4th Annual Meeting of IGCP 591

The Early to Middle Paleozoic Revolution

Estonia, 10-19 June 2014

Abstracts & Field Guide

Institute of Ecology and Earth Sciences, University of Tartu
Institute of Geology at Tallinn University of Technology
Geological Survey of Estonia

4th Annual Meeting of IGCP 591

The Early to Middle Paleozoic Revolution

Estonia, 10-19 June 2014

Abstracts & Field Guide

Edited by

Heikki Bauert, Olle Hints, Tõnu Meidla & Peep Männik

Tartu, 2014

4th Annual Meeting of IGCP 591
The Early to Middle Paleozoic Revolution
Estonia, 10-19 June 2014

Organizing Committee:
Leho Ainsaar (Department of Geology, University of Tartu)
Heikki Bauert (Institute of Geology at Tallinn University of Technology)
Olle Hints (Institute of Geology at Tallinn University of Technology)
Tõnu Meidla (Department of Geology, University of Tartu)
Peep Männik (Institute of Geology at Tallinn University of Technology)
Anne Põldvere (Geological Survey of Estonia)
Oive Tinn (Department of Geology, University of Tartu)

Scientific Committee:
Mikael Calner (Department of Geology, Lund University)
Bradley D. Cramer (Department of Earth and Environmental Sciences, University of Iowa)
Dimitri Kaljo (Institute of Geology at Tallinn University of Technology)
Oliver Lehnert (GeoZentrum Nordbayern, Friedrich-Alexander Universität Erlangen)
Živilė Žigaitė (Evolutionary Biology Centre, Uppsala University)

www.igcp591.org

www.ut.ee

ENVIRONMENTAL INVESTMENT CENTRE
www.kik.ee

TALLINN UNIVERSITY OF TECHNOLOGY
www.ttu.ee

Eesti Geoloogiakeskus
Geological Survey of Estonia
www.egk.ee

Suggested reference format:
Munnecke, A. 2014. The Early Palaeozoic in motion. In: Bauert, H., Hints, O., Meidla, T. & Männik, P. (eds). *4th Annual Meeting of IGCP 591, Estonia, 10 - 19 June 2014. Abstracts and Field Guide*. University of Tartu, Tartu, p. 65.

Bauert, H., Hints, O., Meidla, T. & Männik, P. (eds). 2014. *4th Annual Meeting of IGCP 591, Estonia, 10-19 June 2014. Abstracts and Field Guide*. University of Tartu, Tartu, 202 pp.

Electronic copies of this publication may be obtained from the Department of Geology, Institute of Ecology and Earth Sciences, University of Tartu and Institute of Geology at Tallinn University of Technology.

ISBN 978-9985-4-0822-3

Preface

IGCP Project 591 "The Early to Middle Paleozoic Revolution" was formally started in 2011. The project team that involves 430 participants from 41 countries has repeatedly met in different continents and countries. The present volume was prepared for the 4th annual meeting in Estonia, hosted by the Department of Geology of the University of Tartu and organized in cooperation with the Institute of Geology at Tallinn University of Technology and the Geological Survey of Estonia.

The meeting was held on 10 – 19 June 2014 and attended by nearly 100 participants. This period was divided into three parts. The pre-conference field trip started from Tallinn on 10 June and took people to the key sections of the Ordovician. The scientific sessions were held in Tartu on 13 – 15 June. The post-conference excursion visited Silurian sections in Saaremaa Island and mainland Estonia. It departed from Tartu on 16 June and ended in Tallinn on 19 June.

Sixty-one talks and 36 poster presentations of this meeting summarized recent advances in early to middle Paleozoic geology, palaeontology, geochemistry, biogeography and palaeoecology.

Following the meeting a thematic volume of short papers will be published in the Estonian Journal of Earth Sciences in late 2014, guest edited by Kathleen Histon and Živilė Žigaitė.

The organizers thank all contributors and are particularly grateful to keynote speakers, David Siveter, Bradley Cramer and Axel Munnecke, and the members of the Scientific Committee.

The Organizing Committee acknowledges financial support from the University of Tartu and the Estonian Environmental Investment Centre.

Tõnu Meidla and Olle Hints

On behalf of the Organizing Committee

CONTENTS

New carbon isotopic data from East Baltic suggest shifting the Ordovician/Silurian boundary into the Juuru Regional Stage

Leho Ainsaar[1]*, Tõnu Meidla*[1]*, Heikki Bauert*[2] *and Janika Truumees*[3]

[1] *Department of Geology, University of Tartu, Ravila 14a, Tartu 50411, Estonia; Leho.Ainsaar@ut.ee*
[2] *Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, Tallinn 19086, Estonia*
[3] *GeoConsult Hamburg GbR, Borsteler Chaussee 85-99a, Hamburg 22453, Germany*

The Hirnantian glacial event caused a global biotic crisis, which is well expressed in sea level, facies and faunal changes in tropical shelves of different continents. In marine carbonates of several palaeobasins with complete stratigraphic succession, the glaciation caused the $\delta^{13}C$ values make a positive excursion (HICE), starting in the earliest Hirnantian, reaching a peak of 7‰ followed by a curve plateau, and falling to background values in the mid or late Hirnantian. The fact that this event caused a coeval shifts in carbon and oxygen stable isotope composition of different sedimentary components (biogenic carbonate and apatite, organic matter) makes this interval useful for testing the chemostratigraphic tools in correlation of sedimentary sections.

In the Baltoscandian Basin, carbon isotopes have been helpful for time correlation of different lithostratigraphic units, but construction and comparison of local and regional curves with the global standard curve is complicated due to gaps at the boundaries and within the Porkuni Regional Stage. Comparison of the new detail $\delta^{13}C$ curves across the Porkuni and Juuru Stage of Estonia and Latvia with key sections in other areas suggests some changes in the traditional stratigraphic correlation scheme of East Baltic area. The Ärina Formation, Porkuni Regional Stage, has previously been considered as the early Hirnantian whilst the upper Hirnantian was supposed to be missing in the area and the Varbola Formation was dated as the early Llandovery. However, the basal part of the Varbola Formation, the Koigi Member, falls into the interval of upward declining $\delta^{13}C$ values in the sections of the Pandivere area that represents the latest part of the HICE. This suggests the Ordovician/Silurian boundary falls into the lower part of the Varbola Formation. Similar boundary correlation has been supported by Hints *et al.* (2014) based on $\delta^{13}C$ data from Viki drillcore (Saaremaa Island). The newest data from the Tartu drillcore, southern Estonia, clearly demonstrate that the lower part of the Õhne Formation, Juuru Stage, bears the falling limb of the HICE and is of Hirnantian age. The same can be concluded about the lower part of the Staciunai Formation in the Jurmala core section, Latvia. Establishing the exact level of this boundary within the discussed units requires further studies.

Similar upward correction of the Ordovician/Silurian boundary has been suggested for several carbonate basins by the isotope chemostratigraphic analysis in recent years, including Anticosti Island, southern Ontario, and Upper Mississippi Valley in North America, and Subpolar Urals. These chemostratigraphic corrections of the traditional stratigraphic schemes are in agreement with the former suggestion that the major changes in several fauna groups likely preceded the systemic boundary. The second phase of the global Hirnantian extinction was followed by a slow faunal recovery with appearance of post-extinction biota in the late Hirnantian that obviously included some “Silurian-type” shelly fossil groups. For this reason, the traditional position of the Ordovician/Silurian boundary in many non-graptolitiferous successions should be critically reevaluated.

Hints, O., Martma, T., Männik, P., Nõlvak, J., Põldvere, A., Shen, Y. & Viira, V., 2014. New data on Ordovician stable isotope record and conodont biostratigraphy from the Viki reference drill core, Saaremaa Island, western Estonia. *GFF*, 136, 100–104.

Using palynomorph (chitinozoan) assemblages to unravel the nature of Ordovician limestone-shale alternations in the Oslo-Asker area

Chloé E.A. Amberg[1], Tim Collart[2], Wout Salenbien[2], Thijs R.A. Vandenbroucke[1], Axel Munnecke[3], Øyvind Hammer[4] and Arne Nielsen[5]

[1] *UMR 8217 du CNRS: Géosystèmes, Université Lille 1, SN5, 59655 Villeneuve d'Ascq, France; chloe.amberg@ed.univ-lille1.fr*
[2] *Department of Geology and Soil Science (WE13), Ghent University, Krijgslaan 281-S8, B-9000 Gent, Belgium*
[3] *Geozentrum Nordbayern, Friedrich-Alexander University of Erlangen-Nürnberg, Loewenichstr 28, 91054 Erlangen, Germany*
[4] *Natural History Museum of Denmark, University of Copenhagen, Øster Voldgade 5–7, DK-1350 Copenhagen K, Denmark*
[5] *Natural History Museum, University of Oslo, Sars gate 1, 0318 Oslo, Norway*

The Ordovician system was long known as a greenhouse period, with a short glaciation during the Hirnantian. An emerging body of evidence now suggests that global cooling and the onset of the Early Paleozoic Ice Age (EPI) started much earlier than previously assumed, in the early Katian (Armstrong 2007), or even during the Early-Mid Ordovician (Trotter *et al.* 2008). To test the hypothesis of pre-Hirnantian glaciations, we revisited Floian to Katian sections from the Oslo–Asker area (Nakkholmen Island and Bygdøy) where a series of limestone-shale rhythmites have been identified as short-term palaeoclimatological fluctuations (Nielsen 2004). However, alternatively, such deposits can also be the result of differential diagenesis (Westphal *et al.* 2000). Our methodology integrates chitinozoan micropaleontology and geochemistry (XRF) in order to differentiate between these hypotheses. Here, the detailed palynological study will be presented.

We use chitinozoans as a proxy because they are sensitive to climatic and environmental changes. A true cyclic origin for the rhythmites could thus be recorded by different assemblages in the shales and the limestones, because they are not altered by differential diagenesis. An additional challenge lies within the presence and degree of preservation of the palynomorph assemblages, varying between sections and from bed to bed. Age diagnostic assemblages so far are limited to the *Spinachitina cervicornis* zone, the *Ancyrochitina* n sp. 1 subzone, and the *Belonechitina gamachiana* zone. Less age diagnostic assemblages exist in other parts of the stratigraphy. The assemblages appear to be similar in both lithologies in all sections at least at the genus level. Exceptions exist in the sections on Nakkholmen Island, where in the lower part of the Hovedøya Mbr., *B. gamachiana* is only found in limestones, whereas *B. cactacea* is found preferentially in shales. In the lower Frognarkilen Fm., *A. bornholmensis* is more abundant in the shales and *B. robusta* is more abundant in the limestone samples. Potentially, these species are isolated specialists, responding to environmental changes. However, taken at face value, these specific cases are exceptions rather than the rule, and seem insufficient to suggest the identification of an original cyclic signal.

Armstrong, H.A., 2007. On the cause of the Ordovician glaciation. *In:* Williams, M., Haywood, A.M., Gregory, F.J., Schmidt, D.N. (eds). *Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies*. Special Publications of the Micropalaeontological Society. The Geological Society, London, 101–121.

Nielsen, A.T., 2004. Ordovician Sea-level changes: A Baltoscandian perspective. *In:* Webby, B.D., Droser, M.L., Paris, F. & Percival, I.G. (eds). *The Great Ordovician Diversification Event*. Columbia University Press, New York, 84–93.

Trotter, J.A., Williams, I.S., Barnes, C.R., Lecuyer, C. & Nicoll, R.S., 2008. Did cooling oceans trigger Ordovician biodiversifcation? Evidence from conodont thermometry. *Science*, 321, 550–554.

Westphal, H., Head, M.J. & Munnecke, A., 2000. Differential diagenesis of rhythmic limestone alternations supported by palynological evidence. *Journal of Sedimentary Research*, 70, 715–725.

Stratigraphy of the Ordovician – Silurian transition in the Northern Urals: state of art and problems

Anna I. Antoshkina[1], Lyubov' A. Shmeleva[1] and Peep Männik[2]

[1] *Institute of Geology, Komi Science Centre, Ural Branch, RAS, Syktyvkar, Russia*
[2] *Institute of Geology at Tallinn University of Technology, Estonia; peep.mannik@ttu.ee*

Modernization of stratigraphical schemes of the Timan–northern Ural region requires reliable dating and high-resolution correlation of strata. Due to ecologically highly variable environments and poorly preserved faunas the aim is complicate to achieve. One of the key intervals to be studied is the Ordovician–Silurian transition in general and the system boundary in particular. So far, only two successions across this boundary are known, both on the Kozhym River in the Subpolar Urals (Antoshkina 2008; Beznosova *et al.* 2011). The sections represent different environments: one of them formed in inner shelf (inner platform) and the other one in platform margin (including reefs) conditions. In both sections, rocks are tectonically altered and re-crystallised, fauna is rare and poorly preserved. Sedimentological, biostratigraphical and geochemical studies of the sections allowed recognition of a probable level of the system boundary only. Further studies are required to prove this level as the system boundary or to locate its real position in the succession.

A better preserved but less studied Upper Ordovician–Lower Silurian succession is known to occur on the Ilych River in the Northern Urals (Antoshkina 2003). Here, the rocks are less altered, fossils are more abundant and better preserved. In this region, transect from inner shelf (inner platform) across the platform margin (with upper Katian reefs) to open shelf (in some intervals graptolite-bearing) environments is represented and exposed in number of outcrops. However, no continuous succession across the Ordovician–Silurian boundary is known, and the strata of Hirnantian age recognized, in this region. In the next stage of our study we will concentrate to this region. Of particular importance will be detailed sedimentological (including microfacies) and palaeontological (mainly conodonts and vertebrates) studies. Well preserved rocks and faunas in these sections will hopefully provide data essential for better understanding of the Late Ordovician–Early Silurian environmental history of the Timan–northern Ural region.

Antoshkina, A.I., 2003. *Paleozoic reef building (an example of the northern part of the Urals and adjacent areas)*. URO RAS, Ekaterinburg, 1–303. [in Russian].

Antoshkina A., 2008. Late Ordovician-Early Silurian facies development and environmental changes in the Subpolar Urals. *Lethaia*, 41, 163–171.

Beznosova, T., Majdl', T., Männik, P. & Martma, T., 2011. The Ordovician–Silurian boundary on the western slope of Subpolar Urals. *Stratigraphy and Geological Correlation*, 19, 385–403.

Characterizing the Oldenburg 'Butter Shale' from the Upper Ordovician (Katian) Waynesville Formation along the Cincinnati Arch, USA

***Christopher D. Aucoin*[1]*, Carlton E. Brett*[1]*, Benjamin Dattilo*[2] *and Dan Cooper*[3]**

[1] *University of Cincinnati, Department of Geology, USA.; aucoincd@mail.uc.edu, brettce@ucmail.uc.edu*
[2] *Geoscience Department, Indiana University Purdue University Fort Wayne, USA; dattilob@ipfw.edu*
[3] *Trilobites of America; dancooper@cinci.rr.com*

The Upper Ordovician (Katian) strata of the Cincinnati Arch contain numerous mudstone units known locally as 'butter shales' or 'trilobite shales'. Most of these deposits are heavily collected for their excellently-preserved trilobites. The Oldenburg Butter Shale, however, is a previously-undescribed mudstone package from the Waynesville Formation, known only from limited exposure near Oldenburg, Indiana.

The Oldenburg Shale is a 2 m-thick mudstone package with minor beds of shelly packstones, and calcisiltite-filled gutter casts. It contains abundant articulated trilobites. The mudstone portion contains illite, chlorite, quartz, calcite and traces of dolomite and pyrite. In outcrop, the shale exhibits no obvious bedding and breaks conchoidally. When cut and polished, the mudstone shows a mottled fabric, containing Lingulichnus and Chondrites trace fossils. The shelly units contain brachiopods, gastropods, and bryozoans. The gutter casts are 20–30 cm wide, display hummocky stratification, and contain *Lingulichnus*.

Faunally, the Oldenburg is very unlike surrounding Waynesville strata. Instead of being dominated by brachiopods as is typical, the Oldenburg fauna consists of abundant bivalves (*Modiolopsis*, *Ambonychia*, and *Caritodens*), lingulid brachiopods, and the trilobites (*Isotelus*, and *Flexicalymene*, and rare *Amphilichas* in the upper 30 cm). Articulate brachiopods are represented in the shale to a limited extent by the genera *Zygospira* and *Platystrophia*. The shale also contains bryozoans, orthoconic cephalopods, rare crinoids and conulariids. Conodonts and scolecodonts are a major component of the microfauna.

Taphonomy of the fossils, together with sedimentological features, indicates that this butter shale accumulated rapidly as a series of episodes of distal storm-generated mud and silt flows.

Towards the top of the mudstone is a horizon of small concretions, about 7 cm wide. Overlying the butter shale is the pyrite crusted surface of the Mid-Richmondian Unconformity which removes the Oldenburg shale in most other locations. The concretions present at the top of the shale are the likely product of the prolonged sediment starvation accompanying this unconformity.

Evidence for a Mid-Richmondian Unconformity in the Upper Ordovician (Katian) Strata along the Cincinnati Arch, USA

Christopher D. Aucoin[1], Carlton E. Brett[1] and Benjamin Dattilo[2]

[1] *University of Cincinnati, Department of Geology, USA; aucoincd@mail.uc.edu, brettce@ucmail.uc.edu*
[2] *Geoscience Department, Indiana University Purdue University Fort Wayne, USA; dattilob@ipfw.edu*

The Upper Ordovician (Katian, Richmondian) strata of Ohio, Kentucky and Indiana, long noted for their abundant fossils and excellent exposures, have been subdivided into a series of three 3rd order depositional sequences by Holland and Patzkowsky (1996). Recent detailed field studies in southern Indiana and northern Kentucky suggests a major, regionally angular unconformity within their sequence C5. Evidence for this subtle disconformity includes the progressive southward loss of marker beds and intervals in the middle part of the Waynesville Formation in southern Indiana. This regional truncation has escaped notice despite a century of stratigraphic work, in part because of similarity of facies above and below the erosion surface. However, it appears to be equivalent to a Mid-Richmondian Unconformity recognized Ross and Ross (2002) in central Kentucky. Recent work confirms the significance of this surface.

The Mid-Richmondian Unconformity in southern indiana is situated below a thin condensed interval containing a brachiopod epibole, the “lower *Glyptorthis insculpta* zone”, the base of which marks the traditional boundary between the Clarksville and Blanchester Members of the Waynesville Formation. In down-ramp locations, the surface is characterized by the presence of small crusts of pyrite. Further upramp (to the south), this surface is marked by a change from limestone and shale of the Bull Fork Formation to dolostone and dolomitic shales referred to by previous workers as the Rowland Member of the Drakes Formation. Approximately 15 – 16 meters of strata, present in northern distal section, are absent in the proximal sections on the west side of the Cincinnati Arch. This is explained by both erosional down-cutting beneath the unconformity, and depositional thinning of the shales in the proximal setting. Future correlation work will test the idea that this surface continues further south, eventually removing all of the lowest Waynesville and part of the Arnhem Formation below.

This significant unconformity represents a third-order sequence boundary that splits Holland’s C5 sequence into two parts. Accordingly, we propose that the Blanchester, the uppermost member of the Waynesville, be elevated to a formation.

A Phylogenetic and Paleobiogeographic Analysis of the Ordovician Brachiopods *Eochonetes* and *Thaerodonta*

Jennifer E. Bauer and Alycia L. Stigall

Department of Geological Sciences and Ohio Center for Ecology and Evolutionary Studies, 316 Clippinger Laboratories, Ohio University, Athens, Ohio, 45701, USA; jb964112@ohio.edu, stigall@ohio.edu

The primary objective of this study is to analyze the relative taxonomic positions of the Late Ordovician strophomenid brachiopod genera *Thaerodonta* and *Eochonetes*, which have been alternately synonymized and separated as discrete evolutionary entities. The taxonomic history of these genera is complex, reflecting conflicting opinions about whether or not the species assigned to each genus comprise a distinct evolutionary lineage. The relative validity of these genera and their included species was examined in a combined morphological, phylogenetic, and biogeographic analysis.

Character-based multivariate statistical analyses were conducted to examine generic and species validity. The two genera exhibited a high degree of morphospace overlap. Thus, *Eochonetes* and *Thaerodonta* are interpreted as lacking significant differences among the general morphological attributes analyzed in the multivariate analyses. Although the genera could not be differentiated in morphospace, a series of species were demonstrated to occupy discrete regions of morphospace. Variations in maximum shell width are responsible for much of the morphospace discrimination. Comparison of two internal characters on the plots resulted in complete morphospace overlap whereas combinations of internal and external characters as components or coordinates yielded clear separations. The multivariate analyses also yielded information on species relationships in morphospace. The broad morphospace fields of *Thaerodonta clarksvillensis* and *Eochonetes advena* were interpreted to most closely approximate the ancestral morphological conditions due to the central locations of the polygons on the dorsal and ventral plots respectively.

A phylogenetic hypothesis was generated using 16 operational taxonomic units previously assigned to both genera. The resulting tree topology is inconsistent with the validity of *Thaerodonta* as a discrete taxonomic entity. Thus, *Thaerodonta* is synonymized with *Eochonetes*. Based on phylogenetic topology and morphospace discrimination, three new species should be recognized and two others synonymized. Characters of particular importance in the evolution of the clade are the presence of lateral septa in the dorsal valve interior and the development of hingeline denticulation. Species in lower energy depositional environments (e.g., *E. recedens*) exhibit less deeply incised muscle scars and more poorly developed hingeline denticulation compared to higher energy setting of the mid-ramp (e.g., *E. magna*, *E. mucronata*).

The recovered phylogenetic topology was used to reconstruct biogeographic patterns and determine speciation modes within the genus. Ancestral areas were reconstructed using Fitch Optimization and speciation mode could be resolved for 21 speciation events; 76% were characterized as vicariance events and the remaining 24% were interpreted as dispersal events. Ancestrally, *Eochonetes* occupied an area west of the Transcontinental Arch, and dispersed from this area to the Cincinnati Basin, the Scoto-Appalachia Basin, and the Northern Midcontinent. One species, *Eochonetes clarksvillensis*, was a participant in the Richmondian Invasion into the Cincinnati Basin. Results of this analysis indicate that this lineage dispersed in the Cincinnati region from an area west of the Transcontinental Arch. This differs from the dispersal pathways of other brachiopods, which support a multi-directional pathway for the Richmondian Invasion.

Ordovician Atlas of Ancient Life: From Fossil Identification to the Classroom

Jennifer E. Bauer, Alycia L. Stigall and Adriane R. Lam

Department of Geological Sciences and OHIO Center for Ecology and Evolutionary Studies, 316 Clippinger Laboratories, Ohio University, Athens, Ohio, 45701, USA; jb964112@ohio.edu, stigall@ohio.edu, al8011513@ohio.edu

Museum collections of fossils, along with their associated locality data, provide millions of records representing data on the temporal and geographic distribution of species in deep time. However, to reach their greatest scientific and educational potential, these collections data need to be available on-line and in formats accessible to both professional scientists and can be utilized by the public. Recent efforts in our research group have focused on digitizing specimens of Late Ordovician (Katian) fossils from the Cincinnati, Ohio, USA region and developing outreach materials for K-16 education and avocational paleontologists. Ultimately, much of these data and products are deployed via the www.ordovicianatlas.org interface.

The initial year (2012–2013) of this NSF funded project focused on digitization (cataloging and georeferencing) of the 13,000 specimen collection housed at Ohio University. This is a newly acquired collection donated by an avocational paleontologist and includes detailed geographic and stratigraphic data for a broadly representative set of taxa. The digitization process resulted in a highly detailed, accurate digital which has been made publicly available via the iDigBio portal. By attaching accurately georeferenced latitude/longitude coordinates to each specimen, this collection has generated thousands of mappable data points to augment the digital biogeographic record.

The second year of the project (2013–2014) focused on development and content generation for the website (www.ordovicianatlas.org). The atlas includes dedicated pages for common species and higher taxa in the Cincinnatian strata. Each species page includes paleoecological data, taxonomic details, stratigraphic occurrences, identification in hand sample information, and published descriptions on the species in question. The goal is to create content useful to both professional and avocational paleontologists. Currently, there are over 60 species and more than 165 higher taxa pages visible to the public. The third year of the project (2014–2015) will focus on developing interactive geographic maps of species and transferring content into an "app" for smartphones.

In addition, to creating an identification and systematics reference, the collection has been used to develop lesson plans for K-16 educators (grade school through college). These lessons utilize the well-exposed marine invertebrate fossils of the Cincinnati Arch region to explore concepts in diversity, ecology, and evolution with ties to modern ecosystem function. These lesson plans can be and have been modified for use in elementary to college classrooms as well as in public outreach programs with adults and children.

Integrated Ordovician δ^{13}C chemostratigraphy and chitinozoan biostratigraphy of the Tartu drillcore section, southern Estonia

Heikki Bauert[1], Leho Ainsaar[2], Garmen Bauert[1], Jaak Nõlvak[1], Kairi Põldsaar[2] and Siim Sepp[2]

[1] *Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, Tallinn 19086, Estonia; heikki.bauert@ttu.ee*
[2] *Department of Geology, University of Tartu, Ravila 14a, Tartu 50411, Estonia*

The Baltoscandian region is a well-known key area for global Ordovician biostratigraphic and chemostratigraphic research. The last decade of extensive stable carbon isotope chemostratigraphic studies of the Baltoscandian Ordovician–Silurian carbonate succession have revealed a series of positive δ^{13}C isotope excursions that have shown a great potential for global correlations. The aim of this study is to link the detailed δ^{13}C data of the Middle and Upper Ordovician succession with a high-resolution chitinozoan biostratigraphy. For this purpose, altogether 322 carbonate rock samples from the Tartu-453 drillcore were analyzed for stable carbon and oxygen isotopic composition and a major taxonomic re-assessment of the Ordovician chitinozoans (Lasnamägi to Juuru stages) was carried out. From seven positive isotope carbon excursions (ICE) known to occur in the Ordovician succession in Estonia we were able to recognize in the Tartu drillcore section all but the Paroveja and Rakvere ones.

The **mid-Darriwilian excursion (MDICE)** is characterized by a very broad excursion curve with a considerable temporal extent, spanning from Kunda to Lasnamägi ages. Oxidation has destroyed chitinous organic matter in red-colored limestones and therefore no chitinozoan information is available from the Middle Ordovician Kunda – Aseri stage interval. The declining upper limb of MDICE, however, falls in the lower part of the *Laufeldochitina striata* Zone of the Lasnamägi Stage. The second largest isotopic carbon excursion in Ordovician, the **Guttenberg ICE (GICE)**, is recorded as a broad peak in the highly argillaceous to silty limestones of the late Keila to early Oandu age. The lower and middle parts of the GICE coincide with the upper part of *Spinachitina cervicornis* Zone. Although showing a small rise in δ^{13}C values, but still distinctive **Saunja ICE** is recorded in the aphanitic limestones of the Saunja Formation. The Saunja ICE is located in the upper part of the *Fungochitina spinifera* chitinozoan zone. The presence of the relatively small **Moe ICE** at the base of the Pirgu Stage falls into the redbeds of the Jonstorp Formation and no chitinozoan data are available.

The Late Ordovician **Hirnantian excursion (HICE)** is one of the largest positive δ^{13}C excursions known in the Lower Palaeozoic. The HICE is known to be well delimiting the Hirnantian Stage in the sections. The HICE in the studied Estonian sections usually starts within the *Spinachitina taugourdeaui* chitinozoan zone at the base of the Porkuni Stage. However, the Tartu section contains exceptionally thick argillaceous limestone succession of the Halliku Formation with a 10 meters interval of continuous distribution of chitinozoan *Spinachitina taugourdeaui* in the middle part (242 – 252 m), which seems to precede the main HICE positive shift (2 – 3‰). In other examined Estonian sections the range of this chitinozoan species is always less than 2 meters.

Traditionally, the Ordovician – Silurian boundary in southern Estonia is placed at the top of the oolitic Saldus Formation (Porkuni Stage) and the overlying carbonate rocks of the Juuru Stage are referred to the Silurian. The HICE in Tartu section ends within the highly argillaceous limestones of the Rozeni Member (Õhne Formation) of the Juuru Stage – raising the top of the Hirnantian Stage at least 9 meters from a conventional level. This is in accordance with new chemostratigraphic analyses from several Estonian sections, suggesting the position of Ordovician – Silurian boundary to be placed inside the Juuru Regional Stage. To date, the termination of HICE in the Baltic area does not have a good biostratigraphic control established yet. The small number of pilot studies accomplished so far has recorded only a few chitinozoan taxa in low numbers. In the light of new evidence a further chitinozoan – conodont research is needed to assess their biostratigraphic potential for correlations of the Hirnantian Stage.

Palaeogeographical significance of upper lower Cambrian (provisional Cambrian Series 2) trilobites from Gansu Province, China

Jan Bergström[1]†, Zhiqiang Zhou[2], Per Ahlberg[3] and Niklas Axheimer[3]

[1] *Swedish Museum of Natural History, Department of Palaeozoology, Sweden; † Deceased*
[2] *Xi'an Institute of Geology and Mineral Resources, 438 East You Yi Road, Xi'an 710054, China; zsy1940@163.com*
[3] *Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden; per.ahlberg@geol.lu.se, niklas.axheimer@geol.lu.se*

China is a complex collage of continental blocks and accretionary belts, as well as several smaller blocks and terranes, including amalgamation of the North China plates and the southern marginal areas of Siberia. As fossils are of fundamental importance for interpretation of complex palaeogeographical situations, providing age and geographic constraints in formulation of tectonic models, we have used palaeogeographically and biostratigraphically important trilobites from northwestern China in order to shed some light on early Cambrian plate configurations. Fossiliferous upper lower Cambrian (provisional Cambrian Series 2) rocks crop out sporadically in the Beishan area, northwestern Gansu Province of China. Trilobites have been collected from three measured sections through the Shuangyingshan Formation, a relatively thin, carbonate-dominated unit that is locally exposed in Subei County of the Beishan area. The trilobite fauna from this formation is dominated by eodiscoid and 'corynexochid' trilobites, together representing at least ten genera: *Serrodiscus*, *Tannudiscus*, *Calodiscus*, *Pagetides*, *Kootenia*, Ed*elsteinaspis*, *Ptarmiganoides*?, *Politinella*, *Dinesus* and *Subeia*. Sixteen species have been identified, of which seven are identified with previously described taxa and nine described under open nomenclature. The composition of the fauna, and particularly the presence of species of *Edelsteinaspis*, *Dinesus* and *Politinella*, suggests affinity with Altai–Sayan and marginal Siberian trilobite faunas rather than Gondwanan ones, suggesting that the Middle Tianshan-Beishan Terrane may have been located fairly close to Siberia during middle – late Cambrian Epoch 2. The Beishan trilobite fauna is also similar to a coeval fauna from the Karaganda area in Kazakhstan. This indicates that the Middle Tianshan-Beishan Terrane may have formed part of the Kazakhstan Mid-Plate during Cambrian and Early Ordovician times. Following the closure of the Middle Tianshan Sea during the Darriwilian, the Middle Tianshan-Beishan Terrane was incorporated into the Tarim Plate.

Brachiopods and conodonts in the Llandovery – Wenlock boundary interval in the Timan – northern Ural region

Tatyana M. Beznosova[1], *Peep Männik*[2] *and Lyubov V. Sokolova*[2]

[1] *Institute of Geology, Komi Science Centre of UB RAS, Syktyvkar, Russia; beznosova@geo.komisc.ru*
[2] *Institute of Geology at Tallinn University of Technology, Tallinn, Estonia; peep.mannik@ttu.ee*

Traditionally, due to the lack of other criteria, the Llandovery – Wenlock boundary in the Timan–northern Ural region was identified by the disappearance of the conodont genus *Apsidognathus* (Männik & Martma 2000; Melnikov & Zhemchugova 2000). In Subpolar Urals, above this level, in the lowermost part of the strata of Wenlock age, brachiopod *Spirinella nordensis* (Ljashenko) appears (Beznosova 2008). Although it was known that a gap of considerable duration exists in the Llandovery – Wenlock boundary interval (between the range intervals of *Apsidognathus* and *S. nordensis*) in Subpolar Urals (Beznosova & Männik, 2005) it was believed that *S. nordensis* appears always above the level of disappearance of *Apsidognathus*. In Subpolar Urals, in the section Kozhym-217 occurrences of these two taxa are separated by an interval of 19 m. At the same time, in the upper part of its range, *Apsidognathus* occurs together with brachiopod *Hyattidina* sp. and ostracod *Herrmannina insignes* Abushik. Both of these taxa have been believed to be characteristic of the Wenlock strata in the region only. In the Kozhym-217 section the interval of co-occurrence of these taxa is 17.3 m thick.

Now, more and more data become evident suggesting that composition and distribution of faunas in the Llandovery – Wenlock boundary interval need additional careful study. In section 10Ts on the Shchugor River (Subpolar Urals, about 200 km to south from Kozhym-217) *Apsidognathus* sp. and *S. nordensis* occur together in a 19 m thick interval. On the Shar'yu River (Chernyshev Swell, sections 64 and 65), thickness of the interval of co-occurrences is 14.5 m; in the section on the Bezymyannyj Stream (Chernov Swell) – 125 m. In all these sections, also *Hyattidina* sp. occurs in this interval. Hence, it is evident that some taxa earlier considered to be characteristic of Wenlock only appear already in the upper part of Llandovery (as defined by the distribution of *Apsidognathus*). It is most probable that, in reality, *S. nordensis* (also *Hyattidina* sp. and *H. insignes*) appear in upper Llandovery but, due to a gap in many successions, the interval of their co-occurrence with *Apsidognathus* is usually missing and can be studied in most complete sections only. Also, in some cases re-deposition of older material into younger strata (e.g. *Apsidognathus* into lower Wenlock strata) cannot be excluded. Lithologically, in all sections studied the Llandovery – Wenlock boundary interval is characterized by features indicating to a shallowing event: occurrence of mud cracks, erosional surfaces, intervals rich in variously rounded bio- and lithoclastic material, appearance of microlamination and stromatolitic beds, etc. To explain the situation additional sedimentological and biostratigraphical studies in the region are essential.

Beznosova, T.M., 2008. *Brachiopod communities and biostratigraphy of Upper Ordovician, Silurian and Lower Devonian deposites of the northeastern margin of the Baltica Paleocontinent*. UB RAS, Ekaterinburg. 215 pp.

Beznosova, T.M. & Männik, P., 2005. The Llandovery–Wenlock boundary in the northern part of the Baltica paleocontinent. *Transactions of the Russian Academy of Sciences*, 401A, 374–377.

Männik, P. & Martma, T., 2000. Llandovery–Wenlock boundary in the Subpolar Urals. *Ichthyolith Issues Special Publication*, 6, 64–67.

Melnikov, S.V. & Zhemchugova, V.A., 2000. Lower Silurian stratigraphy of the Timan–Northern Ural region and eustatic fluctuation. *Proceedings of the Estonian Academy of Sciences. Geology*, 49, 85–103.

Stratigraphy, geochemistry and origin of Silurian black shales of the Russian Arctic

Olga K. Bogolepova[1] *and Alexander P. Gubanov*[1,2]

[1] *CASP, University of Cambridge, West Building, 181A Huntingdon Road, Cambridge, CB3 0DH, UK; olga.bogolepova@casp.cam.ac.uk*
[2] *Museum of Evolution, Uppsala University, Norbyvägen 16, SE-75236, Uppsala, Sweden; alexander.gubanov@em.uu.se*

As part of our on-going research on Silurian organic-rich source rocks, a database of Silurian black shales in the Russian Arctic is being compiled from the literature with a complementary data set provided by original fieldwork and associated samples.

Our review of the literature shows that Silurian black shales are well developed in the Russian Arctic. They are recorded from northern Novaya Zemlya, Vaigach and Pai-Khoi, the northern and Polar Urals, East Siberia, Taimyr, Severnaya Zemlya, the New Siberian Islands, Verkhoyansk-Kolyma and Chukotka. In some regions as much as 1000 m of black shales are reported. Sections provide excellent graptolite data allowing good biostratigraphic control and correlation. For these, eleven, areas, we present stratigraphic charts from Llandovery to Pridoli with information on sediment thickness, biostratigraphy and depositional settings. In almost all of the areas examined black shales occur at or near the base of the Silurian. Similar graptolitic shales are also know from other parts of the world (e.g. northern Africa). They represent a synchronous depositional unit, most probably associated with a large-scale anoxic event, related to the early Silurian rapid rise of sea level that followed rapid Late Ordovician deglaciation (Lüning *et al.* 2000).

Our field studies cover Severnaya Zemlya, Taimyr, northern East Siberia, and Kotel'ny Island of the New Siberian islands, where the Silurian sequences contain black graptolitic shale and bituminous limestone intervals. Field and analytical studies have been undertaken to map the rocks, document their stratigraphy, identify the fossils, establish and describe facies, reconstruct the palaeogeography, and determine palaeoenvironmental conditions. The later was achieved by performing major, trace and rare earth element analysis with a focus on specific elements, geochemical proxies and ratios. Some geochemical proxies, including Th/U, V/Cr, and V/(V+Ni), together with sedimentary facies and faunal data indicate anoxic conditions in Central Taimyr during the Telychian, Wenlock, early Ludlow and early Pridoli. It should be noted that no samples have been analysed from the Rhuddanian and Aeronian strata of Taimyr. An anoxic environment is indicated for the Rhuddanian of Kotel'ny Island, and for the Telychian of Severnaya Zemlya. In East Siberia, Th/U ratios indicate anoxic conditions during the Rhuddanian, Ludlow and Pridoli, but oxic conditions during the Aeronian. Other geochemical proxies (e.g. V/Cr, V/(V+Ni) and Ni/Co), suggest rather wide ranging environments through time. The overall geochemical trends are in good agreement with the results of previous palaeontological and sedimentological studies and confirm that the Rhuddanian anoxic environment was a result of a global sea-level rise.

