina snajdri* Conodont Biozone (Fryda *et al*. 2021), which is largely missing in Estonian sections due to the stratigraphic gap (Männik 2014). However, the exact stratigraphic position of the Kaarma lagoonal beds in relation to the Lau event, is not clear; it has been shown both below (Männik 2014) and above (Männik 2015) the *O. snajdri* Conodont Biozone. Recent analysis of faunas (conodonts, vertebrates) in this interval suggests that Sauvere and Himmiste beds are of late Gorstian age (Männik *et al*. 2024) and older than the Lau event.

Chemostratigraphy

We analyzed 17 samples from rock plates collected by Tiia Tuuling (1987; TUG 82 in Tartu University collection) for stable C and O isotopic composition in the laboratory of the Department of Geology, University of Tartu. The bulk rock $\delta^{13}C_{carb}$ values show an upward decreasing trend by 1‰ through the interval, whereas $\delta^{18}O$ values are 2–3‰ higher in the middle part of the lagoonal sediments compared to the surrounding beds. Both values are in the range of normal marine lower Palaeozoic carbonates. The data show no evidence for the Mid-Ludfordian Lau isotope excursion or another distinct trend of the global carbon isotope curve.

Fig. 14.3. Example of lagoonal dolostone from the Kaarma quarry, Paadla Regional Stage. Scale bar 1 cm. The topmost bed from the Kaarma quarry in cross-section, GIT 379-292.

Practical use of the Kaarma dolostone

The Kaarma dolostone can be well processed and is weather-resistant; therefore, it has been widely used as a building and carving stone since medieval times. Examples include the Kuressaare castle, many churches and manor houses in Saaremaa, as well as modern buildings and monuments all over the country (Perens 2012).

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Stop 15: Kaugatuma and Lõo coastal outcrops

Olev Vinn and Ursula Toom

The Přidolian exposures on Saaremaa Island are mostly represented by small coastal cliffs. On the western coast of the Sõrve Peninsula, the Kaugatuma Regional Stage is exposed in several places.

Kaugatuma cliff and coastal outcrop near the cliff

Location: Latitude 58.12036°N, longitude 22.19053°E; Sõrve Peninsula, Saare County, Estonia.
Stratigraphy: Přidoli, Äigu Beds of the Kaugatuma Fm, Kaugatuma RS.
Status: Cliff is under protection; no hammering, but loose material may be collected.
More information: https://geoloogia.info/en/locality/10078

The Kaugatuma cliff (after Einasto 1990) is an about 2.5 m high outcrop (Fig. 15.1) on the western coast of the Sõrve Peninsula, a few kilometres south of its northern neck and about 100 m from the coastline. The cliff is the historical stratotype of the Kaugatuma Regional Stage. The section represents the middle part of the Äigu Beds of the Kaugatuma Formation. The rocks of two different sedimentary facies can be seen in the regressive succession from the base of the section (Fig. 15.2):

0.5+ m – greenish-grey nodular argillaceous wackestone, mainly containing skeletal debris of echinoderms and brachiopods but also ostracods, trilobites, gastropods, bryozoans and fish fragments. The layer was formed in normal marine open-shelf conditions.

1.5+ m – yellow-grey coarse-grained wavy-bedded crinoidal limestone containing skeletal debris of variable grain size. Some bedding plains show erosion marks. Large colonies of *Syringopora blanda* Klaamann (about 30 cm in diameter) are found. The layer was formed in normal marine fore-reef conditions.

The cliff also contains several vertebrate fossils. *Nostolepis striata* Pander, *Gomphonchus sandelensis* (Pander), *Poracanthodes porosus* Brotzen and *Thelodus parvidens* Agassiz occur in the lower part of the section, and *Nostolepis gracilis* Gross is found in the upper part. Most of the chitinozoans of the Kaugatuma cliff represent long-ranging species; only *Salopochitina filifera* (Eisenack) is characteristic of the upper Äigu Beds.

Outcrop on the beach near the Kaugatuma cliff is palaeontologically the most interesting part of the Kaugatuma section. It is the horizontal exposure of rocks on the beach at the northern end of the cliff (at the water line). The beach exposure is one of the world's richest Pridoli crinoid localities (Vinn 2014). The outcrop is about 0.5–0.6 m high and 60–70 m long. The section is represented by yellow-grey, coarse-grained,

Fig. 15.1. Kaugatuma cliff. Photo: Olle Hints, 2021.

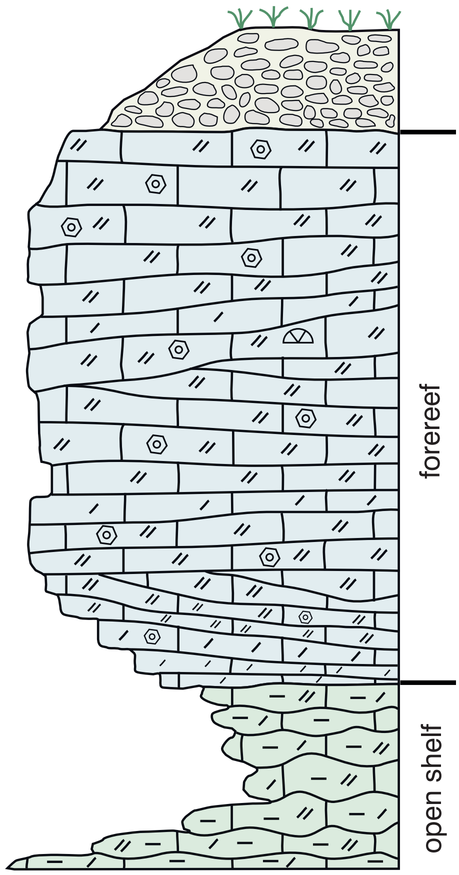

Fig. 15.2. Kaugatuma cliff section after Einasto (1990), from Vinn (2014).

Fig. 15.3. A – ripple marks at the Kaugatuma-Lõo ripple-mark coast, Kaugatuma Regional Stage. **B, C** – beach near the Kaugatuma cliff, Kaugatuma Regional Stage. Scale bars 5 mm. **B** – crinoid grainstone, GIT 403-308; **C** – holdfast of *Enallocrinus* sp., GIT 405-302.

wavy-bedded crinoidal limestones formed in active hydrodynamic conditions and containing overturned stromatoporoids. The section also contains greenish-grey argillaceous limestones and marls formed in a relatively calm shallow-water marine environment. The marl and argillaceous limestone layer is extremely rich in fossils and contains abundant *in situ* buried large crinoid holdfasts of *Enallocrinus* sp.; (Fig. 15.3), open shelf fore-reef *in situ* buried tabulate corals, and stromatoporoids. The other important fossil groups are brachiopods, rugosans, cephalopods, and trilobites. The larger fossils of the argillaceous layer are often heavily encrusted with bryozoans, auloporids, microconchids, cornulitids, and *Anticalyptraea* tubeworms.

Lõo cliff

Location: Latitude 58.096291°N, longitude 22.174472°E; Sõrve Peninsula, Saaremaa, Estonia.
Stratigraphy: Přidoli, Äigu Beds of the Kaugatuma Fm, Kaugatuma RS.
Status: Cliff is under protection; no hammering, but loose material may be collected.
More information: https://geoloogia.info/en/locality/10032

The Lõo Cliff (after Märss 2003) is situated on the western coast of the Sõrve Peninsula, near the Lõo lighthouse, about 2 km to the south of the Kaugatuma cliff. The Lõo cliff is about 1 m high and is overgrown by grass and brushwood, making it hardly visible. The cliff is the type locality for the Lõo Beds of the Kaugatuma RS. The rocks of the cliff are similar to those seen in the upper part of the Kaugatuma cliff – crinoidal limestones with colonies of the coral *Syringopora blanda* Klaamann. In addition to these unbroken tabulate corals, which are preserved in the growth position, many other corals, brachiopods, ostracods, and fish scales occur.

Kaugatuma-Lõo ripple-mark coast (after Einasto 1990)

Location: Latitude 58.11389°N, longitude 22.18408°E; Sõrve Peninsula, Saaremaa, Estonia.
Stratigraphy: Přidoli, Äigu Beds of the Kaugatuma Fm, Kaugatuma RS.
Status: Cliff is under protection; no hammering, but loose material may be collected.
More information: https://geoloogia.info/en/locality/13834

Large east-west directed well-preserved Silurian ripple marks are exposed on a 200 m long seashore between the Kaugatuma and Lõo cliffs (Fig. 15.3), about 1 km south of the Kaugatuma cliff. These are observable only during the low stand of the sea level. Ripple marks are best preserved in a 30 cm thick interval of the section immediately underlying the basal part of the cliff. The distance between the rounded crests is 40–60 cm (max up to 80 cm), with a height of 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. The beds with ripple marks are bioturbated, and the planar trace fossil *Zoophycos* is well-preserved and common (Vinn & Toom 2015).

Fossils

The Kaugatuma outcrops are rich in fossils and have gained the interest of palaeontologists for almost 200 years. In the 19th century, E. Eichwald and Fr. Schmidt actively visited Saaremaa and published the first descrip-

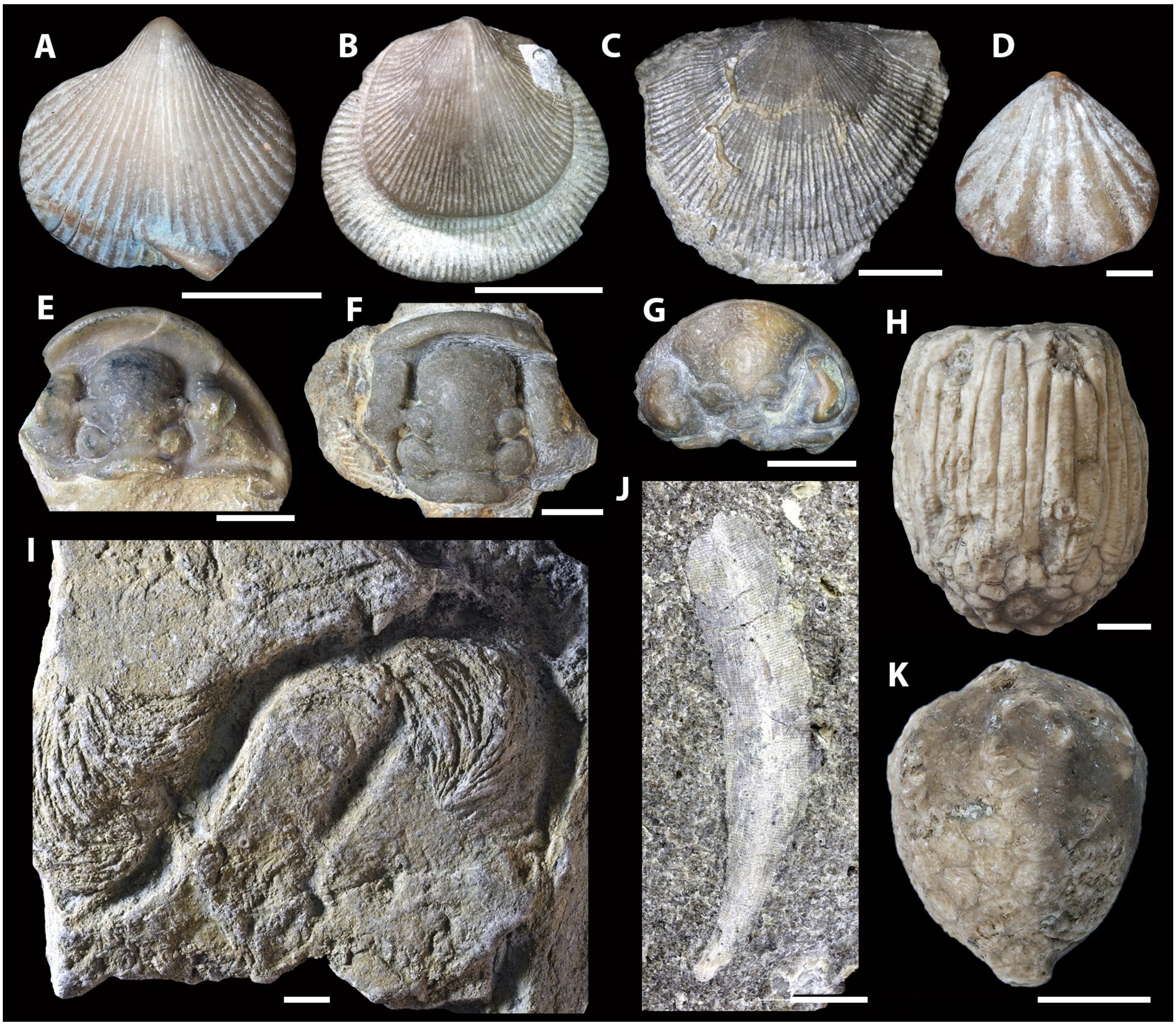

Fig. 15.4. Selected fossils of the Kaugatuma outcrops, Kaugatuma Regional Stage. Scale bars I, J – 1cm; A–C, E–H, K – 5 mm; D – 1 mm. **A–D** brachiopods; **A** – *Homoeospira baylei* (Davidson), GIT 130-159; **B** – *Dalejina hybrida* (J. de C. Sowerby), GIT 128-83; **C** – *Shaleria* (*Janiomya*) *ornatella* (Davidson), GIT 506-1992d; **D** – *Ancillotoechia bidentata* (Hisinger), GIT 173-63. **E–G** trilobites; **E** – *Calymene schmidti* Männil, GIT 187−29; **F** – *Calymene kaugatumaensis* Männil, GIT 187−22; **G** – *Eophacops helmuti* Männil, GIT 328-7; **H, K** crinoids; **H** – *Eucalyptocrinites tumidus* Ausich, Wilson &Vinn, GIT 405−243; **K** – *Saaremaacrinus estoniensis* Ausich, Wilson &Vinn, TUG 1395-3. **I** – planar trace fossil *Zoophycos* isp., GIT 362−47. **J** – bryozoan *Ptilodictya lanceolata* (Goldfuss), GIT 420-113.