Lüning, S., Craig, J., Loydell, D.K., Storch, P. & Fitches, B., 2000. Lower Silurian "hot shales" in North Africa and Arabia: Regional distribution and depositional model. *Earth Science Reviews*, 49, 121–200.

The Silurian of the northern Caucasus, Russia

Olga K. Bogolepova[1], Alexander P. Gubanov[1,2] and Vladimir A. Lavrischev[3]

[1] *CASP, University of Cambridge, West Building, 181A Huntingdon Road, Cambridge, CB30DH, UK; olga.bogolepova@casp.cam.ac.uk*
[2] *Museum of Evolution, Uppsala University, Norbyvägen 16, SE 75236, Uppsala, Sweden; alexander.gubanov@em.uu.se*
[3] *Kavkazgeols'emka, Essentuki, 357600, Russia; lavr@geolog.kmv.ru*

Northern Caucasus is one of the regions within the Greater Caucasus where the Silurian strata have been recorded. Rocks of this age are not particularly widespread, and are usually metamorphosed.

Silurian strata in the northern Caucasus were examined during CASP in July 2013. The main objective of fieldwork was to characterise the Silurian stratigraphy, to restudy sections described earlier by Chegodaev (1977) and Obut *et al.* (1988), and to collect samples for follow-up analyses including biostratigraphy, organic geochemistry, whole rock geochemistry, petrography and provenance. Areas visited include Bichesyn (i.e. Malka River) and Fore Range (i.e. Teberda River, Kyaphar River) tectonic zones.

In the Malka sections, the Silurian comprises the Ullu-Lakhran and Manglai formations. The Ullu-Lakhran Formation, which is 300 m thick, consists mostly of grey to black clayey and siliceous shales. The shales include sandstone intercalations, as well as sandy limestone, which are more developed near the top of the formation. Shales, at some levels, are rich in graptolites (Obut *et al.* 1988). Biostratigraphically, they range from Llandovery to mid Ludlow in age. The overlying Manglai Formation is up to 22 m thick. It is a carbonate unit with several intercalations of black siliceous shales. Limestones yield conodonts (Obut et al. 1988), cephalopods, bivalves, trilobites and gastropods. Their occurrence established the late Ludlow to Pridoli age of the formation.

In the Teberda sections, the Silurian comprises the Achkhiminar Formation. It is a 420 m thick clayey unit with several sandy beds and siliceous shales yielding cherts. In the Kyaphar sections west of the Teberda sections, the 900 m thick Silurian succession is more metamorphosed and is represented by quartz-chlorite-sericite schist with interbeds of fine-grained metasandstone and graphite-bearing chert. Limestones are found in some sections. Silurian graptolites and radiolarians were found in the chert (Somin 2011).

Chegodaev, L.D., 1977. The Lower Silurian of the Fore Range of the northern Caucasus. *Soviet geology*, 12, 50–57. [in Russian].

Obut, A.M., Morozova, F.I., Moskalenko, T.A. & Chegodaev, L.D. 1988. *Graptolites, conodonts and stratigraphy of the Silurian, Lower Devonian of the northern Caucasus*. Nauka, Novosibirsk, 221 pp. [in Russian].

Somin, M.L. 2011. Pre-Jurassic Basement of the Greater Caucasus: Brief Overview. *Turkish Journal of Earth Sciences*, 20, 545–610.

Biostratigraphy of early vertebrates on Gotland

Oskar Bremer and Henning Blom

Uppsala University, Evolutionary Biology Center, Dept. of Organismal Biology, Uppsala, Sweden; oskar.bremer@ebc.uu.se; henning.blom@ebc.uu.se

The Silurian rocks on the island of Gotland, Sweden, have historically attracted much attention thanks to its highly fossiliferous and easily accessible beds, as well as for its relatively continuous Silurian successions. The beds are dominated by limestones and marls ranging from the latest Llandovery to the latest Ludlow. The different stratigraphical units on Gotland display great variation in facies both temporally and spatially, with shallow water sediments dominating in the northeast and deeper water sediments more commonly occurring in the southwestern parts of the island. This has provided a good picture of the different depositional environments in the Baltic basin when these sediments were accumulated.

The first vertebrates from Gotland were reported over 100 years ago by Josef Victor Rohon in 1893, and in 1895 Gustaf Lindström described two heterostracan head-shields collected at the Gannor locality, which is the most complete vertebrate material reported from the Silurian of Gotland. However, many fragmentary remains and a plethora of scales have been reported by a number of authors since then. The most extensive biostratigraphic study of Gotland vertebrates was carried out by Doris Fredholm in the late 1980's. She reported occurrences of isolated scales and occasionally larger fragments of heterostracans, thelodonts, anaspids, osteostracans, acanthodians, and actinopterygians through a majority of the Gotland stratigraphy. During the last couple of decades, much progress has been made in unraveling the correlations and relationships of the different sedimentary units on Gotland. Furthermore, a number of events coupled with variations in lithology, stable isotopes, and extinctions have been identified, three of which have been recognized globally. In a more recent study, Eva K. Nilsson investigated how the vertebrate fauna was affected during one of these events.

In the current study, samples from previous works are taxonomically revised and placed in an updated stratigraphy that also incorporates the various facies of the units. This forms the basis for an extensive study of vertebrate biostratigraphy on Gotland, which will place emphasis on faunal variations coupled to differing environments. With the aid of up-to-date correlations of the sediments on Gotland to other parts of the Baltic basin, and by complementary sampling on Gotland, we hope to fill in the gaps and explain the patterns that we see, such as: the scarcity of vertebrates in the oldest beds on Gotland, the sudden appearance of a wide array of forms in the mid-Sheinwoodian, potential faunal differences between deeper water sediments and shallower environments, and the effect of the previously mentioned events on vertebrate faunas. Can these observations be explained by a lack of samples and/or sampling of unfavorable facies? Furthermore, this study may also form a good model for investigations of faunal dynamics and environmental preferences of Silurian vertebrates in a global context.

Contours of an Ancient Seafloor: Ecological Controls on Depositional Gradients in Upper Ordovician Strata of Southern Ohio and North – Central Kentucky, USA

Carlton E. Brett, Thomas J. Malgieri, Michael Karaus and Carlos Ferry

Department of Geology, University of Cincinnati, Cincinnati, Ohio 45221, USA; carlton.brett@uc.edu

Limestones and shales of the Grant Lake Formation (Upper Ordovician; Katian; Maysvillian) are well exposed in the Cincinnati Arch of southern Ohio and north central Kentucky, and highly fossiliferous. These rocks also document gradual change in lithofacies and biofacies from offshore nodular, phosphatic, brachiopod-rich limestones and marls to very shallow olive gray platy, laminated dolostones with desiccation cracks and sparse ostracodes, southward along a gently sloping ramp. This study uses facies analysis in outcrop to determine paleoenvironmental parameters, particularly those related to water depth (e.g., position of the photic zone and shoreline, and environmental energy). Within a tightly correlated stratigraphic interval (Mount Auburn and Sunset members), we document the occurrence of paleoenvironmental indicators, including desiccation cracks, and light-depth indicators, such as red and green algal fossils, and oncolites. Mapping of facies belts on both sides of the Cincinnati Arch suggests an approximately E–W depositional strike. The deepest water environments, exposed near Hamilton, Ohio, comprise nodular bedded, phosphatic limestone facies, dominated by the robust brachiopod *Vinlandostrophia ponderosa*. These facies were deposited within the shallow euphotic zone, as indicated by the presence of cyclocrinitid green algae and microendolith assemblages in brachiopod shells (Vogel & Brett 2009), and thus, approximately 20 – 40 m of water for semi-turbid water in subtropical shelf settings (average depth of 30 m used in calculations). The northernmost appearance of desiccation cracks in age-equivalent tidal flat facies (Terrill Member), just north of Richmond, Kentucky (200 km to the south), constrains the position of the contemporary shoreline and allows for the first semi-quantitative assessment of the slope of the Ordovician seafloor at this time. This implies a very gentle ramp with a gradient of about 10 – 20 cm of water depth increase per kilometer in a northward direction. Assuming a uniform gradient of 15 cm/km, the depth of bioturbated, mollusk-rich, micritic limestones, representing intertidal to "lagoonal" environments in the Terrill Member, exposed about 10 to 40 km to the north of Richmond would be about 1.5 to 6 m. Cross-bedded skeletal grainstones facies ("coarse clastic limestone member" of mappers) with abundant oncolites and stromatoporoids, indicative of shoal settings, present between 40 and 120 km to the north, would represent depths of 6 to 18 m, in reasonable accord with estimates of normal wave base in epeiric seas (5 – 15 m). By determining such ecological parameters, this study provides a better understanding of paleogeography and environments during the time of important ecological change.

Vogel, K. & Brett, C.E., 2009. Record of microendoliths in different facies of the Upper Ordovician in the Cincinnati Arch region USA: The early history of light-related microendolithic zonation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 281, 1–24.

Brachiopod geochemistry: new information for the Ordovician and Silurian of Estonia

Giuseppe Buono, Meidla Tõnu and Leho Ainsaar

Tartu University, Geology Department, Ravila 14A, 50411 Tartu, Estonia; gbuono.geo@gmail.com, giuseppe.buono@ut.ee

Published data about bulk rock $\delta^{13}C$ in Baltic countries allowed to build a continuous Middle Ordovician (Floian) – Silurian stable carbon isotopic curve. Less attention has been dedicated to stable isotopes in fossil shells, especially regarding calcitic shells in the Baltoscandian Paleobasin.

In this study we try take steps toward to fill this gap. We collected more than 80 specimens (mainly brachiopods, but also 4 trilobites, 1 rugose coral), coupled with correspondent samples of rock matrix, from 15 different localities of central-western Estonia (including the islands of Saaremaa, Hiiumaa and Vormsi). The samples were analyzed for stable isotopes of C and O.

Due to low resolution, most of the second-order stable carbon isotopic excursions, except for the Ireviken Event, are not well reflected in the new $\delta^{13}C_{rock}$ and $\delta^{13}C_{brach.}$ data. The low carbon isotopic values from the shells collected from the Porkuni sections (the lowermost Hirnantian) are likely due to altered primary values, judging from the preservation of the specimens.

More interesting are the results from $\delta^{18}O_{brach}$ values. Few specimens from the lower Darriwillian and the middle-upper Floian show sensibly higher values than those reported in literature from other brachiopod data (in particular from Laurentia and Southern China paleocontinents). The same happens also for many samples from Katian. Silurian values (lower Sheinwoodian, upper Ludfordian, Pridoli) show values that are similar to those reported for Gotland. Reading those values in terms of paleotemperatures may suggest the following:

(A) Katian high values support a cooling suggested according to the Katian $\delta^{13}C_{rock}$ isotope excursions (Ainsaar et al. 2010);

(B) Ordovician values evidence a thermal latitudinal gradient when compared with those from Laurentia, in concordance with paleogeography and with brachiopods paleobioprovinces (cf. Harper *et al.* 2013);

(C) during Silurian the isotopic values tend to be similar to those from Laurentia, and this is also compatible with northward shifting of Baltica paleocontinent.

It is still important to notice that, apart from temperature, $\delta^{18}O$ is susceptible to many other environmental changes.

Additionally, direct comparisons from same layers specimens show as $\delta^{13}C_{brach}$ is almost always higher than $\delta^{13}C_{rock}$ and this is supported also by sparse results from literature. The few tests with trilobites and corals show that $\delta^{13}C$ and $\delta^{18}O$ values are in similar range to those obtained from brachiopods.

Ainsaar, L., Kaljo, D., Martma, T., Meidla, T., Männik, P., Nõlvak, J. & Tinn, O., 2010. Middle and Upper Ordovician carbon isotope chemostratigraphy in Baltoscandia: A correlation standard and clues to environmental history. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 294, 189–201.

Harper D.A.T. et al., 2013. Chapter 11. Biodiversity, biogeography and phylogeography of Ordovician rhynchonelliform brachiopods. *In:* Harper, D.A.T. & Servais, T. (eds). *Early Palaeozoic Biogeography and Palaeogeography*. Geological Society, London, Memoirs, 38, 127–144.

Deformation in *Estonirhynchia estonica* from the Paramaja member (Jaani Stage, Wenlock, Estonia)

Giuseppe Buono[1], Mena Schemm-Gregory[2] and Tõnu Meidla[1]

[1] *Tartu University, Geology Department, Ravila 14A, 50411 Tartu, Estonia; gbuono.geo@gmail.com, giuseppe.buono@ut.ee.*
[2] *Centro de Geociências da Universidade de Coimbra, Largo Marquês de Pombal, Coimbra, Portugal (1976–2013)*

A low diversity fossil assemblage dominated by rhynchonellid brachiopod *Estonirhynchia estonica* and subordinately by the rugose coral *Phaulactis* sp. have been sampled on Paramaja shore (Paramaja, north-western Saaremaa, Estonia) from bluish-grey calcitic marlstones ascribed to the Paramaja Member of Jaani Formation (Silurian, Wenlock, Sheinwoodian). The richer and more diverse fauna from same locality described in literature came presumably from lower part of the section, that is now overgrown. According to the sedimentary characteristics, the deposition took place in a quiet-water environment near the boundary of the open shelf and transition belts, during a transgressive episode.

Estonirhynchia specimens in this location are always found to be fully articulated and their shell ultrastructure is extremely well preserved. Macroscopically, however, most of the „thin-shelled“ brachiopods show plastic deformation and a thin compact marly covering, while the „thick-shelled“ corals look basically undeformed. This pattern is compatible with a post-burial compression of the brachiopods shells due to sediment compaction and to the loss of shell rigidity after the decomposition of the organic material. Measurements on deformed specimens allowed to estimate a sediment compaction up to 0.65 mm and, considering size of the specimen (about 1.2 – 1.7 cm in diameter), this is comparable to the total range of compaction of this marly unit.

Micro- and ultrafacies in end-Ordovician (Late Hirnantian) microbial-coral reefs, Anticosti Island, Quebec

Ariane Castagner and André Desrochers

Department of Earth Sciences, University of Ottawa, Ontario, K1N 6N5, Canada; acast097@uottawa.ca, andre.desrochers@uottawa.ca

The superbly exposed Ordovician/Silurian (O/S) succession on Anticosti Island in the Gulf of St. Lawrence was deposited south of the paleoequator on an active foreland basin along the eastern margin of Laurentia. The sudden appearance of abundant oncolites and microbial-coral reefs near the O/S boundary marks the Anticosti succession at the same time of a major faunal turnover (conodont, chitinozoan, acritarch, shelly faunas). These microbial limestones, a prominent regional marker unit on Anticosti Island known as the Laframboise Member, formed mainly during the peak interval of the main Hirnantian positive isotopic carbon excursion. The Laframboise microbial-coral reefs contain numerous meter size biohermal structures previously described as metazoan or coral-stromatoporoid reefs. The abundant mudstone–wackestone matrix associated with these reefs, however, remains largely undescribed. This fine-grained matrix is massive in outcrop, but displays a polymud fabric with distinct spatial relationships in thin sections and under the SEM. The primary "mud" (M1) shows evidence of early induration, and the subsequent generation of mud (M2), differ in grain size, color, bioclast content, and texture. M1 shows millimetric laminations with a pelletoidal fabric encrusting the large reef metazoans. Calcimicrobes associated with M1 are locally abundant including *Wetheredella*, Rothpletzella and *Girvanella*. The M1 mud is interpreted as an indurated network of microcrystalline material of microbial origin formed in situ while the M2 mud represents infiltrated depositional lime mud. The conventional mechanisms for reef growth including frame building or binding by organisms based on the preserved megafauna do not constitute an appropriate analytical basis on which to explain the Laframboise reefs. Large metazoans in the Laframboise reefs played only a passive role in that they simply provided the substrate for the extensive development of encrusting microbial and calcimicrobial components. The widespread occurrence of microbial deposits at a time of abrupt changes in oceanography, climate, and global carbon cycle appears a distinct signature at the O/S boundary within the Anticosti succession.

Micro- and ultrafacies of a microbial reef from the Mulde Event interval (Homerian, middle Silurian) from Podolia, western Ukraine

Ariane Castagner[1], *Emilia Jarochowska*[2], *Axel Munnecke*[2] *and André Desrochers*[1]

[1] *Department of Earth Sciences, University of Ottawa, Canada; acast097@uottawa.ca, adesro@uottawa.ca*
[2] *GeoZentrum Nordbayern, Fachgruppe Paläoumwelt, Universität Erlangen, Germany; emilia.jarochowska@gzn.uni-erlangen.de, axel.munnecke@fau.de*

The Mulde event (lower Homerian, Wenlock) of the Silurian is characterized by a positive $\delta^{13}C$ isotope excursion, a stepwise extinction of the hemipelagic fauna (such as graptolites and conodonts) and an increase in microbial deposits. There is little known whether the proliferation of microbialites is due to reduced grazing, increased seawater saturation state or an increase in the nutrient supply. We have studied a Mulde Event-associated reef from the Muksha Formation in Bagovytsya, Podolia, Western Ukraine. The goal of this study is to identify the main components and structure of this reef and to further investigate the microproblematica present. The samples collected are being processed through the analyses of thin sections and with SEM. Preliminary results show some unusual characteristics for a Silurian reef, such as low abundance of rugose and tabulate corals. The framework of this reef is dominated by different constructors, such as stromatoporoids and heliolitid corals and the binding by calcimicrobes, which are found encrusting the stromatoporoids and shells and also forming oncoids. Several microproblematica are present, such as *Girvanella*, *Rothpletzella* and *Hedstroemia*, along with porostromate problematica. This study will attempt to further identify *Hedstroemia* and the porostromate problematica through SEM analyses which have revealed a recrystallized structure with possible microdolomite, indicating an originally high-Mg calcite composition. Dwellers include ostracods, trilobites, crinoids, brachiopods, bryozoans and rostroconchs. The reef is characterized by elevated $\delta^{13}C$ values, suggesting that the atypical composition resulted from altered seawater chemistry. Our observations may help to constrain the environmental controls on the development of microbial- and microproblematica-dominated deposits during the Mulde Event. This is a contribution to the International Geoscience Programme (IGCP) Project 591 – The Early to Middle Paleozoic Revolution.

Restudy of the Llandovery conodont sequence on the Upper Yangtze Platform, South China

Zhongyang Chen and Chengyuan Wang

Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China; jeffchanczy@gmail.com, cywang@nigpas.ac.cn

Llandovery strata are widely distributed on the Yangtze Platform. In the lower part they are mostly constituted by graptolite-bearing shales and assigned to the Lungmachi Formation on the Upper and Middle Yangtze Platform (Fan e*t al.* 2011). The graptolite fauna from the Lungmachi Formation has been studied for decades and the biozonation for regional and global correlation has been generally established (Chen & Lin 1978; Wang *et al.* 1987; Fan *et al.* 2013). The strata above the Lungmachi Formation, which include the Hsiaohopa, Rongxi, Xiushan and Huixingshao formations in ascending order, are mostly composed of mudstones and limestones with very few graptolite records. They are therefore subdivided and correlated mainly by conodonts and chitinozoans.

During the latest years, although some palaeontologists have focused on the strata above the Lungmachi black shales and established a conodont biostratigraphic framework for regional correlation (Wang and Aldridge 2010; Wang *et al.* 2010), there are still some serious arguments on the subdivision and correlation of these strata. First, the Lower Member of the Xiushan Formation (in the Chongqing City area) has few graptolite and conodont records, so it is hard to determine its age. Second, the age of the Rongxi Formation, the lower marine red bed of Silurian, is still uncertain. No graptolite key taxa have been found. Both, chitinozoan and conodont researches suggested a conflict with biostratigraphic assignments. The argument on whether there is a hiatus between the Rongxi and Xiushan formations still exists. As a result, the age of the top of the Rongxi Formation cannot be constrained by the age of the strata above, which is determined by conodonts (Wang *et al.* 2010). Third, although there are a few limestone interlayers in the upper part of the Lungmachi Formation, the conodonts from those rocks have not been studied. In conclusion, it is necessary and important to restudy these strata.

As the first step of the research, in 2013 we collected bulk samples for conodont analysisfrom the Xiushan Formation of Datianba Section in Chongqing and the upper part of the Lungmachi Formation in the Shuanghe Section in the Sichuan Province. Sixty samples were collected from these two sections. Their ongoing study will help us solve the correlation problem of the Llandovery strata on the Upper Yangtze Platform.

Chen, X. & Lin Y.K., 1978. Lower Silurian graptolites from Tongzi, northern Guizhou (in Chinese). M*em Nanjing Inst Geol Palaeont.*, 12, 1–106.

Wang, C.Y. & Aldridge, R.J., 2010. Silurian Conodonts from the Yangtze Platform, South China. *Special papers in Palaeontology,* 83, 1–136.

Wang, C.Y., Chen, L.D., Wang, Y., et al., 2010. Affirmation of *Pterospathodus eopennatus* Zone (Conodonta) and the age of the Silurian Shamao Formation in Ziqui, Hubei as well as the correlation of the related strata. *Acta Palaeontologica Sinica*, 49, 10–28.

Wang, X.F., Ni, S.Z., Zhen, Q.L., et al., 1987. *Biostratigraphy of the Yangtze Gorge Area 2: Early Palaeozoic Era*. Geological Publishing House, Beijing. 641 pp. [in Chinese]

Fan, J.X., Wu, L., Chen, Z.Y., et al., 2013. Biostratigraphy of the Wufeng-Lungmachi black shales at Qilin, Xingwen County, Sichuan Province. *Journal of Stratigraphy*, 37, 513–520.

High-Resolution Event Stratigraphy (HiRES) and the Quantification of Stratigraphic Uncertainty

Bradley D. Cramer[1], Thijs R.A. Vandenbroucke[2] and Gregory A. Ludvigson[3]

[1] *Department of Earth and Environmental Sciences, University of Iowa, Iowa City, Iowa 52242, USA; bradley-cramer@uiowa.edu*
[2] *Géosystèmes, UMR 8217 du CNRS, Université de Lille 1, Villeneuve d'Ascq 59655, France*
[3] *Kansas Geological Survey, University of Kansas, Lawrence, Kansas 66047, USA*

The ability to resolve the stratigraphic record of Earth history is critical to understanding past global change events and the range of natural variability within the global paleoclimate. The ocean-atmosphere-biosphere Earth system operates on geologically very short timescales and we must be able to resolve the stratigraphic record of past events on similar timescales if we are to understand the cause-and-effect relationships operating within the system. Global resolution ≤100 kyr is commonly available when evaluating events from the Cenozoic Era, but such resolution is less common for older portions of Earth history. The introduction of High-Resolution Event Stratigraphy (HiRES) more than two decades ago revolutionized the ability to resolve the Mesozoic stratigraphic record of global change, and a similar revolution is currently underway for the Paleozoic as well. Here, we demonstrate the application of the principles of HiRES to the Paleozoic stratigraphic record, discuss the quantification of chronostratigraphic uncertainty, and highlight the current deep-time Earth history revolution that has the potential to open the entire Phanerozoic record to the evaluation of short timescale global climate dynamics.

High-frequency paleoenvironmental fluctuations recorded in end-Ordovician (late Hirnantian) microbial-coral-stromatoporoid bioconstructions, Anticosti Island, eastern Canada

André Desrochers, Ariane Castagner and Alain Mauviel

Department of Earth Sciences, University of Ottawa, Ontario, K1N 6N5, Canada; andre.desrochers@uottawa.ca, acast097@uottawa.ca, amauv097@uottawa.ca

The superbly exposed Ordovician/Silurian (O/S) succession on Anticosti Island in the Gulf of St. Lawrence was deposited south of the paleoequator on an active foreland basin along the eastern margin of Laurentia. The sudden appearance of abundant oncolites and microbial-coral-stromatoporoid reefs near the O/S boundary marks the Anticosti succession at the same time of a major faunal turnover (conodont, chitinozoan, acritarch, shelly faunas). These microbial limestones, a prominent regional marker unit on Anticosti Island known as the Laframboise Member of the Ellis Bay Formation, formed mainly during the peak interval of the main Hirnantian positive isotopic carbon excursion. Our study focuses on the stratigraphic architecture of the Laframboise bioconstructions at the west end of Anticosti Island forming meter size biohermal structures previously described as metazoan or coral-stromatoporoid reefs. The amount of microbialites fluctuates in these bioconstructions, but forms up to 70% of the reef volume. Their development can be divided into high-, medium-, and low-frequency reef-growth phases. All studied bioconstructions show major surfaces of reef growth interruption followed by minor terrigenous mudstone deposition delimiting high-frequency reef-growth phases or elementary units traceable laterally into well-bedded deposits. Each elementary unit is made of two main sub-units: first, an encrusting succession of microbilalites and associated calcimicrobes (*Wetheredella*, *Rothpletzella* and *Girvanella*) and second, a coral or stromatoporoid boundstone with various encrusters. Medium-frequency reef-growth phases include several elementary units alternating active reef-growth phases with thick-bedded lateral carbonate deposits and less active reef-growth phases with thin-bedded more argillaceous lateral deposits. The Laframboise bioconstructions developed an overall lenticular shape during a single low-frequency reef-growth phase with a first phase of narrow and vertical reef expansion, and a second phase of lateral reef expansion, until final reef termination associated with a period of subaerial exposure. At the scale of the elementary units, microbial sub-unit are interpreted to reflect nutrient-richer conditions and developed to the detriment of phototrophic- or heterotrophic-dominated assemblages of corals and stromatoporoids. The bioconstruction development was punctuated by high frequency ecological crises during which microbialites occurred exclusively at the reef surface. Our study shows that three main orders of climatic oscillations and/or sea level changes could have regulated the amount of terrigenous materials and nutrients delivered on the sea floor, which in turn controlled the carbonate production and accumulation as well as the reef development of the Laframboise bioconstructions.

Ordovician succession at Moyero River, Siberia: preliminary results of recent investigations

Andrei Dronov[1]*, Alexander Timokhin*[2] *and Alexander Kanygin*[2]

[1] *Institute of Geology, Russian Academy of Sciences, Pyzhevsky per. 7, Moscow, 119017, Russia; dronov@ginras.ru*
[2] *Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of Russian Academy of Sciences. Acad. Koptyug 3, 630090, Novosibirsk, Russia; KanyginAV@ipgg.nsc.ru*

Ordovician outcrops along the Moyero River valley compose one of the most complete and best exposed Ordovician sections on the entire Siberian Platform. However, due to difficulties in accessibility the section has not been visited by geologists during the last 37 years. In 2013, a special expedition was organized in order to re-investigate this key section. Preliminary results of the field work are as follows: 1) The Upper Ordovician (Sandbian – Katian) Dzerom Formation (Chertovskian, Baksian and Dolborian regional stages) is represented by cool-water carbonates. Similar to the Mangazea and Dolbor formations on the south-western margin of the Tungus basin, the sediments are dominated by intercalation of greenish-grey siltstones and grey bioclastic limestones. Trilobites, brachiopods and ostracods are the most common bioclasts, associated with a significant number of bryozoans, pelmatozoans and mollusks. The most typical and widespread sedimentary structures are indicative for storm-induced sedimentation. 2) Despite significant efforts, no K-bentonite beds have been found in the Dzerom formation. Absence of any traces of volcanic eruptions along the eastern margin (in present day orientation) of the Siberian Platform contradicts popular palaeogeographic interpretations (www.scotese.com) and points to the position of a subduction zone along the western but not the eastern margin of the Siberian palaeocontinent at this time. 3) In the relatively thick (31 m) Kirensko-Kudrinian interval of the section, two depositional sequences instead of one previously established on the south-western margin of the Tungus basin have been identified. 4) In the quartz sandstones of the uppermost Kirensko-Kudrinian regional stage (Moyero Formation) abundant well-preserved *Cruziana* trace fossils have been found for the first time. These *Cruziana* traces differ markedly from contemporaneous *Cruziana* of the Gondwanan affiliation. 5) Massive thick-bedded *Thalassinoides* ichnofabrics have been identified in limestones of the Volginian regional stage (lower part of the Moyero Formation). This could be regarded as an independent evidence for a near equatorial position of this part of the Tungus basin in Darriwilian times.

This is a contribution to the IGCP Project-591 “The Early to Middle Paleozoic Revolution”.

Financial support for this research was provided from the Russian Foundation for Basic Research Grants № 13-05-00749 and № 14-05-00047.

Chemostratigraphy and age of the Boda Limestone (Siljan, Sweden)

***Jan-Ove R. Ebbestad*[1]*, Anette E.S. Högström*[2]*, Åsa M. Frisk*[3]*, Tõnu Martma*[4]*, Dimitri Kaljo*[4]*, Björn Kröger*[5] *and Helje Pärnaste*[4]**

[1] *Museum of Evolution, Uppsala University, Norbyvägen 22, SE-752 36 Uppsala, Sweden; jan-ove.ebbestad@em.uu.se*
[2] *Tromsø University Museum, Natural Sciences, NO-9037 Tromsø, Norway; anette.hogstrom@uit.no*
[3] *Paläontologisches Institut und Museum, Karl Schmid-Strasse 4, 8006 Zürich, Switzerland; asa.frisk@pim.uzh.ch*
[4] *Institute of Geology at Tallinn University of Technology, Ehitajate 5, Tallinn 19086, Estonia; tonu.martma@ttu.ee, dimitri.kaljo@ttu.ee, helje.parnaste@ttu.ee*
[5] *Finnish Museum of Natural History, P.O. Box 44, FI-00014 University of Helsinki, Finland; bjorn.kroger@helsinki.fi*

The Boda Limestone and its huge carbonate mounds in environs of another famous landmark of Sweden – the Siljan impact crater – have attracted researcher's attention for many years. Let's note only recent discussions about the age of the mounds, correlation with global glacial processes and climate cooling or warming. Our task was to refine the chemostratigraphy of the Boda Formation (below abbreviated Fm.) and coupled with biostratigraphical data create a basis for clarifying the above problems.

Eight sections were studied in five quarries. Two sections each in Kallholn, Osmundsberget, and Solberga, and one each in Östbjörka and Jutjärn. Sections in the three first quarries show the contact with the overlying Aeronian Kallholn Fm. After a gap follows downwards the Glisstjärn Fm. and the Boda Limestone Fm. subdivided into the Upper Boda Member (formal) and the Boda Core Member (informal). The deepest beds of the Boda Limestone and transitional layers to the Fjäcka Shale were studied at Osmundsberget 1.

Carbon isotope studies in these sections produce closely comparable $\delta^{13}C$ curves across the area. Four levels with positive $\delta^{13}C$ excursions are identified, three of these fit well into the framework of Baltic carbon isotope zones (BC) and can be named as the Moe (BC12), Paroveja (BC14) and HICE (BC16+17). That correlates the whole studied interval well with the East Baltic Pirgu and Porkuni regional stages. In addition, a new excursion is identified in BC13 that needs additional study. The Moe excursion is possibly identified also in the intermound section at Amtjärn, a few meters above the Fjäcka Shale, in good agreement with an excursion in the Borenshult core, Östergötland. The late Katian age of *Holorynchus* is clearly demonstrated in Siljan, where it occurs in the BC15, and its co-occurrence with the chitinozoan *Belonechitina gamachiana* in Estonia supports a Katian age for the *B. gamachiana* Biozone (Bz). The HICE is identified in five sections, and the main peak occurring at or close to the *Hindella* beds (~unit B of the Upper Boda Member) falls according to integrated bio-chemo-correlation within the *Metabolograptus persculptus* Bz. The younger Hirnantia–Dalmanitina fauna and the *Ozarkodina hassi* Bz in units B–D of the Upper Boda Member is thus entirely within the *M. persculptus* Bz, while the older *Hirnantia–Dalmanitina* fauna correlates with the *M. extraordinarius* Bz.

First record of the early Sheinwoodian carbon isotope excursion (ESICE) from the Barrandian area of northwestern peri-Gondwana

Jiri Frýda[1,2], *Oliver Lehnert*[3,4] *and Michael Joachimski*[3]

[1] *Czech Geological Survey, Klárov 3/131, 118 21 Prague 1, Czech Republic*
[2] *Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Kamýcká 129, Praha 6 – Suchdol, 165 21, Czech Republic; bellerophon@seznam.cz*
[3] *GeoZentrum Nordbayern, Universität Erlangen, Schlossgarten 5, D-91054 Erlangen, Germany; oliver.lehnert@fau.de, michael.joachimski@fau.de*
[4] *Department of Geology, Lund University, Sölvegatan 12, 223 62 Lund, Sweden; oliver.lehnert@geol.lu.se*

The early Sheinwoodian carbon isotope excursion (ESICE) is known from several palaeocontinents in the Silurian tropics and subtropics. The $\delta^{13}C$ record from the Prague Basin located in a rift-basin system on the northwestern peri-Gondwana shelf represents the first data of this stable isotope event from higher latitudes. Despite the ESICE, all the other famous Silurian $\delta^{13}C$ excursions associated with different bioevents such as the late Aeronian *sedgwickii* Event, the Homerian Mulde event, the Ludfordian Lau Event or *kozlowskii* event, and the Silurian/Devonian boundary event have been reported from the study area.

Oxygen isotope data from the Eastern Baltic suggest a strong shift into icehouse conditions during the Early Sheinwoodian and represent, beside coeval diamictites in western peri-Gondwana an evidence of an early Silurian glaciation. The expression of this glacial in the Prague Basin has already been discussed with respect to the deposition of early Sheinwoodian limestones successions during a time of a glacially-driven major sea-level drop. These shallow water limestones formed around the volcanic centres and after redeposition they were intercalated into the fine-grained graptolite-bearing siliciclastics of the Motol Formation. In one of those successions, in the Lištice section near Beroun, a large limestone package slipped downslope probably due to seismic activity in this volcanically highly active zone.

In the front part of the slid limestone megaslab internal deformation, brecciation and folding is visible as well as soft sediment deformation within the sediment matrix in which it was sliding and where it got stacked. The partly disrupted limestone unit rests on a very irregular erosional surface on top of the graptolitic shales of the *Octavites spiralis* Biozone. During sliding downslope the slab was stretched and in its backpart, where it was partly disrupted and represents some badly sorted megabreccia, less and less limestone beds are preserved until one last bed is disappearing upslope towards the volcanic center within the graptolitic shales.

A parauthochtonous section throughout the limestone unit at Lištice has been sampled about 15 m back from its deformed front where the beds still seemed to be intact and not tectonically disturbed even when internal thrusting and sliding during its downslope redeposition cannot be excluded. The bulk of the limestone is partly silicified and has a high admixture of volcanoclastic components. 39 $\delta^{13}C$ samples have been taken throughout this 1.75 m thick succession dominated by extremely fine-grained laminated grainstones with intercalated coarser-grained bioclastic pack- to grainstones with brachiopod and crinoids as well as some thin brachiopod layers. The $\delta^{13}C$ analysis of those carbonates revealed very high values of $\delta^{13}C$ up to 4.10‰ which are far above $\delta^{13}C$ background values for early Sheinwoodian strata of about 1‰. Our interpretation is that these isotopically heavy shallow water limestones formed during the ESICE.

Carbon isotope chemostratigraphy of the Llandovery in northern peri-Gondwana: new data from the Barrandian area, Czech Republic

Jiří Frýda[1,2] and Petr Štorch[3]

[1] *Czech Geological Survey, Klárov 3/131, 118 21 Prague 1, Czech Republic*
[2] *Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Kamýcká 129, Praha 6 – Suchdol, 165 21, Czech Republic; bellerophon@seznam.cz*
[3] *Institute of Geology, Academy of Sciences of the Czech Republic, Rozvojová 269, 165 02 Praha 6, Czech Republic; storch@gli.cas.cz*

On-going systematic search for major $\delta^{13}C$ excursions in Silurian strata of the Perunica microplate (western peri-Gondwana) revealed five of them: a) the one associated with the late Aeronian graptolite *sedgwickii* Event, b) an early Sheinwoodian (Ireviken) positive $\delta^{13}C$ excursion, c) the late Homerian (Mulde) positive $\delta^{13}C$ excursion, d) the mid-Ludfordian excursion associated with the conodont Lau and graptolite *kozlowskii* events, and e) the Silurian–Devonian boundary (Klonk) excursion which is associated with several bioevents. Present study is heading to a creation of complete $\delta^{13}C$ curve across Silurian strata of the Perunica microplate. Here we report first $\delta^{13}C_{org}$ and TOC data from the uppermost Ordovician to lower Telychian successions based on study of three most complete and best biostratigraphically dated sections (Řeporyje, Radotín tunnel, and Hlasná Třebaň) of the Prague Basin.

The Ordovician/Silurian boundary interval was studied at the Radotín tunnel section and is characterized by a distict change in $\delta^{13}C_{org}$ as well as in TOC values. Typical uppermost Ordovician $\delta^{13}C_{org}$ values, about -26‰, decrease by about 5‰ to -31‰ in lowermost Rhuddanian strata (*A. ascensus* Biozone). This significant negative shift in $\delta^{13}C_{org}$ values is linked with a rapid increase of TOC values, from about 0.25% in the uppermost Ordovician strata to about 2% TOC in graptolite-rich black shale that appears just above the base of the Silurian to ca 6% TOC in the lowermost Aeronian strata. The negative shift in $\delta^{13}C_{org}$ values of about 4 – 6‰ was recorded within *N. persculptus* Biozone in several areas (Arctic Canada, South China, and Scotland), well below the Ordovician/Silurian boundary. This fact, along with firmground developed at the interface between topmost Ordovician mudstone and black shale of the *ascensus* Biozone, may suggest non-deposition including the upper part of the *persculptus* Biozone at the Radotín tunnel section.

The $\delta^{13}C_{org}$ values are slowly, but significantly rising from the *A. ascensus* Biozone to end of the Rhuddanian, reaching $\delta^{13}C_{org}$ values about -30‰ in the *C. cyphus* Biozone. This slow positive trend in $\delta^{13}C_{org}$ values resembles data obtained from some other areas such as the Arctic Canada and North Africa. The TOC values are steady (about 6%) across the middle and upper Rhuddanian strata in the Prague Basin. Both $\delta^{13}C_{org}$ and TOC values in Aeronian to lower Telychian strata are more variable than those in the Rhuddanian. The $\delta^{13}C_{org}$ values fluctuate between -30 and -27‰, and the TOC values between 4 – 7%, with exception of the late Aeronian *S. sedgwickii* Biozone where a distinct positive excursion in $\delta^{13}C_{org}$ was documented. At this level, $\delta^{13}C_{org}$ values rapidly increase forming a strong positive $\delta^{13}C_{org}$ excursion with a peak shift of at least 7‰ whereas TOC values temporarily dropped.

Data on graptolite faunal dynamics and diversity trends from the Rhuddanian to lower Telychian strata of the Prague Basin revealed a close link to the $\delta^{13}C_{org}$ record. The most distinct faunal turnover in graptolite communities was recorded at level of the posivive $\delta^{13}C_{org}$ excursion within the *S. sedgwickii* Biozone, similarly as in late Aeronian successions abroad.

The lower Silurian “black shales” from SE Anatolia and the Taurides, Turkey

M. Cemal Göncüoğlu[1]*, Valery Sachanski*[2] *and Huseyin Kozlu*[3]

[1] *METU, Department of Geological Engineering, 06531 Ankara, Turkey; mcgoncu@metu.edu.tr*
[2] *Bulgarian Academy of Sciences, Geological Institute, 1113 Sofia, Bulgaria*
[3] *Cigdem Mah.1575 Sok. 41/22, Cankaya, Ankara, Turkeyt@geol.lu.se*

To establish the stratigraphical position and the exact age of the lower Silurian black shales in the NW Gondwanan SE Anatolia and Tauride terranes, several sections were measured and sampled for graptolites and conodonts. In most of the studied sections in the Taurides, Hirnantian glacio-marine siltstones with channel-type sandstone bands and lenses form the substratum of the measured sections. Graptolite data obtained in this study suggests that Lower Silurian is almost complete in the Taurides and includes more than one black shale interval.

In the Korudag section in SE Anatolia, the measured section is thrust-bounded and the Hirnantian glaciomarine succession was not encountered. In this area, the black shales with a few sandstone interlayers reach their maximum thickness of about 50metres, and include only in the lower 10 metres some graptolites. The lowermost data-point in the section was determined and graptolites belong to the *Cor. cyphus* Zone of the Rhuddanian. The following data point yielded graptolites of lower Aeronian age. In the Cat section in SE Anatolia, where a tectonically disrupted slice with black shales was systematically sampled, the relatively well-preserved lower interval included a rich graptolite fauna indicating a Rhuddanian age.

In the Eastern Taurides, the Silurian succession rests with a transgressive contact on the glacio-marine siliciclastics. The lower black shale level, >10 m thick, comprises laminated, black siliceous mudstones (lydites) with graptolite-rich shales including *Par. acuminatus* (GGZ) of the early Rhuddanian. The following 5 – 6 meters thick second black shale level ends up with a 0.5 – 1 m thick calcarenite band with “Orthoceras”. The fourth black shale level is about 8 – 10 meters thick and is followed by grey mudstones and sandstones. The upper part of this succession is represented by an alternation of nodular limestones, rich in nautiloids, and dark grey shales.

In Tekmen and Ovacık sections at the Mediterranean coast and in several sections in the Eastern Taurides, graptolites of *Cyst. vesiculosus* GGZ through *Sp. guerichi* GGZ have been found within the lower black shale levels. Graptolites of late Telychian age (from *Mcl. griestoniensis-Mcl. crenulata* to *Cyrt. lapworthi – Cyrt. insectus* GGZ) are not recorded, however, the lowest “Nautiloid Limestones” in this part of the succession yielded latest Llandovery – earliest Sheinwoodian conodonts. Late Sheinwoodian and Homerian graptolites (*Cyrt. rigidus – Cyrt. perneri*, *Col. deubeli – Col. praedeubeli* and *Col. ludensis* GGZ) are only found in the Pekmezköy and Gürleşen areas, where the black shale deposition commences and the lowermost limestone bed is younger than late Homerian in age.

In the Kemer area in the Western Taurides, the glaciomarine units are transgressively overlain by gray quartz-arenites, followed by black shales alternating with black nodular limestones. The conodont data from the nautiloid limestone level above the uppermost black shale interval corresponds to the *O. spiralis* Zone of Telychian.

To conclude, the black shale intervals are common in the Lower Silurian (Llandovery) in the Taurides and SE Anatolian Autochthon at the northern edge of the Arabian Peninsula. A detailed survey based on graptolites indicates these “hot shales” are mainly concentrated in the Rhuddanian – Telychian interval and comprise intervals of lean siliciclastics.

Towards a new synthesis of Early Palaeozoic biogeography and palaeogeography

David A.T. Harper[1] *and Thomas Servais*[2]

[1] *Palaeoecosystems Group, Department of Earth Sciences, Durham University, Durham DH1 3LE, UK; david.harper@durham.ac.uk*
[2] *UMR 8217 Geosystémès, CNRS-Université de Lille 1, 59655 Villeneuve d'Ascq Cedex, France; Thomas.Servais@univ-lille1.fr*

Nearly 25 years ago the benchmark volume edited by Christopher Scotese and Stuart McKerrow, the so-called 'Green Book', marked a turning point in Palaeozoic biogeography and geography. The 40 contributions were dominated by studies on Palaeozoic biogeography including substantial new data and cutting-edge papers on palaeoclimatology, palaeomagnetism together with the distribution of climatically-sensitive sediments. Since 1990 there have been major advances in the taxonomy of Early Palaeozoic organisms, the correlation of Lower Palaeozoic rocks together with numerical methods for the analysis of fossils and their distributions. Moreover and most significantly, there has been a quantum leap in the accuracy and precision of palaeogeographic reconstructions, reconciling in many cases palaeomagnetic data with the distribution of fossil organisms. The Early or (Lower) Palaeozoic was an interval characterized by a major radiation of marine life, including not only the 'Cambrian Explosion', but also the 'Great Ordovician Biodiversification' and the 'end Ordovician extinction'. A new description and synthesis of Early Palaeozoic biogeography and palaeogeography (Harper and Servais [editors], 2013, Geological Society Memoir 38) provides a real prospect to not only refine continental distributions and provinces but also identify oceanic circulation and upwelling zones together with migrational patterns and species pumps.

Vertebrates of the Downton Bone Bed

Luke Hauser

University of Portsmouth, School of Earth & Environmental Sciences, Burnaby Building, Burnaby Road, Portsmouth, PO1 3QL, UK; luke.hauser@port.ac.uk

The Downton Bone Bed (DBB), from the upper Silurian (Ludlow Series) of the Welsh borders, occurs within an interbedded siltstone and sandstone facies in the *Platyschisma* Shale Member of the Downton Castle Sandstone Formation. The term "bone bed" is misleading with respect to the Silurian as the bulk of the vertebrate material is in the form of denticles which histologically are more similar to teeth so perhaps "tooth bed" would be a more accurate term.

The extraction of the vertebrate material has been a considerable challenge as the rock lacks calcium carbonate cement; therefore most acids typically used in microvertebrate extraction have had no effect. Recently, a number of methods were used on a single piece of the DBB and resulted in the entire rock disaggregating, these methods included: mechanical fragmentation, immersion in paraffin, rapid freeze/thaw (in liquid nitrogen) and microwaving. The results of this have been much better than expected and the extracted material is well preserved.

The DBB contains some of the best preserved Silurian vertebrates in the UK. Unlike the Ludlow Bone Bed, which has mostly black material, the DBB's vertebrate remains are well preserved and light brown to tan in colour. This means that, potentially, the denticle histology can be studied.

The DBB vertebrate assemblage is made up primarily of the single thelodont species present: *Paralogania ludlowiensis*. There are also two genera of acanthodian: *Poracanthodes porosus* and *Nostolepis linleyensis*. This low diversity suggests that the "Downton Sea" was a restricted environment, which is in agreement with the sedimentological and the ichnological data from the section.

Spatial and temporal scale problems in data-model comparison studies: challenges for understanding Paleozoic climate states

Achim D. Herrmann[1], *Stephen A Leslie*[2] *and Kenneth G. Macleod*[3]

[1] *Coastal Studies Institute and Department of Geology and Geophysics, Louisiana State University, Baton Rouge, Louisiana, 70803, USA; aherrmann@lsu.edu*
[2] *Department of Geology and Environmental Science, James Madison University, Harrisonburg, VA 22807, USA; lesliesa@jmu.edu*
[3] *Department of Geological Sciences, University of Missouri, Columbia, MO 65211-1380, USA; MacLeodK@missouri.edu*

Despite recent progress, high-resolution numerical climate models are still too computationally intensive to fully resolve transient, long-term climate simulations of thousands to millions of years that are relevant for understanding the impact of geological processes on climate change in the past. Rather, paleoclimate simulations focus on a few initial boundary conditions that often reflect extreme conditions for the particular climate being modeled. Such simulations only represent snapshots of the potential climate for the modeled time period without taking into account potential feedbacks loops or environmental thresholds for climate change. On the other hand, most climate data obtained from sedimentary deposits record integrated signals over long intervals and do not reflect the most extreme climate conditions. These differences cause potential problems for the interpretation of model-data datasets. Furthermore, validating the results of numerical models with climate proxies is also challenging as the grid size of numerical climate models that are often employed are so large that they cover entire sedimentary basins that had environmental gradients.

In this presentation we focus on the early Late Ordovician of North America to illustrate these challenges. In Middle and Upper Ordovician strata of the eastern North American mid-continent, 14 stratigraphic sequences are identified. Of these 14 sequences, 6 are Mohawkian in age and are designated as M1 through M6. The M4–M5 sequence boundary is a possible climatic turning point. This boundary coincides with several distinct lithological changes suggesting a transition from warm-water to cool-water conditions within the shallow epicontinental sea of Laurentia during the early Late Ordovician. The close temporal association of frequent and large volcanic events, including two of the largest Phanerozoic volcanic eruptions (i.e., Deicke and Millbrig eruptions), with this environmental change has lead to hypotheses that causally link volcanism with climate change during this time period. The estimated dense rock equivalent of the Late Ordovician Deicke K-bentonite Bed has been estimated to have been larger than the Toba ash fall (Indonesia, 75 kyr). As the eruption of Toba has been identified as a potential contributing factor in the transition of warm to cool climates and might have caused a bottleneck for human evolution, the Deicke and Millbrig events could, or should, have impacted Late Ordovician earth systems. Temperature estimates using oxygen isotopes spanning the Deicke and Millbrig indicate that they did not cause long-term cooling consistent with numerical model results of the Toba Eruption that show that the climate system recovers within decades. However, the model also shows the short-term cooling during the "volcanic winter" is significant (10–17K). In short, the problem of model data comparisons remains. Significant change examined well with numerical experiments likely cannot be resolved using traditional stratigraphic proxies, and, conversely long-term impacts of continuous volcanic activity during the early Late Ordovician cannot be resolved using current numerical models.

Early Katian (Late Ordovician) faunal successions and the GICE: examples from the East Baltic

Linda Hints[1], Olle Hints[1], Dimitri Kaljo[1], Björn Kröger[2], Peep Männik[1], Tõnu Martma[1] and Jaak Nõlvak[1]

[1] *Institute of Geology at Tallinn University of Technology, Ehitajate 5, 19086 Tallinn, Estonia; Linda.Hints@ttu.ee*
[2] *Finnish Museum of Natural History, P.O. Box 44 (Jyrängöntie 2), 00014 University of Helsinki, Finland*

Early Katian time was characterized by pronounced biotic turnovers and changes in facies patterns within the Baltoscandian Palaeobasin. It is also marked by the global Guttenberg carbon isotope event (GICE). In this study we integrate early Katian (Keila and Oandu regional stages) palaeontological and geochemical data from the eastern Baltic in order to clarify temporal and spatial relationships of faunas distributed from shoals to deeper shelf environments and establish new correlation criteria.

Within three main facies belts (North Estonian and Lithuanian facies belts and Livonian Tongue) of the East Baltic at least four distinct early Katian faunas can be differentiated, which belong to the Keila and Oandu stages.

(1) In most part of the North Estonian Facies Belt, the Kahula Formation (Fm) of the Keila Stage with diverse fauna is characterized by low $\delta^{13}C$ values. Due to a gap of varying duration at the Keila–Oandu boundary, no clear carbon isotope signature can be identified that could be used as a chemostratigraphic marker for this boundary. However, the Keila–Oandu boundary is marked by lithological changes and is biostratigraphically clear due to substantial faunal turnover.

(2) In the NW Estonian part of the North Estonian Facies Belt, the reef complex (Vasalemma Fm) and its lateral equivalents (Saue and Lehtmetsa members of the uppermost Kahula Fm) expose the two-peak GICE, known in some other Baltic, Swedish and Laurentian successions. The $\delta^{13}C$ excursion shows a decrease in isotope values in between the peaks in the Lehtmetsa and Saku members, which by faunal data are commonly dated as belonging to the Keila and Oandu stages, respectively.

(3) In the transitional facies zone between the Estonian Facies Belt and Livonian Tongue the study interval is represented by the Kahula and Variku fms, characterized by faunas partly coinciding with those in shallow shelf. The GICE occurs within the uppermost Kahula and lowermost Variku fms. The falling limb of the GICE corresponds to the strata with the *Tetrada* ostracod fauna and is considered as the uppermost part of the Keila Stage. This dating is supported by frequent occurrence of Tetrada-group ostracods in the Lehtmetsa Member in northern Estonia. The largest part of the Variku Fm corresponds to the post-GICE interval. It comprises the *Amorphognathus* "*ventilatus*" conodont fauna and, considering also other faunal data, is assigned to the Oandu Stage. A rich fauna, dominated by brachiopods, is known from the Lukštai Fm of the Oandu Stage in the Lithuanian facies belt. Common species of that fauna occur in the upper part of the Variku Fm and in the Hirmuse Fm of the Oandu Stage in northern Estonia.

(4) In the Livonian Tongue (southern Estonia and Latvia), marls of the Blidene Fm contain a characteristic association of shelly fauna, which shares several taxa with the Swedish successions. The main part of the GICE occurs in the upper Blidene Fm, whereas the falling limb corresponds to the marly-shaly Mossen Fm, which is correlated with the Variku Fm in Estonia.

The combination of isotope and palaeontological data enables correlation of different biofacies and improvement of temporal resolution regionally. The East Baltic data seem to fit well with those from the Fjäcka section in Sweden, where the $\delta^{13}C$ excursion compares well with the lithological and faunal changes. The falling and rising limbs of the GICE and its two-peak appearance in some sections deserve further detailed examination in order to provide a correlation criterion for the base of the Oandu Regional Stage.

Estonian geocollections information system focusing on Early to Mid Paleozoic rock record, fossils and analytical data from Baltoscandia

Olle Hints[1], *Mare Isakar*[2], *Kairi Põldsaar*[3], *Annette Talpsep*[4], *Sander Tint*[1], *Ursula Toom*[1] *and Kristjan Urtson*[1]

[1] *Institute of Geology at Tallinn University of Technology, 19086 Tallinn, Estonia; olle.hints@ttu.ee, ursula.toom@ttu.ee, kristjan.urtson@ttu.ee, sander.tint@ttu.ee*
[2] *Geological Museum, University of Tartu, Vanemuise 46, Tartu, Estonia; mare.isakar@ut.ee*
[3] *Estonian Museum of Natural History, Lai 28A, Tallinn, Estonia; kairi@loodusmuuseum.ee*
[4] *Department of Geology, University of Tartu, Ravila 14a, Tartu 50411, Estonia; annette.talpsep@ut.ee*

Most geological collections of Estonia – from single mineral grains to drill cores and from microfossil preparations to individual fossil specimens – characterise Early to Mid Paleozoic environments and biota of the Baltoscandian paleobasin, Baltica paleocontinent. These collections are extensively used in Cambrian to Devonian research by Estonian as well as foreign geologists. In order to organise various types of data related to these collections, aid curatorial work, and make the collections more accessible for research and education, development of national geocollections database started more than 10 years ago. Now this system is being redesigned and extended to facilitate multi-institutional usage, support wider range of data objects and user needs, and utilise modern web technologies. Most important new developments include a possibility to deposit original research data sets, make them publicly accessible when appropriate, assign digital object identifiers (doi numbers), and run various analysis on combined data sets on-line.

The data are stored on central relational database server, on replicated hardware and with multiple backup solutions. The software components are based on various open source technologies (Linux, MySQL, Python, Django, PHP etc). Data entry and editing is primarily done via web-based applications. Public access to the data is enabled through the national geocollections portal (http://geokogud.info), where data from multiple institutions can be searched for fossil specimens, rock samples, drill cores, localities, references, regional stratigraphy etc. Additionally, dedicated interfaces are being created for Baltoscandian fossil taxa (http://fossiilid.info), and analytical research data (http://ermas.geokogud.info). The latter provides, for instance, access to raw data on Ordovician and Silurian stable isotope analyses and bentonite geochemistry from the Baltic region. It will also include map visualisations, vertical log creation and on-the-fly statistical analysis based on R scripts.

Currently the system holds data on more than 0.2 million Paleozoic fossil specimens and rock samples, ca 20% of them complete with digital images. By the end of 2014, the system will also include ca 40000 analyses characterising various properties of Baltoscandian rock record and fossil occurrences. Well over 95% of all the data in the Estonian geocollections information system, including full resolution media files, are available for download, usage and redistribution under the Creative Commons BY-NC and Open Data Commons attribution licences. The specimen-level data are also made available through international data networks and online resources, notably the GeoCASe (Geosciences Collection Access Service; http://geocase.eu), GBIF (Global Biodiversity Information Facility; http://gbif.org) and Europeana (http://europeana.eu). Moreover, development of open API is in progress and will enable using the Estonian geoscience data by third party applications and creating automatic data exchange protocols. The planned national developments include integration with the geoscience data of the Estonian Geological Survey and Estonian Land Board and linking with Estonian eBiodiversity information system (http://elurikkus.ut.ee).

Acknowledgements. Development of the Estonian geocollections information system has been supported by the national R&D projects NATARC and ERMAS.

Tremadocian black shales from eastern Baltic Palaeobasin – revisiting geochemical and sedimentological heterogenity

Rutt Hints, Alvar Soesoo, Sigrid Hade, Margus Voolma, Toivo Kallaste and Siim Tarros

Institute of Geology at Tallinn University of Technology, 19086 Tallinn, Estonia; rutt.hints@ttu.ee, alvar.soesoo@ttu.ee, sigrid.hade@ttu.ee, margus.voolma@ttu.ee, toivo.kallaste@ttu.ee, siimtarros@gmail.com

The Tremadocian black shales of the Türisalu Fm. form an extensive organic- and clay-rich siliceous mudstone complex in north-east of Baltic Palaeobasin. Characterized by high content of U, Mo, V and some chalcophile elements the complex is potential future resource of number of metals (Hade & Soesoo 2014). Our recent findings suggest that the Türisalu Fm. exemplifies preservation of transgressive but rather shallow water highly reducing marine muds with spatially heterogeneous properties (Voolma *et al*. 2013; Hints *et al.* 2014).

In order to examine vertical geochemical variability of the Türisalu Fm. in closer detail we studied two drill core sections, less than 1 km apart, from the Suur-Pakri Island, NW Estonia. Altogether 374 samples were analysed by means of XRF. It appeared that the 4.6–5.5 m thick black shale complex is characterized by prominent cm-scale vertical heterogeneity of enriched trace elements. V and Mo presented, as expected, moderately strong correlations with organic matter content, whereas U covariance with organic matter appeared to be less clearly defined. We hypothesize that sequestration of U could have been additionally controlled by increased advective or diffusive fluxes of U(VI) or by microbially enhanced U-fixation. The comparison of trace element patterns from the two sections showed that V, Mo and U profiles seem to match considerably well if general trends are considered, whereas smaller-scale variation of those metals and elements like Zn, Ni, Pb and As demonstrated no clear correspondence. In contrast, the major element and mineral composition appeared to be remarkably invariable throughout the vertical section of the Türisalu Fm. It is characterized by high K content and K-feldspar – quartz – illite-smectite plus pyrite assemblage.

Deciphering of metal and organic matter distribution patterns might be aided by parallel recording of black shale microfabrics. The recent studies of the Türisalu Fm. from Baltic Klint outcrops have revealed pervasive signs of dynamic deposition of the mud, bioturbation, traces of microbial mats, lenses of sponge spicules and significant variations in microporosity (Hints *et al.* 2014). We suggest that the black shales of the Türisalu Fm. formed as the result of event deposition by sediment-laden flows and under high primary productivity conditions supported by local recycling of P. Dynamic of sediment water interface and fluctuation of redox structure of sedimentary environment probably had strong control over development of cm-scale trace metal heterogeneity in primary mud.

Hade, S. & Soesoo, A., 2014. Estonian graptolite argillites revisited: a future resource. *Oil Shale*, 13, 4–18.

Hints, R., Hade, S., Soesoo, A. & Voolma, M., 2014. Depositional framework of the East Baltic Tremadocian marginal black shale revisited. GFF. doi:10.1080/11035897.2013.866978.

Voolma, M., Soesoo, A., Hade, S., Hints, R. & Kallaste, T., 2013. Geochemical heterogeneity of Estonian graptolite argillite. *Oil Shale*, 30, 377–401.

The application of geometric morphometrics and morphing techniques in a study of Silurian brachiopod genus *Dicoelosia*

***Bing Huang*[1] *and David A.T. Harper*[2]**

[1] *State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, 39 East Beijing Road, Nanjing 210008, China; bhuang@nigpas.ac.cn*
[2] *Department of Earth Sciences, Durham University, Durham DH1 3LE, UK; david.harper@durham.ac.uk*

The distinctive brachiopod *Dicoelosia* King, 1850 is characterized by a strongly bilobed outline. To date studies have concentrated on its functional morphology, taxonomy and evolution; little attention has been paid to its ontogeny. Here, we map population variation by PCA for 75 specimens distributed across five species of *Dicoelosia*. Using geometric morphometrics with landmarks for some 40 specimens, the ontogenic trends in *D. cathaysiensis* are compared with those of *D. biloba.* In addition, the ontogenic pathway in *D. cathaysiensis* is investigated by morphing with control points, a new technique introduced here to palaeontology. Combining the results above, the ontogeny of the key character of the genus, emargination, is modeled. Within single populations taxa may develop from broad weakly-emarginate forms into those that are elongate and deeply emarginate. Since the identification of the genus and its species depends on external morphological characters, the definition of ontogenetic trends in each species is essential for taxonomic discrimination. Substantial population variation exists in many of its species; however, the morphing technique provides a method of simulation, predicting the full range of ontogenetic variation in given populations.

Traces of explosive volcanic eruptions in the Upper Ordovician of the Siberian Platform

Warren D. Huff[1], *Andrei V. Dronov*[2], *Brian Sell*[3], *A.V. Kanygin*[4] *and T.V. Gonta*[4]

[1] *Department of Geology, University of Cincinnati, OH 45221-0013, USA; huffwd@ucmail.uc.edu*
[2] *Geological Institute, Russian Academy of Sciences. Pyzhevsky per. 7, 119017, Moscow, Russia; dronov@ginras.ru*
[3] *Earth and Environmental Sciences, University of Michigan, Ann Arbor, Michigan 48109, USA; bksell@umich.edu*
[4] *Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of Russian Academy of Sciences. Acad. Koptyug 3, 630090, Novosibirsk, Russia; kanyginav@ipgg.nsc.ru*

In recent years eight K-bentonite beds have been discovered in the Upper Ordovician of the Tungus basin on the Siberian Platform. All the beds were identified in the outcrops of the Baksian, Dolborian and Burian regional stages, which correspond roughly to the Upper Sandbian, Katian and probably lowermost Hirnantian Global Stages (Bergström *et al.* 2009). The four lowermost beds from the Baksian and Dolborian Regional Stages were studied in detail. They are represented by thin beds (1 – 2 cm) of soapy light gray or yellowish plastic clays and usually easily identifiable in the outcrops. The beds were traced in the outcrops over a distance of more than 60 km along the Podkamennaya Tunguska River valley.

All K-bentonite beds have been found within the Upper Ordovician cool-water carbonate succession. The four lowermost K-bentonite beds, which were sampled, have been studied by powder X-ray diffraction (XRD) and scanning electron microscopy (ESEM) together with energy dispersive X-ray analysis. Modeling of the XRD tracings using NEWMOD showed the samples consist of R3 ordered illite-smectite with 80% illite and 20% smectite plus a small amount of corrensite, which is a regularly interstratified chlorite-smectite. A minor amount of quartz is indicated by peaks at 4.21Å and 3.33Å. The presence of a chlorite phase indicates a primary magma rich in Fe and Mg. And the low percent of smectite in both mixed-layer phases reflects a high degree of burial metamorphism since the time of their origin. The K-bentonites provide evidence of intensive explosive volcanism on or near the western (in present day orientation) margin of the Siberian craton in Late Ordovician time.

The K-bentonite beds from the Baksian and Dolborian regional stages (Katian) of the southwestern part of the Tungus basin in Siberia are thus derived from the alteration of volcanic ash falls. All four beds contain volcanogenic euhedral zircon and apatite phenocrysts. Zircon crystals from the uppermost K-bentonite bed within the Baksian regional stage provides a $^{206}Pb/^{238}U$ age of 450.58±0.27 Ma. The timing of volcanism is surprisingly close to the period of volcanic activity of the Taconic arc near the eastern margin of Laurentia. It looks like Taconic arc has its continuation along the western continental margin of Siberia and both of them constitute a single Taconic-Yenisei volcanic arc. Field studies of the Upper Ordovician succession along the Moyero River in the vicinity of the Anabar shield demonstrate an absence of K-bentonite beds along the eastern margin (in present day orientation) of the Siberian Platform. This contradicts popular palaeogeographic interpretations (www.scotese.com) and points to the position of a subduction zone along the western but not the eastern margin of the Siberian palaeocontinent at this time.

Financial support for this research was provided from the Russian Foundation for Basic Research Grant № 13-05-00749.

Bergström, S.M., Chen, X., Gutierres-Marco, J.C. & Dronov, A., 2009. The new chronostratigraphic classification of the Ordovician System and its relations to major regional series and stages and to $\delta^{13}C$ chemostratigraphy. *Lethaia*, 42, 97–107.

Provenance of the Baltic Ediacaran: U–Pb ages of detrital zircon from the Kotlin sandstone in western Estonia by LA-ICPMS

Yukio Isozaki[1], Anne Põldvere[2], Heikki Bauert[3], Kazumasa Aoki[1], Shuhei Sakata[4] and Takafumi Hirata[4]

[1] *University of Tokyo, Japan; isozaki@ea.c.u-tokyo.ac.jp*
[2] *Geological Survey of Estonia, Tallinn, Estonia*
[3] *Institute of Geology at Tallinn University of Technology, Estonia*
[4] *Kyoto University, Japan*

In order to add more information on the provenance history of Baltica, we conducted dating of detrital zircon grains from a Ediacaran sandstone from Estonia. The examined sandstone sample originates from the Kotlin Stage of the Velise-97 drill core (398 m depth, drilled near Velise village in western Estonia) and consist of a fresh, grey to purplish maroon-gray, fine-grained or silty sandstone. By using LA-ICPMS at Kyoto University, we determined U – Pb ages of 60 detrital zircon grains and measurements of 53 grains were plotted on the Concordia Line. Most of the analysed grains cluster in an age interval between 1673 and 1535 Ma (latest Paleo- to early Mesoproterozoic), whereas a small group of zircons revealed an age spectrum from 1922 to 1765 Ma (Paleoproterozoic), only one zircon grain represents the exceptionally old age of 2866 Ma (Mesoarchean). The present age determinations from central Baltica shows that the Ediacaran basin received abundant terrigenous clastics mainly from a Meso-Paleoproterozoic crust with minor contribution of much older Paleoproterozoic to Mesoarchean basement. The recorded age intervals clearly correspond to three distinct geologic units widely distributed in Baltoscandia: the Rapakivi granites (1600–1400 Ma), the crystalline rocks of the Svecofennian orogen (1800 – 1600 Ma), and over 2400 Ma old rocks of the Karelian block, respectively. The overall age spectrum and the dominance of the Rapakivi-derived zircon grains are in good accordance with the regional basement geology of central Baltica along the Gulf of Finland. Particularly noteworthy is the absence of Neoproterozoic zircon grains in the Ediacaran sandstone, which is in a sharp contrast with the age population of detrital zircon from the Cambrian Tiskre sandstone of Estonia, characterized by abundance of 800 – 600 Ma grains (Põldvere *et al.* 2014). This conspicuous contrast in zircon age spectra of the Ediacaran and Cambrian sandstones can be explained by a major change in basin geometry in south-central Baltica during the Dominopolian age of earliest Cambrian (Nielsen & Schovsbo 2011). This change in basin geometry might reflect the tectonic episode relevant to the collision between Baltica and some Gondwanan fragments.

Nielsen, A.T. & Schovsbo, N.H., 2011, The Lower Cambrian of Scandinavia: Depositional environment, sequence stratigraphy and palaeogeography. *Earth Science Reviews*, 107, 207–310.

Põldvere, A., Isozaki, Y., Bauert, H., Kirs, J., Aoki, K., Sakata, S. & Hirata, T., 2014. Detrital zircon ages of Cambrian and Devonian sandstones from Estonia, central Baltica: a possible link to Avalonia during the Late Neoproterozoic. *GFF*, 136, 214-217.

Glauconite in the Cambrian-Lower Ordovician succession of the East Baltic

Tatiana Ivanovskaya and Andrei Dronov

Institute of Geology, Russian Academy of Sciences, Pyzhevsky per.7, Moscow, 119017, Russia; ivanovskaya@ginras.ru, dronov@ginras.ru

Green glauconite grains are widespread in the Cambrian and Ordovician strata of the East Baltic. The highest concentration of the glauconite particles is known from the Lower Ordovician Leetse Formation of northern and central Estonia and the Zebre Formation of southern Estonia and Latvia (Hunneberg and Billingen regional stages). This stratigraphic unit was traditionally known as “Glauconite sandstone” and attributed to the Upper Latorp depositional sequence. In this study globule layer silicates of glauconite composition from the Middle Cambrian glauconite-bearing sandstones (Kibartay Regional Stage, Latvia, Vergale 50 borehole, 1040 – 1045 m) and poorly cemented glauconitites from the Lower Ordovician Leetse and Zebre formations (Latvia, Vergale 50 borehole, 993 – 995 m, and Estonia, Parila F-109 borehole, 98.9 – 98.1 m) have been studied. The rocks of various compositions (limestone, sandstone, clayey rocks) with 50% or more of glauconite content are called here glauconitites.

Glauconitites from the Upper Latorp depositional sequence consist of poorly cemented green glauconite grains and glauconite cement masses of the same colour. Specific features of the glauconite grains and their dense packing are similar to those in authigenic glauconitites of the same age from the Toolse phosphorite deposit in Northern Estonia. Mineralogical studies of monomineral fractions of the glauconite grains performed by a complex of modern chemical and physical methods (X-ray diffraction, scanning electron microscopy, classical chemical and micro-probe analysis etc.) allowed detailed determination of crystal-chemical characteristics of the clay minerals. Globular dioctahedral 2:1 layer silicates represented by glauconite-smectite (≤ 10% expandable layers). They are characterized by a high 3D ordering (polytype 1Md (60°). The b parameters of the unite cell varies from 9.08–9.09 Å. The studied layer silicates are represented by low-charged glauconite ($^{VI}Fe3+$ = 0.96 – 1.15, ^{VI}Al =0.64 – 0.37, K = 0.68 – 0.74 f. u., $^{VI}Al/^{VI}Al+ {}^{VI}Fe3+$ = 0.24–0.40). Glauconite of the Middle Cambrian is characterized by a higher ratio $^{VI}Al/^{VI}Al+ V^{I}Fe3+$ and lower content of K (0.68 f. u.). The glauconite grains seem to be originated by synthesis from colloidal solutions in the early diagenetic zone with the active influence of microorganisms.

For mass glauconite formation conditions with a temperature below 15°C and a pH around 8 are favourable. These conditions are in accordance with the palaeogeographical position of the Baltic palaeocontinent during the Early Ordovician. The other important factors for a high glauconitization are low sedimentation rate and accessibility of favorable substrates. Because glauconitization occurs in contact with sea-water, the presence of glauconite grains in the sediment reflect a low rates of sedimentation or/and hiatuses in sedimentation. The glauconitites from the Upper Latorp depositional sequence seems to represents a condensed section underlined by transgressive surface and associated with a prominent transgression. Mass glauconitization at this stratigraphic level could be explained by: 1) mass appearance of carbonate substrates for the first time in the Ordovician of Baltoscandia; 2) low rate of sedimentation due to transgression, and 3) low sea-water temperature.

Financial support for this research was provided from the Russian Foundation for Basic Research Grants № 13-05-00749, 13-05-00127 and 14-05-00323.

Carbonate tsunami deposit from the Mulde Event (Homerian, middle Silurian) of Podolia, Ukraine: lateral redeposition versus temporal mixing constrained using stable carbon isotopes

Emilia Jarochowska and Axel Munnecke

GeoZentrum Nordbayern, Fachgruppe Paläoumwelt, Universität Erlangen-Nürnberg, Loewenichstr. 28, 91054 Erlangen, Germany; Emilia.Jarochowska@fau.de, Axel.Munnecke@fau.de

Correlations of $\delta^{13}C$ trends are used as a precise stratigraphic tool in the Paleozoic, even though they are commonly based on shallow-water carbonate record, characterized by low stratigraphic completeness. Identification of erosion and large-scale redeposition events taking place during the periods of $\delta^{13}C$ anomalies contributes to the improvement of such correlations, and to the understanding of their relationship with sea-level and climate development. An example of event deposition leading to amalgamation of lithologies characterized by a wide range of $\delta^{13}C$ values is presented from the lowering limb of the Mulde Excursion, a global $\delta^{13}C$ excursion reaching an increase of +5.17‰ in the studied sections in Podolia, Ukraine. The high-energy deposit is introduced as the Makarivka Member of the Ustya Formation, and a tsunami origin is proposed for it based on its internal sedimentary architecture. The core of the Makarivka Member is emplaced within a tidal flat succession and formed by a polymict conglomerate of sand- to boulder-sized clasts derived from a broad scale of subtidal facies, and a heterolithic unit composed of grainstone and mudstone laminae. The conglomerate is interpreted to reflect the strongest landward-directed current in the tsunami run-up phase, and the heterolith – alternating high-density landward currents, stagnant intervals allowing mud and land-derived debris to settle, and backwash flows. The diversity of sources of the redeposited material is reflected by scattered $\delta^{13}C_{carb}$ of conglomerate clasts (-0.26‰ to +2.06‰) compared to homogenous (1.31‰ to 1.58‰) values in the matrix. The systematic shift in $\delta^{18}O_{carb}$ values (-6.19‰ in clasts and -4.26‰ in the matrix) suggests that the two components belong to different sedimentary or diagenetic pools.

The Ustya Formation represents a highstand systems tract following a sequence boundary and a stratigraphic gap reflected in the succession in Podolia by the lack of the second $\delta^{13}C$ peak of the Mulde Excursion. The presence of clasts characterized by a broad range of $\delta^{13}C_{carb}$ values may result from the erosion and reworking of an interval directly underlying the Ustya Formation. The emplacement of the Makarivka Member postdates, however, the onset of the peritidal sedimentation, indicating that the conglomerate could not be formed as a transgressive lag. Instead, it may result from the appearance of tsunami waves during the transition of the continental margin of Baltica to a foreland basin and the development of subduction zone in the southern parts of the Tornquist Ocean.

Preliminary conodont, $\delta^{13}C$ and sequence stratigraphy across the Mulde Event (Homerian, middle Silurian) in the carbonate platform environments of Podolia, Ukraine, and Podlasie Basin, E Poland

Emilia Jarochowska[1], Axel Munnecke[1], Alyssa Bancroft[2], Wojciech Kozłowski[3], David C. Ray[4], Konstantin Frisch[1] and Ariane Castagner[5]

[1] *GeoZentrum Nordbayern, Fachgruppe Paläoumwelt, Universität Erlangen-Nürnberg, Loewenichstr. 28, 91054 Erlangen, Germany; Emilia.Jarochowska@fau.de*
[2] *Department of Geology and Physics, Lake Superior State University, 650 West Easterday Av., Sault Sainte Marie, 49783 Michigan, USA*
[3] *Institute of Geology, University of Warsaw, Al. Żwirki i Wigury 93, 02089 Warsaw, Poland*
[4] *Neftex, 97 Jubilee Avenue, Milton Park, Abingdon, Oxfordshire, OX14 4RW, UK*
[5] *Department of Earth Sciences, University of Ottawa, Ottawa, ON K1N 6N5, Canada*

The Silurian succession in Podolia, western Ukraine, represents a low-relief epeiric carbonate ramp developed in arid climate. We have investigated six sections in the Dniester River Valley with respect to the sedimentary record of sea-level changes and associated turnover of conodont fauna across the Mulde (Homerian, middle Silurian) positive stable carbon isotope excursion (CIE) interval. The onset of the excursion is recorded in the uppermost part of the Sursha Fm., developed as thickly bedded nodular crinoidal grainstone and yielding *Ozarkodina bohemica longa* and abundant *Panderodus* spp. conodont fauna. The top of the Sursha Fm. is a scoured, cemented surface marking the onset of a rapid regression leading to the deposition of brachiopod shell beds cut by multiple erosional surfaces and intercalated by mudstone layers indicating progradation of terrigenous material. This interval records the increase of $\delta^{13}C_{carb}$ values from 0.49‰ (all VPDB) to 2.59‰ within 45 cm, and terminates with a scalloped firmground surface mineralized with iron. The overlying beds are dominated by calcareous green algae and oncoids, indicating an abrupt shift towards shallow environments within the upper photic zone, and suggesting that the firmground formed at a sequence boundary. The overlying early transgressive interval is characterized by further rapid rise of $\delta^{13}C_{carb}$ values up to 5.17‰ and the presence of condensed beds yielding abundant phosphatic microfossils ("bone beds") and low-diversity conodont fauna dominated by *O. excavata* and *O. confluens*. The deepening trend is associated with $\delta^{13}C_{carb}$ values between +3‰ and +5‰ in bioturbated mudstones, and terminates with the deposition of a brachiopod shell bed at the inferred maximum flooding surface. Subsequent progradation is visible in the increased frequency of oncoidal intercalations and finally the development of a microbial-stromatoporoid-coral mound belonging to the Muksha Fm., truncated by another sequence boundary. Elevated $\delta^{13}C_{carb}$ values across this interval do not show the characteristic drop and the second peak, observed elsewhere. Due to lack of basinward located sections in Podolia, we have attempted a preliminary correlation with age equivalent succession in the Widowo IG-1 core located in the Podlasie Basin, eastern Poland, where the CIE interval is recorded in the Sursha Fm., indicating that it represents shallow-water platform environment just slightly deeper than the environments represented in Podolian sections during this interval. Based on the presence of the second Mulde peak in this core, we infer that the plateau of elevated $\delta^{13}C_{carb}$ values in Podolia corresponds in fact to the lower peak, and the second sequence boundary between the Muksha Fm. and overlying Ustya Fm. is associated with a sedimentary gap encompassing most of the upper peak. The Ustya Fm. is interpreted as a highstand systems tract based on its aggradational to progradational stacking pattern in tidal flat facies. Its lower part records the return of $\delta^{13}C_{carb}$ values from above 3‰ to the baseline (close to 0‰) level within 2 m, the elevated values are, however, partially the result of redeposition of clasts from deeper-water facies, which we propose to be a result of a tsunami event (Jarochowska & Munnecke, this volume). Grainstone beds associated with the tsunamite yielded diverse *Ctenognathodus* spp. and large, robust conodonts belonging to the *O. confluens* lineage, characteristic for very shallow-water environments, and the polymictic conglomerate forming the core of the tsunamite – very abundant thelodont scales. Our observations support the interpretation that the double-peaked character of the Mulde CIE and associated changes in the conodont faunas are tightly linked to two regressive episodes, which are recorded across different basins and likely represent a global (glacio)eustatic trend.