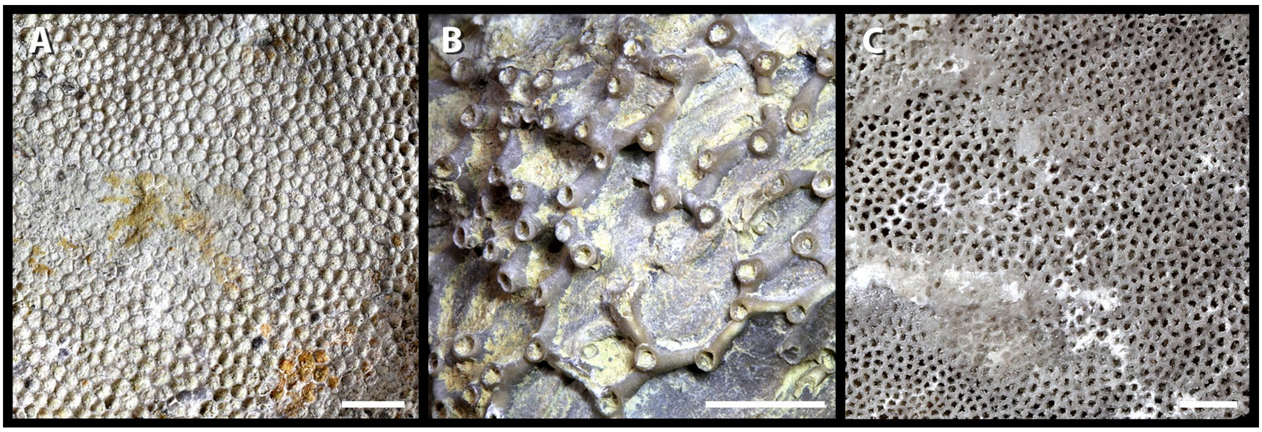

Fig. 15.5. Selected tabulate corals of the Kaugatuma cliff, Kaugatuma Regional Stage. Scale bars 5mm. **A** – *Favosites hisingeri* Milne-Edwards et Haime, GIT 90-40; **B** – *Aulopora amica* Klaamann, GIT 354-889-1; **C** – *Multisolenia reliqua* Sokolov, GIT 180-537.

tions and faunal lists (Eichwald 1854; Schmidt 1858) of outcrops. For now, more than 100 species are identified in Kaugatuma outcrops (Vinn et al. 2024). The crinoid assemblage at Kaugatuma is impressive. Ausich and his coauthors (2012, 2015) have identified eight different genera: *Calliocrinus, Desmidocrinus, Enallocrinus, Eucalyptocrinites, Methabocrinus, Protaxocrinus, Saaremaacrinus* and *Velocrinus*. Corals and stromatoporoids are common in the section. Sokolov (1952, 1955) and Klaamann (1962) have identified 11 species of the tabulate coral's genera *Aulopora, Favosites, Multisolenia, Paleofavosites, Subalveolites* and *Syringopora*. The record of rugose corals is incomplete and needs revision. Stromatoporoid assemblage consists of three species, including *Densastroma astroites* (Rosen). It is noteworthy that Baron von Rosen was the first to use thin sections for the investigation of stromatoporoid structure (1867). Most diverse macrofossils at Kaugatuma outcrops are bryozoans, represented by 17 species of the genera *Astroviella, Callocladia, Cyphotrypa, Eichwaldictya, Eostenopora, Eridotrypella, Fenestella, Fistulipora, Leptotrypa, Leptotrypella, Mediaporina, Orbipora, Orthopora* and *Ptilodictya* (Pushkin et al. 1991). Six species of trilobites are recorded from these outcrops, the most abundant of which are calymenids (Männil 1983).

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Stop 16: Ohesaare cliff

Tiiu Märss

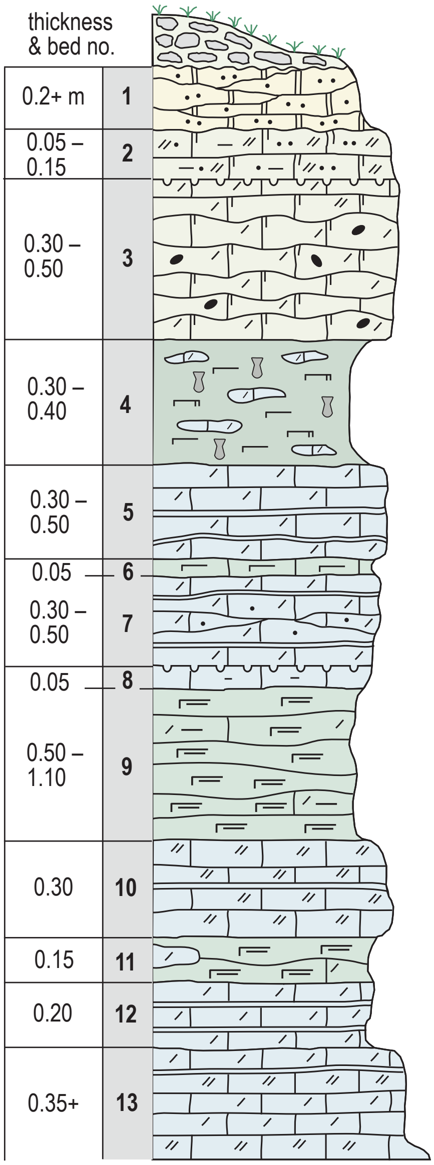
Location: Latitude 58°0´2˝N, longitude 22°1´10˝E; Sõrve Peninsula, Saare County, Estonia.
Stratigraphy: Přidoli, Ohesaare Fm, Ohesaare RS.
Status: Cliff is under protection; no hammering, but loose material may be collected.
More information: https://geoloogia.info/en/locality/12270

The following text is modified after Märss and Nestor (2014).

The Ohesaare (or Ohessaare) cliff is located on the western coast of the Sõrve Peninsula near Ohesaare village, 2.5 km southwest of Jämaja church. Carbonate rocks of two facies belts, the high-energy shoal belt and open shelf belt, which formed in the regressive succession, can be seen in this outcrop.

The lower beds of the Ohesaare RS, the highest stage in the Silurian of Estonia, are exposed here. This outcrop serves as a stratotype of the Ohesaare RS and is one of the best-known Silurian localities in Estonia. Being a famous fish locality, it has been known already since the pioneering work by C. Pander in 1856. It also has attracted attention as the outcrop with the youngest Silurian sedimentary rocks exposed in the entire Baltic area. The rocks in the section correspond to the *Monograptus transgrediens* graptolite biozone, indicating a late Pridoli age (Hints 2008) and contain a rich association of different fossils, including fishes, brachiopods, molluscs, trilobites, trace fossils, ostracods, conodonts, etc.

The Ohesaare cliff is over 600 m long and up to 4 m high. The total thickness of the exposed bedrock is 3.5 m, whereas the thicknesses of individual beds vary considerably throughout the extent of the outcrop.



Description of the section

The section is characterised by the intercalation of thin-bedded limestones and marlstones. The intervals containing relatively few thin marlstone interlayers form three protruding ledges in the cliff section: I – beds 2–3, II – beds 5–7, III – beds 10–13. Limestones are mostly with a biomicritic texture (skeletal packstone) in the middle part of the section but biosparitic (skeletal grainstone) in its upper part (bed 2) and especially in the lower parts (beds 10 and 13). A few lens-shaped intercalations of cross-bedded, fine-grained, pelletal-skeletal grainstones are also found in the middle part of the section, in beds 7 and 9.

Marlstone interlayers may have very high clay content – in some instances, plastic carbonate clays can be observed. The rocks in the upper beds of the outcrop (1–4) are somewhat dolomitized.

Some distinct interlayers are found in this rather monotonous section. The lower part of the section reveals a layer of coarse-grained skeletal grainstone to coquinoid rudstone (bed 10) with a 3–5 cm thick interbed of argillaceous marlstone in the middle. A 2–5 cm thick interlayer of fine-grained limestone (bed 8), pierced by thin vertical burrows filled with light green marl, occurs 0.5–1.0 m higher. Still 0.3–0.5 m higher, there is a thin (5 cm) interlayer (bed 6) of light green calcareous marlstone containing vertical cracks with brownish granular infilling.

A layer of greenish-grey marlstone (bed 4), containing abundant shells of *Grammysia obliqua* buried in a living position, forms a distinct recession in the upper half of the cliff. The section ends with an up to 20 cm thick layer (bed 1) of fissile, wavy- to cross-bedded laminated calcareous siltstone preserved only in the southern end of the cliff section. It is underlain by a 5–15 cm thick interbed (bed 2) of light grey silty skeletal grainstone, the upper surface of which bears large ripple marks, and the lower boundary displays a hardground.

Fig. 16.1. Ohesaare cliff after Märss & Nestor (2014).

Fig. 16.2. Southernmost part of the Ohesaare cliff. Photo: Olle Hints, 2024.

The hardground is encrusted by microconchids and bryozoans (Vinn & Wilson 2010); also, *Trypanites sozialis* borings are abundant (Knaust et al. 2023)

Fossils

The Ohesaare cliff is characterised by rich and diverse shelly fauna (Vinn et al. 2024). The most abundant macrofossils are brachiopods represented by *Collarothyris collaris* (Rubel), *Delthyris magna* Kozłowski, *D. elevata* Dalman, *Homoeospira baylei* (Davidson), *Levenea canaliculata* (Lindström), *Microsphaeridiorhynchus nucula* (Sowerby), *Morinorhynchus orbignyi* (Davidson), *Morinorhynchus rubeli* Musteikis & Cocks, *Protochonetes piltenensis* Rybnikova, *Protochonetes striatellus* (Dalman), *Salopina conservatrix* (McLearn), *Salopina submedia* (McLearn) and *Stegerhynchus pseudobidentatus* (Rybnikova). High abundance of bryozoans compared to other eastern Baltic Silurian sections is noteworthy. The bryozoan fauna was described in detail by Pushkin et al. (1990), who identified sixteen species from the Ohesaare cliff, including the most common *Fistulipora przhidolensis* Kopajevich. Many bryozoans show intergrowth with rugosans, cornulitids, hederelloids and hydroids (Vinn et al. 2021a, 2021b, 2022; Zapalski et al. 2022). Molluscs are represented by the most common bivalve *Grammysia obliqua* (McCoy); *Pteronitella retroflexa* (Wahlberg), *Palaeopecten danbyi* (McCoy), and *Modiolopsis complanata* Sowerby are also recorded. Cephalopods, bivalves and gastropods are represented by several genera and species (Sinitsyna & Mironova 1978; Kiselev et al. 1990). The fossils of trilobites are also common; the most numerous are calymeniids and proetiids (Männil 1983, 1987). Corals occur at certain levels in the middle part of the section. Corals are mainly represented by several species of *Favosites* and rugose corals by *Entelophyllum* and *Tryplasma* (Mõtus & Hints 2007). The middle part of the section (beds 5–10) has also yielded the cornulitids *Cornulites baranovi* Vinn & Toom (Vinn & Toom 2020) and the tentaculitids *Tentaculites scalaris* Schlotheim and *Lonchidium inaequale* Eichwald (Vinn et al. 2023). The association of microfossils, particularly ostracods, is very diverse (Sarv 1970).

Macroscopic vertebrate fossils are rare, *e.g.* shields of the heterostracan *Tolypelepis undulata* Pander, plates of the osteichthyan *Lophosteus superbus* Pander and jaw bones of acanthodians. Vertebrate microremains, on the contrary, are common and form bonebeds in several levels of the section.

The content of terrigenous material is high in the Ohesaare section, probably due to the intense influx of fine siliciclastic material into the basin at the final stage of its development. The input of the siliciclastic material contributed to the preservation of trace fossils such as *Chondrites, Cruziana, Helicodormites, Lockeia, Palaeophycus, Protovirgularia, Skolithos, Rusophycus* and *Zoophycos* (Toom 2019).