The Mulde (Homerian, middle Silurian) positive $\delta^{13}C$ excursion at Whitman's Hill, Herefordshire, UK

Emilia Jarochowska[1], David C. Ray[2], Jan-Filip Päßler[1], Graham Worton[3] and Axel Munnecke[1]

[1] *GeoZentrum Nordbayern, Fachgruppe Paläoumwelt, Universität Erlangen-Nürnberg, Loewenichstr. 28, 91054 Erlangen, Germany; Emilia.Jarochowska@fau.de*
[2] *Neftex, 97 Jubilee Avenue, Milton Park, Abingdon, Oxfordshire, OX14 4RW, UK; daveray01@yahoo.com*
[3] *Dudley Museum and Art Gallery, St. James' Road, Dudley, West Midlands DY1 1HZ, UK*

The Homerian was a time of two short-lived perturbation in the global carbon cycle, known as the Mulde carbon isotope excursion (CIE); these positive CIEs are recorded upon many paleocontinents (Cramer *et al.*, 2012). Although there is no agreement as to the sea-level changes associated with these CIEs, they have been particularly well constrained in the English Midlands, allowing for precise linking of geochemical and sequence stratigraphic data (Cramer *et al.*, 2012; Ray *et al.*, 2010; 2013).

Whitman's Hill Quarry, located in the central part of the Midland Platform, exposes an approximately 40 m thick Homerian succession, spanning the upper Coalbrookdale Formation and most of the Much Wenlock Limestone (MWL) Formation (Lower Quarried Limestone and Nodular Beds members). At least 10 parasequences can be distinguished and correlated with coeval sections across the northern Midland Platform (Ray *et al.*, 2010; 2013), indicating two regressive episodes separated by a transgression. We present a high resolution (5 to 20 cm intervals) $\delta^{13}C_{carb}$ curve, showing a very rapid increase of values from the baseline level (average 0.08‰, SD 0.64‰, all values reported with respect to VPDB) to 1.99‰ within the uppermost 1.4 m of the Coalbrookdale Fm. The steepest increase of $\delta^{13}C$ values is associated with the regressive basal parasequence of the Lower Quarried Limestone Member of the MWL Fm., where they rise to 4.60‰ within 70 cm. Overall, the $\delta^{13}C$ curve in Whitman's Hill Quarry shows very good agreement with the $\delta^{13}C$ development in northern Midland Platform (Marshall *et al.*, 2012): the lower peak of the Mulde Excursion reaches the highest values (max. 4.83‰) within the early transgressive systems tract (TST), corresponding to the Lower Quarried Limestone Member. This interval is marked by the development of microbial carbonates: oncoids and massive bioherms dominated by micritic, presumably microbial fabrics. The $\delta^{13}C$ values decrease within the following late TST in the lower part of the Nodular Beds Member, where an abrupt, short-lived drop is recorded. The upper part of the Nodular Beds Mb., representing highstand systems tract, shows slightly lower values – average 2.60‰, SD 0.50‰, which begin to rise again in the uppermost part of the section. In summary our data support the observation that both peaks of the Mulde CIE are closely associated with two marked regressions that can be correlated with sections in Baltica and Laurentia, and may reflect two globally recorded glacioeustatic cycles (Ray *et al.*, 2010).

Cramer, B.D., *et al.*, 2012. U–Pb (zircon) age constraints on the timing and duration of Wenlock (Silurian) paleocommunity collapse and recovery during the "Big Crisis". *Geological Society of America Bulletin*, 124, 1841–1857.

Marshall, C., *et al.*, 2012. High resolution $\delta^{13}C_{carb}$ stratigraphy of the Homerian (Wenlock) of the English Midlands and Wenlock Edge. *Bulletin of Geosciences*, 87, 669–679.

Ray, D.C., *et al.*, 2010. Late Wenlock sequence stratigraphy in central England. *Geological Magazine*, 147, 123–144.

Ray, D.C., *et al.*, 2013. Late Wenlock sequence and bentonite stratigraphy in the Malvern, Suckley and Abberley Hills, England. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 389, 115–127.

Bio-chemostratigraphical correlation of upper Silurian sections along the western coasts of Estonia and Latvia: problems and solutions

Dimitri Kaljo[1], Rein Einasto[2], Tõnu Martma[1], Tiiu Märss[1], Viiu Nestor[1] and Viive Viira[1]

[1] *Institute of Geology at Tallinn University of Technology, Ehitajate 5, 19086 Tallinn, Estonia; dimitri.kaljo@ttu.ee, tonu.martma@ttu.ee, tiiu.marss@ttu.ee, viiu-kai.nestor@ttu.ee, viive.viira@ttu.ee*
[2] *TTK University of Applied Sciences, Pärnu mnt 62, 10135 Tallinn, Estonia; rein.einasto@hot.ee*

This project was initiated for testing the ideas of ecostratigraphy that were popular in the 1980s – 1990s of the last century. Unfortunately not all initiators are among us now. Here, we discuss five drill core sections located on the east coast of the Baltic Sea. Three of them, Kaugatuma and Ohesaare on the Sõrve Peninsula in Estonia, and Kolka in the Kurzeme Region of Latvia, are located close to the Silurian shore, and two more Latvian ones (Ventspils and Pavilosta) in the offshore area. The study interval embraces the entire upper Silurian from the Paadla (Ludlow) to the Ohesaare Regional Stage (Pridoli) or, in terms of lithostratigraphy, the Torgu, Kuressaare, Kaugatuma (Äigu, Lõo), Ohesaare, Dubysa, Pagegiai (Mituva, Engure), Ventspils, Minija and Jura (Targale) formations. This terminology reflects changes in three main lithofacies associations, beginning from the shoreface: (1) different lime- and dolostones with marl intercalations representing a shallow carbonate shelf dominating in the Sõrve and Kolka sections; in the upper and middle parts of the Ventspils, and the upper part of the Pavilosta core; (2) marls with limestone nodules and rare interbeds formed on the gentle slope of the carbonate shelf, and occupying most of the lower part of the Ventspils core and the middle part of the Pavilosta core; (3) relatively deep-water graptolitic marls and argillites in most of the lower part of the Pavilosta core and a little in the bottom of the Ventspils core. Sporadic occurrences of macrofossils (stromatoporoids, tabulate corals, brachiopods, trilobites, graptolites) show a community pattern that is in harmony with changing facies. Microfossils (ostracodes, and especially recently published chitinozoans, conodonts and microvertebrates) enable more perfect biostratigraphical zonations. Still, discrepancies between biostratigraphy based on different fossil groups remain. To understand them, we performed 260 whole-rock carbon isotope analyses from the Ohesaare, Ventspils and Pavilosta cores. Integrated $\delta^{13}C$ data made it easier to trace several synchronous biostratigraphical datum planes through different facies boundaries.

Mean grain size of the siliciclastic component of the Pirgu – Porkuni sedimentary rocks of the Aizpute-41 core indicating pre-Hirnantian start of the glaciation

Enli Kiipli, Sven Siir, Tarmo Kiipli and Toivo Kallaste

Institute of Geology at Tallinn University of Technology, Ehitajate 5, 19086 Tallinn, Estonia; enli.kiipli@ttu.ee

The Hirnantian glaciation is considered a culmination of the Late Ordovician cooling (Brenchley *et al.* 1994). The formation of ice sheets started earlier (Loi *et al.* 2010). Grain size analysis of the siliciclastic component of the sedimentary rocks of the Aizpute-41 drillcore shed light to the glaciation development in the Pirgu (Late Katian) and Porkuni (Hirnantian) stages. The Aizpute core is situated in West Latvia, in the 'Livonian Tongue', the deeper part of the Ordovician Baltic Basin. The section is relatively complete and allows the tracking of environmental changes across the Ordovician–Silurian transition. Our analysis reveals large-scale grain size fluctuations in the Pirgu and Porkuni stages in comparison with the pre-Pirgu (Sandbian – early Katian) and post-Hirnantian parts of the succession. The mean grain size (MGS) data are paralleled with the Si/Al ratio: higher MGS correspond to higher Si/Al values, and lower MGS to lower Si/Al. The MGS maximums and highest Si/Al are caused by addition of very fine sand. The samples of minimal grain size values contain a portion of very fine clay. MGS is interpreted as being a proxy for transgressions and regressions. The causes for sea level changes can be either eustatic resulting from waxing and waning of ice sheets, or regional and local tectonic movements. The MGS trend toward higher values is common for the Pirgu and Porkuni stages. The Gondwana glaciation ends at the Ordovician–Silurian boundary and so does the fluctuation of MGS. This suggests that the observed grain size fluctuation is caused by eustatic sea level changes. The start of the larger fluctuations at the lower Pirgu Stage points to glaciation-related sea level change long before the Hirnantian. Tectonic component in MGS comes from the moderate rise of average background values of MGS from Sandbian up to the Llandovery, and maybe even longer, reflecting a long-lasting uplift of the Fennoscandian Shield, leading to the degradation of the Baltic carbonate basin in late Silurian.

Brenchley, P.J., Marshall, J.D., Carden, G.A.F., Robertson, D.B.R., Long, D.G.F., Meidla, T., Hints, L. & Anderson, T.F., 1994. Bathymetric and isotopic evidence for a short-lived Late Ordovician glaciation in a greenhouse period. *Geology*, 22, 295–298.

Loi, A., Ghienne, J.-F., Dabard, M.P., Paris, F., Botquelen, A., Christ, N., Elaouad-Debbaj, Z., Gorini, A., Vidal, M., Videt, B. & Destombes, J. 2010. The Late Ordovician glacio-eustatic record from a high-latitude storm-dominated shelf succession: The Bou Ingarf section (Anti-Atlas, Southern Morocco). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 296, 332–358.

Baltic Early Paleozoic bentonite database: tracking time, tectonic evolution and marine environmental signatures

Tarmo Kiipli, Toivo Kallaste, Rutt Hints and Olle Hints

Institute of Geology at Tallinn University of Technology, Ehitajate 5, 19086 Tallinn, Estonia; tarmo.kiipli@ttu.ee

The Ordovician – Silurian sedimentary succession of Baltoscandia hosts numerous altered volcanic ashes, commonly referred to as bentonites. These beds provide exceptional stratigraphic marker horizons and aid reconstructing tectonic and environmental history. In the eastern Baltic, approximately 150 individual bentonites have been identified, particularly in the Sandbian – Katian and Telychian – Sheinwoodian intervals.

In the course of studies during the past 20 years a database of distribution and thickness of bentonites, and their geochemical and mineralogical properties has been created. It contains data on more than 600 samples from Estonia, Latvia and Lithuania, complemented with records from Sweden, Denmark, Norway, Ukraine and Moldova. Most samples in the database are characterised by bulk XRF analyses of major components and trace elements (Kiipli *et al.* 2011, 2013), and measured and modelled XRD spectra of pyroclastic K-Na-Ca-sanidine (Kiipli *et al.* 2014). Proportion of the Na-Ca component in sanidine phenocrysts revealed by XRD has proved especially useful for fingerprinting individual beds. For example, the proposed correlation table of Telychian bentonites of Estonia, Latvia and Gotland includes 63 tracable eruption layers (Kiipli *et al.* 2012). Combined with biostratigraphy, stable isotope records, and emerging new radiometric dates, these data can be used for building a high-resolution temporal framework for the region (Kiipli *et al.* 2010, 2011, 2012, 2013, 2014). The growing database can be used for searching correlations with newly obtained data, for composing distribution and thickness maps of particular beds, and for creating sedimentological thickness models of host sediment between the correlated horizons. Furthermore the dataset could be used for tracing of tectonic evolution of Baltica, e.g. for following the volcanogenic signatures of Iapetus closure and docking with Avalonia. Not less importantly, the recorded geochemical variations in bentonites across different facies of Baltoscandian Basin provide additional tool for understanding the ashfall-related environmental perturbations and biotic turnovers.

The Baltic bentonite database is now being made accessible online as part of the Estonian geocollections information system (http://ermas.geokogud.info). In addition to this dynamic database, individual subsets of the data are attached to individual publication records (see the links below).

Kiipli, T., Einasto, R., Kallaste, T., Nestor, V., Perens, H. & Siir, S., 2011. Geochemistry and correlation of volcanic ash beds from the Rootsiküla Stage (Wenlock – Ludlow) in the eastern Baltic. *Estonian Journal of Earth Sciences*, 60, 207–219. http://geokogud.info/reference/1586.

Kiipli, T., Kallaste, T., Kiipli, E. & Radzevičius, S., 2013. Correlation of Silurian bentonites based on the immobile elements in the East Baltic and Scandinavia, *GFF*, 135, 152–161. http://geokogud.info/reference/2557.

Kiipli, T., Kallaste, T. & Nestor, V., 2010. Composition and correlation of volcanic ash beds of Silurian age from the eastern Baltic. *Geological Magazine*, 147, 895–909. http://geokogud.info/reference/1203.

Kiipli, T., Kallaste, T. & Nestor, V. 2012. Correlation of upper Llandovery – lower Wenlock bentonites in När (Gotland, Sweden) and Ventspils D3 (Latvia) drill cores: role of volcanic ash clouds and sea currents in forming of bentonite distribution area. *Estonian Journal of Earth Sciences*, 61, 295–306. http://geokogud.info/reference/2533.

Kiipli, T., Radzevičius, S. & Kallaste, T., 2014. Silurian bentonites in Lithuania: correlations based on sanidine phenocryst composition and graptolite biozonation – interpretation of volcanic source regions. *Estonian Journal of Earth Sciences*, 63, 18–29. http://geokogud.info/reference/2544.

Evolutionary history of the *Gothograptus* lineage, retiolitids (Graptolithina)

Anna Kozłowska

Instytut Paleobiologii PAN, ul. Twarda 51/55, PL-00-818 Warszawa, Poland; akd@twarda.pan.pl

The retiolitid fauna is one of the characteristic graptolite elements of the Palaeozoic seas and oceans. They are unique among graptolites in having cortex as the dominating component of rhabdosomes instead of the typical fusellar tissue. During the upper Homerian and Gorstian the *Gothograptus* evolutionary lineage evolved towards simplification of rhabdosome. The genera *Gothograptus*, *Baculograptus*, *Neogothograptus*, and *Holoretiolites* occur continuously from the *lundgreni* to the *praedeubeli* biozones. Typical morphological characters of their rhabdosomes are finite growth, an ancora umbrella having six meshes, narrow elongate rhabdosomes ended by tubular appendix, and in most species singular genicular hoods. The hoods are built on cortical bandages forming reticulated meshes or continuous layers of dense, parallel bandages. The hoods of particular species have similar construction, different shape and sizes varying from small to large. During astogeny hoods became larger and thicker due to the addition of successive bandages of different directions. Species belonging to the oldest genus *Gothograptus* have the largest and the most variable hoods, which may extend proximally covering a part or the whole ventral wall of the theca. One diagnostic generic feature of gothograptids is the position of the nema. It is attached to the lateral wall in *Gothograptus* and *Baculograptus*, and free in *Neogothograptus* and *Holoretiolites*. The first known representatives of genus *Gothograptus* appeared in the *lundgreni* Biozone. They are represented by *G. kozlowskii* Kozłowska-Dawidziuk, 1990, *G. obtectus* Kozłowska-Dawidziuk, 1990 and *G. storchi* Lenz and Kozłowska, 2006. The oldest species of *Gothograptus* have the most variable and complicated proximal ends, densely reticulated rhabdosomes and diverse apertural hoods. *G. obtectus* has genicular structures of veil shape, unique for retiolitids, which covers the aperture of the theca and extends to cover the aperture of the previous. The latest and well known species, *G. nassa* from the *nassa* biozone has solid genicular hoods built of densely packed parallel bandages. They are almost identical to the proximal thecal hoods of *G. kozlowskii* and *N. eximinassa* from the *praedeubeli* biozone. Later species of *Neogothograptus* were possibly derived directly from *Gothograptus* and flourished continuously from the *praedeubeli* biozone up to the *scanicus* biozone, having nine species. It seems that they inherited the ability to generate genicular hoods from the earlier *Gothograptus* species. The great similarity of their rhabdosome features, and almost identical genicular hoods of *N. eximinassa* suggest its close ancestral relationship with *G. kozlowskii* and *G. nassa*. Species of *Neogothograptus*, like all Ludlow retiolitids display a strong tendency to reduction of reticulum and genicular hoods. The latest species of *N. purus* and *N. melchini* possess a rhabdosome with no reticulum and genicular structures. Much greater reduction of rhabdosomes, following the general trend, occurs in the youngest forms of gothograptids belonging to *Holoretiolites*. Four of its species, *H. mancki*, *H. erraticus*, *H. manckoides*, and *H. atrabecularis*, have extremely reduced small rhabdosomes with a simple proximal end, no reticulum, and genicular hoods. They represent the last forms of the *Gothograptus* lineage.

Pan-regional occurrence of detrital dolomite in the Lau event interval – is the mid-Ludfordian CIE triggered by eolian dust?

Wojciech Kozłowski

Institute of Geology, University of Warsaw, ul. Żwirki i Wigury 93, PL-02-089 Warsaw, Poland; wlkozlow@uw.edu.pl

Middle Ludfordian circum-equatorial carbonate rocks record one of the largest Carbon Isotope Excursions (CIE) in the Phanerozoic, reaching up to +11.21‰ (VPDB; see review in Jeppsson *et al.* 2012). High $\delta^{13}C_{carb}$ values are combined with conodont and graptolite extinctions, as well as sea-level fall and dynamic climate changes (see review in Munnecke *et al.* 2010).

Silurian rocks between northern Poland and western Ukraine represent a narrow foreland basin of Tornquist branch of the Caledonian orogen. The basin was asymmetrical with two different types of hinterlands. From the east, basin was limited by an extensive carbonate platform, whereas the opposite shore represented a orogenic prism, delivering clastic material to the rapidly subsiding foredeep. Comparison of individual sections representing various sedimentary regimes allowed to extract the pan-regional record of the studied event from the sum of observed facies changes.

The most distinct common phenomenon is the negative natural gamma-ray excursion, coupled with low rock magnetic susceptibility. The anomalies have been noted from carbonate platform, through the basin axis to proximal foredeep setting (Dniester escarpment in Ukraine, Gołdap IG-1, Żebrak IG-1, Pasłęk IG-1 and Lębork IG-1 cores). Petrographical observations revealed a pan-regional occurrence of rock-forming carbonate silt (dolomite and calcite) independent of the sedimentary setting and hinterland type.

The Silurian in the Lębork IG-1 core (proximal foredeep setting) is composed of clastic rocks. Despite the regressive conditions, the CIE interval is characterized by the presence of laminated marls and dolomites with open-shelf fossils assemblage. The rocks are composed of rock-forming minute crystals of dolomite and calcite without any addition of neritic carbonate grains. The syn-sedimentary origin and detrital character of the grains is suggested by the occurrence of common changes in the grain size both in dolomite and quartz.

The CIE in the Lębork IG-1 (proximal foredeep) and Pasłęk IG-1 (basin axis) cores reaches up to +8.6‰ (VPDB), which may indicate that the observed grains are the potential carrier of the heavy $\delta^{13}C_{carb}$ signatures. This suggestion is confirmed independently by $\delta^{13}C_{carb}$ curves mirroring the MS curves in all studied sections in the basin. However, dolomite grains recently separated from the marls in the Mielnik IG-1 core show constant $\delta^{13}C$ values (around +0.0‰) across the CIE interval, indicating extrabasinal origin of the dolomite grains and exclusively intra-basinal formation of the CIE.

The subaerial provenance of the dolomite is confirmed by the facies record in the Ataki and Braga sections of the Dniester escarpment (Ukraine). At least a part of the 'sparitic' dolomites of the Isakivtsy Formation in Podolia are in fact doloarenites with cross-bedded lamination and calcite bioclasts preserving original mineralogy, and probably represent proximal marine to terrestrial sources of detrital dolomite. At this moment the most probable hypothesis of pan-regional dolomite accumulation is its eolian transport from the emerged carbonate platform top, due to sea-level lowstand coupled with enhanced global gustiness (see Kozłowski & Sobień 2012).

Jeppsson, L., Talent, J.A., Mawson, R. et al., 2012. Late Ludfordian correlations and the Lau Event. *In:* Talent, J.A. (ed). *Earth and Life*. International Year of Planet Earth. Springer, 653–675.

Kozłowski, W. & Sobień, K., 2012. Mid-Ludfordian coeval carbon isotope, natural gamma ray and magnetic susceptibility excursions in the Mielnik IG-1 borehole (Eastern Poland) – Dustiness as a possible link between global climate and the Silurian carbon isotope record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 339–341.

Munnecke, A., Calner, M., Harper, D.A.T. & Servais, T., 2010. Ordovician and Silurian sea-water chemistry, sea level, and climate: a synopsis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 296, 389–413.

Age, facies, and geometry of the Katian (Upper Ordovician) pelmatozoan-bryozoan-receptaculite reefs of the Vasalemma Formation, northern Estonia

Björn Kröger[1], Linda Hints[2] and Oliver Lehnert[3]

[1] *Finnish Museum of Natural History, University of Helsinki, PO Box 44, Jyrängöntie 2, 00014, Helsinki, Finland; bjorn.kroger@helsinki.fi*
[2] *Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, 19086, Tallinn, Estonia*
[3] *GeoZentrum Nordbayern, Universität Erlangen-Nürnberg, Fachgruppe Krustendynamik, Schlossgarten 5, D-91054 Erlangen, Germany*

The reefs of the Vasalemma Formation, early Katian (Late Ordovician) of northern Estonia, have been identified for the first time more than a century ago. However, their exact stratigraphic position at the Keila / Oandu stage boundary interval and their lithological composition remained poorly known.

The reefs bodies are no more than 15 m thick and sometimes reach dimensions of more than 50 m in diameter. We distinguish four dominant facies types within the reef core limestones: 1) a bryozoan framestone – bindstone, 2) an echinoderm framestone – bindstone, 3) a receptaculite-bryozoan-microbial framestone, and 4) a tabulate bafflestone. Except for the tabulate bafflestone, all facies types occur in the youngest and oldest intervals of reef growth. Generally, a tendency can be observed with a dominance of echinoderm framestones low in the formation, and at the base of individual reefs towards a more receptaculite dominated facies at the top of the formation.

The reef growth can be constrained to the latest Keila age, based on the development during the rising limb and the peak interval of the Guttenberg Isotopic Carbon Isoptope Excursion (GICE). The reef termination falls within a 2nd order seal level lowstand, the Frognarkilen Lowstand Event, and lead partly to a subaerial exposure of the reefs. The dead reefs subsequently drowned rapidly during Nakkholmen Drowning Event at the Oandu/Rakvere stage boundary.

Parsimony analysis of endemicity of a Late Ordovician faunal migration: Identifying the invasion pathways and mechanisms of a regional invasion event

Adriane R. Lam and Alycia L. Stigall

Department of Geological Sciences, Ohio University, Athens, Ohio, USA; al211513@ohio.edu, stigall@ohio.edu

The Late Ordovician (Katian: Cincinnatian) strata of the C4 and early C5 sequences in the area around Cincinnati, Ohio, USA record a regional invasion event, the Richmondian Invasion, which is marked the by the first appearance of over 60 genera in the Cincinnati Basin. Prior studies of this time interval have identified several potential source areas for the invaders; however, the exact timing, migration pathways, and dispersal mechanisms are not fully understood. In addition, the Richmondian Invasion has traditionally been considered an isolated event; however, it is probably more accurately interpreted as a regional manifestation of the more widespread *Hiscobeccus* expansion.

The classical interpretation is that the Richmondian Invaders migrated from equatorial waters of Laurentia in a unidirectional fashion. Some taxa, such a corals, may have immigrated along this pathway. However, this explanation disagrees with recent phylogenetic data and appears intractable for at least some taxa. Notably, paleoequatorial members of some invasive brachiopod lineages were hypercalcified, although the Richmondian invaders were not. For these lineages, invaders were more likely sourced from peripheral basins of Laurentia. In this analysis, we test the presence and directionality of migration pathways at multiple time intervals and among a variety of clades.

In this study, Parsimony analysis of endemicity (PAE) and similarity indices are utilized to examine shifting patterns of endemicity and taxonomic connectivity between tectonic basins of central and marginal Laurentia and Baltica during time slices correlated to the C1 to C6 sequences of the Cincinnatian Series. Basins analyzed include the Cincinnati basin, Upper Mississippi Valley, Anticosti Island, Nashville Dome, Appalachian basin, and Estonian platform. Area cladograms were evaluated to identify dispersal events occurring between sequences by identifying shifts in associations among basins through time. Paleoceanographic conditions within Laurentia were interpreted from stratigraphic information and ocean circulation models and compared to dispersal events to determine mechanisms and pathways of faunal migration.

Results indicate that invasive taxa arrived in the Cincinnati region in multiple temporally discrete invasion events and from multiple geographic regions. Analyses recovered a complex series of dispersal pathways operating via “stepping stone” dispersal during the Cincinnatian interval. For example, analyses recovered a discreet pathway taken by some invasive taxa from Anticosti Island, Canada, into the Cincinnati region. Dispersal occurred from Anticosti Island to the Upper Mississippi Valley during the C2 sequence. Similarity indices support close area relationships between Anticosti Island, the Upper Mississippi Valley, and the Cincinnati basin. Subsequent dispersal occurred from the Upper Mississippi Valley into the Cincinnati basin. Basin infilling led to breaching of major arches between basins and opened additional dispersal pathways. Surface currents and hurricanes moving from the northeast likely contributed to dispersal of organisms from Anticosti Island into surrounding basins. Hypothesized dispersal routes and timing are further supported by examining larval development and transport modes.

Diagenetic fate of the Palaeozoic lingulate brachiopod shells

***Liisa Lang*[1], *Signe Vahur*[2] *and Kalle Kirsimäe*[1]**

[1] *Department of Geology, University of Tartu, Tartu, Estonia; Liisa.Lang@ut.ee, Kalle.Kirsimae@ut.ee*
[2] *Institute of Chemistry, University of Tartu Tartu, Estonia; Signe.Vahur@ut.ee*

Potential use of fossil skeletal apatites for palaeoenvironmental and phylogenetic reconstructions is significantly hampered by their complex postmortem changes. Understanding the nature and extent of these changes is important for accurate chemical and structural interpretations.

Scanning electron microscopic (SEM) studies of the apatitic shells of lingulate brachiopods from the sandstones of Cambrian–Ordovician boundary beds in Estonia and NW Russia reveal a heterogenic preservation of shell structures. Fine curved nanofibrils, interpreted as phosphatized biopolymers (Lang *et al.* 2011), are occasionally preserved, while in other shells the shell structures cannot be distinguished due to the presence of possibly authigenic apatite, which may have a different chemical composition. Infrared (ATR FT-IR) and energy dispersive spectroscopic (EDS) mapping of Cambrian *Ungula ingrica* shells from Estonia showed laminated alternation of apatite phases with different chemical compositions. Chemical differences between these apatite phases are expressed in the content of fluorine and carbonate anions in apatite crystal lattice. The phase with higher fluorine and carbonate anion content is possibly a late diagenetic apatite, while the phase with relatively lower fluorine and carbonate anion content can be interpreted as recrystallized skeletal apatite, the latter is composed of apatite crystals similar in size to modern brachiopods. Our study shows that if there are some original features of shell apatite preserved, then these can most probably be found from compact laminae even in the case of poorly preserved shell structures.

Lang, L., Uibopuu, E. & Puura, I., 2011. Nanostructures in Palaeozoic linguloid brachiopods. *Memoirs of the Association of Australasian Palaeontologists*, 41, 359–366.

Early Palaeozoic evolution of the Caledonian foreland basin – new data from the sedimentary record in the Siljan impact structure (Central Sweden)

Oliver Lehnert[1,2], Guido Meinhold[3], Arzu Arslan[4], Ulrich Berner[5], Mikael Calner[2], Jan Ove Ebbestad[6], Warren D. Huff[7] and Michael M. Joachimski[1]

[1] GeoZentrum Nordbayern, Lithosphere Dynamics, University of Erlangen-Nürnberg, Schloßgarten 5, D-91054, Erlangen, Germany; oliver.lehnert@fau.de, michael.joachimski@fau.de
[2] Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden; mikael.calner@geol.lu.se
[3] Geowissenschaftliches Zentrum der Universität Göttingen, Abteilung Sedimentologie/ Umweltgeologie, Goldschmidtstraße 3, D-37077 Göttingen, Germany; guido.meinhold@geo.uni-goettingen.de
[4] Midland Valley Exploration Ltd, 144 West George Street, G22HG Glasgow, United Kingdom; arzu@mve.com
[5] Petroleum System Analysis, Statoil ASA, Sandsli, Norway; ULRB@statoil.com
[6] Museum of Evolution, Uppsala University, Norbyvägen 16, SE 752 36 Uppsala, Sweden; Jan-Ove.Ebbestad@em.uu.se
[7] Department of Geology, University of Cincinnati, Geology/Physics Building, Cincinnati, OH 45221-0013, USA; huffwd@ucmail.uc.edu

As a relict of a Late Devonian bolide impact, Europe's largest impact structure in the Siljan district of central Sweden represents an important puzzle piece for reconstructing the Early Palaeozoic history at the western margin of Baltica. Around its central uplift of more than 30 km in diameter, late Tremadocian through late Silurian strata were preserved in a ring-shaped depression from post-impact erosion. In this "Siljan Ring" exposures are limited, and hence drill cores are important for reconstructing the complex geologic evolution of this area.

The stratigraphy investigated in four core sections (upper Tremadocian – Wenlock) provides information about different facies belts which are likely related to the Ordovician – Silurian foreland basin development at the western shelf of Baltica. A large set of data allows reconstruction of changes in level-bottom ecosystems, relative sea level and palaeoclimate. For example, Ordovician palaeokarst development at certain levels can be correlated to other parts of Baltica and therefore suggests subaerial exposure of the Baltoscandian basin during major sea-level lowstands. K-bentonites serve as excellent chronostratigraphic time-lines in the stratigraphic framework. Numerous volcanic ash beds recorded in deeper settings reflect multiple eruptions related to the Kinnekulle and Osmundsberget K-bentonites and lead to a higher resolution of the volcanic record.

During the late Middle Ordovician, the Siljan area was some 100 km away from the Caledonian front and affected by the tectonic movements to the west; the Caledonian forebulge reached the western region of the ring and a backbulge basin formed on the shelf to the east. In the early Silurian, the forebulge moved further to the west due to supracrustal loading by Caledonian thrust sheets and a backbulge basin filled by a thick siliciclastic succession formed in the western part of the 'Siljan Ring'. The progradation of a delta system in the upper part of this succession reflects a regression in an overall subsiding basin, possibly due to a global sea-level drop during the Sheinwoodian (early Wenlock) glaciation exposing the forebulge area to the west. Biomarker and geochemical data of the Silurian siliciclastics reflect deposition in a wide range of lacustrine to brackish and marine environments and support deposition in a backbulge basin developed in the eastern part of the Caledonian foreland basin system.

δ13C chemostratigraphy in the late Tremadocian through early Katian (Ordovician) carbonate succession of the Siljan district, Central Sweden

Oliver Lehnert[1,2], Guido Meinhold[3], Rongchang Wu[2], Mikael Calner[2] and Michael M. Joachimski[1]

1 GeoZentrum Nordbayern, Lithosphere Dynamics, University of Erlangen-Nürnberg, Schlossgarten 5, D-91054, Erlangen, Germany; oliver.lehnert@fau.de, michael.joachimski@fau.de
[2] Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden; Mikael.Calner@geol.lu.se, Oliver.Lehnert@geol.lu.se, Rongchang.Wu@geol.lu.se.
[3] Geowissenschaftliches Zentrum der Universität Göttingen, Abteilung Sedimentologie/ Umweltgeologie, Goldschmidtstraße 3, D-37077 Göttingen, Germany; guido.meinhold@geo.uni-goettingen.de

Based on $\delta^{13}C$ data from two drillcores in the Late Devonian Siljan impact crater, we present a first continuous carbon isotope record ranging from the Late Tremadocian to the early Katian of central Sweden. The densely sampled Lower–Middle Ordovician succession in the Mora 001 core (127 samples) overlaps with the record from the Middle–early Upper Ordovician strata in the Solberga 1 core (210 samples). Late Tremadocian and Floian units are extremely condensed and contain large stratigraphic gaps. Multiple hardgrounds, sometimes with minor karstic overprint, imply times of erosion and/or non-deposition. Like in other parts of Sweden, the Dapingian and Darriwilian succession is characterised by a relatively complete sedimentary record and low sedimentation rates.

There is a Late Tremadocian positive $\delta^{13}C$ excursion, which needs to be dated by conodonts, followed by the known long-term rise of $\delta^{13}C$ values during the Floian and Dapingian, culminating in the uppermost part of the Latorp and basal part of the Lanna Formation. Then, values decrease towards the Lower Darriwilian during the deposition of the lower Täljsten interval displaying a negative $\delta^{13}C$ excursion that is observed in various sections on Baltica. In our $\delta^{13}C$ analysis, this negative shift is termed as the Darriwilian negative isotopic carbon excursion (DNICE, minimum $\delta^{13}C$ value 0.23‰), which represents a characteristic intrabasinal chemostratigraphic marker and includes the most negative $\delta^{13}C$ values measured in the Darriwilian $\delta^{13}C$ curves of Baltoscandia. It is not so obvious in the published records of pre-MDICE strata from Laurentia (including the Argentine Precordillera) and South China.

In the upper transgressive part of the Täljsten interval, $\delta^{13}C$ values start to rise and shift into the expanded middle Darriwilian isotopic carbon excursion (MDICE, maximum $\delta^{13}C$ value 1.84‰). The MDICE is well developed and displays a tripartite subdivision in its peak interval, which has been observed also in the Tingskullen core from northern Öland. The deposition of the upper Holen Formation through the top of the interval including the Skarlöv, Seby and Folkslunda limestones spans the peak interval of the MDICE comprising three smaller "positive excursions" separated by two small "negative excursions". Between the pronounced positive excursions of the MDICE and the GICE, the latter located in the Freberga Formation, there are two smaller positive excursions which have to be investigated for their potential to correlate on an intrabasinal scale. For example, in some Sandbian sections in the Eastern Baltic area there are also some less pronounced excursions. The highest $\delta^{13}C$ value of GICE is 2.10‰. The KOPE $\delta^{13}C$ excursion is at the transition of the Freberga Formation to the Slandrom Formation and within the latter unit reflected by a maximum $\delta^{13}C$ value of 1.07‰. Its falling limb is partly cut off by the basal fault of a major fault zone in the Solberga 1 core.

Allogenic succession and its environmental controls in Late Ordovician reefs of the Xiazhen Formation at Zhuzhai, southeast China

***Qijian Li*[1]*, Wolfgang Kiessling*[1] *and Yue Li*[2]**

[1] *GeoZentrum Nordbayern, Section Palaeoenviromental Research, University of Erlangen-Nürnberg, Erlangen, Germany; qijianli@hotmail.com, wolfgang.kiessling@ fau.de*
[2] *Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing, People's Republic of China; yueli@nigpas.ac.cn*

Various Late Ordovician (late Katian) reef complexes are reported from the border area between the Jiangxi and Zhejiang provinces of southeast China (Bian *et al.* 1996). One of the best-known examples of low-relief coral–stromatoporoid reefs is exposed in Zhuzhai (Yushan, Jiangxi). The lower part of the Xiazhen Formation here contains two main reefal units with a total thickness of 7.4 m. The reefs are metazoan-dominated and most reef builders are in growth position. Based on detailed line transects we provide the first quantitative assessment of framework density and paleontological data from these reefs. Stromatoporoids, tabulate and rugose corals constitute the framework and cover 44–53% of the reef. Abundant stromatoporoids dominate the lower reefal unit (22.4–31.2%). Tabulate corals are the main reef builders (reaching up to 49.4%) in the second unit where stromatoporoids are relatively rare (< 2%). A vertical succession from a *Plasmoporella–Clathrodictyon* community in the lower unit to an *Agetolities–Catenipora* community in the upper unit is evident. Compared to stromatoporoids, tabulate corals show a higher tolerance to turbidity and flourished in the more muddy facies of the upper unit. This allogenic succession between the two units was probably driven by the increasing terrestrial input with northwestward expansion of the Cathaysian Land. Then the ongoing Cathaysian orogeny led to a short-term exposure of the sea floor in the studied area, which terminated the reef growth.

Bian, L.Z., Fang, Y.T. & Huang, Z.C., 1996. On the types of Late Ordovician reefs and their characteristics in the neighbouring regions of Zhejiang and Jiangxi Provinces, South China. *In:* Fan, J.S. (ed). *The ancient organic reefs of China and their relations to oil and ga*s. Marine Press, Beijing, 54–75. [in Chinese]

Mollusk surges in the lower – middle Darriwilian (Middle Ordovician) of Sweden

Anders Lindskog and Mats E. Eriksson

Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden; anders.lindskog@geol.lu.se, mats.eriksson@geol.lu.se

Apart from the scattered, large cephalopod conchs that have given the rock type its name, mollusk fossils are relatively rare in the Middle Ordovician (Dapingian – Darriwilian) 'orthoceratite limestone' of Sweden. However, an interval in the lower – middle Darriwilian stands out as being unusually rich in various types of mollusks. At Kinnekulle, south-central Sweden, gastropods become relatively abundant close to the lower Darriwilian Volkhov – Kunda Baltoscandian Stage boundary, and their numbers increase significantly into the Kundan. This increase is most apparent in the microscopic (meiofaunal?) realm. A distinct peak in abundance is seen in and around the 'Täljsten', an interval of rocks long known for its deviant lithologic properties and unusually rich fossil fauna, straddling the boundary between the lower and middle Kunda (close to the Dw1 – Dw2 boundary). In acid-insoluble microfossil residues from this interval, the abundance of microgastropod steinkerns is typically on the order of tens of thousands – and sometimes more than a hundred thousand – specimens per kilogram of rock. Hyoliths, which are otherwise exceptionally rare, are also relatively abundant in the 'Täljsten', as are putative bivalves. Moreover, from a macroscopic perspective, the beds enclosing the 'Täljsten' are noticeably enriched in cephalopod conchs. Gastropods and other small mollusks become relatively rare again in the upper half of the Kundan. Point counting of skeletal grains in thin sections reveals that the relative abundance of gastropods fluctuates in a pulse-like, possibly cyclic, manner throughout the studied succession. Comparison to the overall paleontologic and sedimentologic development suggests a correlation to sea level, and thus that gastropod abundance can be used as a proxy for relative water depth. The highest abundances are associated with inferred lowstand intervals. Closely similar abundance patterns are observed also in coeval successions in Skåne, southernmost Sweden, and on the island of Öland in the Baltic Sea, suggesting that the increase in mollusks was a geographically widespread phenomenon. From a global perspective, these mollusk-rich beds coincide with the main phase of the Great Ordovician Biodiversification Event, a time of exceptional continental submergence, widespread volcanic activity, and an enhanced influx of extraterrestrial matter to Earth. A better understanding of the links between faunal and sedimentary dynamics may provide key information about the environmental development during this eventful time in Earth history.

Enhanced concentrations of extraterrestrial chromite in Middle Ordovician strata at Lynna River, northwestern Russia

Anders Lindskog[1], Birger Schmitz[2], Anders Cronholm[2] and Andrei Dronov[3]

[1] *Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden; anders.lindskog@geol.lu.se*
[2] *Department of Physics, Lund University, P.O. Box 118, SE-221 00 Lund, Sweden; birger.schmitz@nuclear.lu.se, anders.cronholm@nuclear.lu.se*
[3] *Institute of Geology, Russian Academy of Sciences, Pyzhevsky per. 7, Moscow, 119017, Russia; dronov@ginras.ru*

Several fossil ordinary (L-)chondritic meteorites have been found in c. 467 Ma Middle Ordovician (Darriwilian, Kunda Baltoscandian Stage) 'orthoceratite limestone' in Sweden, and studies have shown that coeval strata, both in Sweden and abroad, host anomalously high concentrations of sediment-dispersed chromite grains with typical ordinary chondritic composition (extraterrestrial chromite, EC). These findings have been interpreted as resulting from a temporarily enhanced influx of extraterrestrial matter following the catastrophic disruption of the L-chondrite parent body in the asteroid belt close to this time. We investigated the abundance and stratigraphic distribution of sediment-dispersed EC grains (>63 µm) in limestone⁄marl beds at Lynna River, St. Petersburg region, northwestern Russia. Three samples from beds around the boundary between the Volkhov (BII) and Kunda (BIII) Baltoscandian stages, which coincides with the boundary between the *Asaphus lepidurus* and *Asaphus expansus* trilobite zones, yielded only two EC grains in 38.2 kg of rock (average 0.05 grains kg^{-1}). Five samples from a stratigraphically higher-lying interval, across the boundary between the *Asaphus expansus* and *Asaphus raniceps* trilobite zones ($BIII_{\alpha}-BIII_{\beta}$ boundary), yielded a total of 496 EC grains in 65.5 kg of rock (average 7.6 EC grains kg^{-1}, maximum 10.2 grains kg^{-1}). This stratigraphic distribution of EC grains agrees well with those at previously studied localities in Sweden and China, as do the overall chemical characteristics of the grains. The grain concentrations in the most EC-rich beds at Lynna River are two to three times higher than at the other localities. This is possibly due to the combined effect of a relatively high-energy (tempestite) depositional environment and large-scale sea-level dynamics. In the most enriched beds, EC grains are typically c. 50 times more abundant than terrestrial chrome spinel and about as common as ilmenite (*sensu lato*), being outnumbered only by quartz. The general lack of EC grains in the stratigraphically lower-lying sample interval likely reflects that these beds formed before the disruption of the L-chondrite parent body (or before this event left a conspicuous enough trace in the geologic record here on Earth). The collective results indicate that all or most of the EC grains in the overlying enriched interval stem from the disruption of the L-chondrite parent body, and that there indeed was a significant increase in the flux of ordinary chondritic debris to Earth in the wake of this event.

Palynology through the early Wenlock Ireviken Event

Rhian Llewellyn

School of Earth & Environmental Sciences, University of Portsmouth, Burnaby Building, Burnaby Road, Portsmouth, PO1 3QL, UK; rhian.llewellyn@port.ac.uk

The lower part of the Sheinwoodian (lower Wenlock, Silurian) is well known for its major positive carbon isotope excursion and extinction events, affecting in particular the graptolites and conodonts.

The temporal relationship between the isotope excursion, associated environmental change and the extinction events is the subject of much debate. The aim of this project is to conduct a high resolution palynological study through the Sheinwoodian of Buttington Quarry, Wales, in order to establish the relative timing of the graptolite extinction with respect to the carbon isotope excursion and to establish the impact of the associated environmental changes on the microplankton.

This study focuses on chitinozoans and acritarchs. A high resolution chitinozoan biostratigraphy of the section has been established to complement the graptolite biostratigraphy of the section (Loydell *et al.* 2014). The base of the measured section is within the *margaritana* chitinozoan Biozone (as previously reported by Mullins & Loydell 2002). The FADs of the biozonal indices *Cingulochitina bouniensis* and *Salopochitina bella* are recorded from successive higher stratigraphic levels within the section.

Acritarchs are particularly valuable in palaeoenvironmental studies – different morphotypes reflect, in particular, distance from the shore and have been used successfully as proxies for sea-level change (e.g. Stricanne *et al.* 2006). For the ongoing second stage of this study, quantitative studies revealing relative abundance of the different morphotypes will be complemented by detailed analysis of environmentally diagnostic characters such as number and length of processes. Particular attention will be paid to acritarch assemblages from levels where rapid and major fluctuations in the $\delta^{13}C_{carb}$ values are recorded (see isotope curve presented by Loydell *et al.* 2014).

Loydell, D.K., Frýda, J., Butcher, A. & Loveridge, R.F., 2014. A new high-resolution $\delta^{13}C_{carb}$ isotope curve through the lower Wenlock Series of Buttington Quarry, Wales. *GFF*. doi:10.1080/11035897.2013.865668.

Mullins, G.L. & Loydell, D.K. 2002. Integrated lower Silurian chitinozoan and graptolite biostratigraphy of Buttington Brick Pit, Wales. *Geological Magazine*, 139, 89–96.

Stricanne, L., Munnecke, A. & Pross, J., 2006. Assessing mechanisms of environmental change: Palynological signals across the Late Ludlow (Silurian) positive isotope excursion ($\delta^{13}C$, $\delta^{18}O$) on Gotland, Sweden. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 230, 1–31.

Significance of discontinuity surfaces in a subtidal-dominated carbonate succession: the end-Ordovician (Hirnantian) Ellis Bay Formation, Anticosti Island, eastern Canada

Alain Mauviel and André Desrochers

Department of Earth Sciences, University of Ottawa, Ontario, K1N 6N5, Canada; amauv097@uottawa.ca, andre.desrochers@uottawa.ca

The superbly exposed, tectonically undeformed, Ordovician-Silurian (O/S) carbonate succession exposed on Anticosti Island in the Gulf of St. Lawrence was deposited south of the paleoequator on an active foreland basin along the eastern margin of Laurentia. Abundant ice conditions on the globe at the end-Ordovician and the resulting high-amplitude eustasy should have left distinctive stratigraphic imprints on paleotropical carbonate ramps. Previous workers described the Anticosti succession as a complete record of marine carbonate sedimentation that never reached intertidal or supratidal facies suggesting that depositional conditions were entirely subtidal. Discontinuity surfaces are common in the Anticosti succession, but their significance is poorly understood. Using sequence stratigraphic concepts, we examined (including petrographic, CL, SEM and stable isotope work) the distribution of diagenetic and depositional features associated with a regional discontinuity surface capping the oncolitic and reefal subtidal limestones at the top of the end-Ordovician (Late Hirnantian) Ellis Bay Formation on Anticosti Island. Our observations allow us to decipher a complex diagenetic and depositional scenario associated with this discontinuity surface including: i) an early meteoric diagenetic stage following subaerial exposure recorded below the discontinuity surface (e.g. small karstic cavities, vadose crystal silt, isotopic signature); ii) a shoreline ravinement stage during the initial transgression recorded at, or above, the discontinuity surface (e.g. irregular erosional relief, encrusting organisms, pebble lag); and iii) a rapid drowning stage during the maximum transgression recorded at, or above, the discontinuity surface (e.g. pyritic hardground, borings, glauconite lag). Our study suggests that discontinuity surfaces may record periods of subaerial exposure and meteoric diagenesis in spite of the apparent absence of intertidal or supratidal facies in a succession. Our study suggests also that "ice-house" carbonate platforms, such as the Ellis Bay carbonate ramp, are influenced by high-amplitude, rapid falls and rises in sea level, resulting in subtidal-dominated sequences separated by discrete subaerial exposure surfaces.

A New Date for the 'Kalkberg' K-Bentonite, and the Calibration of the Silurian – Devonian Boundary

Neo E.B. McAdams[1], Mark D. Schmitz[2], Mark A. Kleffner[3], James R. Ebert[4] and Bradley D. Cramer[5]

[1] *University of Iowa, Iowa City, Iowa 52242, USA; neo-buengermcadams@uiowa.edu*
[2] *Boise State University, Boise, Idaho 83725, USA; markschmitz@boisestate.edu*
[3] *The Ohio State University at Lima, Lima, Ohio 45804, USA; kleffner.1@osu.edu*
[4] *SUNY College at Oneonta, Oneonta, New York 13820, USA; James.Ebert@oneonta.edu*
[5] *University of Iowa, Iowa City, Iowa 52242, USA; bradley-cramer@uiowa.edu*

The 'Kalkberg' K-bentonite (KKB), which was originally described from the Kalkberg Formation of the Helderberg Group, in Cherry Valley, New York State, provides the radioisotopic date which is stratigraphically closest to the Silurian – Devonian boundary. It was dated at 415.48 ±2.71 Ma, and said to occur in the early Lochkovian *Icriodus* (now *Caudicriodus*) *woschmidti* conodont zone (Tucker *et al.* 1998). However, the reported age of the bentonite, the formation it is assigned to, and the biostratigraphic zonation of the surrounding strata are problematic in light of new, more precise dating techniques and improved litho- and biostratigraphy. New lithostratigraphic information indicates that the KKB falls in the stratigraphically overlying New Scotland Formation of the Helderberg Group (Ebert *et al.* 2007). New conodont samples bracketing the KKB returned very poor yields, which included no biostratigraphically diagnostic taxa. However, chitinozoan biostratigraphy shows that the New Scotland Formation is middle Lochkovian in age (Bevington *et al.* 2010). We have analyzed the KKB using chemical abrasion-isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS) and the EARTHTIME U-Pb tracer (ET535 spike), and utilized new biostratigraphic information to more precisely correlate its age. This information will ultimately help us to quantify uncertainties in the calibration of the Silurian – Devonian boundary.

Bevington, K.S., Ebert, J.R. & Dufka, P., 2010 Early Devonian (Lochkovian) chitinozoan biostratigraphy of the lower Helderberg Group, Appalachian Basin, New York State and the age of the "Kalkberg" K-bentonite. *Geological Society of America Abstracts with Programs*, 42, 136.

Ebert, J.R., Johnson, E., Grimes, A., Routh, R., Pechenik, N., McCredy, R. & Bowler, J., 2007. The Kalkberg Formation (Helderberg Group, L. Dev., Lochkovian) at Cherry Valley, New York Is Actually New Scotland – Preliminary Results of Sedimentologic and Stratigraphic Investigations. *Geological Society of America Abstracts with Programs*, 39, 60.

Tucker, R.D., Bradley, D.C., Ver Straeten, C.A., Harris, A.G., Ebert, J.R. & McCutcheon, S.R., 1998. New U–Pb zircon ages and the duration and divison of Devonian time. *Earth and Planetary Science Letters*, 158, 175–186.

An upper Silurian coral-stromatoporoid biostrome at Katri, western Estonia: a combined palaeoecological study of stromatoporoids and corals

Mari-Ann Mõtus[1] *and Steve Kershaw*[2]

[1] *Institute of Geology at Tallinn Technical University, Ehitajate tee 5, 19086 Tallinn, Estonia; mari-ann.motus@ttu.ee*
[2] *Brunel University, Institute for the Environment, Uxbridge UB8 3PH, UK; stephen.kershaw@brunel.ac.uk*

A coral-stromatoporoid biostrome at Katri in western Estonia, of middle Ludlow age, is partly exposed in a coastal site ca. 1 m high and 150 m long. The biostrome has 5 layers of skeletal carbonate, here divided into Facies 1 (grainstone-packstone, layers 1, 3 and 5) and Facies 2 (wackestone, layers 2 & 4). Severe pressure solution prevents clear distinction of original sedimentary relationships and morphologies of the abundant stromatoporoids and tabulate and rugose corals which constructed the biostrome. However, Facies 1 & 2 have major faunal differences. Facies 1 is rich in "*Stromatopora*" *bekkeri* and *Plectostroma scaniense* as low to high domical stromatoporoids up to ca. 30 cm basal length; and tabulate *Favosites forbesi* in bulbous to high domical form up to ca. 25 cm basal length. In Facies 2, all three taxa are present, but much smaller and less common. In Facies 2, the most abundant stromatoporoid is laminar *Syringostromella borealis* up to 30 cm basal length; the most abundant coral is erect branching *Laceripora cribrosa*, as scattered fragments up to 20 cm long; neither taxon occurs in Facies 1. Six other stromatoporoid taxa, 5 other tabulate and 6 rugosan taxa occur uncommonly in the biostrome, mostly in both facies. The Katri biostrome is slightly younger but similar facies to those in the middle Ludlow Hemse Group on Gotland ca. 250 km to WSW; however, *Clathrodictyon mohicanum* and *Lophiostroma schmidtii*, abundant on Gotland, are missing in Katri. In Gotland biostromes, all stromatoporoid taxa occur together, contrasting facies separation in Katri. Corals are abundant in the Gotland biostromes, but taxonomy awaits full study. Overall, the Katri and Gotland deposits indicate wide distribution of stromatoporoid and coral biostromes in a large shallow marine carbonate platform. Stromatoporoid assemblage differences indicate either that environmental restrictions prevented their uniform distribution, or different taxa had variable abilities to propagate across the sea floor in this large area.

The Early Palaeozoic in motion

Axel Munnecke

GeoZentrum Nordbayern, Fachgruppe Paläoumwelt, Universität Erlangen-Nürnberg, Loewenichstrasse 28, 91054 Erlangen, Germany; Axel.Munnecke@fau.de

In the past two decades many researchers from different disciplines directed their focus to the Early Palaeozoic. Special attention was attracted by the Great Ordovician Biodiversification Event, the end-Ordovician mass-extinction, and the strong, short-lived $\delta^{13}C$ and $\delta^{18}O$ excursions of the Late Ordovician and Silurian. Numerous studies where published, documenting high-resolution sea-level curves as well as geochemical and palaeontological data from almost all over the globe. Nevertheless, the steering mechanisms for these events are still highly controversial, and a general consensus is lacking. For example, a simple cause-and-effect relationship between glacial cooling and extinction no longer accounts for the anomalous geological and geochemical signatures that characterize the end-Ordovician event. As the stratigraphic resolution is continuously increasing new models evolve and try to combine processes such as changing oceanic circulation, shifts of latitudinal temperature gradients, migrating climatic belts, atmospheric CO_2 content, changes in continental weathering and/or wind-derived nutrient input, rapid eustatic sea-level changes, or deep-ocean anoxia to explain the Early Palaeozoic world. This talk will give a brief summary of the recent development in this field.

Lower Telychian ironstone deposits in the Podlasie Basin, NE Poland: $\delta^{13}C$ and conodont stratigraphy

Axel Munnecke[1]*, Emilia Jarochowska*[1]*, Peep Männik*[2]*, Thijs R.A.Vandenbroucke*[3]*, Olle Hints*[4]*, Nicole Hartinger*[1]*, Oliver Lehnert*[5]*, Warren Huff*[6]*, Wojciech Kozłowski*[7] *and Poul Emsbo*[8]

[1] *GeoZentrum Nordbayern, Fachgruppe Paläoumwelt, Universität Erlangen-Nürnberg, Loewenichstr. 28, 91054 Erlangen, Germany; Axel.Munnecke@fau.de*
[2] *Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, Tallinn, 19086, Estonia*
[3] *Université Lille 1 - Sciences et Technologies, UMR 8217 du CNRS: Géosystèmes, Avenue Paul Langevin – bât. SN5, 59655 Villeneuve d'Ascq cedex, France*
[4] *Institute of Geology, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia*
[5] *GeoZentrum Nordbayern, Universität Erlangen-Nürnberg, Schloßgarten 5, 91054, Erlangen, Germany*
[6] *Department of Geology, University of Cincinnati, 500 Geology/Physics Building, Cincinnati, OH, 45221-0013, USA*
[7] *Institute of Geology, University of Warsaw, Al. Żwirki i Wigury 93, 02089 Warsaw, Poland*
[8] *US Geological Survey, UBox 25046, MS 973, Denver, Colorado 80225, United States*

The lower Telychian is marked by widespread ironstone deposits associated with a positive stable carbon isotope excursion (Munnecke & Männik 2009; McLaughlin *et al.* 2012), occurring within the *Pterospathodus eopennatus* conodont Superzone in Baltica and Laurentia (Munnecke & Männik 2009; Sullivan *et al.* 2014), and possibly associated with the Valgu (end-*irregularis*) Event defined as a drop in conodont abundance and temporal disappearance or extinction of some conodont taxa, taking place within this Superzone (Männik 2005). We present data from the Narew IG-2 core in the Podlasie Basin, NE Poland, recording the lower Telychian in marly mudstone to wackestone facies of an open shelf setting. The iron-enriched interval is characterized by two levels of goethite oolites, and its upper part – by variegated, red and yellow bioturbated marl with limonite concretions. It coincides with an abrupt drop in total gamma-ray and elevated $\delta^{13}C_{carb}$ values reaching +1.5‰ above the background level. Preliminary conodont extractions yielded *P. amorphognathoides angulatus* and *Ozarkodina polinclinata estonica* from the upper part of the ironstone interval, indicating a younger age (*P. amorphognathoides angulatus* Zone) than the Valgu Event, suggesting possible correlation with coeval condensed strata in Laurentia, and associated with flooding following the sea-level lowstand during the Valgu Event (McLaughlin *et al.* 2012; Sullivan *et al.* 2014).

Männik, P., 2005. Early Telychian Valgu Event – some preliminary data from Estonia. *Evolution of Life on the Earth: Proceedings of the III International Symposium. Tomsk State University*, 134–137.

McLaughlin, P.I., et al., 2012. Beyond black shales: The sedimentary and stable isotope records of oceanic anoxic events in a dominantly oxic basin (Silurian; Appalachian Basin, USA). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 367–368, 153–177.

Munnecke, A. & Männik, P. 2009. New biostratigraphic and chemostratigraphic data from the Chicotte Formation (Llandovery, Anticosti Island, Laurentia) compared with the Viki core (Estonia, Baltica). *Estonian Journal of Earth Sciences*, 58, 159–169.

Sullivan, N.B., Brett, C.E., McLaughlin, P.I., Kleffner, M.A. & Cramer, B.D., 2014 Correlation of the Waco Member of the Alger Shale Formation (Silurian; Llandovery; Telychian) in east-central Kentucky and south-central Ohio. *GFF*. doi:10.1080/11035897.2013.876657.

Interpretation of the early Palaeozoic climate changes based on the tropical $\delta^{18}O$ variations

Elise Nardin

Géosciences Environnement Toulouse, Observatoire Midi-Pyrénées, CNRS, 14 av. E. Belin, 31400 Toulouse, France; elise.nardin@get.obs-mip.fr

The hypothesis of a long-term greenhouse (no continental glaciers) period during the early Palaeozoic has been recently redesigned as an Ordovician long-term cooling trend leading to a Hirnantian–Middle Silurian glacial period, based on global rise in $\delta^{18}O$, general increase in the pole-equator climatic gradient, punctual glaciological markers, supposed glacioeustatic sea-level changes and modelling studies. Uncertainties concern six icehouse periods (presence of continental glaciers) in the late Floian, mid Darriwilian, early-mid Katian, early Sheinwoodian, mid Homerian, and late Ludfordian (eustatic changes but no glaciogenic record) and the hypothetical warmer late Katian Boda Event.

The purposes of this study are to validate the supposed cold and warm periods (with absence of glaciogenic record), to distinguish local from global events, and to evaluate the timing and the tempo of the climate changes (onsets and offsets), using other proxies such as extensive databases of $\delta^{18}O$ measurements on carbonate and apatite, and spatio-temporal inventories of the $\delta^{13}C$ excursions and of the biological and stratigraphic events for the Cambrian to Silurian period.

Preliminary results reassert the Cambrian-Katian increase and the Silurian plateau for both tropical $\delta^{18}O_{carb}$ and $\delta^{18}O_{phos}$. Positive peaks of $\delta^{18}O$ confirm the Hirnantian-Rhuddanian (glaciogenic evidence), Sheinwoodian and Homerian (bioevents and sea-level fall), as global glacial events. The Aeronian glacial period is not highlighted by the tropical $\delta^{18}O$ signals, suggesting its local scale, as well as all the other inferred climatic events. Reconstructed temperature using both $\delta^{18}O$ signals could match with icehouse periods during the Sandbian-Aeronian and the Sheinwoodian-early Ludfordian intervals. The late Katian plateau of moderate to high $\delta^{18}O$ values would advocate for a relatively cold period during the Boda Event.

Time series analyses may suggest climate changes during the late Floian and the early Darriwilian shown by large amplitudes in $\delta^{18}O$ values. Older periods are characterized by low but relatively rare $\delta^{18}O$ values, implying relatively warm climate. Spectral analyses might indicate combined influence of obliquity and eccentricity processes driving $\delta^{18}O$ changes during the Late Ordovician and the Silurian.

REE spectra of apatite of lingulate shells from Cambrian-Ordovician boundary beds of the Baltic Basin

Jüri Nemliher[1] *and Kadri Mikkelsaar*[1,2]

[1] *Institute of Geology at Tallinn Technical University, Ehitajate tee 5, 19086 Tallinn, Estonia; jyri.nemliher@ttu.ee*
[2] *Steiger OÜ, Männiku tee 104, Tallinn 11216, Estonia; kadri.mikkelsaar@gmail.com*

A set of samples (altogether 17) of Cambrian to Lower Ordovician lingulated brachiopod shell apatite from the Lava section in the east to Hiiumaa (K 31 drillcore) in the west and Tartu (drillcore 453) in the south was studied by ICP-MS (Thermo Scientific X Series2) using standard technique. The species used were *Ungula convexa*, *U. ingrica*, *Schmidtites celatus* and *Obolus ruchini O. apollinis*, originating from Sablinka, Ülgase, Kallavere and Tosna sections. As a comparative material, the apatite of shells of Recent lingulates *Lingula anatina* (the Pacific, near Cebu Island) and *Discinisca tenuis* (the Atlantic, near Lüderitz) were used.

The content of ΣREE in the apatite of shells of Recent lingulates falls into range of 540 to 5400 ppb, being systematically higher for *D. tenuis* from Atlantic. We explain this phenomenon by considerably higher content of organic matter in the shells of *L. anatina*.

REE spectrums of the apatite of shells of Recent lingulates correlate 1:1; exceptionally, the content of La and Tm is higher in the apatite of the studied *L. anatina* shells. We attribute all REE elements content to being substituted into apatite lattice, replacing Ca^{2+} in its crystal structure. Here, the "excess" (difference from 1:1 function) of La and Tm (about 30 and 10%, respectively) in the material from Cebu Strait is explained by the influence of volcanic activity at the Philippine active margin vs passive margin of the Atlantic.

ΣREE content in the apatite of shells of studied fossil lingulates was recorded to be ~10^5 times higher than in the Recent ones. The rate of enrichment in ΣREE was found to be more or less random, probably depending on the age of formation and/or depth of origin. Thus, most concentrated in ΣREE samples recorded of Middle Cambrian age (Sablinka) and the westernmost region of studied area (Hiiumaa) – 0.412 and 0.769 wt%, respectively. Most likely, the rate of substitution of REE into apatite crystal lattice depends on the degree of diagenetic maturation of shell biomineral component. On the other hand, during post mortem development, obviously a part of apatite is added into fossil's volume, being in equilibrium with pore-space solutions, i.e. facies-dependent, i.e. abiogenic.

REE spectrums of apatite of shells of fossil lingulates, normalized vs. Recent, display rather similarity with the Recent ones of the Atlantic. Basically, spectrums of REE of studied fossil apatites are slightly enriched in light REE; the main pattern, however, is similar to those coming from the Atlantic. Different behavior in relative content of both La and Tm, detected. Here it is explained by achievement of equilibrium of primarily secreted bioapatite with post mortem/diagenetic environment in the conditions of ancient passive margin of the Obolus-Sea. Note that $Ca/REE_{pattern}$ ratio should be primarily predicted by (large-scale tectonic) situation of the environment of ancient lingulates water chemistry.

Within the distribution pattern of REE metals in the apatite of fossil lingulates, Eu has been found to concentrate/deplete most volatile. This phenomenon, however, does not correlate with the pattern of ΣREE or the age of formation.

Our overall conclusion is that the content and spectra of REE bounded into phosphorous-bearing mineral apatite of fossil lingulate shells are informative and, most likely, have recorded the features of diagenetic history of the Cambro–Ordovician palaeo-sea deposits.

Global and regional diversity of Cambrian acritarchs

Hendrik Nowak, Claude Monnet, Thomas Servais and Thijs R.A. Vandenbroucke

CNRS-UMR 8217 Géosystèmes, Université Lille1, 59655 Villeneuve d'Ascq, France; hendrik.nowak@etudiant.univ-lille1.fr, claude.monnet@univ-lille1.fr, thomas.servais@univ-lille1.fr, thijs.vandenbroucke@univ-lille1.fr

In order to reconstruct the diversity of Cambrian acritarchs (*s.l.*) with modern quantitative methods, occurrence data sourced from 104 studies were compiled into a presence/absence database. This data pool now comprises more than 5000 records indicating the presence of over 700 species and about 170 genera throughout the Cambrian system. Various methods were applied to calculate global and regional taxonomic diversity indices and to test for documentation biases. To some extent, the evolution of the diversity of acritarchs is also a hypothetical proxy for phytoplankton diversity trends during the Cambrian.

The global total species diversity (the number of species present in a given stage) was low in the lowermost Cambrian, high between the Stages 3 and 5, again comparatively low in most of the Series 3 and the Furongian and reached a maximum in the Stage 10. The Stage 10 is marked by a high origination and extinction, and also by an abnormally high amount of singletons (taxa occurring in only one time bin). There is a small and not significant correlation between the number of studies per stage and the diversity, thus indicating a limited influence of monographic diversity. Normalised diversity (i.e. number of species ranging through a stage plus half the number of taxa originating and/or disappearing in that stage) peaks in the Stages 4 and 10. The genus diversity is somewhat similar to the species diversity, but with less pronounced changes and muted peaks in the Stages 3 and 10. The analysis of poly-cohorts for survivorship (percentage of taxa constituting the assemblage of a given stage still present in a later stage) and prenascence (percentage of taxa from a given stage already present in an earlier stage) does not show any abrupt changes in extinction/origination rates.

Baltica, parts of peri-Gondwana and Gondwana (including northern Africa, Avalonia, Iberia and Sardinia) and South China are currently the only regions with sufficient available records to warrant diversity analyses on a regional scale. The diversities of both species and genera on Baltica mostly mirror the global curves, as the latter are heavily influenced by the extensive data from this region. On the Gondwanan margin and South China, diversity is generally lower than on Baltica. The lower Cambrian diversity high is only evident on Baltica. The diversity curves from Baltica and Gondwana start to rise in the Jiangshanian before reaching their maximum in the Stage 10. While the differences between the regional and global curves suggest a certain biogeographical differentiation and a limited significance of global data for regional studies, the common extreme diversity peak in the uppermost Cambrian Stage 10 seems to mark a truly widespread, perhaps global, pattern.

Modelling the distribution and diversification of Ordovician – Silurian chitinozoans: CONOP approach to Baltoscandian data compilation

Liina Paluveer, Viiu Nestor, Jaak Nõlvak, Garmen Bauert and Olle Hints

Institute of Geology at Tallinn University of Technology, Ehitajate 5, 19086 Tallinn, Estonia; liina.paluveer@ttu.ee; viiu-kai.nestor@ttu.ee; jaak.nolvak@ttu.ee; garmen.bauert@ttu.ee; olle.hints@ttu.ee

Chitinozoans are among the most common and biostratigraphically useful microfossils in the Ordovician and Silurian marine rocks. The Baltoscandian record of chitinozoans is renowned by generally excellent preservation, well-elaborated biozonal schemes and some of the largest collections worldwide. In our previous studies (Hints *et al.* 2011; Paluveer *et al.* 2014) we compiled and analysed distributional data bases of the Ordovician and Silurian chitinozoans using quantitative stratigraphic approach with CONOP9. This method has proved very useful for automatic correlation as well as for high-resolution biodiversity analysis of large data sets (Sadler 2012; Goldman *et al.* 2013). The aim of this study is to extend this approach and combine Baltic Ordovician and Silurian data on chitinozoans into a single occurrence-level database and produce a best-fit quantitative stratigraphic model. The latter can then be used for providing new insights into the macroevolutionary patterns of this cryptic fossil group and its possible drivers, and assess the biostratigraphic value of individual species.

The compiled database contains ca 5500 productive samples and 30000 occurrence records of 340 taxa (including species yet to be formally described). The samples derive from 66 sections from Estonia, Latvia, Lithuania, Poland, and Kaliningrad region, characterizing different settings within the Baltoscandian paleobasin. A best-fit distribution and correlation model was created using computer-assisted numerical sequencing program CONOP9 (see Sadler 2012 for details), showing generally good correspondence with our previous results (Hints *et al.* 2010; Paluveer *et al.* 2014). In respect to biostratigraphy, the model revealed excellent to above-average fit of most conventional index species and, moreover, pointed to several taxa that could potentially be incorporated into the regional biozonal scheme. Only few zonal taxa, notably the Silurian *Margachitina margaritana*, showed large misfit values. The updated taxonomic richness curve suggests that chitinozoans thrived in Baltoscandia during the Darriwilian and Sandbian, when their standing diversity might have exceeded 40 species. A small crisis coincided with the basal Katian (GICE), followed by a major late Katian – Hirnantian decline and extinction, with ca 10 species crossing the system boundary. The Silurian diversity peaks in the Telychian and late Sheinwoodian – early Homerian reach ca 30 species. Notably the three-fold increase in the number of sections in the database, compared to Paluveer *et al.* (2013), extended this estimate only by few species. The main Silurian biotic crises for chitinozoans correspond to the Ireviken and Mulde events and associated environmental changes. However, the Lau Event is not clearly expressed in the current model and we suggest that it was less severe for chitinozoans compared to the Hirnantian, Ireviken and Mulde events.

Acknowledgements. This study is contribution to IGCP 591 and has been supported by the Estonian Research Council projects ETF9039, PUT378 and ERMAS.

Goldman, D., Bergström, S.M., Sheets, H.D. & Pantle, C., 2013. A CONOP9 composite taxon range chart for Ordovician conodonts from Baltoscandia: a framework for biostratigraphic correlation and maximum-likelihood biodiversity analyses. *GFF*, doi:10.1080/11035897.2013.809549.

Hints, O., Nõlvak, J., Paluveer, L. & Tammekänd, M., 2011. Conventional and CONOP9 approaches to biodiversity of Baltic Ordovician chitinozoans. *In:* Gutiérrez-Marco, J.C., Rábano, I. & García-Bellido, D. (eds). *Ordovician of the World*. Instituto Geológico y Minero de España, Madrid. Cuadernos del Museo Geominero, 14, 243–249.

Paluveer, L., Nestor, V. & Hints, O., 2014. Chitinozoan diversity in the East Baltic Silurian: first results of a quantitative stratigraphic approach with CONOP. *GFF*, doi:10.1080/11035897.2013.873987.

Sadler, P.M. 2012. Integrating carbon isotope excursions into automated stratigraphic correlation: an example from the Silurian of Baltica. *Bulletin of Geosciences*, 87, 681–694.

A new U–Pb zircon age and graptolite fauna for the Bellewstown Terrane, eastern Ireland, constrain Dunnage Zone correlations

Matthew Parkes[1], Brian McConnell[2], Quentin Crowley[3] and Adrian Rushton[4]

[1] *Natural History Museum, Merrion Street, Dublin 2, Ireland; mparkes@museum.ie*
[2] *Geological Survey of Ireland, Beggars Bush, Dublin 4, Ireland; brian.mcconnell@gsi.ie*
[3] *Department of Geology, School of Natural Sciences, Trinity College, Dublin 2, Ireland; crowleyq@tcd.ie*
[4] *Natural History Museum, Cromwell Road, London, SW7 5BD, UK; a.rushton@nhm.ac.uk*

The Bellewstown Terrane is an Ordovician volcanic arc fragment within the Iapetus suture zone of eastern Ireland, bounded to the north by the Slane Fault against the Grangegeeth Terrane, and to the south by the Lowther Lodge Fault against the Leinster Terrane. Early Ordovician slates and siltstones with slump breccies and coticules (Prioryland Formation) are overlain by an early to mid-Ordovician volcanic sequence (Hilltown Formation), a probable Darriwilian limestone (late Llanvirn Bellewstown Member) and the Sandbian Carnes Formation, comprising tuffaceous shales with a diverse fauna. The terrane is generally regarded as 'intra-Iapetus' in affinity, with a syn-volcanic early Ordovician shelly fauna that is neither Laurentian nor Gondwanan and a post-volcanic Sandbian fauna that is more typically Avalonian. The terrane has thus been compared to arc sequences in the Exploits Subzone of Newfoundland.

New quarry exposures within the Hilltown Formation reveal a graptolite fauna in shale overlying a felsic tuff. Zircons extracted from sand-grade tuff are exclusively prismatic and primary in appearance. U-Pb dating of the zircons by LA-ICP-MS (n=75) gives a 'TuffZirc' age of 474.1 +1.1-2.5 Ma (Floian: Arenig).

Characterisation of the new graptolite fauna reveals pendent *Didymograptus* with long slender siculae typical of the Llanvirn and distinct from the mid-Arenig types; diplograptids *Climacograptus* and *Pseudoclimacograptus* which appear around the base of the Darriwilian and *Nicholsonograptus fasciculatus*, a distinctive species that also occurs at or above the base of the Llanvirn. Overall, the fauna is consistent with the *artus* Biozone.

The new isotopic age for the tuff appears to contradict the graptolite faunal age data, but further fieldwork and collecting have been included a current drilling programme of two short boreholes in the critical interval. New data from this work and possible resolutions of age determinations will be presented and correlations between Bellewstown and other intra-Iapetan volcanic terranes will be suggested.

The Cotton Formation at Forbes, central New South Wales: a window into a Silurian deep-water environment

Ian G. Percival[1], Geoff Thomas[2] and Lawrence Sherwin[3]

[1] *Geological Survey of New South Wales, Londonderry, Australia; ian.percival@industry.nsw.gov.au*
[2] *Museum Victoria, Melbourne, Australia; fossilgt@gmail.com*
[3] *Geological Survey of New South Wales, Orange, Australia; lawrence.sherwin@trade.nsw.gov.au*

The early Silurian Cotton Formation is well exposed in a quarry at Cotton Hill, 11 km northwest of Forbes in central New South Wales. The predominant lithology is a deeply weathered off-white siliceous siltstone, extremely well-bedded and easily fissile, which preserves a diverse deep-water biota. Fossils include dendroids and graptoloids of the late Llandovery *Spirograptus guerichi* Zone, several species of trilobites, a small plectambonitoid brachiopod and a lingulate brachiopod, platyceratid gastropods, orthoceratoid nautiloids, ostracodes, hyolithids, a favositid coral (possibly allochthonous), sponges (represented by disaggregated spicules), and rare starfish and crinoids.