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Fig. 16.3. Selected fossils from the Ohesaare cliff, Ohesaare Regional Stage. **A–E, I** brachiopods; **A** – *Delthyris (Delthyris) magna* Kozlowski, GIT 130-221; **B** – *Delthyris (Delthyris) elevata* Dalman, GIT 130-217; **C** – *Collarothyris collaris* (Rubel), GIT 130-194; **D** – *Homoeospira baylei* (Davidson), GIT 130-155; **E** – *Stegerhynchus pseudobidentatus* (Rybnikova), GIT 173-53; **I** – *Protochonetes piltenensis* Rybnikova, GIT 554-2309. **F** – bivalve *Grammysia obliqua* (McCoy), GIT 403-158. **G** – crinoid *Cicerocrinus osiliensis* (Jaekel), GIT 405-242. **H** – trilobite *Calymene conspicua* Schmidt, GIT 187-41. **J** – cornulitid *Cornulites baranovi* Vinn & Toom, GIT 412-4. **K, M** tentaculitids; **K** – *Tentaculites scalaris* Schlotheim, GIT 403-751-2; **M** – *Anticalyptraea calyptrata* Eichwald, GIT 403-123-1. **L** – rugose coral *Entelophyllum articulatum* (Wahlenberg), GIT 403-5. **N** – hydrozoans on the bryozoan *Fistulipora przhidolensis* Kopajevich. **O–P** tabulate corals; **O** – *Favosites forbesi* Milne-Edwards & Haime, GIT 90-36; **P** – *Aulopora amica* Klaamann, GIT 403-136-2. Scale bars: L – 5 cm; F, H, 0, P – 1 cm; A, B, E, G, I, J, M – 5 mm; C, D, K, N – 1 mm.

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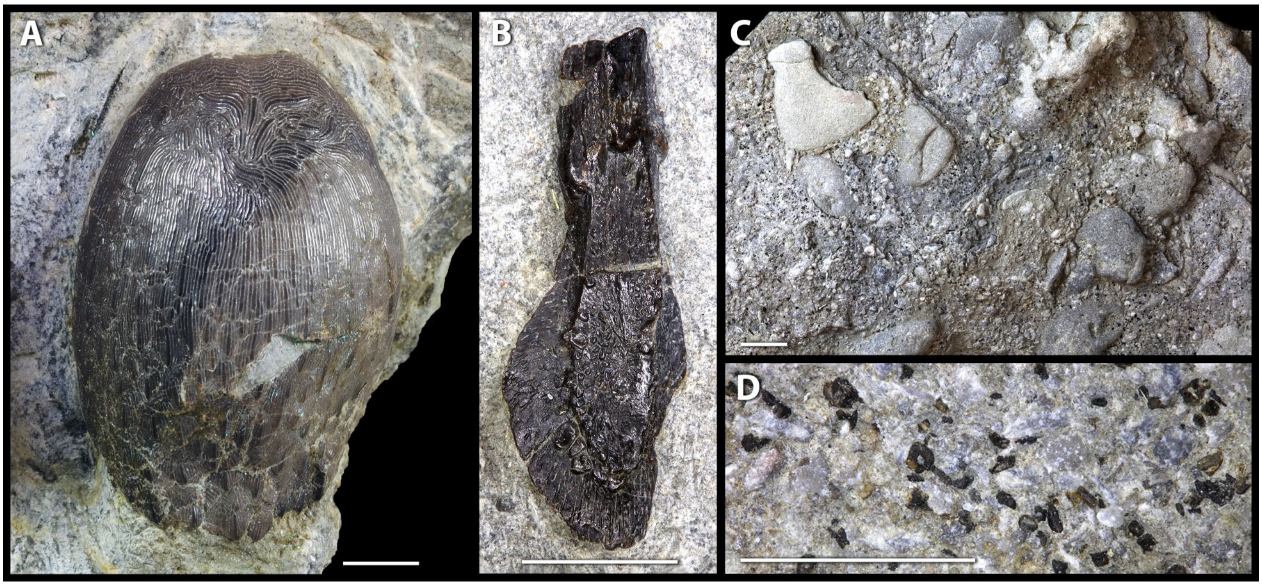

Fig. 16.4. Vertebrate fossils of the Ohesaare cliff, Ohesaare Regional Stage. Scale bars C – 1 cm; A, B, D – 5 mm. **A** – *Tolypelepis undulata* Pander, TUG 68-1; **B** – *Gomphonchus sandelensis* (Pander), GIT 232-255; **C, D** – conglomerate with microremains of vertebrates, D close-up, GIT 403-1.

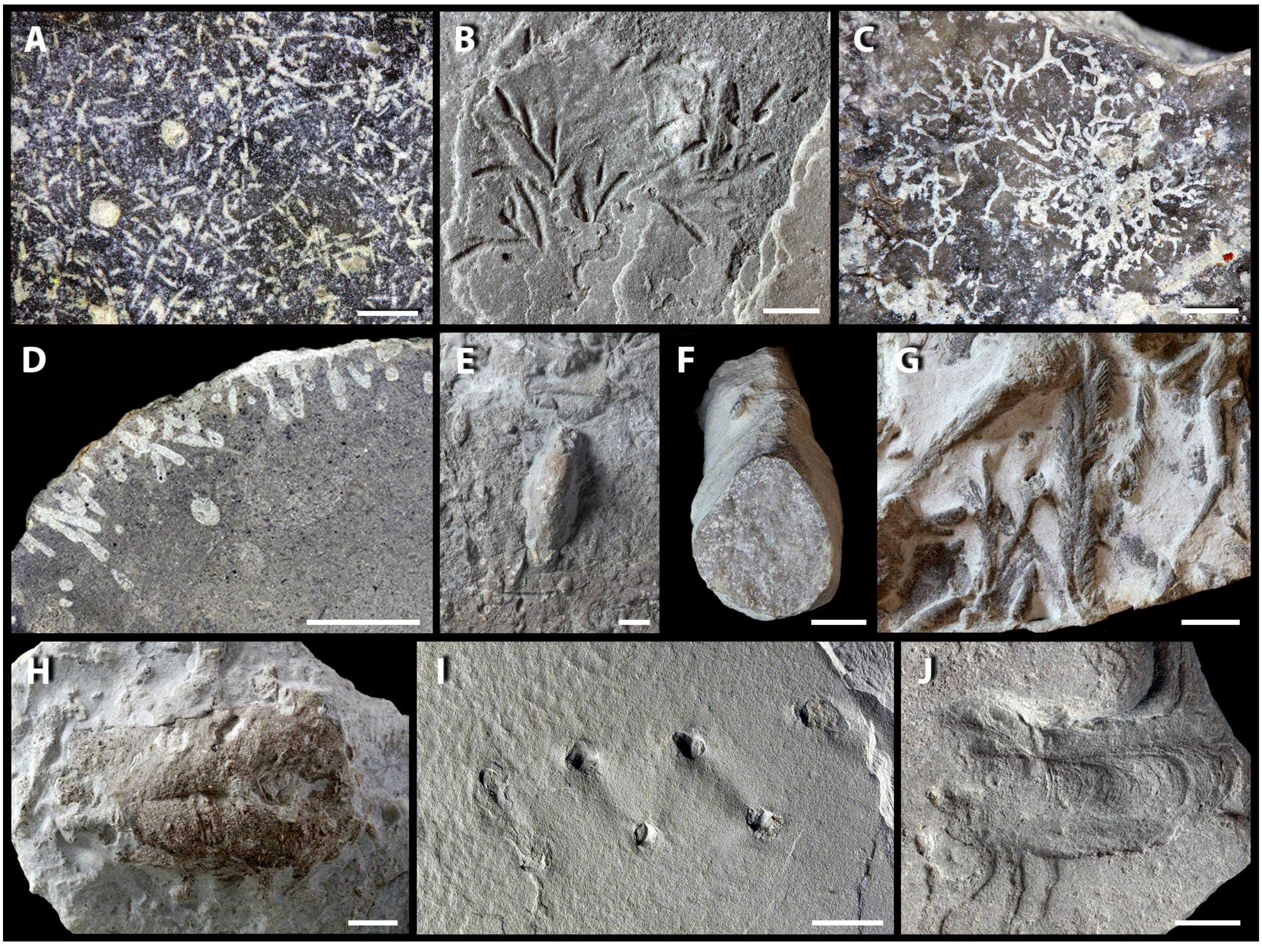

Fig. 16.5. Selected trace fossils from the Ohesaare cliff, Ohesaare Regional Stage. Scale bars D, E, G–J – 1 cm; B, F – 5mm; A, C – 1mm. **A**, **C, D** bioerosional trace fossils on the hardground**;** **A** – abundant bryozoans borings, GIT 403-604-1; **C** – dendritic bioerosional traces GIT 403-634-2; **D** –dense *Trypanites socialis* Eisenack borings in cross-section, GIT 362-783. **B** – *Chondrites* isp. GIT 403-602. **E**, **F, G** bivalve traces; **E** – *Lockeia siliquaria* James, GIT 362-772; **F** – *Oravaichnium carinatum* Stachacz, Knaust & Matysik, GIT 363-955; **G** – *Protovirgularia pennata* (Eichwald), GIT 156-996-1. **H** – trilobite trace *Rusophycus* isp., GIT 362-682. **I**, **J** polychaete traces in bedding-plane view; **I** – corkscrew-shaped trace *Helicodromites* isp., GIT 362-11; **J** – *Rhizocorallium* isp., GIT 403-613.

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Stop 17: Kaali meteorite craters

Jüri Plado

Location: Main crater, latitude 58°22'22"N, longitude 22°40'10"E; Saare County, Estonia.
Stratigraphy: Rocks exposed around the main crater belong to the Paadla RS, Ludlow.
Status: The craters are under protection; no hammering.
More information: https://geoloogia.info/locality/14994

The Kaali meteorite crater field consists of nine structures (Fig. 17.1), including the main crater, which is 105–110 meters in diameter. These craters formed in a layered target of Quaternary till overlying Silurian dolostones (Paadla Stage, Ludlow). The discovery of meteoritic iron in the summer of 1937 by Reinwald (1938) concluded a long search for the origin of the Kaali structures. This search was first published in 1827 when naturalist J.W.L. von Luce described circular topographic features and uplifted, fractured dolomite blocks at the Kaali site (Reinvaldt 1933). Consequently, several earlier hypotheses about their origin, such as gas explosions, clay oozing, karst weathering, rock-salt solution from salt domes, anhydrite expansion by hydration, or human excavation (as reviewed by Spencer 1938; Aaloe 1963 and Raukas et al. 2005), were rejected.

The Kaali craters were placed under heritage protection in November 1937. However, continuous destructive excavations, farming, and road-building activities have partially ruined the original shapes and structures, especially those of the satellite craters. After the collapse of the USSR, Kaali became a famous and frequently visited natural monument due to its spectacularly exposed impact features, which include a perfectly round shape and a prominent rim with outcrops of outward-tilted dolostone layers on the inner slope. In 2005, a local nonprofit company established a museum to feature local geology and introduce meteoritics, exemplified by the Kaali craters.

After World War II, research focused on (i) collecting and studying remnant pieces of the meteorite and micrometeorites throughout the crater field, (ii) characterising

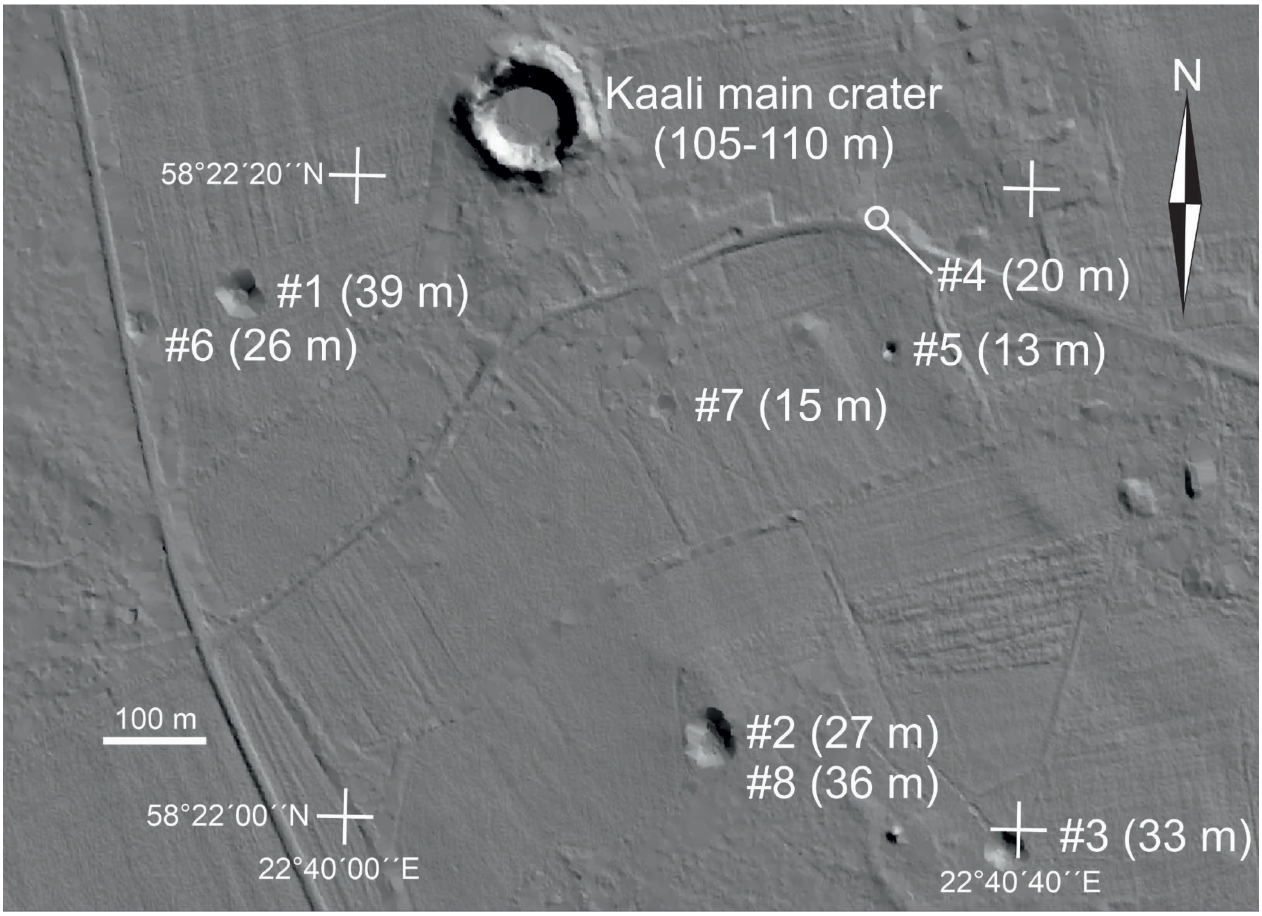

Fig. 17.1. LiDAR map (Estonian Land Board) of the Kaali crater field with all the identified circular structures and their diameters indicated. The location of the main crater to the crater field favours an SSE azimuth of the projectile.

the structure of the craters through extensive excavations and some geophysical methods, (iii) finding links between the impact and archaeological finds, and (iv) dating the event.

Several kilograms of coarse octahedrite of class IAB (Spencer 1938; Bronšten 1962; Aaloe 1968) have been collected at Kaali (Fig. 17.2). In addition to iron, the material contains 7.25 wt% of Ni and is rich in rare elements such as Ir, Ga, Ge, Re, Pt, and Au (Yavnel 1976; Kracher et al. 1980). Mineralogical studies (Yudin 1968) of fragments from the Kaali crater field revealed typical iron meteorite minerals such as kamacite (mean abundance = 96.8 vol%), taenite (1.8 vol%), and schreibersite (1.7 vol%) (Yudin and Smyshlyayev 1963).

Fig. 17.2. A piece of Kaali meteorite, deposited at the Natural History Museum, University of Tartu (specimen number TUG 1758-14). Photo: Mare Isakar.

Based on the sizes of the Kaali structures and the compositions of the target and projectile, Bronšten and Stanyukovich (1963) estimated the initial mass of the projectile to be between 400 and 10,000 tons and its velocity between 15 and 45 km s^{-1}, which were reduced to 20–80 tons and 10–20 km s^{-1} now of impact, respectively.

The ESE direction of incidence was suggested by Reinvaldt (1933) while describing the triangled funnel at the bottom of the fractured dolostone of crater #4, which opened in 1927. However, the distribution of the structures in the field favours an SSE direction (Krinow 1960), as the largest crater is located at, or near, the downrange boundary of the crater strewn field (e.g., Passey and Melosh 1980). However, while tracing an ellipse of distribution with free flight of imagination, a wide range of directions from east to south may be considered (Fig. 17.1).

The estimates of the age of the Kaali impact structure (Saaremaa Island, Estonia) vary significantly among different authors, ranging from ~6400 to ~400 years before the current era (BCE), a discrepancy of up to 6000 years (Fig. 17.3). In the latest study by Losiak et al. (2016), age was determined using ^{14}C dating of charred spruce material found within the proximal ejecta blanket, making it directly related to the impact structure and not susceptible to potential reservoir effects. The results indicate that the Kaali crater most likely formed shortly after 1530–1450 BCE (3237 ± 10 14C years BP). Saaremaa was already inhabited when the bolide struck the Earth, suggesting that humans probably witnessed the crater-forming event. However, there is no evidence that this event caused significant changes in the material culture (e.g., known archaeological artefacts) or patterns of human habitation on Saaremaa.

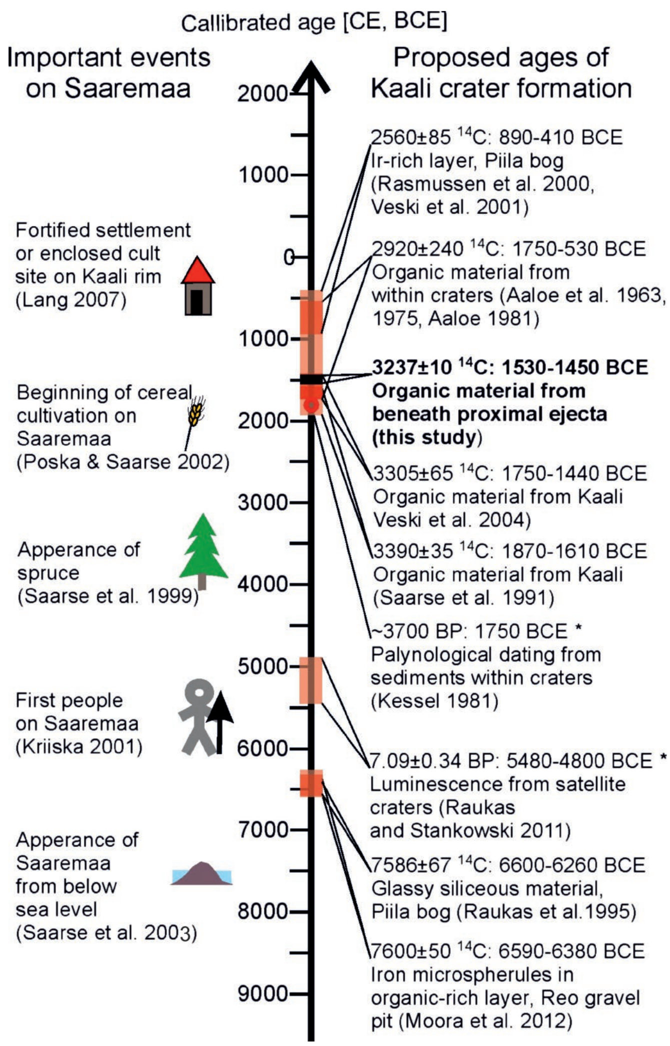

Fig. 17.3. Ages of the Kaali impact crater proposed in the literature, along with the ages of other events important for the geological history of Saaremaa (such as the appearance of the island from below sea level). The ages marked with * are based on methods different from the 14C method (luminescence and palynological dating). All other ages are based on the 14C method; the first number represents the uncalibrated 14C age, and the second number shows the calibrated ages determined with the IntCal13 atmospheric curve (Reimer et al. 2013) and OxCal v4.2.4 program (Ramsey and Lee 2013). The size of the box corresponds to calibrated time ranges (95.4% probability)—except for palynological estimation that is given without error bars. The figure was initially published by Losiak et al. 2016.

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Stop 18: Tori Põrgu ("Tori Hell")

Tõnu Meidla and Peep Männik

Location: Latitude 58°29´1˝N, longitude 24°48´59,9˝E; Pärnu County, Estonia.
Stratigraphy: Middle Devonian, Eiffelian, Tori and Tamme Mb-s of the Pärnu RS.
Status: Cliff is under protection; no hammering, but loose material may be collected.
More information: https://geoloogia.info/en/locality/13573

Fig. 18.1. Tori outcrop, left bank of the Pärnu River in Tori. Photo: Tõnu Meidla.

Fig. 18.2. The westernmost part of the Tori outcrop near the bridge. Photo: Tõnu Meidla.

The Tori outcrop (Fig. 18.1) is widely known as the 'Tori Hell' because of a cave in it. However, the former deep cave collapsed stepwise during the 20th century. The escarpment is situated on the left bank of the Pärnu River under Tori cemetery and reaches further to the west, up to the bridge across the Pärnu River (Fig. 18.2). The length of the outcrop wall is ca 400 m, height reaches up to 8 m.

Tori Põrgu is the stratotype of the Pärnu RS, the Pärnu Formation and the Tori Member of the latter. This is the most representative outcrop of this interval in the East Baltic.

Stratigraphy

The fossiliferous sandstones cropping out near the historical Tori Manor were first mentioned already in the middle of the 19th century (Sokolov 1844). Orviku (1930) described the rocks exposed in this locality first as the "basal beds of the Middle Devonian", re-naming them later as the Tori Sandstone (Orviku 1932). He subdivided the unit

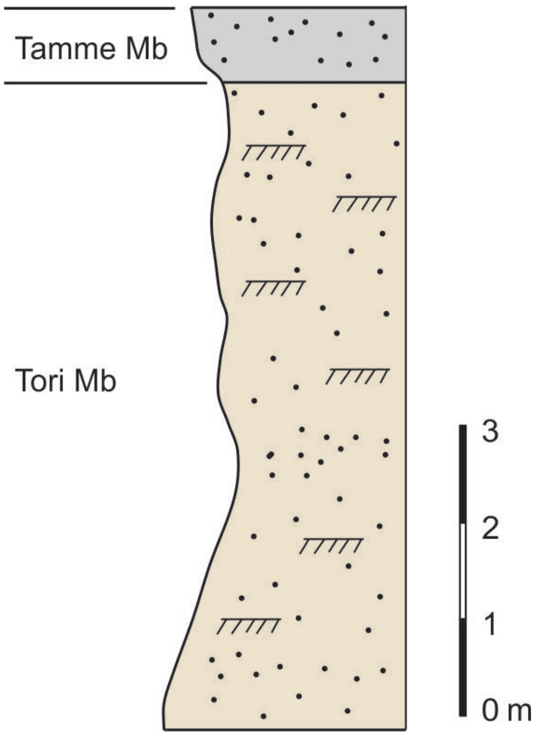

Fig. 18.3. The Tori section, modified from Kleesment (1991). For the details see the description.

into the lower *Aulacophycus* and the upper 'trochiliscid sandstone', corresponding to the Tori Mb and the Tamme Mb of the Pärnu Formation, respectively, in the modern sense. The sandstone was earlier referred to as the Pärnu Beds (Obruchev 1933) and the Pärnu Stage by E. Mark-Kurik (Mark 1958). Based on the fish fossils, Gross (1942) assigned the rocks to the *Guerichosteus heterolepis* Zone (Eifelian; former *Schizosteus heterolepis* Zone). The Tori outcrop is the type locality of the zonal species.

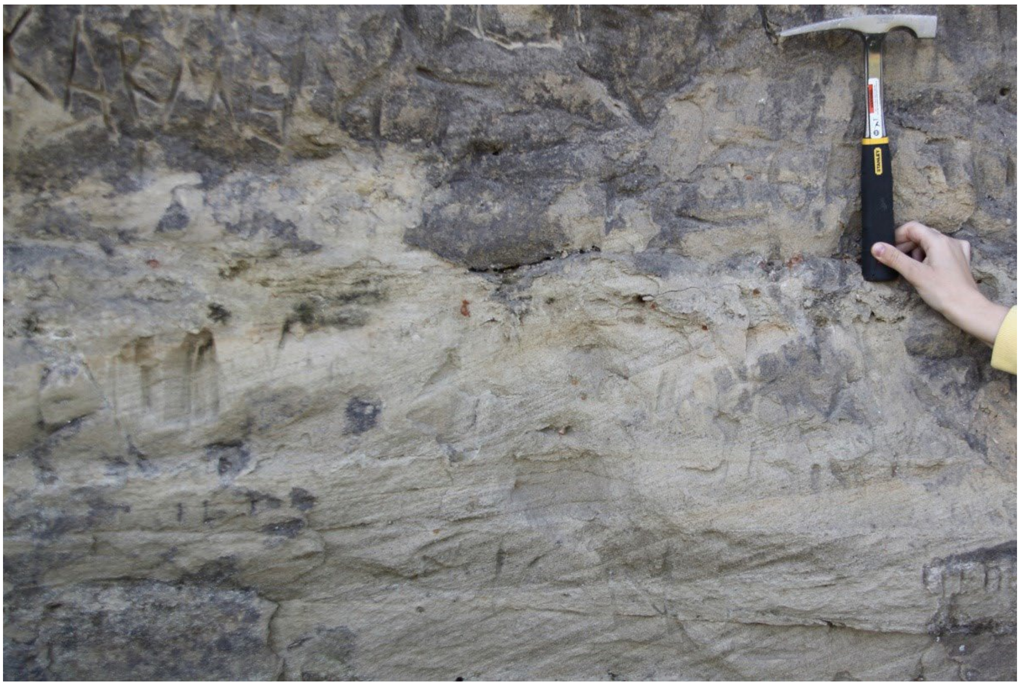

Fig. 18.4. Cross-bedded sandstone in the lower part of the Tori Member. Photo: Tõnu Meidla.