A palaeoecological study of the Cotton Formation has not previously been undertaken. The assemblage comprises pelagic, nektic and benthic components. A quantitative assessment of the biota is not possible, due to the lack of extensive bedding plane exposure, and the unrepresentative nature of fossil collections (often strongly biased towards trilobites) taken from rocks in the quarry. However, the fauna is sufficiently diverse and abundant to be documented qualitatively as an unusual, even rare, window into a Silurian deep-water environment. Apart from the echinoderms, the faunal assemblage of the Cotton Formation in the Cotton Hill quarry is analogous to that characterising the Malongulli Formation of the Molong Volcanic Belt in central NSW, and the Gunningbland Shale and the Jingerangle Formation in the Junee–Narromine Volcanic Belt to the west, all of which are Late Ordovician (late Eastonian to Bolindian, i.e. late Katian) in age. A comparable depositional environment is envisaged for the early Silurian Cotton Formation, interpreted as an outer shelf to upper slope setting in very calm, deep water below storm wave base. The trilobite exoskeletons in particular show minimal evidence of posthumous disruption by currents or scavengers. Amongst the trilobites, *Odontopleura* (*Sinespinaspis*) *markhami* is dominant, comprising about 99% of all trilobite remains in the Cotton Formation, whereas *Aulacopleura pogsoni* and *Raphiophorus sandfordi* are rare. The trilobites are confined to a thin layer within the quarry that largely lacks graptoloids, but which is rich in ostracodes and sponge spicules.

Benthic components of the fauna indicate that the ocean floor was oxygenated. The presence of starfish and crinoids, though rare, is especially interesting. Deep-water communities with starfish have previously been described from the late Silurian and Early Devonian of Australia (Strusz & Garratt 1999), specifically the Melbourne Trough in Victoria, where they are assigned to Benthic Assemblage 6. However, these occurrences are typically found in sandstone, with graptolites preserved in interbedded mudstones. The Cotton Formation biota differs in its pronounced association with sponges, reflecting (along with its Late Ordovician antecedents) a previously undescribed community variant.

Strusz, D.L. & Garratt, M.J., 1999. Australian communities. *In:* Boucot, A.J. & Lawson, J.D. (eds). *Paleocommunities – a case study from the Silurian and Lower Devonian*. Cambridge University Press, Cambridge, 177–199.

Faunal communities and biostratigraphy of the late Silurian Molong Limestone, central New South Wales

Ian G. Percival[1], *John Pickett*[1], *Michael Engelbretsen*[2], *David Mathieson*[2] *and John Farrell*[3]

[1] *Geological Survey of New South Wales, Londonderry, Australia; ian.percival@industry.nsw.gov.au, picketj@bigpond.net.au*
[2] *Biological Sciences, Macquarie University, North Ryde, Australia; mengelbretsen@hotmail.com, dmath@exemail.com.au*
[3] *jfarrell@pnc.com.au*

A 1550 m thick measured section through the late Silurian Molong Limestone at Foys Creek, immediately north of Molong in central New South Wales, yields significant biostratigraphic information. A precise age of 424.3 ± 1.8 Ma ($^{206}Pb/^{238}U$; using the Temora standard) was obtained by SHRIMP II analysis of zircons from a weathered tuff layer approximately 7 m thick interbedded with limestone in the middle part of the section. This constrains the maximum limit of the *Polygnathoides siluricus* conodont Zone of earliest Ludfordian age, the lower part of which is recognised 250 m above the tuff in a limestone bed that also yielded *Ancoradella ploeckensis*. This age is important in that it lies nearly medially within a 7 Myr gap separating radiometric dates in the early and late Silurian that were published in GTS2012 (Schmitz in Gradstein *et al.* 2012).

Much of the Molong Limestone is massive to thickly bedded and commonly only sparsely fossiliferous, with fossils concentrated at particular levels. One bed immediately underlying the tuff is characterised by a highly distinctive shallow water association dominated by large (~40 cm diameter) megalodontid bivalves provisionally assigned to *Megalomoidea*, associated with occasional trimerellide brachiopods and long-spired murchisonid gastropods. In the bed overlying the tuff, this assemblage has been entirely replaced by one with *Kirkidium*-like pentamerid brachiopods. Apart from some trilobites (*Sphaerexochus*) low in the section, the remainder of the Molong Limestone at Foys Creek is largely devoid of shelly fauna, with rugose (*Palaeophyllum*) and tabulate corals (sarculinid, favositids, halysitids) and stromatoporoid banks predominating. The interpreted environments extend from lower Benthic Assemblage 1 for the '*Megalomoidea*' shell bank, with mostly articulated and probably *in situ* bivalves, to lower BA 2 occupied by the stromatoporoid and coral mounds which may have acted as wave barriers. The close stratigraphic linkage of the '*Megalomoidea'* shell bank with the immediately overlying tuff bed and the absence of megalodontids from higher in the section imply a catastrophic local extinction event when volcanic ash smothered the shell bank.

Gradstein, F.M., Ogg, J.G., Schmitz, M.D. & Ogg, G.M., 2012. *The Geologic Time Scale 2012. Appendix 2: Radiometric ages used in GTS2012 (M.D. Schmitz).* Elsevier, Amsterdam.

The record of Phanerozoic Arthropod zooplankton and their trophic impact

Vincent Perrier, Mark Williams and David J. Siveter

Department of Geology, University of Leicester, University Road, Leicester, Leicester, LE1 7RH, UK; vp110@leicester.ac.uk; mri@leicester.ac.uk; djs@leicester.ac.uk

Arthropods are a major component of the marine zooplankton and likely have occupied this ecospace since the early Cambrian, co-evolving with several major plankton groups through the Phanerozoic. Examination of the fossil and molecular record of Phanerozoic arthropod zooplankton allows elucidation of the timing and strategies (e.g. preadaptation; planktonic larval stages) of major plankton colonisation events, and the feedbacks these events have elicited in marine plankton structure and food supply to the benthos including the development of suspension feeders. These data show that zooplankton have arisen independently across several arthropod groups, indicating the adaptability of the arthropod body plan to fundamental environmental change that includes intervals of prolonged ocean anoxia, and catastrophic collapses of the marine ecosystem.

Tipping-points in the Ordovician climate

Alexandre Pohl[1], Yannick Donnadieu[1], Guillaume Le Hir[2], Christophe Dumas[1], Jean-François Buoncristiani[3] and Emmanuelle Vennin[3]

[1] *Laboratoire des Sciences du Climat et de l'Environnement UMR 8212 - CNRS-CEA-UVSQ, CEA Saclay, Orme des Merisiers, 91191 Gif-sur-Yvette cedex, France; alexandre.pohl@lsce.ipsl.fr*
[2] *Institut de Physique du Globe de Paris, Université Paris7-Denis Diderot, 1 rue Jussieu, 75005 Paris, France*
[3] *Laboratoire Biogeosciences UMR/CNRS 6282, Université de Bourgogne, 6 Bd Gabriel, 21000 Dijon, France*

The Ordovician is a particular time in Earth history, since it has undergone the onset of extended ice-sheets under otherwise high CO_2 concentrations. A CO_2 drop is today envisaged to reconcile these data. To study the Ordovician climatic transition, we propose here an approach by numerical climate modelling. Sensitivity tests were lead with a general circulation model with coupled components for ocean, atmosphere and sea ice (FOAM, the Fast Ocean Atmosphere Model). A 3.5% weaker solar constant was set, and the influence of CO_2 concentration on climate was investigated between 2 times its preindustrial atmospheric level (1 PAL = 280 ppm) and 16× PAL. The experiments were conducted on 3 continental configurations at 470 Ma, 450 Ma and 430 Ma.

Contrary to previous studies that mostly used non-dynamic slab mixed-layer ocean models, we find that the temperature-CO_2 relationship is highly non-linear when ocean dynamics is taken into account. Two climatic modes are suddenly accessed as atmospheric forcing slowly decreases. For high CO_2 concentrations, a hot climate and absence of sea ice characterise the warm mode. For slightly lower values, climate enters a runaway icehouse marked by much colder temperatures and spread of sea ice. Hence, a slight CO_2 decrease could be enough to induce a sharp cooling. We show that the tipping-point is due to a strong climatic instability in the quasi-oceanic Ordovician Northern Hemisphere, and that the palaeogeographical evolution reduces this instability, thus delaying the tipping-point over geological time. The tipping-point is crossed between 12× PAL and 8× PAL at 470 Ma, between 8× PAL and 6× PAL at 450 Ma and between 4× PAL and 2× PAL at 430 Ma.

Modelling results were compared to the published $\delta^{18}O$ tropical sea-surface temperatures. During the Katian, the best match is obtained for 8× PAL (i.e. within the warm mode). During the Hirnantian, the best match is reached for 6× PAL, implying that the tipping-point was crossed during the glacial maximum. Our Katian CO_2 value is consistent with recently published estimates based on isotope fractionation between organic and inorganic carbon during photosynthesis (ε_p). For the Hirnantian, the published latitudinal temperature gradients inferred from the high-latitude micropaleontological data also suggest a maximum match for 6× PAL. FOAM was finally asynchronously coupled to an ice-sheet model (GRISLI, GRenoble Ice-Shelf and Land Ice) to investigate continental ice growth within the warm climatic mode during the Katian. The obtained ice-sheet volume is consistent with the $\Delta^{47}CO_2$ estimates reported in the literature.

Our study therefore proposes a new explanation for the sudden onset of the Hirnantian glacial maximum that does not require any sharp drop in CO_2. Our results furthermore support the onset of large ice-sheets before the Hirnantian.

Liquefaction-induced soft-sediment deformations in early Palaeozoic marine sediments of the Baltoscandian Basin: evidence for seismic shock or rapid deposition?

Kairi Põldsaar[1,2] and Leho Ainsaar[2]

[1] *Estonian Museum of Natural History, Lai 29, Tallinn, Estonia; kairi.poldsaar@ut.ee*
[2] *Department of Geology, University of Tartu, Ravila 14a, Tartu 50411, Estonia; leho.ainsaar@ut.ee*

Pervasive horizons of meter-scale soft-sediment deformation structures are found in two distinct Palaeozoic intervals of siliciclastic marine sediments in NW Estonia. The deformations occur in the early Darriwilian (Middle Ordovician) shallow marine carbonate-rich sandstone facies (Pakri Formation) and in the middle Cambrian (Series 2) tide-influenced nearshore sandstone facies (Tiskre Formation). Our objective was to systematically document, map, categorize, and analyse the various soft-sediment deformation structures in both beds. Detailed facies assessment along with other study results enabled us to identify the vastly different triggering mechanisms causing the liquefaction deformation in both cases.

Although, the soft-sediment deformation structures in both the Pakri and Tiskre beds share common features such as the presence of up to 0.5 m load casts and flame structures, some ball-and-pillow morphologies, and other related plastic deformation structures, there were also notable differences recorded. Most profoundly, the areal extents of the two deformed intervals differ in large borders. The deformations within the Pakri Formation extend up to 9000 km^2 over NW Estonia to SE Sweden, whilst the Cambrian ones, although often comparable in size and type, remain within approximately 10 km outcrop along the coastal cliff in NW Estonia. The deformed interval of the Pakri Formation is distinctly bounded by undeformed layers from the top and below throughout the entire distribution area (except for the Osmussaar Island where the deformations have been the most devastating and incorporate also older sediments). On the contrary, the soft-sediment deformation structures within the Tiskre Formation occur at several (often onlapping) horizons within the thick-layered sandstone cross-beds. The deformation horizons are continuous for up to several hundred meters, but always fade away together with thinning out of their cross-bedded host layer. Specific soft-sediment deformation structures indicative for earthquake induced liquefaction such as sedimentary dykes, autoclastic breccias, sand volcanoes, and fluidization channels are missing in the Cambrian beds. Instead, flow-rolls and slump folds indicative of lateral stress and sediment mobilisation were documented in the latter case.

Evidently, the deformation structures described from the Pakri Formation formed during a single seismic event, up to magnitude 7 or higher, which caused liquefaction and fluidization of the water-saturated unconsolidated shallow marine sediments within almost the entire sandstone unit. The deposition and deformation of the Pakri Formation fall within the Middle Ordovician meteoritic bombardment period which resulted from the disruption of a large parent body in the asteroid belt approximately 470 Ma ago, hence suggesting a potential impact-origin for the earthquake in the tectonically stable region. In addition, previous studies have documented some impact metamorphic shock lamellae (i.e. PDFs) and abundant extraterrestrial chromite grains from the deformed sediments.

In the case of the Tiskre Formation, earthquake-induced liquefaction was excluded due to the lack of sufficient sedimentological proof. Instead, rapid sedimentation, subsequent loading and slumping on the slopes of sand-bars or channel walls were concluded as the most likely triggering mechanism for the deformation.

Preliminary report on the Upper Wenlock δ[13]C excursion in the Ledai-179 drill core (Eastern Lithuania)

Sigitas Radzevičius[1], Audrius Norkus[1], Tõnu Meidla[2], Leho Ainsaar[2], Andrej Spiridonov[1] and Antanas Brazauskas[1]

[1] *Department of Geology and Mineralogy, Vilnius University, M. K. Čiurlionio 21/27, LT-03101 Vilnius, Lithuania; sigitas.radzevicius@gf.vu.lt*
[2] *Department of Geology, University of Tartu, Ravila 14a, 50411 Tartu, Estonia*

The latest Wenlock is a dynamic time interval in the Silurian, marked by profound environmental and biotic changes. Nonetheless, the exact pattern of geobiological perturbations in late Wenlock of the Baltic region is insufficiently explored. Here we present a chemostratigraphic study of the Silurian section from the Ledai-179 drillcore, representing shallow marine environment of the south-eastern part of the Baltic basin. The upper Wenlock and lower Ludlow interval of this section has been divided into Birštonas, Nevėžis, Širvinta and Neris formations by Paškevičius *et al.* (1994). The Birštonas Formation (713.9 – 649.9 m depth) consists predominantly of wackestones, the Nevėžis Formation (649.9 – 658 m) is composed of grey dolomitic marlstones, the Širvita Formation spans (628 up to 611.3 m) is dominated by reddish, laminated dolomitical marlstones, and the uppermost Neris Formation (611.3 to 582.9 m) is composed of greyish, laminated dolostone.

The samples for stable carbon isotope analysis were collected from the 703.3 – 598.7 m interval, approximately at every meter. The carbon stable isotopic composition of the samples was analyzed in the Department of Geology of the University of Tartu.

The $\delta^{13}C$ values are moderately stable and range from -0.95 up to 0.18‰ in the Birštonas Formation, but rise rapidly up to 2.47‰ at 650.4 – 646.1 m depth in the lower part of the Nevėžis Formation, and fall to 1.66‰ at the 639 m depth (middle part of the Nevėžis Formation). The $\delta^{13}C$ values rise again to 2.21 ‰ at the 630.8 m depth. This double maximum of the isotopic curve in the Nevėžis Formation is followed by a return to the low $\delta^{13}C$ values in the uppermost part of the Nevėžis formation. The $\delta^{13}C$ values gradually fall from 1.54‰ (at 627.7 m) to negative at 621.2 m depth and decrease further down to -1.95 ‰ at 612.3 m in the Širvinta Formation. The Neris formation is characterized by negative $\delta^{13}C$ values fluctuating in the range of -5.39 and -1.96 ‰.

The highest $\delta^{13}C$ values in the Nevėžis formation could be interpreted as the Middle Homerian positive carbon isotope excursion above the Mulde extinction event. It remains unclear for the time being whether the two peaks of the $\delta^{13}C$ values in the Nevėžis Formation correspond to the Global Middle Homerian carbon isotope double peak (Cramer *et al.* 2012), or just one of the two peaks.

Cramer, B.D., Brett, C.E., Melchin, M.J., Männik, P., Kleffner, M.A., McLaughlin, P.I., Loydell, D.K., Munnecke, A., Jeppsson, L., Corradini, C., Brunton, F.R. & Saltzman, M.R., 2011. Revised correlation of Silurian Provincial Series of North America with global and regional chronostratigraphic units and $\delta^{13}C$ chemostratigraphy. *Lethaia*, 144, 185–202.

Paškevičius, J., Lapinskas, P., Brazauskas, A., Musteikis, P. & Jacyna, J., 1994. Stratigraphic revision of the regional stages of the Upper Silurian part in the Baltic Basin. *Geologija* (Vilnius), 17, 64–87.

New data on acritarchs from the Upper Ordovician of the Tungus basin, Siberian Platform

Elena Raevskaya[1] *and Andrei Dronov*[2]

[1] *FGUNPP "Geologorazvedka", Knipovich str., 11, block 2, Saint-Petersburg, 191019, Russia; lena.raevskaya@mail.ru*
[2] *Institute of Geology, Russian Academy of Sciences, Pyzhevsky per.7, Moscow, 119017, Russia; dronov@ginras.ru*

Distinctive late Ordovician acritarch assemblages are described for the first time from from four separated outcrops along the Bolshaya Nirunda River, a right tributary of Podkamennaya Tunguska about 60 km downstream from the village of Baykit in Siberia (sample collections in the year 2009). The outcrop area is located on the southern margin (in present day orientation) of an extensive epicontinental Tungus basin on the Siberian Platform between Katanga and Yenisei Lands. The studied stratigraphic interval include uppermost Baksian, Dolborian, Nirundian and Burian regional stages, which correspond to the Katian, and probably to the lowermost Hirnantian stages of the Ordovician. The whole succession is dominated by intercalation of greenish-grey siltstones and grey bioclastic limestones, which are interpreted as cool-water carbonates. Trilobites, brachiopods and ostracods are the most common bioclasts with a significant number of bryozoans, pelmatozoans and mollusks. The most typical and widespread sedimentary structures are indicative for storm-induced sedimentation.

Almost all of the 80 processed palynological samples contain acritarchs of good preservation. Although the majority mainly yields pylomate sphaeromorphs and simple acanthomorphs such as *Baltisphaeridium*, *Goniosphaeridium*, *Micrhystridium*, *Solisphaeridium* of long stratigraphic ranges, at least four subsequent acritarch assemblages can be recognized providing particular taxonomic characteristics of the studied strata. Exceptionally diverse is acritarch assemblage from the Dolbor regional stage that includes aside from the transitional taxa several unique, probably endemic, morphotypes (not described before), and a number of distinctive species, well known outside of Siberia. Among them the most abundant are *Dicommopalla macadamii* Loebl., *Sacculidium inornatum* Rib. *et al.*, *S. macropylum* (Eis.) Rib. *et al.*, *Peteinosphaeridium* aff. *armatum* Tong. *et al.*, *Dactylofusa (Moyeria) cabottii* (Cram.) Mill. et Eams, and some others. Worth to note that these taxa represent different microphytoplankton 'provinces' which existed in the Ordovician, and whose distribution was controlled mainly by paleolatitudes, position of paleocontinents and circulation of ocean water masses. Thus, *D. macadamii* is most typical for warm-water basins of Laurentia, while *S. inornatum*, *S. macropylum*, *P. armatum* are distinct elements of Baltic and South China temperate-water assemblages. In contrast, *D. (Moyeria) cabottii* is most common in cold-water settings along the Peri-Gondwana border and North China (Tarim). Having in mind that Siberian palaeocontinent was located in a low-latitude tropical area during the entire Ordovician, the presence of the latter acritarch in the assemblage from the Dolbor regional stage can demonstrate (in addition to lithological evidences) that cool-water currents penetrated in the Upper Ordovician into the epicontinental Tungus basin of the Siberian Platform.

Future taxonomic investigations are required to estimate the variety of the discovered acritarchs. Remarkable percentage of the widespread acritarchs in these Siberian assemblages gives the obtained palynological material strong potential to improve the interregional biostratigraphic correlations, and to play significant role in biogeographic reconstructions.

This is a contribution to the IGCP Project-591 "The Early to Middle Paleozoic Revolution". Financial support was provided from the Russian Foundation for Basic Research Grant № 13-05-00746.

Acritarch based biostratigraphy of the Ordovician in Moscow syneclise, East-European Platform

Elena Raevskaya[1] *and Alexey Zaitsev*[2]

[1] *FGUNPP "Geologorazvedka", Knipovich str., 11, block 2, Saint-Petersburg, 191019, Russia; lena.raevskaya@mail.ru*
[2] *M.V. Lomonosov Moscow State University, 1 Leninskie Gory, 119991 Moscow, Russia; alz@geol.msu.ru, alzaitsev@rambler.ru*

Taxonomy and distribution of acritarchs in the Ordovician of Moscow syneclise (East-European Platform) have not been revised since mid 1970'ties. Published records are no longer reliable as they were based on outdated systematics of acritarchs and referred to old stratigraphic subdivisions, some of which had been substantially revised afterwards. In order to improve regional stratigraphy and correlation with the International Stratigraphic Chart, as well as to diminish correlation difficulties between Moscow basin and a better-studied Baltoscandian basin, dedicated biostratigraphic investigations were initiated. This contribution represents first results of acritarch studies carried out in more than 70 core samples from three boreholes (Pestovskaya-1, Liubimskaya-1, and Lezhskaya-1, which penetrate the entire Ordovician sequence in the central part of the Moscow basin. Obtained palynological material is characterized by good preservation of palynomorphs and appropriate abundance, although richness and diversity of acritarchs decreases upwards the sections due to increasing dolomitization.

The most comprehensive in respect of core availability (62.6%) is the Pestovskaya-1 borehole located in the most western part of the Moscow Syneclise, in the Novgorod region, some 20 km west to south west from a small town of Pestovo. This Ordovician succession consists of about 350 m of alternating carbonate and terrigenous rocks. It is represented by a succession of the Ukhra, Semetsovo, Volkhov, Obukhovo, Polomet', Berezaika, Griaznovo, Shundorovo, Khrevitsa, Meglino, Ratynya and Varlygino formations, within the depth interval of 852.15 – 1201.4 m. The majority of these formations are replaced in the other two sections, following lateral facial change towards the center of the syneclise that causes obvious difficulty in its correlation.

Six acritarch assemblages have been recognized from the Tremadocian to Sandbian interval, allowing correlation between the boreholes. The assemblages are comparable with those established in the Saint-Petersburg region, and have been traced through several type sections inside and outside of Baltoscandia. The first assemblage includes among the most characteristic taxa A*thabascaella playfordii* Martin, *Caldariola glabra* (Mart.) Mol. et Rush., *Stelliferidium* spp., *Peteinosphaerydium* spp. and is dated by late Tremadocian. The second one is distinct by predominance of *Cymatiogalea messaoudiensis* Jard. et al. var. *inconnexa* Serv. et Mol. and appearance of numerous *Phopaliophora*? *asymmetrica* Raev. et al. Discovering of the later species permits recognition of the base of the Folian Stage in the studied sections. Assemblage with *Rhopaliophora florida* Yin et al., *Ropaliophora* spp., *Stelomorpha composta* Yin et al., *Peteinosphaeridium tenuifilosum* Tong. et al., *P. armatum* Tong. et al. suggests attribution of the enclosing strata to the late Floian. The next assemblage comprises abundant *Baltisphaeridium* accompanied by *Pachysphaeridium christianii* (Kjell.), *Peteinosphaerydium hymenoferum* (Eis.) Fens. et al., *Sacculidium* sp. and many others, and is possibly Dapingian in age. High diversity of peteinoid taxa, together with diverse *Pachysphaeridium*, *Sacculidium*, *Verychachium*, etc., as well as occurrence of *Ordovicidium elegantulum* Tap. et Leobl. in the subsequent assemblage, is typical for the Darriwilian. The last assemblage comprises late Ordovician species such as *Aremoricanium rigaudiae* Deunff, *Orthosphaeridium* sp., and is correlated to the Sandbian.

This is a contribution to the IGCP Project 591 "The Early to Middle Paleozoic Revolution". Financial support was provided from the Russian Foundation for Basic Research Grant № 13-05-00746.

Resolving brachiopod species richness data in the recovery interval of the end-Ordovician mass extinction: A combined quantitative and qualitative approach using Synchrotron X-ray Tomographic Microscopy and Micro-CT 3D Scanning

Christian M.Ø. Rasmussen[1], Mats E. Eriksson[1] and David A.T. Harper[2]

[1] *Department of Geology, Lund University, Sölvegatan 12, S-223 62 Lund, Sweden; christian.rasmussen@geol.lu.se*
[2] *Department of Earth Sciences, Durham University, Durham DH1 3LE, UK; david.harper@durham.ac.uk*

The end-Ordovician mass extinction event had a significant impact on most animal groups at that time. The taxonomic loss has been estimated at 85% at the species level; however, the ecological disruption appears to have been remarkably weak through the crisis interval. Although various phyla experienced huge losses, the effects seem to have been most prominent at lower taxonomic ranks. For instance, within one of the largest groups of shelly benthos, the rhynchonelliformean brachiopods, up to 70% of all genera went extinct. Only a few families disappeared, but their relative frequency changed radically. In the wake of the end-Ordovician mass extinction one group of brachiopods, the Pentamerida, became extremely successful. As the members of this order are virtually impossible to study taxonomically without using destructive and time-consuming serial sectioning techniques to investigate their internal structures, brachiopod diversity estimates are somewhat imprecise and often speculative during the early Silurian recovery interval. With the application of the cutting edge Synchrotron X-ray Tomographic Microscopy (SRXTM) and Micro-CT 3D scanning (XRCT) techniques, new and better resolved species richness data for pentamerids are now possible. Thus, we have employed SRXTM and XRCT as tools to both quantitatively and qualitatively acquire detailed taxonomic information. The resulting data can be used for 3D-reconstructions of internal and external anatomy as well as for generating virtual serial section images. By combining these imaging techniques, different sizes ranges can be targeted; whereas SRXTM produces images of specimens less than one centimetre, the XRCT technique allows for specimens up to 15 centimetres to be analysed. This permits a thorough study of the various pentamerid species, which may vary greatly in size and shape but have very stable interior characters. Our results suggest that SRXTM and XRCT are powerful tools for the study of Early Palaeozoic brachiopods and have the potential to significantly increase our understanding of the phylogenetic evolution of this very successful group of rhynchonelliformean brachiopods.

Integrating bed-by-bed palaeobiological and geochemical proxies through the onset of the Great Ordovician Biodiversification Event on Baltica

Christian M.Ø. Rasmussen[1,2], Clemens V. Ullman[3], Kristian G. Jakobsen[2,4], Anders Lindskog[1], Jesper Hansen[2,5], Thomas Hansen[2,5], Mats E. Eriksson[1], Andrei Dronov[6], Robert Frei[3], Christoph Korte[3], Arne T. Nielsen[2] and David A.T. Harper[2,7]

[1] *Department of Geology, Lund University, Sölvegatan 12, S-223 62 Lund, Sweden; christian.rasmussen@geol.lu.se, mats.eriksson@geol.lu.se, anders.lindskog@geol.lu.se*
[2] *Natural History Museum of Denmark, University of Copenhagen, Øster Voldgade 5-7, 1350 Copenhagen K, Denmark; arnet@snm.ku.dk*
[3] *Department of Geosciences and Natural Resource Management, University of Copenhagen, Øster Voldgade 10, 1350 Copenhgen K, Denmark; cu@ign.ku.dk, robertf@ign.ku.dk, korte@ign.ku.dk*
[4] *Ministry of Industry and Minerals, Maneq 1A 201, P.O. Box 930, 3900 Nuuk, Greenland; krgj@nanoq.gl*
[5] *Akvaplan-Niva, High North Research Centre, 9296 Tromsø, Norway; jha@akvaplan.niva.no; thh@akvaplan.niva.no*
[6] *Geological Institute of the Russian Academy of Sciences, Moscow, Russia; dronov@ginras.ru*
[7] *Department of Earth Sciences, Durham University, Durham DH1 3LE, UK; david.harper@durham.ac.uk*

The Great Ordovician Biodiversification Event (GOBE) had a massive impact on marine biodiversity levels. Notably the suspension feeding benthos experienced substantial increases in species numbers, but planktonic organisms also increased in species richness. Although global bibliographic datasets using various statistical methods seem to disagree as to exactly when, during the Late Cambrian – Devonian interval, the main spike in diversity occurs, the rock record is more coherent, showing the main radiation commencing during the middle Ordovician Darriwilian Stage. During the last 15 years, our project has tracked the GOBE signal on the palaeocontinent of Baltica, bed-by-bed, through the upper Floian – Darriwilian (Billingen – Kunda) interval based on a number of field campaigns targeting several localities in the Eastern Baltic region; data are from a number of different facies belts. All fossils groups were collected, but the main focus has hitherto been on trilobites and rhynchonelliformean brachiopods, of which more than 15,000 and 30,000 specimens respectively, have been collected and analysed. This high sampling intensity was essential to track the onset of the GOBE with unprecedented temporal resolution through the stable, intracratonic setting at mid-palaeolatitudes on the margins of the Moscow Basin. Within the rhynchonelliformean brachiopods, the collected material clearly demonstrates the main diversity spike to originate rapidly within the lowermost Kunda Regional Stage. Subsequently, ecostratigraphically defined systems tracts were constructed on the basis of well-defined, statistically supported biofacies, which again were grounded on bed-by-bed biostratigraphical correlations based on brachiopods. These tracts indicate a fluctuating sea level, which, due to the intracratonic setting and the relatively short time span of the succession, is considered as eustatically controlled. To further support the palaeoclimatological signal, which is likely to have driven this fluctuating sea level, stable isotope geochemistry was conducted on the collected material, again bed-by-bed, extracting pristine calcite from the secondary layer of the brachiopod shells. In all, 400 isotope samples were analysed for Oxygen, Carbon and trace elements from 140 beds at the main locality in Putilovo Quarry, and 94 beds at the Lynna River valley section; the two localities represent different facies settings. These geochemical proxies closely mirror the statistically supported palaeoecological proxies, indicating that sea level oscillations were clearly controlled by climate. This conclusion is further supported by more than 50 radiogenic $^{87}Sr/^{86}Sr$ isotope samples obtained from the brachiopod valves through both sections, which in addition confirm the absolute time frame of the studied interval.

New data on stratigraphy and lithology of Wenlock deposits in the Chernyshev Swell

Dmitry N. Shebolkin[1] *and Peep Männik*[2]

[1] *Institute of Geology, Komi Science Centre, Urals Branch of RAS, Russia; drk80@mail.ru*
[2] *Institute of Geology at Tallinn University of Technology, Tallinn, Estonia; peep.mannik@ttu.ee*

Due to complicated tectonics of the region and lack of detailed studies, Lower Silurian lithology and stratigraphy in the Chernyshev Swell area are poorly known. Recently, a succession of Silurian strata was studied in a section (Iz’’yayu-479) on the Iz’’yayu River, southern part of the Chernyshev Swell. The 18 m thick succession consists of lithologically highly variable rocks of shallow-water origin. Intervals of different lithologies might be very thin: often even in one thin section up to three clearly different lithologies can be observed. The main types of rock recognized include various litho- and bioclastic limestones, stromatolitic and ostracodal limestones, calcareous conglobreccias, oolithic limestones, etc. Interbeds rich in fine-grained terrigeneous material (mainly silt-size quartz) occur. Some intervals are represented by massive or irregularly bedded, often clotted, dolostone. Boundaries between different lithologies, as a rule, are erosional.

Studies of conodonts and carbon isotopes ($\delta^{13}C_{carb}$) revealed that, most probably, in the studied section of Iz’’yayu-479, the succession corresponds to the upper Telychian–lower Gorstian interval, the Ust’durnayu and (lowermost) Padimejtyvis formations (Shebolkin & Männik 2014). The $\delta^{13}C_{carb}$ curve demonstrates two intervals of higher values interpreted as corresponding to the early Sheinwoodian Ireviken and to the Homerian Mulde positive excursions in sense of Cramer *et al.* (2011), respectively. So far, the studied in the Iz’’yayu River section is the only one known from the Timan – northern Ural region where these two positive $\delta^{13}C_{carb}$ excursions have been recognized. It seems that, although the interval corresponding to Wenlock in the Iz’’yayu-479 section has very small thickness it is (almost) complete, without major gaps. However, additional biostratigraphical studies of the section are needed to prove the conclusions above.

Cramer, B.D., Brett, C.E., Melchin, J.M., Männik, P., Kleffner, M.A., McLaughlin, P.I., Loydell, D.K., Munnecke, A., Jeppsson, L., Corradini, C., Brunton, F.R. & Saltzman, M.R., 2011. Revised correlation of Silurian Provincial Series of North America with global and regional chronostratigraphic units and δ^{13}Ccarb chemostratigraphy. *Lethaia*, 44, 185–202.

Shebolkin, D.N. & Männik, P. 2014. Wenlock deposits in the southern part of the Chernyshev Swell (Timan–northern Ural region). *Litosphere*, 1, 33–40.

The Herefordshire Lagerstätte: Silurian soft-bodied sensations

David J. Siveter

Department of Geology, University of Leicester, University Road, Leicester, Leicester, LE1 7RH, UK; vp110@leicester.ac.uk

Our understanding of the history of life on Earth relies heavily on the fossil record, and especially on rare cases of exceptional preservation, where soft parts of animals and entire soft-bodied animals are preserved. Such exceptionally preserved fossils provide an unparalleled view of animal paleobiology and the true nature of animal biodiversity.

The presentation will illustrate on-going research on spectacular fossils recovered from Wenlock Series rocks (~425 Ma) of Herefordshire in the Welsh Borderland, UK. Representing one of the rare Silurian lagerstätten, this is a biota of global importance. It contains representatives of many major groups of animals, including molluscs, echinoderms, brachiopods, polychaetes, and most especially a range of arthropods. Animals preserved are primarily epibenthic, but infauna and nekto-benthic forms are also represented. The fossils are preserved as three-dimensional calcite void-fills in carbonate nodules and are impossible to extract by standard methods. The specimens are studied using tomographic techniques to produce high fidelity three-dimensional virtual fossils that yield a wealth of palaeobiological information. These fossils are crucial in helping to fill a gap in our knowledge of the history of life, and to resolve controversies about the relationships and evolution of animals still alive today.

Palaeobiology of Early Palaeozioc myodocopes: adaptations heralding pelagic ostracods

David J. Siveter, Vincent Perrier and Mark Williams

Department of Geology, University of Leicester, University Road, Leicester, Leicester, LE1 7RH, UK; djs@leicester.ac.uk, vp110@leicester.ac.uk, mri@leicester.ac.uk

Ostracods occur as tens of thousands of living species. They are also the most abundant group of fossil arthropods, known from countless of their supposed shells from the Ordovician onwards. The vast majority of living and fossil ostracod species are benthic or presumed benthic. Extensive morphological, sedimentological and faunal evidence indicates that ostracods (specifically myodocopes) invaded the water column certainly by the later part (Ludlow) of the Silurian. Recent discoveries of exceptionally preserved myodocope ostracods from late Ordovician (New York State, USA) and early Silurian (Herefordshire, Welsh Borderland) lagersttaten allow insight into the ancient palaeobiology of the group, including details of the body, limbs and eyes, gills and alimentary system. Geological evidence suggests that these Ordovician and early Silurian ostracods were possibly nektobenthic; nevertheless they have anatomical adaptations that were key to facilitating the later ecological shift of myodocopes into the water column.

Conodont communities as complex dynamical systems – multifractals, critical transitions, and oscillations in the fossil record of the mid- to late Pridoli conodonts

Andrej Spiridonov, Antanas Brazauskas and Sigitas Radzevičius

Department of Geology and Mineralogy, Vilnius University, M. K. Čiurlionio 21/27, LT-03101 Vilnius, Lithuania; s.andrej@gmail.com, antanas.brazauskas@gf.vu.lt, sigitas.radzevicius@gf.vu.lt

Conodonts were small marine bilateral animals, which left rich fossil record of teeth-like elements behind them. Many existing paleobiological studies of this clade focus either on their macroevolutionary changes (origination and extinction events), or the controls of composition of their assemblages (that is concentrated on the dynamics of biofacies change). Here we present the comprehensive quantitative study of the long-term dynamics in conodont element abundances through the middle and the upper parts of the Pridoli epoch (Jūra Formation) in the eastern part of the Baltic basin. We investigated conodont abundances together with gamma-ray and stable carbon isotope data from two deep cores of different facial zones – the Šešuvis-11 section from deep water facies, and the Viduklė-61 well from more proximal part of the basin.

The study of temporal variability in the patterns of abundance, based on the lacunarity, rescaled range, and power spectra analyses revealed that the long-term macroecological record of conodonts is characterized by the multifractal structure, the presence of the long-term memory and the 1/f scaling of the spectral power against the frequency (the pattern typical for a pink noise). The most likely explanation of these features of time series is that the abundance dynamics in the conodont guild were controlled by the whole array of processes varying in their impact at very different time scales, and interacting among themselves multiplicatively. The other types of analyses revealed that most probable sources of abundance controls at different scales of temporal hierarchy were the changes in the attributes of physical environment. The mowing-window correlation analyses revealed no statistically significant correlations between gamma-ray intensities and the codonont abundances. Though, the same type of analysis suggests that there were three episodes of differing statistically significant correlations between conodont abundances and the stable carbon isotopic ratios. Those episodes were marked by the changes in the variance production in the time series of abundances and also the carbon isotopes, which pinpoint to the critical nature of those transition to the alternative states, that is they were state shifts in the regional ecosystem functioning. The nonlinear nature of the conodont eco-evolutionary dynamics was also confirmed by the estimation of the maximal Lyapunov exponent, which positive value suggested the chaotic (sensitive to arbitrary initial conditions) nature of abundance change.

In addition to the pervasive nonlinearity and generally low level of predictiveness the spectral analyses of stratigraphic series of abundance change revealed the presence of persistent features of oscillatory change. At least two statistically significant periodicities with very different periods were found (74 Ka, and 950 Ka). Based on the period length and the nature of orbital forcing on Earth's environments, we suggest that those cyclic components originated due to the eccentricity caused modulation of low latitude seasonalities (and temperature) which resulted in the changes in nutrient production, and subsequent ecological (and evolutionary) disturbances.

Vicariance versus dispersal: relating biogeography and speciation within Late Ordovician (Katian) marine invertebrates of Laurentia

Alycia L. Stigall

Department of Geological Sciences and OHIO Center for Ecology and Evolutionary Studies, 316 Clippinger Laboratories, Ohio University, Athens, Ohio, 45701, USA; stigall@ohio.edu

Speciation is a critical process for the formation and maintenance of biodiversity. The process of speciation itself is predicated on discontinuation of gene flow between ancestral and descendant populations. The disruption of gene flow typically occurs following environmental changes, either gradual or abrupt, which are often tied to geographic changes. Necessarily, every speciation event occurs at a specific geographic location, during a specific interval of geologic time, within a specific evolutionary lineage. Consequently, the pattern and process of speciation is best studied within a phylogenetic framework. In this paper, I examine some of the key geologic factors that influenced the rate and style of speciation within several clades of Late Ordovician (Katian) marine invertebrate clades that were primarily Laurentian in distribution.

Detailed examination of speciation requires development of species-level phylogenetic hypotheses. This analysis utilizes previously published phylogenetic hypotheses for rhynchonelliform brachiopods, trilobites, and graptolites form Late Ordovician deposits of Laurentia. Clades whose stratigraphic ranges include Sandbian and Katian global stages, which relates to the Mohawkian and Cincinnatian series of the North American nomenclature, were targeted for inclusion. This temporal interval encompasses orogenic activity of the Taconian orogeny, multiple carbon isotope excursions – including the GICE excursion, inferred changes in oceanographic mixing – such as the development and reduction of upwelling in eastern Laurentia, and associated global cooling.

Speciation mode and biogeographic patterns are examined with a phylogenetic biogeographic analysis utilizing Fitch Optimization and Lieberman-modified Brooks Parsimony Analysis. Initial analyses indicate a fundamental shift in speciation mode – from a vicariance to dispersal dominated macroevolutionary regime – correlated with the boundary between the Sandbian to Katian Stages. This boundary corresponds to the onset of renewed intensification of tectonic activity and mountain building, the development of an upwelling zone that introduced cool, nutrient-rich waters into the epicontinental seas of eastern Laurentia, and the GICE isotopic excursion. Together, the renewed tectonic activity and oceanographic changes facilitated fundamental changes in habitat structure in eastern North America that reduced opportunities for isolation and vicariance. These changes also facilitated regional dispersal of taxa that led to the subsequent establishment of extrabasinal (= invasive) species and may have led to a suppression of vicariant speciation within Laurentian faunas. This pattern resembles the reduction in vicariance that observed related to enhanced extrabasinal invasions during the Late Devonian Biodiversity Crisis.

Timing of the deposition of the remarkable 'green unit' (early Middle Ordovician) on Öland, Sweden

Svend Stouge[1] *and Gabriela Bagnoli*[2]

[1] *Natural History Museum of Denmark, Geological Museum, University of Copenhagen, Øster Voldgade 5–7, DK 1350, Copenhagen K, Denmark; svends@snm.ku.dk*

[2] *Dipartimento di Scienze della Terra, University of Pisa, Via S. Maria 53, 56125 Pisa, Italy; gabriella.bagnoli@unipi.it*

In Early – Middle Ordovician the Orthoceras Limestone formed an extensive and relatively uniform carbonate cover on the platform of Baltica. However, a distinct 'event' occurred in the early Darriwilian (early Kunda), which in outcrop is recognized as a green horizon in predominantly red limestone facies and can be traced across Baltoscandia; or it is developed as a proximal breccia. Two localities, which display the Darriwilian 'event' in outcrop, are the 1.5 m thick green unit named 'Täljstenen' in Västergötland, central Sweden and the 'Osmussaar Breccia' on Osmussaar Island, northwestern Estonia. Both are famous, because they have been related to meteorite impact(s), although geological processes such as change of sea level, tectonics causing uplifts, earth quake(s) and/or volcanic eruptions have also been considered.

On Öland the strata of the Orthoceras Limestone are well exposed along the western coastal cliffs. The succession is composed of red-yellow-grey-green bedded limestone (wackestone to grainstone) and referred to several formations that can be traced laterally from northern to southern Öland. Detailed field investigations and comparison of several sections on Öland show that the two areas reacted differently to the early Darriwilian 'event'. On northern Öland a heterogeneous green unit, informally named 'formation A+B', overlies the Horns Udde Formation (Dapingian). The fossiliferous 'formation A+B' consists of undular bedded 'dirty green' limestone (glauconitic silty limestone, wacke- and grainstone) with shaly interbeds; phosphate and planar discontinuity surfaces and 'ooid' horizons are characteristic but are not laterally persistent over long distances. Several beds contain disorientated, with respect to bedding, but complete specimens of trilobites and other macrofossils demonstrating that the unit or part of the unit has been redeposited fast (slumping) and immediately after deposition.

The trilobite fauna comprises the *Megistapis limbata*, *Asaphus expansus* and *A. raniceps* and *A. vicarious* zones. Conodonts extend from the uppermost part of the *Baltoniodus norrlandicus* Zone, the *Lenodus antivariabilis*, *L. variabilis* and *Yangzeplacognathus crassus* conodont zones. The overlying strata are assigned to the upper *Y. crassus* and *L. pseudoplanus* conodont zones. Internally, 'Formation A+B' is locally incomplete and a remarkable gap covers the L. variabilis Zone. This gap extends from the Hagudden section in the northwestern region to the Byrum area.

On southern Öland 'formation A+B' is composed of green-red wackestone rich in cephalopods. It includes the green unit named 'Sphaeronites bed' (wacke- and grainstone) overlain by red grainstone and packstone. The major difference between the successions of the northern and southern areas includes the change of colour in outcrop and lack of 'ooids' in the south. The 'Sphaeronites bed' is referred precisely to the *L. variabilis* – lowermost *Y. crassus* conodont zones, which clearly demonstrates that the bed is coeval to and, like 'Täljstenen', was formed by the Darriwilian 'event'.

Possible relationship of the conodonts' and chaetognaths' ancestors

Hubert Szaniawski

Institute of Paleobiology, Polish Academy of Sciences, Poland; szaniaw@twarda.pan.pl

Spine-shaped, organo-phosphatic microfossils informally named protoconodonts are commonly found within marine Cambrian deposits. They are often treated as ancestors of microfossils named paraconodonts, which are similar in terms of composition but are strongly diverse in terms of shape. Paraconodonts are, in turn, usually considered as ancestors of the phosphatic true conodonts (= euconodonts). It is presently known that individual specimens of all three groups were originally elements of multielement apparatuses. However, mutual relationships and evolutionary development of the groups are still unclear. Protoconodonts are probably heterogenic and their transition to paraconodonts is not well documented. Additionally, elements assigned to their most commonly occurring genus *Phakelodus* (Miller, 1984) are in fact grasping spines of early chaetognaths. Thus the relationship of protoconodonts with para- and euconodonts is uncertain. Paraconodonts are strongly diversified and possibly also heterogenic, but the transition of some of their representatives into euconodonts is well documented.

Based on the studies of rich collections of well preserved upper Cambrian and early Tremadocian phosphatic microfossils from Sweden, Poland and Kazakhstan (Malyi Karatau) I can state that some of the supposed conodonts occurring there neither belong to euconodonts nor to paraconodonts but are similar in structure to elements of *Phakelodus*, which is an ancestor of chaetognaths. The statement so far concerns only the genera *Coelocerodontus* Ethington, 1959, Viirodus Dubinina, 2000 and the species assigned by Dubinina (2000) to "*Proacontiodus*" An, 1982. Elements of the genera differ from euconodonts in terms of the lock of the basal body and comparatively thin wall, which is not laminated like in euconodonts but diagonally ribbed. The outer surface of the elements is matte, contrary to the co-occurring elements of true euconodonts, e.g. cordylodids, which are glancing, and at least partly translucent. The elements are evidently secondarily phosphatized. Originally they probably were, like the elements of *Phakelodus*, organic in composition, because some of the specimens have deformations which indicate their primary flexibility. Moreover, structure of the apparatuses of the genera *Coelocerodontus* and *Viirodus* show completely different arrangements of elements than in the apparatuses of euconodonts and paraconodonts. Their elements are matched in shape to each other and certainly functioned in conjunction. As a result, they comparatively often remain articulated even when fossilized. So then also in this respect they are similar to the grasping spines of the genus *Phakelodus*. However, only the longest elements of *Viirodus* and *Coelocerodontus* have similar shape to them. All others are much wider and, contrary to the elements of *Phakelodus*, strongly diversified in shape. They are also not similar in construction to any elements of euconodonts. It seems probable that the animals possessing such apparatuses belonged to a separate evolutionary lineage which diverged in the upper Cambrian from the lineage *Phakelodus* – recent Chaetognatha.

Dubinina, S.V., 2000. *Conodonts and Zonal Stratigraphy of the Cambrian-Ordovician Boundary Deposits*. Nauka, Moscow, 240 pp.

Terrestrial environments in the Devonian of the Holy Cross Mountains (central Poland)

Piotr Szrek[1], Sylwester Salwa[1] and Grzegorz Niedźwiedzki[2]

[1] *Polish Geological Institute-National Research Institute, Rakowiecka 4 Street, 00-975 Warsaw, Poland; piotr.szrek@pgi.gov.pl, sylwester.salwa@pgi.gov.pl*

[2] *Department of Organismal Biology, Evolutionary Biology Centre, Uppsala University, Norbyvägen 18A, 752-36 Uppsala, Sweden; grzegorz.niedzwiedzki@ebc.uu.se*

Environmental interpretation of the Devonian deposits of the Holy Cross Mountains has only partly been highlighted, especially for the lower part of the profile. Recently, the earliest tetrapod tracks and paleosols records from the Zachełmie Quarry (Niedźwiedzki *et al.* 2010; Narkiewicz & Retallack 2014) demonstrate that shallow-marine lagoon was permanently elevated and sparsely vegetated areas during early Middle Devonian. In fact, many authors suggested that the siliciclastic deposits partly represented the Old-Red continental sediments, but until now no definitive evidence for a terrestrial origin of these Lower Devonian deposits have been described. The results of recent fieldwork suggest a considerable change to these earlier points of view. Apart from sedimentological observations that point to marginal-marine and very shallow-water conditions, we have found horizons with plant roots traces and layers interpreted as paleosols showing different stages of pedogenesis. This is the first direct evidence that some areas of the Holy Cross Mtns represented terrestrial conditions during the Lower Devonian and this plant root evidence is one of the oldest ever described. It also casts a new light on terrestrialization processes at the beginning of the Devonian Period. Further studies are directed for detail dating of the deposits based on zircon, sedimentological analysis and paleobiological studies of the rich invertebrate trace fossils and vertebrate remains from paleosol-bearing deposits.

Niedźwiedzki, G., Szrek, P., Narkiewicz, K., Narkiewicz, M. & Ahlberg, P., 2010. Tetrapod trackways from the early Middle Devonian period of Poland. *Nature*, 463, 43–48.

Narkiewicz, M. & Retallack G.J. 2014. Paleosols and paleoenvironments of the earliest tetrapod tracks in the Eifelian of the Holy Cross Mountains, Poland. *Sedimentary Geology*, 299, 74–87.

Platform-scale impact of the End-Ordovician glaciation on the Central Anti-Atlas (southern Morocco): a biostratigraphic framework

Lorena Tessitore[1], Thijs R. A. Vandenbroucke[1], Jean-François Ghienne[2], Marie-Pierre Dabard[3], Alfredo Loi[4], Florentin Paris[3], Pierre Dietrich[2] and Philippe Razin[5]

[1] *UMR 8217 du CNRS: Géosystèmes, Université Lille 1, France; lorena.tessitore@ed.univ-lille1.fr, thijs.vandenbroucke@univ-lille1.fr*
[2] *UMR 7516 du CNRS: Institut de Physique du Globe de Strasbourg, Université de Strasbourg, 1, France; ghienne@unistra.fr, pierre.dietrich@etu.unistra.fr*
[3] *UMR 6118 du CNRS: Geosciences Rennes, Université de Rennes 1, France; marie-pierre.dabard@univ-rennes1.fr; florentin.paris@orange.fr*
[4] *Dipartimento Scienze della Terra, Università di Cagliari, Italia; alfloi@unica.it*
[5] *Géoressources et Environnement, Université de Bordeaux, France; Philippe.RAZIN@ensegid.fr*

The Hirnantian glaciation is well known for providing the backdrop of the end-Ordovician mass extinction. Evidence of this glaciation is widespread in western Gondwana. Where the glaciers reached the sedimentary basins, this resulted in an extensive glacial record, notably in our study area, between Zagora and Alnif (Central Anti-Atlas, southern Morocco). Our efforts are part of an ANR project (French national research foundation) that re-investigates the sedimentology and sequence stratigraphy of these deposits. Our methodology consists of sampling the pre-, syn-, and post-glacial sections at various locations, and using chitinozoan biostratigraphy to correlate these glacial deposits across the different sections. Moreover, this will identify the Katian–Hirnantian boundary, which remains obscure in some areas. An additional challenge comprises the palaeogeographical disparity in chitinozoan data, causing difficulties in establishing an efficient global biostratigraphical correlation framework for the Upper Ordovician (Vandenbroucke *et al.* 2010). Practically, our current aim is twofold:

(i) To correlate sections in the Zagora to Alnif area (Anti-Atlas), where the stratigraphy is obscured due to sedimentary gaps and large incisions caused by the waxing and waning of the ice sheets. Preliminary palynological results show an abundance of palynomorphs in the 'pre-glacial' parts of the section, but little to no data from the parts of the section that record the actual presence of the glacier. A prime target is the correlation of two key areas, the Alnif region (Clerc *et al.* 2013) and the Bou Ingarf section and neighbouring sections around Tazarine (Loi *et al.* 2010).

(ii) To correlate the ice-marginal Anti-Atlas sections described above with those in the Tazekka Massif in northern Morocco (Meseta, Le Heron *et al.* 2008), in an ice-distal position where direct evidence for glaciation is poor.

Here, we present a first overview of our correlations and new data in the Central Anti-Atlas.

Clerc, S., Buoncristiani, J-F., Guiraud, M., Vennin, E., Desaubliaux, G. & Portier, E., 2013. Subglacial to proglacial depositional environments in an Ordovician glacial tunnel valley, Alnif, Morocco. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 370, 127–144.

Le Heron, D.P.,Khoukhi, Y., Paris, F., Ghienne, J.-F. & Le Herissé, A., 2008. Black shale, grey shale, fossil and glaciers: Anatomy of the Upper Ordovician-Silurian succession in the Tazzeka Massif of eastern Morocco. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 245, 200–226.

Loi, A., Ghienne, J.-F., Dabard, M.P., Paris, F., Botquelen, A., Christ, N., Elaouad-Debbaj, Z., Gorini, A., Vidal, M., Videt, B. & Destombes, J. 2010. The Late Ordovician glacio-eustatic ecord from a high-latitude storm-dominated shelf succession: The Bou Ingarf section (Anti-Atlas, southern Morocco). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 296, 332–358.

Vandenbroucke, T.R.A., Armstrong, H., Williams, M., Paris, F, Sabbe, K., Zalasiewicz, J., Nõlvak, J., Verniers, J. & Servais, T. 2010. Polar front shift and atmospheric CO_2 during the glacial maximum of the Early Paleozoic Icehouse. *PNAS*, 107, 14983–14986.

Significance of redox rhythms in the late Llandovery – early Wenlock (middle Silurian) of central Tennessee, United States

James R. Thomka and Carlton E. Brett

Department of Geology, University of Cincinnati, Cincinnati, Ohio 45221, USA; thomkajr@mail.uc.edu, brettce@ucmail.uc.edu

Rhythmic bedding is characteristic of Telychian–Sheinwoodian (late Llandovery–early Wenlock; middle Silurian) strata on the western margin of the Appalachian Foreland Basin, eastern Laurentia. Changes in rhythmite motifs correspond to position along a northeast-southwest-trending epeiric ramp. Upramp settings are characterized by stacked, evenly bedded, fossiliferous carbonates, which grade downramp into thicker deposits comprising decimeter-scale alternations between dolomitic carbonates and marls. These, in turn, grade downramp into thick successions of non-fossiliferous siliciclastic muds that display alternations between red and greenish-gray coloration. Thus, redox rhythms are associated with siliciclastic-dominated sections representing deposition in distal ramp settings near the basin axis. It has been proposed that these redox rhythms reflect migration of water masses with distinct geochemical properties from the basin axis to surrounding areas. An interesting section near Pegram, central Tennessee, United States exposes middle Silurian strata that display redox rhythms. While this is not unusual when taken alone, the redox rhythms occur in shallow-water fossiliferous carbonates rather than offshore siliciclastic mudrocks. Hence, this section is characterized by a lithology associated with proximal, upramp settings, but a rhythmite motif associated with distal, offshore settings elsewhere. This is significant because: 1) it reveals that redox fluctuations transcended the distal mudrock lithofacies, indicating a greater magnitude of time-specificity than previously recognized; and 2) it demonstrates that strata of the proto-Nashville Dome, an isolated topographically positive feature in southern midcontinental Laurentia, were influenced more strongly by basinal water masses than were coeval strata on the broad ramp further north. Additionally, interpretation of the Pegram section in the context of basinal redox evolution allows an enigmatic brick-red siltstone band, one of the only non-fossiliferous intervals of the entire section, to be tentatively interpreted as a possible, relatively subtle expression of an episode of widespread iron mineralization associated with migration of an anoxic water mass. The narrow middle Silurian outcrop belt in Tennessee precludes high-resolution regional documentation of redox rhythm-bearing carbonate intervals; rather, this significant and unusual lithofacies appears restricted to the vicinity of the crest of the proto-Nashville Dome, where exposures are rare. In a larger sense, the widespread occurrence of rhythmic bedding indicates an allocyclic forcing mechanism and suggests an interval of strong regional, and perhaps enhanced, climatic sensitivity. Development of coupled carbonate-marl and redox rhythms represents a predictable, time-specific facies motif reflecting one phase of the geochemical evolution of the Appalachian Foreland Basin.

Early land plant from the lower Silurian (Llandovery, Aeronian) of Estonia

Oive Tinn, Viirika Mastik, Leho Ainsaar and Tõnu Meidla

Department of Geology, University of Tartu, Ravila 14a, Tartu 50411, Estonia; oive.tinn@ut.ee

The Kalana *Lagerstätte* in Central Estonia, of Llandovery (Aeronian, ~435 Ma) age, best known for its impressive non-mineralized algae, revealed fossils of early land plants, which predate all known vascular plant macrofossils, including the earliest *Cooksonia*.

The layers in Kalana *Lagerstätte* correspond to the Raikküla Regional Stage, which biostratigraphically correlates with the *Aspelundia* Superzone. The layers with exceptionally preserved fossils belong to its lowermost interval, the *A. expansa* conodont zone. The fossils and rocks of the locality refer to a nearshore environment, where normal marine carbonate layers with rhynchonelliform brachiopods, tabulate corals and bryozoans alternate with typical thin-bedded lagoonal sediments containing leperditid arthropods and rare eurypterids. The succession contains numerous lenses of gastropod or brachiopod coquina.

Most of the plant remains are preserved as coalified fossils. A number of them comprise naked sterile axes of different length and preservation, fertile axes with lateral sporangia, several short axes with microphylls and disconnected sporangial spikes.

In this study we will focus on the species designated as sp. *A* with the largest collection of fossils. The most conspicuous feature of sp. *A* are the thorn-like sporangia which cover the whole axis and house three-dimensionally *in situ* preserved spores. The spores, all of different size and part of them forming spore aggregates enclosed in membranes, are about an order of magnitude smaller than all previously described cryptospores.

Unlike most land plants these fossils lack stomata. The distinctive walled pores on the outer surface of the plant are possibly air pores, similar to the structures that extant liverworts use for gas exchange. The air pores lead into spheroid air chambers, which can be observed on the inner surface of the epidermal layer.

The long section of the axis reveals peculiar tubular conducting cells, the walls of which are penetrated by irregularly spaced numerous pores. The morphology of these cells is comparable to the hydroid cells of bryophytes.

The overall morphology and unique anatomy does not allow to assign these fossils to any known taxon and they might be considered as members of a previously unknown clade, representing an early stage of land plant evolution.

Polychaetes and the end-Ordovician mass extinction: new data from the basal Silurian Varbola Formation of Estonia

Petra Tonarová[1], Olle Hints[1] and Mats E. Eriksson[2]

[1] *Institute of Geology, Tallinn University of Technology, Ehitajate 5, 19086 Tallinn, Estonia; petra.tonarova@ttu.ee; olle.hints@ttu.ee*
[2] *Department of Geology, Lund University, Sölvegatan 12, SE-223 62, Lund, Sweden; mats.eriksson@geol.lu.se*

Jawed polychaete worms represented a significant component of the early Palaeozoic marine invertebrate communities, as shown by the abundance and diversity of their jaws (scolecodonts) in the sedimentary rock record. General comparison between the Ordovician and Silurian polychaete faunas indicate that they were relatively unaffected by the end-Ordovician mass extinction (Eriksson *et al.* 2013). However, whereas the Late Ordovician scolecodonts are relatively well known, especially in Baltoscandia, the Silurian records primarily cover the latest Llandovery through Ludlow interval (Eriksson *et al.* 2013), leaving the basal Silurian faunas virtually unknown. This obviously complicates the possibility of evaluating the effects of the event in closer detail.

In this study we aim to start closing this stratigraphic gap by documenting the scolecodonts from the basal Rhuddanian (lowermost Silurian) nodular limestones of the Varbola Formation, central Estonia. Altogether 25 samples, comprising more than 10 000 scolecodonts, were studied from the Velise drill core and Reinu Quarry. The abundance of scolecodonts is comparable to that recorded from Upper Ordovician strata, with approximately 300 specimens per kg of rock, but reaching over 2000 specimens/kg in some samples. The polychaete assemblage recorded is rather diverse, containing as many as 18 genera and 30 species, with a maximum of 19 species identified in one sample.

As expected, the Rhuddanian assemblage is dominated by polychaetaspids (*Oenonites*) and mochtyellids (*Pistoprion, Vistulella, Mochtyella*). In some samples, particularly from the upper part of the Varbola Formation, paulinitids (*Kettnerites*) are common, accounting for up to 20% of the fauna. Other families, such as atraktoprionids, xanioprionids and tetraprionids, only comprise a few per cent each. The genus level composition is similar to that of the Late Ordovician faunas, but some differences are observed at the species level: many Hirnantian species are absent and several new species are first recorded in the Rhuddanian. Yet other species seem to have been unaffected by the extinction event. For instance, *Pistoprion transitans*, often predominant in Hirnantian strata, is very common also in the Varbola Formation where it accounts for up to 20%.

These new data suggest that jawed polychaetes endured the end-Ordovician crises seemingly with no, or insignificant, loss in genus and higher level taxonomic diversity and also that a number of species crossed the Ordovician-Silurian boundary. It is possible, however, that some gradual changes in the assemblage structure are related to the Hirnantian event, like the increasing role of paulinitids on Baltica, which likely started during the extinction interval. Detailed analyses of the collection at hand will thus allow new assessment of the response, such as the timing, severity and recovery patterns, of polychaetes to one of the most severe biotic crises of the Phanerozoic.

The research was supported by the European Union through the European Social Fund (Mobilitas grant MJD407).

Eriksson, M.E., Hints, O., Paxton, H. & Tonarová, P., 2013. Ordovician and Silurian polychaete diversity and biogeography. *In:* Harper, D.A.T. & Servais, T. (eds). *Early Palaeozoic Biogeography and Palaeogeography*. Geological Society, London, Memoirs, 38, 257–264.

Correlation and preservation of K-bentonites in the Ordovician and Silurian shales from the Holy Cross Mountains (Poland)

Wieslaw Trela, Ewelina Bąk and Sylwester Salwa

Polish Geological Institute – National Research Institute, Zgoda 21, 25-953 Kielce, Poland; wieslaw.trela@pgi.gov.pl

Numerous K-bentonites of various thickness interrupt the Upper Ordovician and Silurian dark graptolitic shales in the Holy Cross Mountains (HCM). The Ordovician K-bentonites are largely confined to the upper Sandbian and Katian stratigraphic interval. The thickest ash layer (up to 40 cm thick) was reported in the Jeleniów PIG 1 well within the Sandbian *foliaceus* graptolite zone and can be correlated with Kinnekulle and Millbrig K-bentonites in Baltoscandia and North America. This horizon is accompanied by multiple stacked ash beds ranging from 5 to 10 cm in thickness. The Silurian K-bentonites occur in the Zarobiny PIG 1 and Kleczanów PIG 1 wells and are related to the upper Wenlock – lower Ludlow stratigraphic interval. All considered K-bentonites form prominent homogenous horizons with sharp bases except for the thicker ones that reveal discrete normal gradation enhanced by upward transition to fine-grained fraction. Their various thickness and irregular distribution seem to be a reflection of fluctuating volcanic activity, however, the sedimentary features of the background shales suggest that physical and biogenic factors contributed significantly to the preservation of ash beds. The background shales of the Ordovician and Silurian K-bentonites were deposited under overall dysoxic/anoxic bottom waters favorable for preservation of ash layers due to decreased borrowing activity (see Ver Straeten 2004), however, discrete trace fossils clearly indicate that biological processes during intermittent oxic periods might have played an important role in modification of ash beds. The closely spaced K-bentonites appear to reflect their complex history including rapid burial of primary volcanic ash by the muddy sediment preventing it from physical and biological reworking and mixing. Sedimentary structures recorded in background shales, represented not only by sub-millimetric horizontal lamination but also by discrete traces of weak bottom currents, indicate that physical sedimentary processes might have exerted a strong influence on preservation of ash beds.

Distribution and preservation of volcanic ash depends also on atmospheric circulation during the time of volcanic eruption and after it as well as distance between the site of deposition and the center of eruption (Ver Straeten 2004). Similar to the Baltoscandian K-bentonites, the Sandbian-early Katian ash beds in the HCM appear to be accumulated from pyroclastic material delivered by westerlies from the Avalonian volcanoes (see Torsvik and Rehnström 2005). Distribution of pyroclastic material over the HCM area during the late Wenlock–early Ludlow was strongly controlled by SE trade winds. Similar direction of volcanic ash transport postulated for the late Silurian K-bentonites from Podolia was related to an active subduction zone developed close to the southeastern side of Baltica along the northern Rheic Ocean (Huff *et al.* 2000).

Huff, W.D., Bergström, S.M. & Kolata, D.R., 2000. Silurian K-bentonites of the Dnestr Basin, Podolia, Ukraine. *Journal of the Geological Society*, London, 157, 493–504.

Torsvik, T.H. & Rehnström, E.F., 2003. The Tornquist Sea and Baltica-Avalonia docking. *Tectonophysics*, 362, 67–82.

Ver Straeten, C.A. 2004. K-bentonites, volcanic ash preservation and implications for Early to Middle Devonian volcanism in the Acadian orogen, eastern North America. *Geological Society of America Bulletin*, 116, 474–489.

Hirnantian refuge for warm-water ostracods in Baltoscandia

Karin Truuver and Tõnu Meidla

Department of Geology, University of Tartu, Tartu, Estonia; karin.truuver@ut.ee, tonu.meidla@ut.ee

The Kętrzyn IG-1 borehole in north-eastern Poland is situated in the southern part of the Central Baltoscandian Confacies belt area and exposes mostly argillaceous limestones deposited in a distal ramp setting. The Ordovician-Silurian boundary interval was studied for ostracods. The species composition consists mostly of binodicopes and resembles the *Harpabollia harparum* association known from South Estonia, Latvia, Scandinavia and the Carnic Alps. In addition to the species typical of the *Harpabollia harparum* association, polish material also contains some metacopes (e.g. *Pullvillites laevis*, *Silenis* sp., *Longiscula tersa*?) and eridostracans (*Cryptophyllus gutta*, *Cryptophyllus* sp. A), the latter being also the most abundant species of the association. These species are common in Estonian and Latvian pre-Hirnantian, but sparce or absent in the Hirnatian Stage. Genera characteristic of the North Estonian *Medianella intecta* association (*Steusloffina*, *Medianella*, *Microcheilinella*) are nearly absent in Kętrzyn. The faunal differences of these areas can possibly be explained by different position of the studied areas in the Ordovician paleobasin, which deepened in the southwestern direction. North-Estonia, with its endemic association, was situated on the shallower upper part of the shelf, whereas South-Estonia, Latvia and the western part of Lithuania were approximately in the middle of the ramp where water was already deeper. Poland was situated in the deep-water environment near the bottom of the shelf slope, acting as a sort of temporary refuge for some of the pre-Hirnantian species at the onset of the glaciation. This is the first occasion where likely depth differences are recorded in the composition of the cool-water Hirnantian ostracod assemblages.

Palaeozoic reefs below the central Baltic Sea

Igor Tuuling

Department of Geology, University of Tartu, Tartu, Estonia; igor.tuuling@ut.ee

Appearing first in the Middle Ordovician, the reef structures in the shallow cratonic Palaeobaltic Basin became increasingly proliferated towards the end of Ordovician and throughout most of Silurian when Baltica was drifting closer to the equator. They have been described in numerous outcrops and drillings at various stratigraphic levels, both east and west of the Baltic Sea. Extensive seismic profiling, performed since the early 1960s, has revealed a large number of reefs also below the central Baltic Sea, between the Swedish island of Gotland and the Baltic countries. A continuous picture and a dense set of north-south seismic lines, performed during a Swedish–Estonian cooperative study 1990–2004, have enabled, along with seismostratigraphic subdivision of the Ordovician–Silurian sequence, a detailed mapping and description of the submarine reef structures. Varying morphology, dimensions and distribution of the reefs, like their positioning on the basinal slope characterize changes in configuration, bathymetry and development of the Baltic Ordovician–Silurian basin.

In the Ordovician sequence, the reefs occur only in its uppermost seismic unit: abundantly within a 60 km long (N to S) and 50 km wide (E to W) zone offshore NE of Gotland and as a few solitary structures/swarms several hundred meters in width off the Estonian coast. They correlate with the Upper Ordovician reefs known as Boda or Pirgu reefs in Sweden or in Estonia, respectively. A barrier reef-like formation with reefs more than 2 km in diameter and a steeper basinward slope separates back and fore-reef facies zones off NE of Gotland. Down-slope into the ancient basin, the number and diameter of the reefs gradually decrease and instead of flat shallow water patch reefs, conical or pinnacle reefs become dominant.

The present distribution of the Silurian reefs below the central Baltic Sea is highly influenced by later erosion of the Pleistocene glaciers. They appear first abundantly in various Jaagarahu (Wenlock) units offshore Saaremaa as minor solitary reefs together with a wide (~8 km) barrier reef-like formation made up of the largest solitary reefs (~ 4 km in diameter) below the Baltic Sea. The coeval reef facies, being widespread on northern Gotland, has been obviously eroded off the island, from a wide area around the Fårö Deep. Migration of the Jaagarahu barrier-reef towards Gotland, like missing the Rootsiküla (latest Wenlock) and reappearing Paadla (Ludlow) reefs nearby Saaremaa reverberate alternating regressive-transgressive cycles superimposed on a generally SSW-withdrawing Baltic Silurian basin.

The small, conical latest Wenlock and Ludlow catch-up reefs, which developed below the wave base, usually buried below younger Silurian rocks, dominate offshore of the southern half of Gotland. The coeval shallow shelf, high-energy lenticular reefs that are common on and off Saaremaa and on Gotland are largely eroded around Gotland Deep and the mid-Baltic Sea. They are partially preserved only around its less eroded northern slope off Middle Gotland where four distinct seismic units (Klinteberg and Hemse) with gradual southwards shift of back-reef lagoonal to fore-reef biohermal slope transect via a reef barrier were distinguished.

Reconstructing the environmental conditions around the Silurian Ireviken Event combining the carbon isotope composition of bulk and palynomorph organic matter and biomarker data

Thijs R.A. Vandenbroucke[1,2], Megan Rohrssen[3,4], Axel Munnecke[5], Olle Hints[6], Gordon D. Love[3], Woodward W. Fischer[7] and Poul Emsbo[8]

[1] *UMR 8217 du CNRS: Géosystèmes, Université Lille 1, France; Thijs.vandenbroucke@univ-lille1.fr*
[2] *Department of Geology, Ghent University, Belgium*
[3] *Department of Earth Sciences, University of California–Riverside, CA, USA*
[4] *School of Chemistry, Bristol University, UK*
[5] *Paläoumwelt, GeoZentrum Nordbayern, Universität Erlangen-Nürnberg, Germany*
[6] *Institute of Geology, Tallinn University of Technology, Estonia*
[7] *Department of Geological & Planetary Sciences, California Institute of Technology, CA, USA*
[8] *USGS, CMERSC, Denver Federal Center, Denver, CO, USA*

The carbon isotope composition ($\delta^{13}C$) of bulk organic matter and two palynomorph groups (scolecodonts and chitinozoans) from the Llandovery–Wenlock strata of Gotland (E Sweden) are compared to gain knowledge about carbon cycling in the Silurian (sub)tropical shelf environment. The $\delta^{13}C$ values of the palynomorphs are on average 1.3 to 0.7‰ lower than the $\delta^{13}C$ values of the bulk organic matter, with the $\delta^{13}C$ values of the benthic scolecodonts on average 0.6‰ lower than those of the planktonic chitinozoans (Vandenbroucke *et al.* 2013). The difference in carbon isotope composition between both groups of palynomorphs and bulk sedimentary organic matter may reflect the trophic state of the palynomorph source organisms, as well as differences in the composition and preservation of these organic microfossils relative to the bulk of sedimentary organic matter. Differences in carbon isotope composition between chitinozoans and scolecodonts at a given interval, however, may also yield insight into the changing ecological roles of the source organisms through time. Chitinozoans are thought to derive from heterotrophic plankton living in the well-mixed photic zone, whereas scolecodonts derive from polychaete worms, perhaps living as infaunal detritivores. The light $\delta^{13}C$ of scolecodonts in these samples may reflect a biosynthetic pathway, or effects of incorporating chemoautotrophic bacterial biomass during infaunal grazing, resulting in lighter carbon isotopes. Lower $\delta^{13}C$ for the scolecodonts in the middle of the section may represent variations in primary marine productivity (supported by acritarch abundance data), elevated polychaete grazing on chemoautotrophic bacterial biomass, oxidation of organic matter in the bottom waters, or genera effects. In general, however, trends between the three datasets are parallel, indicating similarities in the low frequency, environmentally forced controls. The $\delta^{13}C$ data (for scolecodonts in particular) show a decreasing trend from the base of the section, up to a horizon well below the base the Upper Visby Formation. At this level, and therefore probably several 10 kyrs before the $\delta^{13}C$ increase in the carbonates, the $\delta^{13}C$ organic values increase again by ca. 1‰. This perhaps is an expression of a changed composition of the bulk organic matter associated with the extinction events prior to the Llandovery–Wenlock boundary, or may relate to changes in the activity of chemoautotrophic bacteria. Intriguingly, acritarch census data and emerging biomarker data seem to indicate a fundamental change in primary producer assemblages at the same horizon.

Vandenbroucke, T.R.A., Munnecke, A., Leng, M.J., Bickert, T., Hints, O., Gelsthorpe, D., Maier, G. & Servais, T., 2013. Reconstructing the environmental conditions around the Silurian Ireviken Event using the carbon isotope composition of bulk and palynomorph organic matter. *Geochemistry, Geophysics, Geosystems*, 14, 86–101.

Mollusc shell microstructures through the Cambrian Radiation and Great Ordovician Biodiversification Event

Michael J. Vendrasco and Antonio G. Checa

Departamento de Estratigrafía y Paleontología, Universidad de Granada, Granada, Spain; mvendrasco@fullerton.edu

How and why do fine-scale structures in mollusc shells evolve? Is predation, seawater chemistry, or another factor most important? To help answer such questions, we have hunted for, found and documented many new cases of preserved shell microstructure in the earliest molluscs, from the Terreneuvian to the Late Ordovician. To organize and better mine all data on shell microstructures in Paleozoic molluscs, we have developed a relational database, to eventually become public. A preliminary synthesis of the early Paleozoic record supports the claim that changes in seawater chemistry influenced mollusc shell microstructures during their early history. For example, it appears calcite was more common in molluscs during Cambrian epochs 2 and 3, after the switch to a 'calcite sea'. But the data are also consistent with the hypothesis that the microstructure of the mollusc shell was likewise influenced by predation long before the Mesozoic Marine Revolution. For example, many of the earliest mollusc shells had a high proportion of organic matrix/mineral, but by the Late Ordovician these softer, more flexible shells had been replaced by more mineral-rich shells with tough microstructures such as nacre. Plus, in mollusc-like hyoliths, inner fibrous shell microstructures appear to have transitioned from disorganized to horizontally organized (e.g. lamello-fibrillar) to vertically organized (e.g. crossed lamellar), with each stage representing an increase in fracture resistance. Similar shell microstructure transitions are known for early mollusc lineages. By the Carboniferous, mollusc shell microstructures were distinctly modern. Nacre was common and many species had thick crossed lamellar layers. Evolutionary changes like these are expected if molluscs were keeping pace with increasingly efficient predators through the Paleozoic Era.