Fig. 18.5. Clay pebbles in sandstone of the Tori Member. Photo: Tõnu Meidla.

Description of the section

Fig. 18.3; from the top, after Kleesment (1991):

0.75 m – Tamme Member. Light grey horizontally thin-bedded silty mica-rich sandstone. Small spherical gyrgogonites of charophyte algae (*Trochiliscus*) occur.

7.5 m – Tori Member. Greyish-white and yellowish cross-bedded sandstone (Fig. 18.4). In the lower part, the sandstone is medium-grained, and in the uppermost 5 m fine-grained. The rock contains small Fe-hydroxide pigmented silty clay pebbles, 1–5 cm in diameter; in the lower part, the pebbles are of greenish-grey colour (Fig. 18.5). Fragments of early plants and fossil fishes occur.

Fossils

The outcrop is considered one of the most important localities of Devonian plants in Estonia. They were originally (Thomson 1940) attributed to the psilophyte genus *Aulacophycus* Eichwald, but the group of psilophytes is considered obsolete today. The majority of the fragments found at the site are today tentatively attributed to the pteridophyte genus *Hostinella* Barr ex Stur (class Cladoxylopsida; Kalamees 1988). The presence of two horizons containing plant remains in this section was mentioned already by Orviku (1930).

Another important group of fossils in the sandstones at Tori are vertebrates. Together with the zonal species *Guerichosteus heterolepis* (Preobrazhensky), several other agnathans have been recorded such as *Psammolepis toriensis* (Mark-Kurik), *Afanassiaspis porata* Otto & Laurin, and *Tartuosteus*? sp. (eMaapõu 2024). The list of acanthodian species contains the zonal species *Laiacanthus singularis* Karatajute-Talimaa, accompanied by *Archaeacanthus quadrisulcatus* Kade, *Diplacanthus kleesmentae* Valiukevičius, *Ectopacanthus flabellatus* Valiukevičius (Valiukevičius & Karatajūtė-Talimaa 1986; Glinskiy & Pinakhina 2018). Placoderms (*Actinolepis tuberculata* Agassiz, *Byssacanthus dilatatus* (Eichwald), *Homostius* sp.) and osteichthyes (*Porolepis* sp., *Glyptolepis* spp.) are also recorded (Glinskiy & Pinakhina 2018).

The outcrop was cleaned in 2005, but the material at its base was only partially removed, leaving the most fossiliferous interval buried.

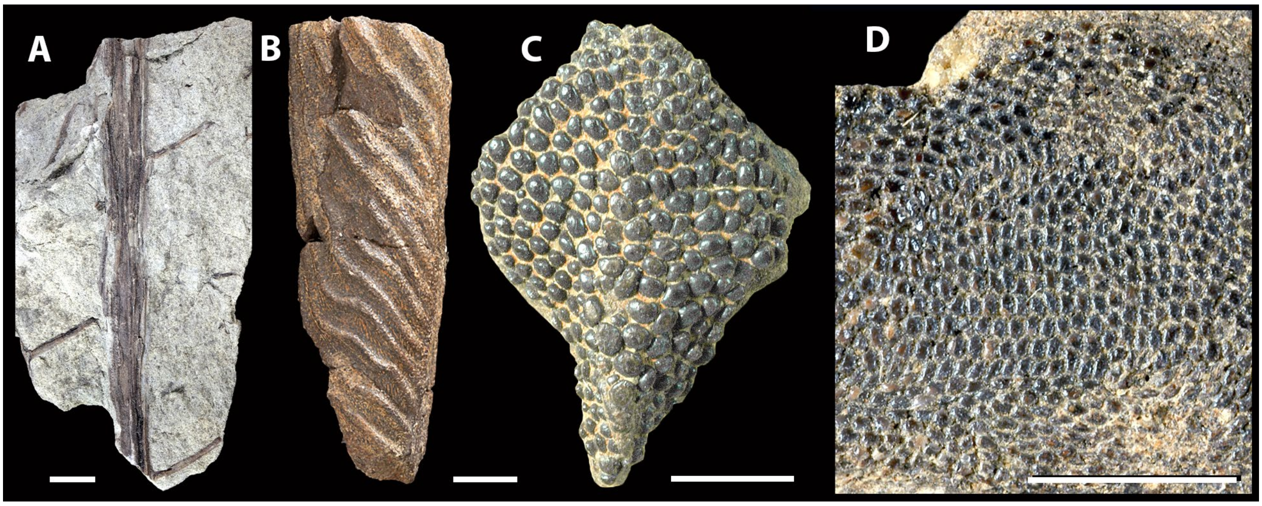

Fig. 18.6. Selected fossils from the Tori Põrgu outcrop, Pärnu Regional Stage. Scale bars A – 1 cm; B–D – 5 mm. **A** – plant remains, GIT 236-19. B–D vertebrates; **B** – fragment of placoderm Homostius sp., GIT 99-42; C, D psammosteids; **C** – tessera of Guerichosteus heterolepis (Preobrazhensky), GIT 116-5; **D** – close-up of Psammolepis toriensis (Mark-Kurik), GIT 116-23.

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Stop 19: Reinu quarry

Olle Hints, Leho Ainsaar, Peep Männik, Tõnu Meidla, Jaak Nõlvak and Ursula Toom

Location: Latitude 59.08768°N, longitude 24.74044°E; Rapla County, central northern Estonia.
Stratigraphy: Latest Katian to Rhuddanian; Pirgu to Juuru regional stages, Adila, Ärina, Varbola and Tamsalu Fm.
Status: Active quarry with high walls – be careful; hammering and fossil collecting are welcome!
More information: https://geoloogia.info/en/locality/16317

The following text is modified from Hints et al. (2023).

The Reinu quarry is located in northern Estonia, 40 km south of Tallinn. The early Silurian limestone of the Varbola Formation, Juuru Regional Stage, has been quarried for crushed stone production since 2007. Today, the quarry is operated by the infrastructure construction and maintenance company TREV-2 Grupp. The limestone aggregates from the Reinu quarry are used mainly in road construction.

The locality has been visited by geologists since the first bedrocks were quarried, and it has served as an excellent and fossiliferous outcrop for the Varbola Formation (Einasto et al. 2007). A number of studies have been published on the material from the Reinu succession, notably on important palaeontological finds (Ausich et al. 2020; Wright & Toom 2017; Jeon et al. 2022), but also on chemostratigraphy (Gul et al. 2021). The Ordovician–Silurian boundary interval was first exposed in the quarry in 2020 within a small, rounded excavation used for water drainage and pumping. In 2022, Ordovician rocks were opened on a larger scale, and they started contributing to the quarry's production. Since then, the topmost Pirgu (latest Katian) and the entire Porkuni (Hirnantian) regional stages have been accessible in the Reinu quarry. This is now the second outcrop of the Ordovician–Silurian boundary interval in Estonia, the other being the Neitla quarry (Männik & Nõlvak 2023). Hirnantian rocks are well known in a few additional sites, notably the old Porkuni quarry (Hints et al. 2000, Hints & Männik 2014).

Studies on Hirnantian strata in the Reinu quarry are currently underway, with only some preliminary results on microfossils and chemostratigraphy published (Hints & Tonarova 2023; Meidla et al. 2023b). The main units identified in the quarry are briefly characterised and discussed below.

(1) The **Adila Formation** (0.3 m; Pirgu Regional Stage, Latest Katian) consists of grey wackestones with several pyritised discontinuity surfaces. It is the lowermost stratigraphic unit exposed only in the deepest part of the quarry. The formation contains organic-walled microfossil assemblage typical of the Pirgu Regional Stage in Estonia, including rare *Spinachitina coronata*, *Cyathochitina campanulaeformis*, *C. kuckersiana*, and *Belonechitina micracantha*. However, no specific zonal chitinozoans were found in the few samples studied. Additionally, abundant scolecodonts, melanosclerites and foramin-

Fig. 19.1. Overview of the Reinu quarry, showing Hirnantian reefs (Ärina Formation, Porkuni Regional Stage) in the lower escarpment and overlying limestones of the Varbola Formation (Hirnantian to Rhuddanian, Juuru Regional Stage). Photo: Olle Hints, 2022.

Fig. 19.2. Ordovician-Silurian boundary beds in the Reinu quarry. Photo: Olle Hints, 2022.

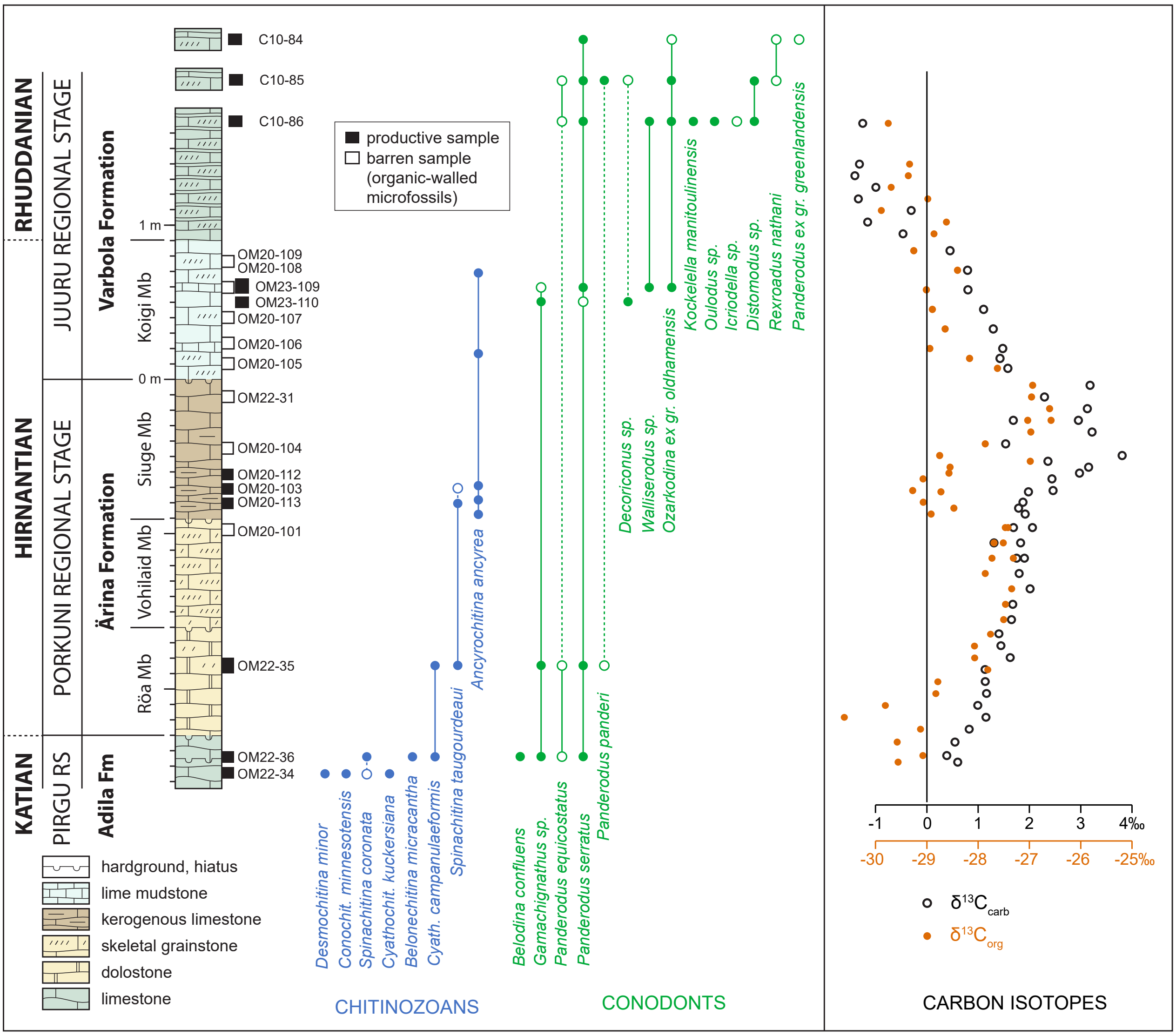

Fig. 19.3. Ordovician-Silurian boundary beds in the Reinu quarry. Distribution of chitinozoan is from Hints et al. (2023), conodont data by Peep Männik (previously unpublished), carbon isotopes from Meidla et al. (2023). Note that the isotope data points are adjusted to fit the boundaries between lithological units, due to the fact that thickness of individual beds varies between the sampling sites within the quarry.

Fig. 19.4. Dolomitised Hirnantian reef the Reinu quarry. The reefal limestone is usually assigned into the Tõrevere Member of the Ärina Formation. Here the reefs are laterally replaced by the kerogenous Siuge Member in distance of few meters. Photo: Olle Hints, 2022.

iferans (*Blastammina* sp.) were found. Poor conodont fauna is dominated by *Panderodus serratus*. Also, few specimens of *Belodina confluens* and *Gamachignathus* sp. were found.(2) The **Ärina Formation** (c. 2.5 m; Porkuni Regional Stage, Hirnantian) consists of various shallow-marine carbonates. The formation is distributed in northern and central Estonia and considered to be primarily early Hirnantian in age, bound by stratigraphic gaps (Meidla et al. 2023a, 2023b). It is commonly divided into the dolostone (**Röa** Member), skeletal grainstone (**Vohilaid** Member), kerogenous limestone (**Siuge** Member) and, in places, dolomitised reef limestone members (**Tõrevere** Member). Ainsaar et al. (2015) showed that the Vohilaid, Siuge and Tõrevere units are reef-related lithotypes rather than true members. In the Reinu quarry, all these units can be identified (Fig. 19.2, 19.3, 19.4, 19.5), but their lateral distribution and thickenss varies between sites, particularly due to organic buildups and uneven erosion during the Hirnantian. A single reef body c. 20 m in diameter was exposed in 2022 (Fig. 19.4) showing a gradual lateral transition from the dolomitised reef limestone (Tõrevere Member) into the kerogenous limestone of the Siuge Member (Fig. 19.1). Shelly fossils are common in the Vohilaid and Siuge members (Fig. 19.7). The Siuge Member is characterised also by abundant benthic microfossil assemblage. The most abundant Ordovician polychaete fauna from Baltoscandia was recently reported from the Siuge Member in the Reinu quarry, with well over 5000 scolecodonts per kg of rock (Hints & Tonarova 2023). Ostracods show similarly rich fauna, study of which is currently in progress. The most kerogenous part of the Siuge Member (sample OM20-113) contains the zonal chitinozoan *Spinachitina taugourdeaui*, confirming the early Hirnantian age of the unit (Kaljo et al. 2008). *S. taugourdeaui* was also identified from the Röa Member (Fig. 19.3); thus, the entire Ärina Formation in the Reinu quarry corresponds to the S. *taugourdeaui* Zone.

(3) The **Varbola Formation** (ca 11 m, Juuru Regional Stage, Hirnantian–Rhuddanian) is represented mainly by the alternation of packstones/grainstones and marl beds in the lower part of the section (Koigi Member) and mainly by wackestones with occasional interbeds of packstones in its middle and upper parts. The formation contains abundant tabulate corals, stromatoporoids, rugosans, brachiopods, echinoderms and other shelly fossils (Fig. 19.6). Microfossil samples have revealed an abundance of benthic forms, notably scolecodonts, but chitinozoans and conodonts and very rare and of very low diversity indicating strong impact of the Hirnantian extinction to these groups. The diversity of conodont fauna increases and new taxa appear in the lower Varbola Fm. However, although these taxa are characteristic of Silurian, as also is *Rexroadus nathani* found higher in succession, all of them appear already in the Hirnantian (Armstrong 1996).

The lowermost part of the formation, the **Koigi Member**, is usually represented by lime mudstones, but in the Reinu quarry, the grainstones containing quartz admixture overlying the Siuge / Tõrevere lithotypes are also assigned to the Koigi Member. Alternatively, these grainstones could be considered as of Kamariku Member, which constitutes the uppermost part of the Ärina Formation. Fig. 19.5 shows the lower boundary of the unit and succession of three rock varieties: (1) brown kerogenous Siuge wackestone, (2) 5-cm-thick grainstone bed, overlain by (3) fine-grained mudstone unit, typical

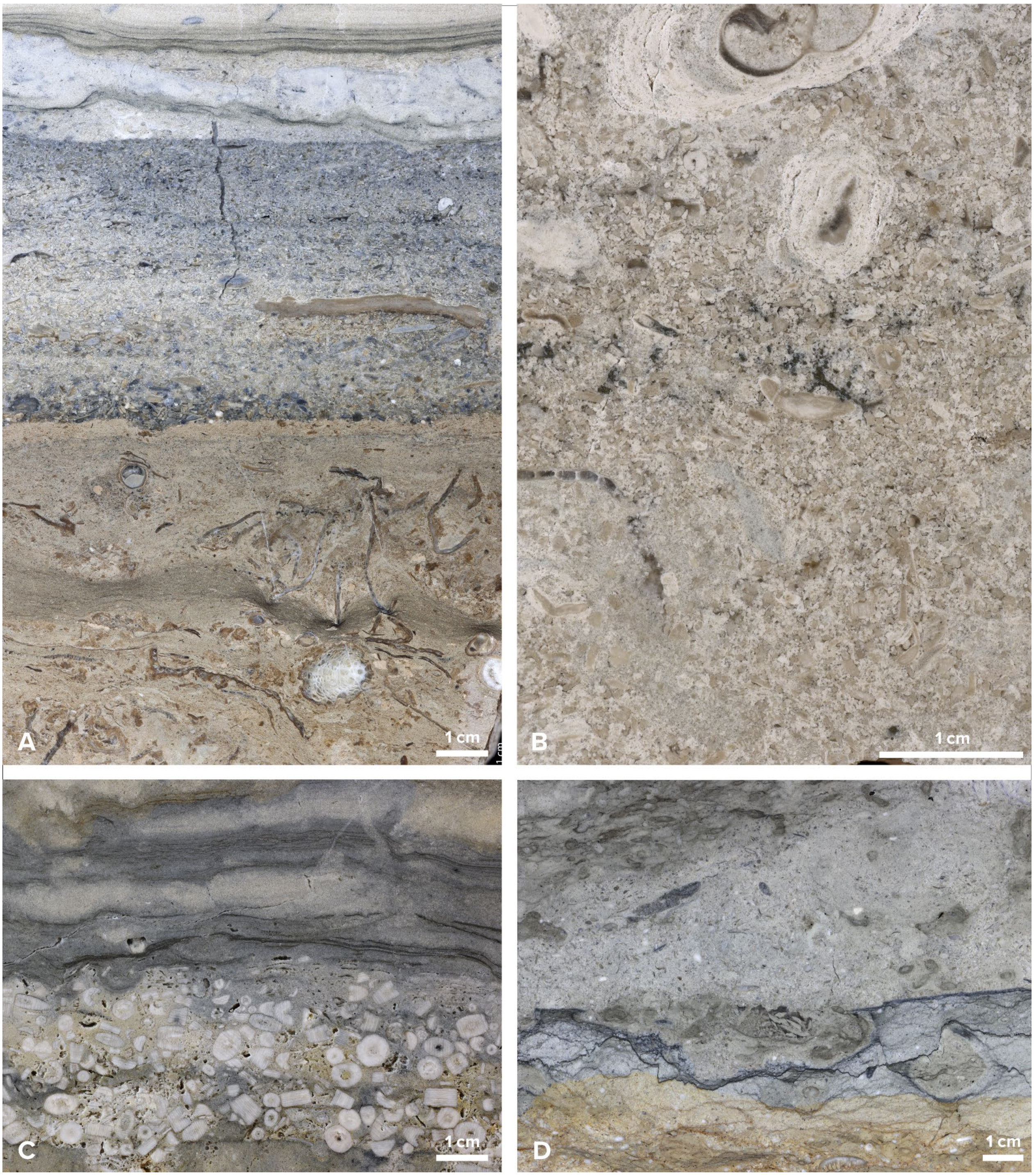

Fig. 19.5. Examples of latest Katian and Hirnantian rocks from the Reinu quarry. **A** – Boundary between kerogenous Siuge Member of the Ärina Formation and grainstone and carbonate mudstone of the Koigi Member, Varbola Formation. **B** – Grainstone of the Vohilaid Member, Ärina Formation. Note the oncolithic overgrowths on some shells. **C** – Dolostone with abundant echinoderm ossicles, Röa Member, Ärina Formation. **D** – Wackestone with a pyritised discontinuity surface, Adila Formation, Pirgu Regional Stage, latest Katian. Sample from the collection of TalTech Department of Geology.

of the Koigi Member. In places, the basal part of the Koigi Member contains a conglomerate with pebbles several cm in size and large fragments of corals and stromatoporoids.

Conventionally, the Ordovician–Silurian boundary has been drawn below the Varbola Formation (and Koigi Member). However, carbon isotope chemostratigraphy, has shown that the Koigi Member represents the falling limb of the Hirnantian Carbon Isotope Excursion. This pattern is also visible in the Reinu succession (Fig. 19.3), where the highest $\delta^{13}C$ values are recorded in the Siuge Member, and the overlying Koigi strata show a gradual decline in $\delta^{13}C$. Biostratigraphic evidence to identify the base of the Silurian is limited in the Reinu quarry. Most likely, the Koigi Member is of late Hirnantian age, whereas the main part of the Varbola formation belongs to the Rhuddanian (Gul et al. 2021; Meidla et al. 2023a). Here, we correlate the Ordovician–Silurian boundary with the upper boundary of the Koigi Member.

(4) The **Tamsalu Formation** (Juuru Regional Stage, Rhud-

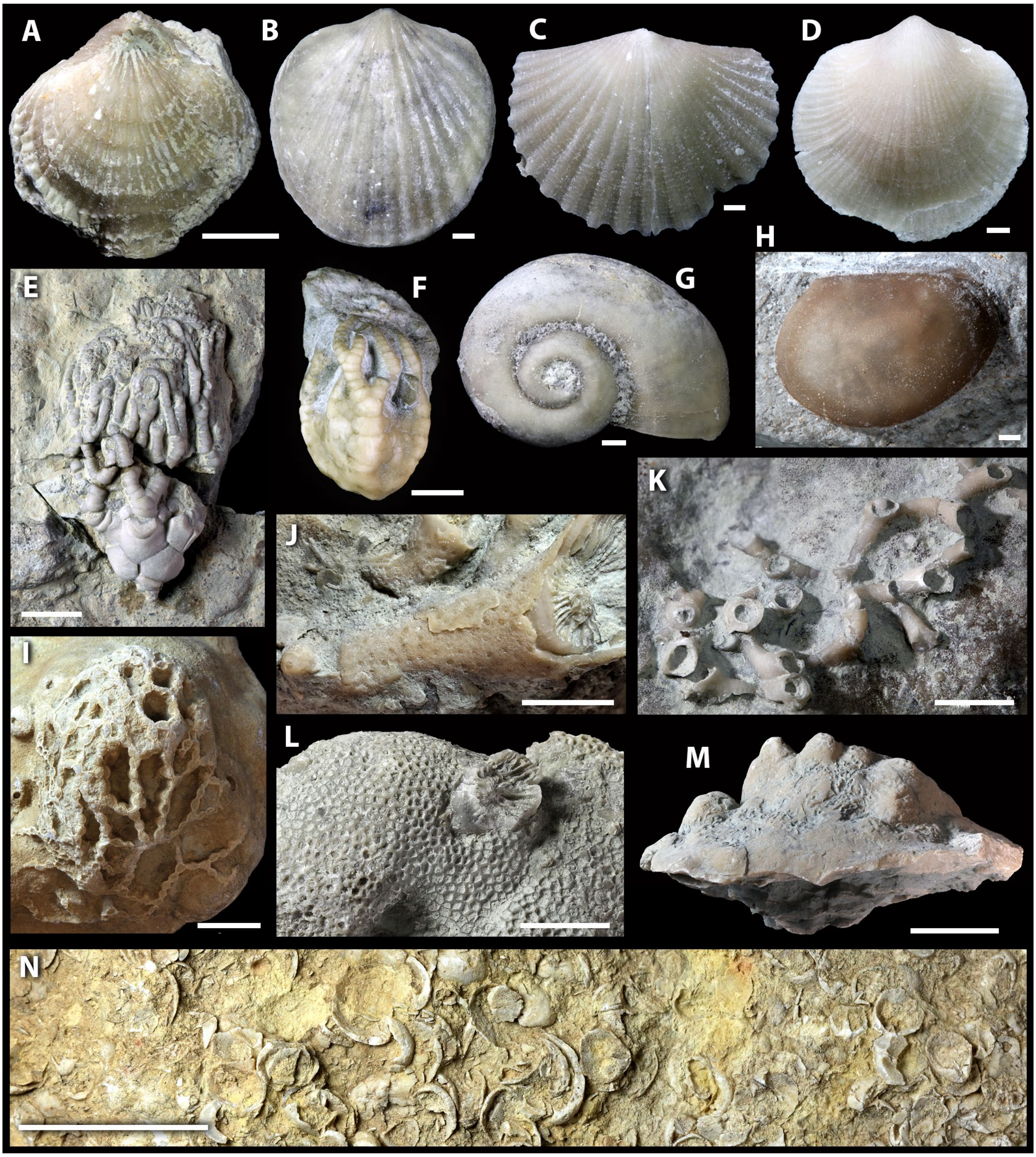

Fig. 19.6. Selected fossils from the Reinu quarry of the Varbola and Tamsalu formations (Rhuddanian). Scale bars: M, N – 5 cm; E, I, L – 1 cm; A, F, J, K – 5 mm; B–D, G, H – 1 mm. **A**–**D** – brachiopods from the Varbola Formation; **A** – *Sypharatrypa hillistensis*, GIT 554-2500; **B** – *Zygospiraella*, GIT 835-1781; **C** – *Hesperorthis hillistensis*, GIT 855-848; **D** – *Onniella trigona*, GIT 554-2501. **E**–**F** – crinoids from the Varbola Formation; **E** – *Euspirocrinus hintsae*, GIT 405-256; **F** – *Paerticrinus arvosus*, GIT 405-255. **G** – gastropod from the Varbola Formation, *Naticonema*, GIT 535-161. **H** – leperditicopid from the Varbola Formation, GIT 368-329. **I**–**L** – corals from the Varbola Formation; **I** – halysitid encrusting stromatoporoid, GIT 666-49-1; **J** – heliolitid encrusting rugose coral *Streptelasma*, GIT 393-75; **K** – auloporid encrusting stromatoporoid, **L** – endobiotic rugose coral *Streptelasma* in *Paleofavosites balticus*, GIT 666-20. **M** – stromatoporoid with bioeroded surface, Varbola Formation, GIT 362-505. **N** – *Borealis borealis borealis* coquina, Tamsalu Formation, GIT 623-1095.

danian) overlying the Varbola Formation has a thickness of less than a metre. It consists of Borealis-limestone – essentially a coquina of brachiopod *Borealis borealis borealis* (Fig. 19.6N) containing in places also abundant corals and stromatoporoids. This rock unit is characterised by very high CaO content and is therefore, a valuable resource for the chemical industry. It is quarried in several localities in central Estonia, notably in the Karinu and Võhmuta quarries (Ainsaar 2004).

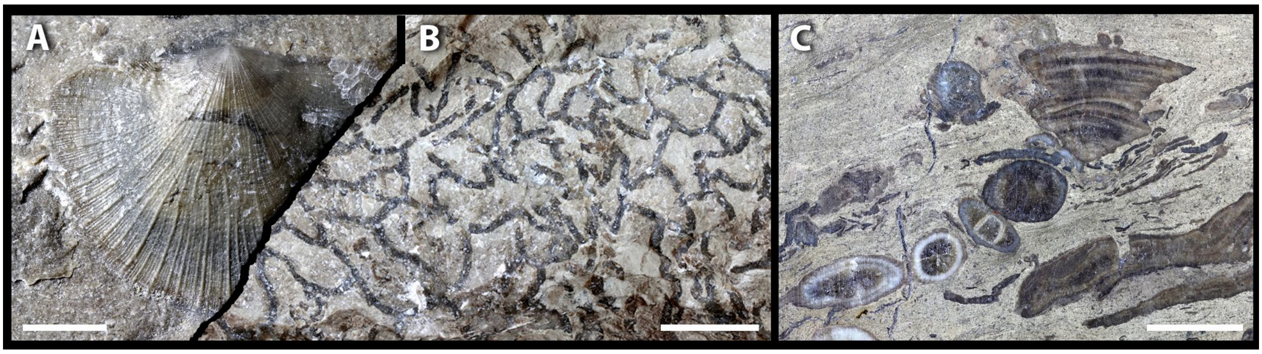

Fig. 19.7. Selected fossils from the Reinu quarry, Ärina Formation (Hirnantian, Ordovician). Scale bars: B, C – 1 cm; A – 5 mm. **A** – brachiopod *Eostropheodonta* GIT 674-698. **B** – tabulate coral *Catenipora*, GIT 734-239. **C** – stromatoporoids and rugose corals, GIT 748-25.

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Stop 20: Sutlema quarry

Björn Kröger and Ursula Toom

Location: Latitude 59.17410°N, longitude 24.61958°E; Rapla County, central northern Estonia.
Stratigraphy: mid-Katian, Nabala and Vormsi regional stages, Saunja and Kõrgessaare formations.
Status: Active quarry, follow safety rules; sampling and fossil collecting welcome!
More information: https://geoloogia.info/en/locality/16318

The following text is based on Kröger and Toom (2023).

The Sutlema quarry is an active quarry c. 30 km south of Tallinn, west of Kohila, Rapla County. The quarry exposes the upper c. 7 m of the Nabala Regional Stage and c. 4 m of the overlying Vormsi Regional Stage, middle Katian (Fig. 20.1).

Stratigraphy

The boundary between the Nabala and Vormsi regional stages in northern Estonia is marked by a prominent discontinuity surface, interpreted as a paleo-karst horizon (Calner et al. 2010). The massive limestone underlying the discontinuity surface belongs to the Saunja Formation, and the relatively high $\delta^{13}C_{carb}$ values (up to 2.39 ‰, Meidla & Ainsaar 2014) are indicative of the Saunja Carbon Isotope Excursion (Baltic Chemostratigraphic Zone BC10, Ainsaar et al. 2010). The Saunja Excursion has been correlated with the middle Katian Waynesville Excursion in North America (Bergström et al. 2012; Meidla & Ainsaar 2014). The overlying strata of the Vormsi Regional Stage correspond to the middle Katian *Amorphognatus ordovicicus* Conodont Zone (Meidla et al. 2023).

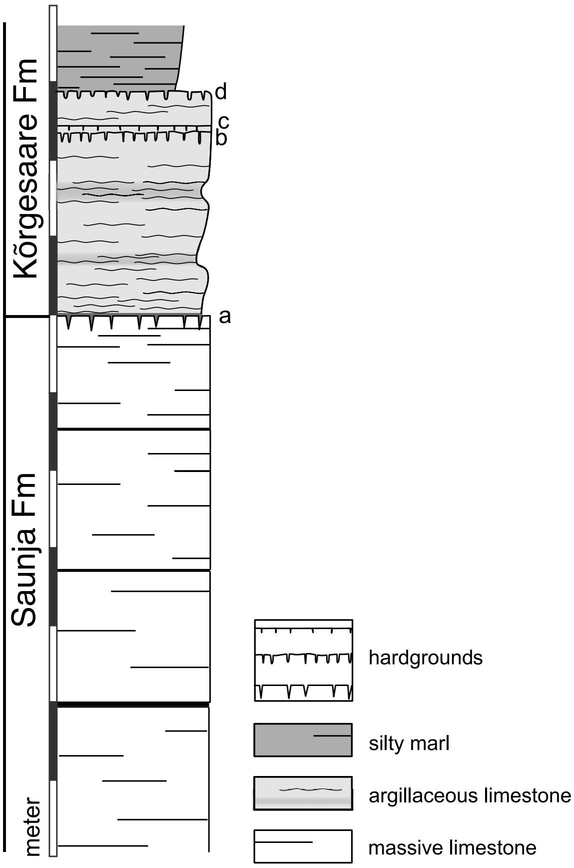

Fig. 20.1. Stratigraphy and lithology of the Sutlema quarry outcrop. Abbrevations: Fm, formation; a-d, denote individual hardground horizons.

Fig. 20.2. Overview of the Sutlema quarry, showing mining of the Saunja limestone (carbonate mudstone), Nabala Regional Stage, Mid-Katian. Photo: Olle Hints, 2022.

Sedimentology

Saunja Formation

The Saunja Formation at Sutlema consists of bedded (10–40 cm), fine-grained (lithographic), and bioturbated limestone with very thin (<1 cm) interlayers. Few interlayers with a thickness of more than one centimetre can be used to distinguish individual 1–2 m thick strata within the formation. Rhythmic bedding of argillaceous and carbonaceous beds is visible on fresh quarry walls (Fig. 20.3A, 20.4). Similar limestone and marl alternations are interpreted as resulting from diagenetic processes (Munnecke et al. 2023). The microfacies can be described as a lime-mudstone to skeletal grainstone with common echinoderm ossicles, microgastropods and fragments of bryozoans and skeletal green algae (Fig. 20.3). The lithology of the Saunja Formation has been described as Baltic limestone facies, in which calcitarchs are common (Kröger et al. 2019). At Sutlema, the abundant and well-preserved burrows of, e.g., *Chondrites*, *Phycodes* and *Planolites* are remarkable (Fig. 20.7C).

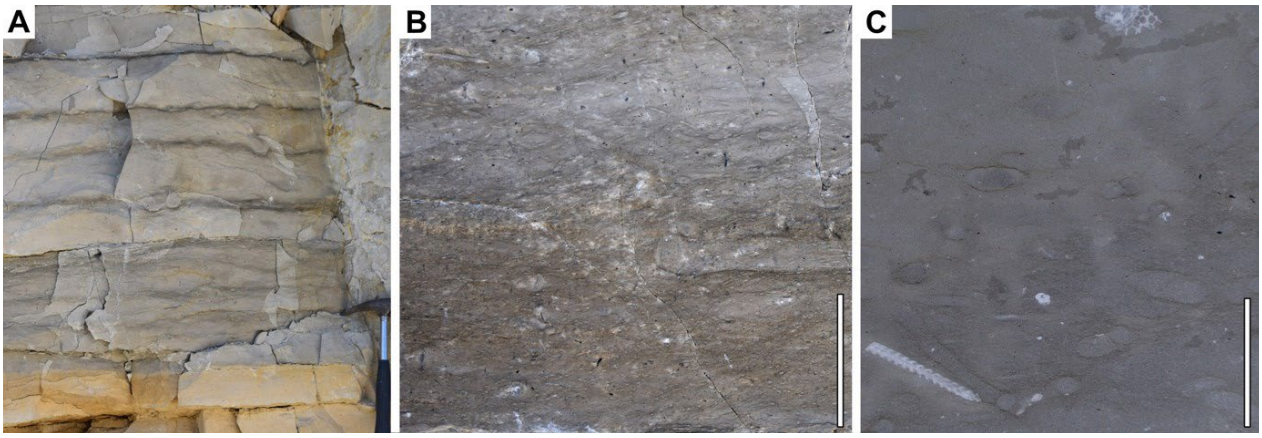

Fig. 20.3. Burrowed limestone of the Saunja Formation, Nabala Regional Stage, Katian, from the Sutlama quarry, Estonia. **A** – field perspective of a fresh outcrop; **B** – Detail of A, note the nested burrow pattern, scale 5 cm; **C** – thin section, with a fragment of brachiopod (lower left), *Coelospheridium* sp. (upper margin), and a micro-gastropod (center right), scale 5 mm.

Fig. 20.4. Limestone of the Saunja Formation, Nabala Regional Stage, Katian, from the Sutlema Quarry, Estonia. Photo: Olle Hints, 2020.

Kõrgessaare Formation

The Kõrgessaare Formation at Sutlema consists of a grey to greenish coloured, wavy bedded to nodular limestone-marl alternation of argillaceous skeletal wackestone (Figs 20.5, 20.6) and marl. The base of the formation is a flat discontinuity surface formed by a hardground on the top of the Saunja Formation. This hardground is heavily burrowed and bored by *Balanoglossites* and *Trypanites* trace-makers and shows signs of karstification (Fig. 20.7B). The burrows reach down to 7 cm into the Saunja Formation and are partly filled with argillaceous wackestone of the Kõrgessaare Formation. The exposed part of the Kõrgessaare Formation consists of a thickening-up sequence with a series of prominent hardgrounds at its top (levels b, c, d in Fig. 20.1). The

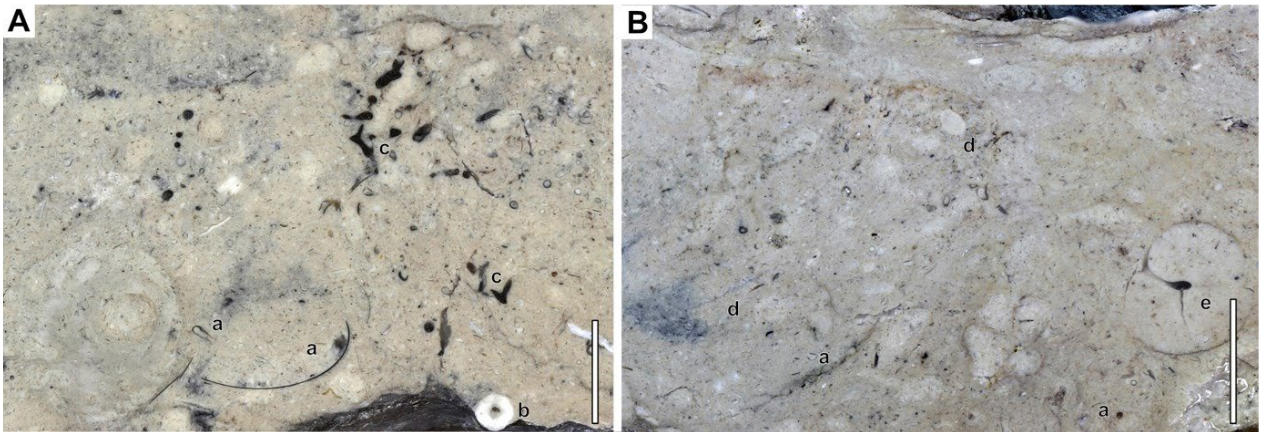

Fig. 20.5. Polished cross section of a burrowed skeletal wackestone from c. 1 m above base of the Kõrgessaare Formation, Vormsi Regional Stage, Katian, from the Sutlama quarry, Estonia. **A** – Detail with abundant trilobite carapace fragments (a), echinoderm ossicle (b) and a hydroid? Colony (c); **B** – Detail with abundant trilobite carapace fragments, bryozoan colony (d) and gastropod (e). Scale bars correspond to 1 cm.

Fig. 20.6. Limestone of the Kõrgessaare Formation, Vormsi Regional Stage, Katian, from the Sutlema Quarry, Estonia. Photo: Gennadi Baranov, 2021.

Fig. 20.7. Selected fossils from the Sutlema quarry, Kõrgessaare and Saunja formations (Katian). Scale bars: A – 50 cm, B, C, H, J, K – 1 cm; E – 5 mm; F, D, G, I – 1 mm. **A** – large borings of *Thalassinoides suevicus* from the Kõrgesaare Formation, field image. **B** – bored, bioeroded and karstified hardground on the top of the Saunja Formation, GIT 881-9. **C** – abundant trace fossil *Chondrites intricatus* on the bedding plane, Saunja Formation, GIT 362-912. **D** – clusters of small faecal pellets of *Coprulus oblongus* filling gastropod, Saunja Formation, GIT 404-686-1. **E** – bioerosional trace fossil *Trypanites sozialis* on hardground, Kõrgesaare Formation, GIT 362-865-2. **F** – algal bioerosional traces, hardground on the top of the Saunja Formation, GIT 881-27-3. **G** – bryozoa *Corynotrypa delicatula* encrusting large brachiopod *Porambonites*, Kõrgessaare Formation, GIT 812-74-1. **H** – bioerosional trace fossil *Trypanites weisei*, hardground on the top of the Saunja Formation, GIT 881-28. **I** – bryozoan holdfast encrusting hardground on the top of the Saunja Formation, GIT 881-26-2. **J**, **K** – tabulate corals from the Kõrgessaare Formation; **J** – *Sarcinula*, GIT 649-9; **K** – *Catenipora,* GIT 734-78**.**

double hardground (levels b and c) is also heavily burrowed, bored, and probably karstified. The uppermost hardground of this sequence (level d) is rough and weakly bored; it is impregnated with phosphatic minerals and partly stained with glauconite. Above this hardground a c. 1 m thick wavy bedded, silty, grey marly layer occurs, rich in rhynchonelliformean brachiopods.

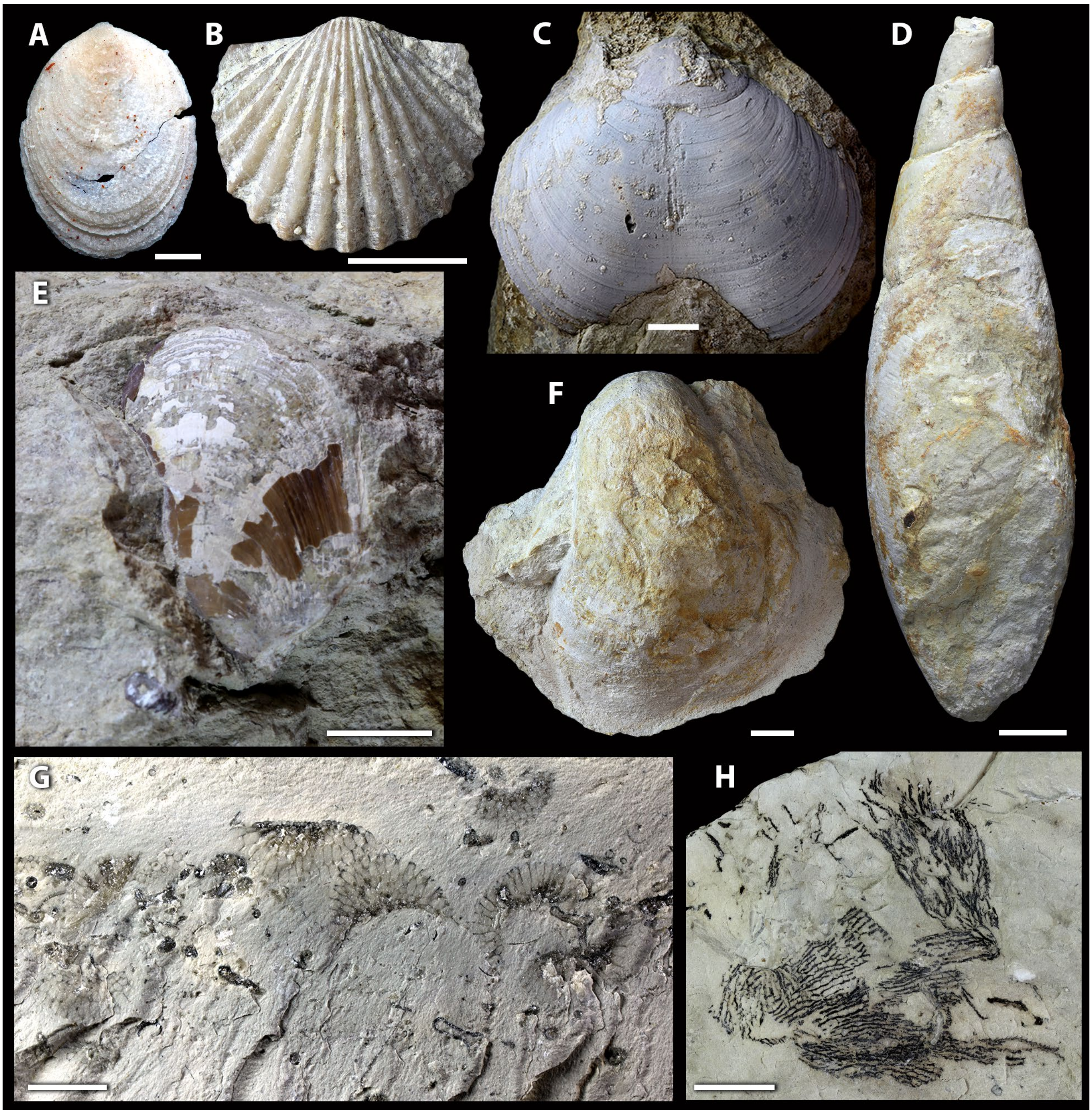

Fig. 20.8. Selected fossils from the Sutlema quarry, Kõrgessaare and Saunja formations (Katian). Scale bars: C–H – 1cm, B – 5 mm, A – 0.5 mm. **A**–**C**, **E** – brachiopods from the Kõrgessaare Formation; **A** – *Pseudopholidops*, GIT 737-254; **B** – *Sulevorthis lyckholmiensis*, GIT 673-488; **C** – *Porambonites gigas*, GIT 673-489; **E** – *Pseudolingula quadrata* in the life position, GIT 810-177. **D**–**F** – gastropods from the Kõrgessaare Formation; **D** – *Subulites subula*, GIT 812-114; **F** – *Salpingostoma kokeni*, GIT 812-100. **G** – algae *Vermiporella* and *Coelosphaeridium* from the Saunja Formation, GIT 812-54. **H** – dendroid *Dictyonema* from the Saunja Formation, GIT 812-1-2.

Fauna and Flora

Fossils are relatively rare but highly diverse in the Saunja Formation. A rich flora of calcareous skeletal algae occurs (e.g., a form provisionally assigned to *Coelospheridium*, the green algae *Vermiporella*, and the receptaculite *Tettragonis sulcata* (Fig. 20.9C). Poriferans are abundant. Molluscs are relatively well preserved with gastropods (e.g., *Murchisonia*, *Subulites*), cephalopods (e.g., *Striatocycloceras*), and bivalves present. Well-preserved dendroid graptolites, tentaculids such as *Palaenigma wrangeli* and enigmatic carbonaceous remains of colonial organisms, here tentatively identified as hydroids (Fig. 20.9A) are remarkable.

Fossils are abundant in the Kõrgessare Formation. Large gastropods are common (e.g., *Hormotoma*, *Fusispira*, *Megalompha*, *Subulites*, *Salpingostoma*, *Sinuites*). They are most abundant in the layer c. 10 cm above the base of the formation. Cephalopod occurrences include endocerids and the orthocerid *Striatocycloceras*. From the marly horizons within the Kõrgessare Formation, a rich fauna of cornulitids has been described (Vinn et al. 2022). Coral occurrences include tabulates (e.g., *Catenipora*, *Heliolites*, *Protaraea*, *Propora*, *Sarcinula*) and rugosans (Fig. 20.7). Small craniid *Pseudopholidops* and the large linguliid *Pseudolingula quadrata*, which occurs

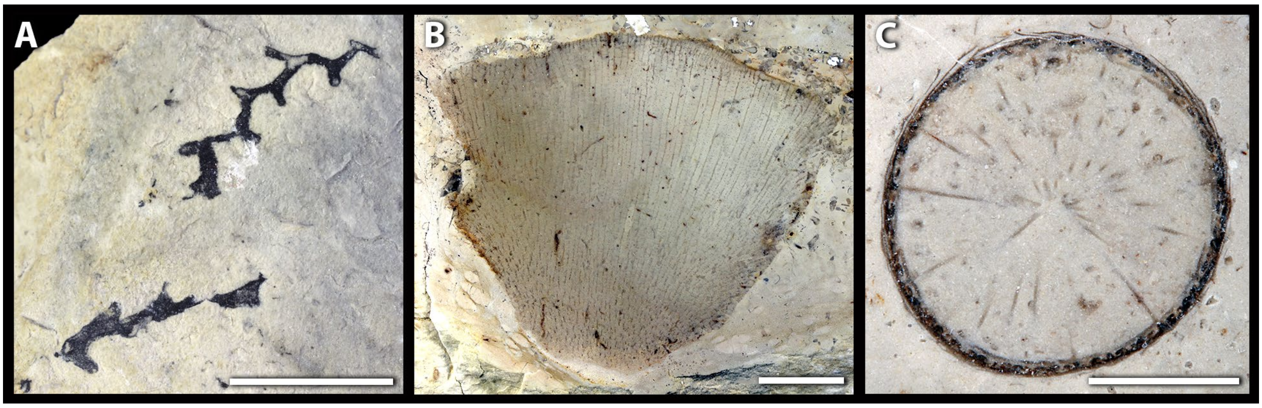

Fig. 20.9. Selected fossils from the Sutlema quarry. Saunja Formation (Katian). Scale bars: A, B – 1 cm; C – 5 mm. **A** – remains of colonial organisms, tentatively determined as hydroids, GIT 812-39. **B** – anthaspidellid sponge, GIT 812-24. **C** – retceptaculitid *Tettragonis sulcata*, GIT 812-23.

in life position (Fig. 20.8E), are common. Rhynchonelliformeans collected from the Kõrgessare Formation in the Sutlema quarry include, e.g., *Bekkeromena*, *Boreadorthis recula*, *Glyptorthis*, *Kiaeromena* (*Bekkeromena*) *vormsina*, *Neoplatystrophia*, *Nicollela*, *Plaesiomys saxbyana, Porambonites gigas*, *Sampo hiiuensis*, *Sulevorthis lyckholmiensis*, *Triplesia* and *Vellamo verneuilii*. Several shelly fossils are encrusted by bryozoans of *Corynotrypa delicatula* (Fig. 20.7G).

The epizoans of the hardgrounds include cornulitids, crinoids, bryozoans, brachiopods, and tabulate corals. The bioerosional ichnofauna of the hardgrounds is abundant, consisting of the shallow-marine firmground trace fossil *Balanoglossites triadicus.* The hard-substrate boring *Trypanites* and algal bioerosional traces are most common (Fig. 20.7E, F, H). The ichnogenus *Trypanites* is represented by three species*,* shallow *T. socialis,* elongated *T. weisei,* and course-changing *Trypanites* isp.

The degree of bioturbation of the Kõrgesaare Formation is high, with a characteristic branching burrow system of *Thalassinoides*. Gastropods of the Saunja and Kõrgessaare formations are frequently filled with small faecal pellets. They occur as massive clusters of ichnospecies *Coprulus oblongus* and more rarely represent the ichnogenus *Tubularina* (i.e., burrows filled with sparry calcite and coprolites). Ichnogenera recorded from steinkerns of gastropods are *Pilichnus* and *Palaeophycus*.

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Field Excursions

August 20, 2024
August 22-25, 2024