A new eurypterid Lagerstätte from the upper Silurian of Pennsylvania

***Matthew B. Vrazo*[1]*, Jeffrey M. Trop*[2] *and Carlton E. Brett*[1]**

[1] *Department of Geology, 500 Geology/Physics Building, University of Cincinnati, Cincinnati, Ohio 45221-0013, USA; vrazomb@mail.uc.edu, brettce@mail.uc.edu*
[2] *Department of Geology, O'Leary Center, Bucknell University, Lewisburg, Pennsylvania 17837, USA; jtrop@bucknell.edu*

Eurypterids are generally rare in the fossil record, but occasionally occur in abundance. The genus *Eurypterus*, in particular, is well known from certain upper Silurian *Lagerstätten* of the northern Appalachian basin (New York and Ontario), but occurs far less frequently in the central and southern Appalachian basin (Pennsylvania, Maryland and West Virginia, respectively) where it has been documented only a handful of times. The recent discovery of an exceptionally preserved mass assemblage of *Eurypterus* cf. *remipes* in the Tonoloway Formation (Ludlow/Pridoli) of Pennsylvania provides new information on the behavior and life habitat of the genus in this region. Eurypterids at this locality are found in thinly laminated, calcareous shale deposited within the lower intertidal to shallow subtidal zone of a coastal mudflat. Rare associated fauna of limited diversity, and evaporitic and desiccation features in associated beds, suggest a stressed environment with variable salinity. Most eurypterids are disarticulated and fragmentary, but several fully articulated, exceptionally preserved specimens were found. Exoskeletal features and taphonomic indices values indicate a molt, rather than death assemblage, and the presence of juveniles, in conjunction with arthropod trackways, suggests that *Eurypterus* sp. may have molted *en masse* in the vicinity of the burial site. Sequence stratigraphic interpretation of the site suggests that preservation of eurypterid remains is the result of occupation of preferred, but ephemeral environmental (salinity) conditions during a transgression. The occurrence of this new *Lagerstätte* within the upper Silurian succession of the central Appalachians, an interval which had previously yielded only rare fragmentary remains, indicates that eurypterids were more prevalent in this region than previously thought.

Preliminary report of a late Hirnantian shelly fauna in Shiqian, northeastern Guizhou, southwest China

Guangxu Wang and Renbin Zhan

State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, 39 East Beijing Road, Nanjing 210008, China; gxwang@nigpas.ac.cn, rbzhan@nigpas.ac.cn

It is believed that the lower – middle Hirnantian Kuanyinchiao Formation, which contains typical *Hirnantia* brachiopod fauna, was conformably underlain by black graptolitic shales and unconformably overlain by late Rhuddanian shales or mudstones in South China. Re-examination of several O-S boundary sections in Shiqian, northeastern Guizhou Province, southwest China suggests that approximately 1 m-thick limestone below the lower Silurian Lungmachi Formation, previously thought to be equivalent to the Kuanyinchiao Formation, is probably of late Hirnantian age and represents postglacial deposits. This horizon yields comparatively abundant shelly fossils, including tabulate and rugose corals, conodonts and stromatoporoids. Its age determination is mainly based on the tabulate corals proven to be with Silurian affinity, and its overlying strata corresponding to the *t* graptolitic biozone at a nearby section. Such new data will contribute to understand how these marine animals survived the second pulse of the end-Ordovician mass extinction.

Several key factors influencing *Cyrtograptus* Carruthers identification

Wang Jian, Wang Xin, Zhang Ju, Fu Lipu, Meng Yong and Li Rongshe

Xi'an Center Geological Survey, China Geological Survey, Xi'an Youyidonglu, Rd. 438, 710054, China; wangjian_7610@163.com, 27906810@qq.com, zhangju.0331@163.com, xaMyong@gov.cn, xaFlipu@gov.cn, xaLirongshe@gov.cn

The genus *Cyrtograptus* Carruthers, 1867 (Boucek 1933) may be diagnosed as follows: Rhabdosome consisting of one main stipe and one or more thecal cladia without sicular cladia. The main stipe generally logarithmically spirally coiled (Huo 1986), helically in the proximal part, less curved in the distal part, sometimes thecal cladia. Thecal cladia producing secondary and higher order cladia. Thecae of the monograptid type generally have one or two lateral apertural spines (Ge 1994). The characteristics of the genus *Cyrtograptus* are readily differentiated from other genera, although incomplete fragments or immature specimens are not easy to distinguished from *Monograptus*. A further problem is the confusion of one species for another, so it's important to study more factors to differentiate. When studying *Cyrtograptus* of China, the authors analysed multiple aspects of the specimens as follows:

Theca is the most important part of rhabdosome, because every sample contain theca, but sicula of mature specimens are not always preserved. There are not many samples to study *Cyrtograptus* sicula, which is usually regarded as the starting point of the rhabdosome, such as exactly judging the location of the first cladium. In the same rhabdosome, proximal and distal thecae are different. There are long thecal spines in some species, such as *Cyrto. sakmaricus*. Two theca repeat distance (2TRD) is one of the important indicators for comparison. The location of the first cladium is regarded as key factor, for example, there are more thecae in *Cyrto. insectus* and less in *Cyrto. centrifugus*. Initial curvature of the primary stipe appears different in different species, for example, *Cyrto. sakmaricus* has a tighter proximal part than *Cyrto. insectus*, but there is not any rotating in *Cyrto. lundgreni*. The width of the same species are relatively stable, even in the same larva and adult, such as *Cyrto. sakmaricus* (Wang et al. 2014). The main stipe of the rhabdosome shows different widths in different species, for example, *Cyrto. centrifugus* and *Cyrto. lundgreni.* Different species have different number of cladia, for example *Cyrto. sakmaricus* has much more caladium than *Cyrto. centrifugus*. This characteristic reflects the number of theca between adjacent cladia. Some species have the second or more order cladia and the others have only the first, for example, *Cyrto. murchisoni* and *Cyrto. sakmaricus.*

According to the above analysis, the author thinks that all the factors that influenced *Cyrtograptus* identification can be sorted as follows: (1) the form of theca; (2) the proximal rotation of rhabdosome; (3) the number of cladia; (4) the width of main stipe; (5) the location of the first caladium; (6) the number of theca between adjacent cladia; (7) the stretching direction of main stipe; (8) having the second order caladium; (9) the form of sicula; (10) having thecal spine.

Acknowledgments. This paper is a contribution to the Science and Technology Department of Foreign Affairs, China Geological Survey Project 1212011120144 and 1212011120142, the National Natural Science Foundation of China (No. 41302006) and the IGCP Project 591 "The Early to Middle Paleozoic Revolution".

Boucek, B., 1933. Monographie der obersilurischen Graptolithen der familie Cyrtograptidae. *Trav. Inst. Geol. Paleont. Univ. Chales Praha*, 1, 1–84.

Huo, S., 1986. A mathematical study of the *Cyrtograptus sakmaricus* lineage with discussions of the evolutionary trends in this lineage. *In:* Hughes, C.P. & Rickards, R.B. (eds). Palaeoecology and Biostratigraphy of Graptolites. *Geological Society Special Publication*, 20, 197–205.

Ge, M., 1994. *Cyrtograptus* of China. *In:* Chen Xu, B.-D. Erdtmann and Ni Yunan (eds). *Graptolite Research Today*, 101–112.

Wang, J., Štorch, P., Wang, X., Zhang, J., Meng, Y., Fu, L. & Li, R., 2014. C*yrtograptus sakmaricus* Koren' from Langao, Shaanxi Province, China. *GFF*. doi: 10.1080/11035897.2014.888472.

A link in the chain of the Cambrian zooplankton: bradoriid arthropods invade the water column

Mark Williams[1], Vincent Perrier[1], Thijs R.A. Vandenbroucke[2], David J. Siveter[1] and Thomas Servais[2]

[1] *Department of Geology, University of Leicester, University Road, Leicester, Leicester, LE1 7RH, United Kingdom; mri@le.ac.uk*
[2] *UMR 8217 du CNRS: Géosystèmes, Lille1University, Villeneuve d'Ascq, 59655, France*

Bradoriids were small arthropods with a bivalved carapace and they possessed a global distribution for about 20 million years beginning about 521 Ma (onset of Cambrian Epoch 2). Most bradoriids were benthic, as signaled by their anatomy, lithofacies distribution, faunal associates, and strongly provincial signal. Evidence for a well-developed circulatory system that resembles those of modern myodocopid ostracods, suggests that many bradoriids had an active lifestyle, and they clearly favoured oxygenated seas, with an environmental range exclusive of the dysoxic facies occupied by phosphatocopid arthropods. Most bradoriids were extinct by the end of the Drumian Age (mid Cambrian Epoch 3). The post-Drumian interval is characterized by widespread dysoxic shelf facies in Britain and Scandinavia and by the abundance of phosphatocopids. Co-occurring with the phosphatocopids in black mudstone lithofacies is the large (adults greater than 5 mm long) bradoriid *Anabarochilina primordialis*, which possessed a latitudinal range from the tropics to high southern latitude. Its wide environmental and geographical range, coupled with a carapace morphology that indicates possession of a circulatory system, and an active mode of life in well-oxygenated waters, indicates that it was zooplanktonic. The earliest *Anabarochilina* species (from Cambrian Epoch 2) appear to have been shelf marine and benthic. Given a benthic antecedent, what anatomical, physiological and environmental feedbacks facilitated the passage of *Anabarochilina* into the water column? Further, does it display a pattern of zooplankton colonization that is replicated in colonization events by other arthropod zooplankton in the Palaeozoic? The presence of *Anabarochilina* in the water column signals a macro-zooplankton tier in Cambrian food webs.

Middle Ordovician *Saucrorthis* fauna: Implications for the great Ordovician biodiversification event (GOBE)

Renbin Zhan, Xiaocong Luan, Guangxu Wang and Yan Liang

State Key Laboratory of Palaeobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, China; rbzhan@nigpas.ac.cn

The Middle Ordovician *Saucrorthis* fauna is a brachiopod fauna characterized by the small-shelled, costate eponymous genus, and the predominance of some orthides and strophomenides such as *Orthambonites*, *Parisorthis*, *Leptellina*, *Calyptolepta*, etc. Although being recognized as a typical regional fauna known in South China, Sibumasu and northern Iran, the *Saucrorthis* fauna has its longest geological range (the whole Darriwilian), widest geographic and palaeogeographic distribution, most abundant constituents, and most complicated palaeoecological differentiation in South China covering an area of thousands kilometers long and wide (the Upper Yangtze Platform) from nearshore shallow water to offshore deeper water benthic settings. Palaeoecologically, the brachiopod constituents of the *Saucrorthis* fauna are various in shell sizes ranging from tiny shells smaller than 3 mm long and wide, such as *Leangella*, *Protoskenidioides* and some *Saucrorthis* itself, to medium to large shells even over 30 mm, such as Porambonites, *Yangtzeella*, etc. The typical cool water trilobite *Neseuretus* is found to be associated with this fauna at some localities in northern Iran and Sibumasu. Hence, it is suggested that the *Saucrorthis* fauna might live in a deeper benthic environment with a cooling climate. Macroevolutionarily, the origin and flourishing of the *Saucrorthis* fauna represents the second pulse (diversity acme) of the great Ordovician biodiversification event (GOBE) of brachiopods in South China, which was just consistent with the first brachiopod diversity acme on a global scale.

Multivariate and cladistic analyses were conducted on some representatives of the *Saucrorthis* fauna in South China, Sibumasu and northern Iran using another Darriwilian brachiopod fauna from southern Tibet (the *Aporthophyla* fauna) as an outgroup. It shows that there are more than 50 brachiopod genera involved, amongst which more than 70% are confined to just one locality, and none of the genera are known to occur in three localities or more. Except for the eponymous genus, there are very few common constituents between any two representatives of the *Saucrorthis* fauna. In other words, there are no common constituents for this fauna except *Saucrorthis* itself. The similarity coefficient between any two representatives of the *Saucrorthis* fauna is rarely over 0.5 in CA diagram, and all representatives are widely scattered in the PCA diagram. So, in South China, strong endemism made a great contribution to the second pulse of the Ordovician brachiopod radiation, which might also be true to the international trend.

Geographic distribution of the Kuanyinchiao Formation (Hirnantian) in South China and its paleogeographic implications

Linna Zhang[1,2], Junxuan Fan[2] and Qing Chen[3]

[1] *Graduate University of Chinese Academy of Sciences, Beijing 100049, China; zhanglinna88@gmail.com*
[2] *State Key Laboratory of Palaeobiology and Stratigraphy, NIGPAS, Nanjing 210008, China; fanjunxuan@gmail.com*
[3] *Key Laboratory of Economic Stratigraphy and Palaeogeography, NIGPAS, Nanjing 210008, China; qchen@nigpas.ac.cn*

The Hirnantian Epoch, approximately 2 myr long, is an important geological time interval that recorded significant geological and evolutionary events of the latest Ordovician. During this interval, the Kuanyinchiao Formation was widely deposited in South China, especially in the Upper Yangtze region, which yields a diverse *Hirnantia* shelly fauna (Rong 1979). The Kuanyinchiao Formation is mainly composed of grey limestone and calcareous mudstone. It usually conformably overlies the Wufeng Formation and conformably underlies the Lungmachi Formation, both of which are composed mostly of black shales and are significant source rocks for oil and gas. However, both the base and top boundaries of the Kuanyinchiao Formation are slightly diachronous (Rong *et al.* 2002). Quantitative reconstruction of the distribution of the Kuanyinchiao Formation is essential for our understanding of its temporal and spatial distribution.

The distributions of the Kuanyinchiao Formation were reconstructed in both two- and three- dimensions based on nearly 100 sections in the Upper Yangtze region by using the ArcGIS software. We can get the following conclusions at present. First, the thickness of the Kuanyinchiao Formation in the Upper Yangtze region is relatively small, mostly less than 1m. The region with larger depositional thickness lies in the north of the Guizhou Province and in the southeastern corner of the Chongqing City, both of which are very close to the Central Guizhou Oldland. The thickness decreases gradually to the north. Second, the contour map of the thickness shows a stripped distribution from east to west, which is parallel with the paleocoastline.

Rong, J.Y., 1979. The *Hirnantia* fauna of China with the comments on the Ordovician-Silurian boundary. *Acta Stratigraphica Sinica*, 3, 1–29. [in Chinese]

Rong, J.Y., Chen, X. & Harper, D.A.T., 2002. The latest Ordovician *Hirnantia* Fauna (Brachiopoda) in time and space. *Lethaia*, 35, 231–249.

Rare earth and trace elements in fossil vertebrate biomineral as indicators of palaeoecology and palaeoenvironment

Živilė Žigaitė[1], Alexandre Fadel[1,2], Henning Blom[1], Alberto Pérez-Huerta[3], Teressa Jeffries[4] and Per E. Ahlberg[1]

[1] Subdepartment of Evolution and Development, Department of Organismal Biology, Uppsala University, Norbyvägen 18A, 752 36 Uppsala, Sweden; zivile.zigaite@ebc.uu.se
[2] Laboratoire Géosystèmes, Université Lille 1, CNRS UMR8217, Villeneuve d'Ascq 59655, France
[3] Department of Geological Sciences, University of Alabama, 2018 Bevill Building, Tuscaloosa, AL 35487, USA
[4] Imaging and Analysis Center, Science Facilities Department, Natural History Museum, Cromwell Road, London SW7 5BD, UK

Rare earth and trace element compositions have been studied in a range of early vertebrate micromeric dermoskeletal remains from Silurian and Devonian deposits of Northern Europe. The results suggest that the REE patterns in fossil bioapatite do not show any recognizable specific taxonomic behavior, but have rather well-expressed differences of REE compositions in relation to the internal histology and biomineral structure of vertebrate scales, the taphonomic conditions, and early diagenetic history. The potential of Europium (Eu) and Cerium (Ce) anomalies to reveal taphonomic and palaeoenvironmental regimes have been assessed through the range of thelodont and chondrichthyan taxa. The shale normalized compilation of Lanthanum (La) and Ytterbium (Yb), and La and Samarium (Sm) ratios proved to be indicative of terrestrial freshwater influence during the stages of early diagenesis, while the bell-shaped REE patterns referred to typical marine environment. Altogether, REE and trace element geochemistry from the analysed vertebrate fossils suggests its ability to indicate: (1) geological age difference between sympatric taxa (2) long-distance depositional reworking, and (3) stratigraphical reworking. As concerns the inter-taxon and inter-specimen compositional differences, there was no evidence of taxon-specific REE uptake in the microfossils analysed. In contrast, the REE and trace element uptake appeared to be tissue-selective, and their concentrations in the bioapatite of enamel were significantly lower than those recorded in the dentine.

Author index

4th Annual Meeting of IGCP 591

The Early to Middle Paleozoic Revolution

Estonia, 10-19 June 2014

Field Guide

Pre-conference excursion: Ordovician of Estonia

10 – 12 June 2014

Post-conference excursion: Silurian of Estonia

16 – 19 June 2014

Estonia – a Palaeozoic country

Tõnu Meidla

Department of Geology, University of Tartu, Estonia

Estonia lies on the southern slope of the Fennoscandian Shield where the thickness of the sedimentary cover is gradually increasing southwards. The northern border of the distribution of the sedimentary cover roughly divides the Gulf of Finland into the Shield and platform parts.

The main features of the regional crustal structure were formed during the Svecofennian orogeny. Estonia is located in the area of a relatively thick crust (46–51 km, decreasing to 41–44 km in Saaremaa, Puura & Vaher 1997). Most of the crystalline basement comprises the Palaeoproterozoic (1.8–1.9 Ga) Svecofennian orogenic complex, subjected to high-grade metamorphism. The gneisses of amphibolite facies in northern Estonia represent an extension of the major structural units of southern Finland.

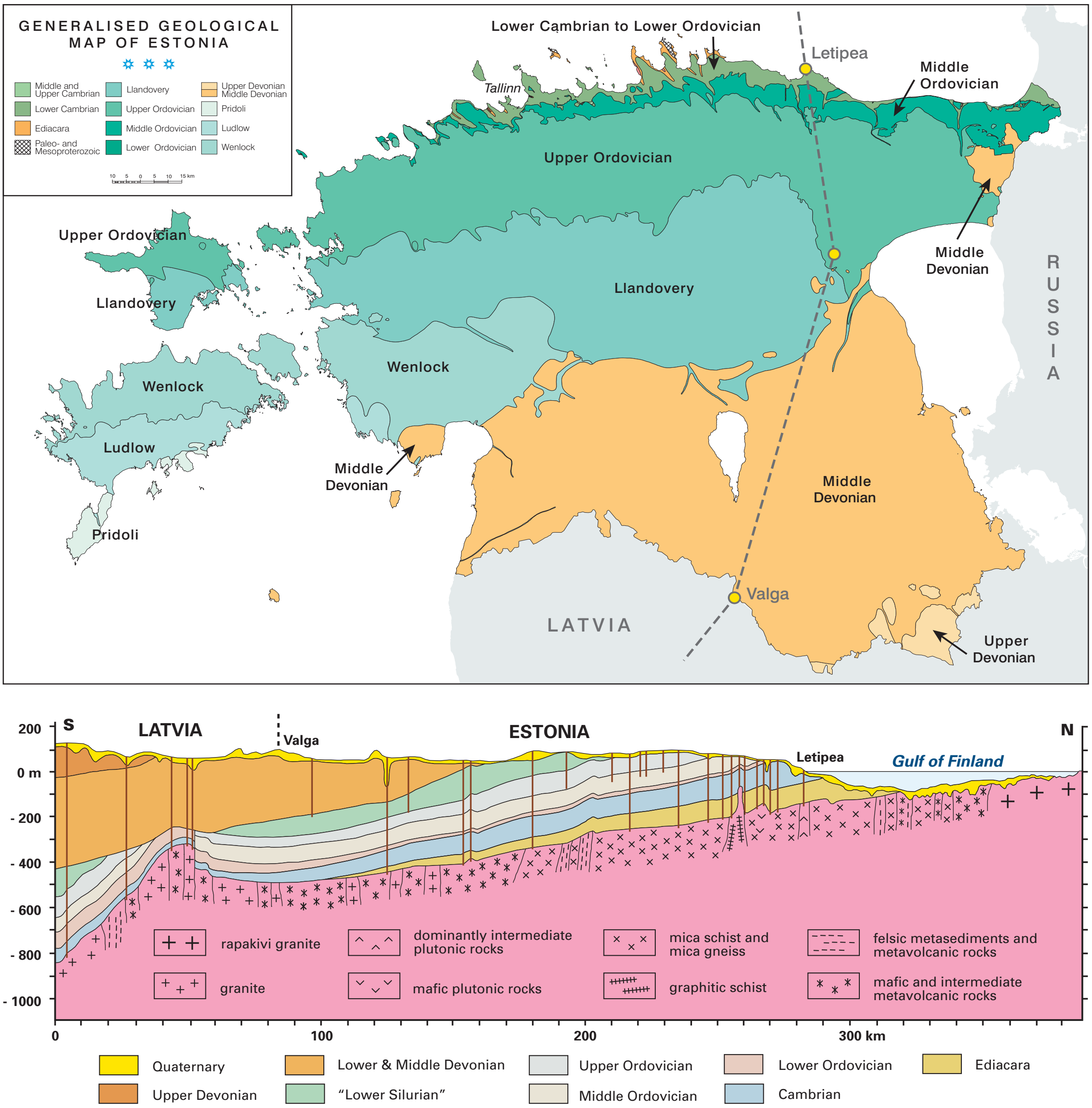


Fig. 1. Generalised geological map of Estonia with a cross-section (after Puura & Vaher 1997), showing outcrop areas of lower and middle Paleozoic rocks as well as a southward dip of Proterozoic crystalline basement (the map is compiled by the Estonian Geological Survey; http://www.egk.ee).

The metamorphic complexes in southern Estonia comprise granulite facies gneisses belonging to the Belarussian – Baltic granulite subdomain (Puura 1997). The Svecofennian 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 in Saaremaa (Puura et al. 1997). The crystalline basement was subjected to long-lasting erosion (1.4 – 0.6 Ga) that resulted in the formation of a peneplane. The sedimentary units and magmatic rocks from this period, although known in other parts of the Svecofennian region, are not found in Estonia. The crystalline rocks occasionally display evidence of weathering that may reach up to a depth of 100 m into the basement (Puura 1997; Puura & Vaher 1997b).

The weathered surface of the crystalline basement is covered with the Ediacaran – Devonian sedimentary succession. The sedimentary cover, mostly comprising the Lower – Middle Palaeozoic, is already 100 m thick in northernmost Estonia, less in northern near-coastal islands and over 800 m in southeastern Estonia (Puura & Vaher 1997b). This nearly regular change in the thickness of the sedimentary cover reflects southward dipping of the upper surface of the crystalline basement. Although the bedding of the sedimentary bedrock in Estonia looks nearly horizontal or displays minor local deformations, it is still generally dipping at 8 – 15′ (about 2 – 4.5 m/km) to the south. In the geological map (see illustration on the back cover of this volume) the outcrop belts of the series and stages display a roughly west – east oriented pattern.

Because of the prevailing age of the sedimentary rocks Estonia is often called "a Palaeozoic country". The Ediacaran (previously referred to as the Vendian Complex of the Vendian System) occurs in the subsurface of northern, northeastern and eastern Estonia. This unit bears a signature of relatively cool-water sedimentation as the Baltica Palaeocontinent was located in high latitudes in the late Ediacaran (Cocks & Torsvik 2005) and sandstones and clays are prevailing in Estonia.

The overlying Cambrian is distributed nearly all over Estonia. The rocks are predominantly sandstones, except for the lowermost Cambrian that comprises the Blue Clay, the silty clay unit of great thickness. The Cambrian rocks, mostly sandstones, crop out in several coastal sections, whilst clays are mainly exposed in clay pits near the northern Baltic coast.

Sandstones and some clay-rich formations, all in a very limited thickness, are also characteristic of the Lower Ordovician. The Middle and Upper Ordovician are represented by various limestones that are locally dolomitized and contain very thin volcanic interbeds (K-bentonites) at several levels. A specific feature of northeastern Estonia is the presence of early Late Ordovician kukersite oil shale. The Upper Ordovician marks a transition from cool-water to tropical carbonate sedimentation as the Baltica Palaeocontinent reached the southern tropical latitudes (Cocks & Torsvik 2005). The Ordovician rocks are well exposed in coastal outcrops and escarpments, active pits and quarries of different age. However, the Upper Ordovician outcrops display only a limited part of this unit that occasionally may reach about 100 m. The signature of the Hirnantian glaciation is recorded in the sedimentary succession of Estonia but is more clearly observable in the subsurface because of a gap in the outcrop area caused by the glacioeustatic sea level drop.

The Silurian System has a more limited distribution in Estonia. The Llandovery is still widely common in the mainland of Estonia (except for its northern, eastern- and southernmost parts) and in western islands, but the distribution areas of younger series are shifted to the southwest and the Přidoli is restricted to a very small area only in southern Saaremaa. The limestones and dolomites bear a signature of tropical sedimentation and limited volcanic activity in the neighbouring areas. The rocks are relatively well exposed in Saaremaa Island and in smaller islands, but locally also in the mainland. The exposures, however, demonstrate only a minor part of the total succession reaching over 400 m.

The distribution of the Devonian System is restricted to southern Estonia, except for a small "island" in northeastern Estonia where the Middle Devonian domerites and sandstones of very limited thickness overlie the Upper Ordovician kukersite oil shale deposit. The Devonian succession is mainly composed of sandstones. An exception is the carbonate lowermost Upper Devonian that is of very limited distribution in southeastern Estonia. The lower Devonian occurs only in the subsurface in a narrow area in South Estonia. The Middle and Upper Devonian are often exposed in river valleys of South Estonia and in occasional sand and clay pits.

The initial thickness of the sedimentary cover seems to have been higher. The total thickness of the Ordovician, Silurian and Devonian sedimentary strata in North Estonia may have reached 1000 m, whilst the maximum sediment load was obviously reached in the Late Devonian (Kirsimäe *et al.* 1999). The succeeding very long erosional period resulted in bedrock topography that displays cores of some major uplands observable in modern topography, as well as the depressions of the Gulf of Finland and lakes Peipsi and Võrtsjärv (Tavast 1997). The Quaternary glaciation was the last stage of erosion of the sedimentary bedrock. The glaciers removed an up to 60 m layer from the bedrock surface (Tavast 1997), which leaves almost no chance of discovering any strata in Estonia that are younger than the Devonian or older than the Quaternary.

The accumulation of Quaternary sediments during the Pleistocene and Holocene resulted in the formation of a nearly continuous layer of glacial, glacifluvial and glaciolacustrine sediments, covered with various Holocene deposits that are mostly thin and have 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. Locally the thicknesses may be over 200 m, whilst the thicknesses over 100 m are fairly common in South Estonia (Haanja and Otepää heights) and in the Gulf of Finland (Raukas & Kajak 1997). The bedrock topography, uneven thickness of the Quaternary cover and postglacial land rise have shaped the modern topography of Estonia. The average height of the area is about 50 m a.s.l., and 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., whilst its relative height is only about 60 m (Raukas 1997). 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 forming a discontinuous 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 that 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 drinking water consumed in Estonia in the mid-1990s (Vallner & Savitskaja 1997). Middle–Upper Ordovician, Silurian and Upper Devonian carbonate rocks are nowadays widely exploited in numerous quarries. Sand, gravel and peat deposits are in active use. Other resources are less important.

References

Cocks, L. R. M. & Torsvik, T. H., 2005. Baltica from the late Precambrian to mid-Palaeozoic times: the gain and loss of a terrane's identity. *Earth-Science Reviews*, 72, 39–66.

Kirsimäe, K., Jørgensen, P. & Kalm, V. 1999. Low-temperature diagenetic illite-smectite in Lower Cambrian clays in North Estonia. *Clay Minerals*, 34, 151–163.

Puura, V. 1997. Basement features. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 163–167.

Puura & Vaher, 1997. Deep structure. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 163.

Puura, V. & Vaher, R. 1997b. Cover structure. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estoni*a. Estonian Academy Publishers, Tallinn, 167–177.

Puura et al., 1997. Precambrian basement. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 27–34.

Raukas, A. 1997. Location and topography. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 9–14.

Raukas, A. & Kajak, K. 1997. Quaternary cover. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 125–136.

Tavast, E. 1997. Bedrock topography. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 252–255.

Vallner, L. & Savitskaja, L. 1997. Groundwater extraction and safe yield. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 159–162.

The Ediacaran and Cambrian systems in Estonia

Tõnu Meidla

Department of Geology, University of Tartu, Estonia

The formation of the sedimentary cover in the area of Estonia started in the late Ediacaran. Ediacaran sediments (previously referred to as the Vendian Complex of the Vendian System) are distributed in northern, northeastern and eastern Estonia. The maximum thickness of the strata that are attributed to the Valdai Group is about 123 m in the northeasternmost part of their distribution area in Estonia (Mens & Pirrus 1997). Ediacaran strata occur in Estonia in the subsurface only. The closest outcrops are known in the westernmost Leningrad Region and Kotlin Island, in the eastern part of the Gulf of Finland.

This unit has traditionally been considered a product of cool-water sedimentation as the Baltica Palaeocontinent was located in intermediate southern latitudes in the late Ediacaran (Cocks & Torsvik 2005). According to Pirrus (1992) and Grazhdankin *et al.* (2005), the climate was humid. No carbonates are known in the Ediacaran of Estonia and neighbouring areas.

The lowermost part of the Ediacaran sedimentary succession is largely composed of material derived from the weathering crust of the crystalline basement and redeposited in the nearshore zone of a huge water body transgressing from the east. The lower part of the Ediacaran comprises a unit of immature quartz-feldspar sandstone that represents also the most widely distributed part of the Ediacaran succession. This unit is overlain by a succession of laminated greenish-grey claystone intercalated with light-coloured very fine sand- and siltstones rich in quartz and K-feldspar. The dominant clay mineral is illite, but kaolinite and, to a lesser extent, illite-smectite and chlorite are also present (Raidla *et al.* 2006). The laminated clays grade into a relatively mature sandstone unit (less than 10% of feldspar) and the proportion of kaolinite is increasing in its upper part (Mens & Pirrus 1997).

Based on a sparse record of acritarchs and presumable algae (*Vendotaenia*, *Aataenia*) from its middle, clay-rich part, the Ediacaran succession in Estonia is attributed to the Kotlin Stage. Considering the age estimates for the base of the Valdai Group (about 570 Ma, Semikhatov 2000), we may suppose that the Ediacaran succession in Estonia represents a relatively small segment of the upper Ediacaran.

The Cambrian System is distributed in nearly all of Estonia, with its thickness reaching about 150 m (in Saaremaa, Rõõmusoks 1982). The general Ediacaran palaeogeographic pattern persisted in the Terreneuvian. The emerging four-fold subdivision of the Cambrian System (Babcock *et al.* 2005) has not yet been correctly adopted to the Cambrian of Estonia but the second (unnamed) series seems to correspond approximately to the interval of the Dominopol' to Rausvė stages.

The Cambrian System lies over the Ediacaran with a substantial gap comprising the Rovno Stage (Mens & Pirrus 1997). The Cambrian succession begins with the Blue Clay (Lontova Formation), an extensive unit of silty illitic clays, laterally grading into a unit of interbedded claystones and sandstones in the western islands of Estonia. Upwards the claystone slowly grades into silt- and sandstones that represent the dominating rock type in the Cambrian of Estonia. The succession of sandstones seems to be relatively continuous in the second (unnamed) series of the Cambrian (though minor gaps have been reported), particularly in West Estonian islands, but higher up only rare sandstone lenses have occasionally been preserved. The sandstones are often poorly fossiliferous but based on the correlation with the sedimentary succession in Latvia that is better dated, the presence of both the third (unnamed) series and the Furongian Series can be established at least in some parts of Estonia (Mens & Pirrus 1997).

In the lower–middle parts of the Cambrian, the clay-rich units are fossiliferous at some localities. The most diverse assemblage is known in the Lontova and Lükati formations (Mens & Pirrus 1977, 1997), containing sabelliditids, platysoleniids, archegastropods and other groups, often problematic. The pure sandstones of the same interval are characterized by a scanty fossil record or may occasionally be unfossiliferous. The fossil record improves in the Furongian where conodonts make their appearance and linguliformean brachiopods are common.

The succession of the Cambrian–Ordovician boundary strata is the most representative in North Estonia, in the vicinity of Tallinn, where several sandstone units underlie the Kallavere Formation, the famous phosphorite-bearing formation that formerly was entirely attributed to the basal Ordovician. The lower boundary of the Ordovician System is currently drawn at the appearance level of the conodont species *Cordylodus lindstroemi* (Puura & Viira 1999) and lies within the Kallavere Formation. According to the new boundary version, the phosphatic brachiopod coquinas that occur in the lower part of the formation in the vicinity of Tallinn are currently attributed to the Cambrian (Heinsalu & Viira 1997).

The Cambrian System is the oldest part of the sedimentary succession that crops out in Estonia. The Cambrian rocks, mostly sandstones, are exposed in several coastal sections, whilst the clays are exposed predominantly in old and active clay pits near the northern coast of Estonia.

References

Babcock, L.E., Peng, S.C., Geyer, G. & Shergold, J.H., 2005. Changing perspectives on Cambrian chronostratigraphy and progress toward subdivision of the Cambrian System. *Geoscience Journal*, 9, 101–106.

Cocks, L. R. M. & Torsvik, T. H., 2005. Baltica from the late Precambrian to mid-Palaeozoic times: the gain and loss of a terrane's identity. *Earth-Science Reviews,* 72, 39–66.

Heinsalu, H. & Viira, V., 1997. Pakerort Stage. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 52–58.

Mens, K. & Pirrus, E., 1977. *Stratotype sections of the Cambrian of Estonia*. Valgus, Tallinn, 1–68. [in Russian].

Mens, K. & Pirrus, E., 1997. Vendian. Cambrian. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 25–51.

Pirrus, E., 1992. Freshening of the late Vendian basin on the East European Craton. *Proceedings of the Estonian Academy of Sciences. Geology*, 41, 3, 115–123.

Raidla, V., Kirsimäe, K., Jõeleht, A., Bityukova, L., Shogenova, A. & Šliaupa, S., 2006. Lithology and diagenesis of the poorly consolidated Cambrian siliciclastic sediments in the northern Baltic Sedimentary Basin *Geological Quarterly*, 50, 4, 395–406.

Rõõmusoks, A., 1982. *Eesti aluspõhja geoloogia*. Tallinn,Valgus, 1–224. [in Estonian].

Semikhatov, M.A., 2000. Refined Isotopic Ages of Lower Boundaries of the Upper Riphean, Vendian, Upper Vendian and Cambrian, *In: Dopolneniya k stratigraficheskomu kodeksu Rossii. Dopolnenie 4 (Supplements to the Stratigraphic Code of Russia. Supplement 4)*, St. Petersburg, Vseross. Geol. Inst., 95–107.

The Ordovician System in Estonia

Tõnu Meidla[1], Leho Ainsaar[1] and Olle Hints[2]

[1]*Department of Geology, University of Tartu, Estonia*

[2]*Institute of Geology at Tallinn University of Technology, Estonia*

Ordovician rocks are widespread in the Baltoscandian region. The main distribution area of Ordovician strata in the East European Platform extends from the Baltic Sea islands in the west to the vicinity of Moscow in the east and from the Gulf of Finland 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 the magnificent sections of the Baltic–Ladoga Klint, in other coastal and river bank sections, old and new limestone quarries and open-cast pits of northern Estonia and northwestern Russia. Good accessibility of geological exposures and excellent preservation of fossils and sedimentary structures attracted the attention of investigators already in the early 19th century when the strata were described and figured by O. M. L. v. Engelhardt (1820), W. Strangways (1821), E. Eichwald (1825) and others. The researchers have been interested in the characteristic Cambrian to Middle Ordovician succession, represented by several distinctive rock units (the Cambrian Blue Clay, phosphatic brachiopod coquina, *Dictyonema* argillite, dark green glauconite sandstone and a wide variety of limestone units above).

The main features of the Ordovician stratigraphy were first outlined by F. Schmidt in his thorough monographic paper of 1858. The general pattern of his geological map, presented in the same volume, is well recognized in the modern geological maps of the bedrock of Estonia. The generally simple geological structure of the area, with almost horizontal strata, only 2–5 m/km dipping to the south, results in nearly latitudinal orientation of the outcrop belts of the Ordovician stages in northern Estonia (see the geological map of Estonia on the back cover of the present volume).

The main part of the Ordovician succession in northern Estonia is composed of limestones, with some intercalations of kukersite oil shale concentrated mainly in the Kukruse Stage. Only the basal Ordovician strata comprise a relatively thin succession of clastic sediments – sandstones, argillites and clays of the Pakerort and Varangu stages, overlain by the glauconitic sand- and siltstones of the Hunneberg and Billingen stages. The transition from the terrigenous to carbonate rocks in the Billingen Stage is marked by the appearance of calcareous interbeds in the siltstones, which grade into the first limestone/dolomite unit, the Toila Formation. 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 cold-water carbonates deposited in a sediment-starving shallow marine basin. The sedimentation rates have increased upwards. Changes in sedimentation rates in the calcareous main part of the Ordovician succession are in obvious correlation with the carbonate production rates. The corals make their first appearance in the Upper Ordovician, and the first carbonate buildups can be recorded in about the same interval, emphasizing a striking change in the overall character of the palaeobasin.

Generally the 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 & Einasto 1997). During the Middle and Upper Ordovician the climatic change resulted in an increase in the carbonate production and sedimentation rate on the carbonate shelf, whereas the deposition pattern was controlled by the accommodation space available there.

The details, but also the problems of the Ordovician geology in the subsurface area in central and southern Estonia were first revealed only in the 1950s. A large number of drill cores, obtained in the course of an extensive drilling programme in the 1950s–1980s, revealed a marked difference between the stratigraphic successions in the outcrop area and southern Estonia. 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. As the term "confacies" is unique (being exclusively used for the Ordovician of Baltoscandia), a different terminology that is widely applied in newer publications has been introduced by Harris *et al.* (2004; Fig. 1). The micropalaeontological and macrofaunal studies of the core sections have also revealed the distinctive biogeographic differentiation pattern, characteristic of the Ordovician rocks (e.g. Männil 1966; Männil *et al.* 1968; Männil & Meidla 1994; Meidla 1996). Although the biofacies pattern is 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; Tuuling & Floden 2013 and references therein), but also new detailed (micro-)palaeontological investigations (*e.g.* Tinn & Meidla 2001) might produce valuable new information in this field.

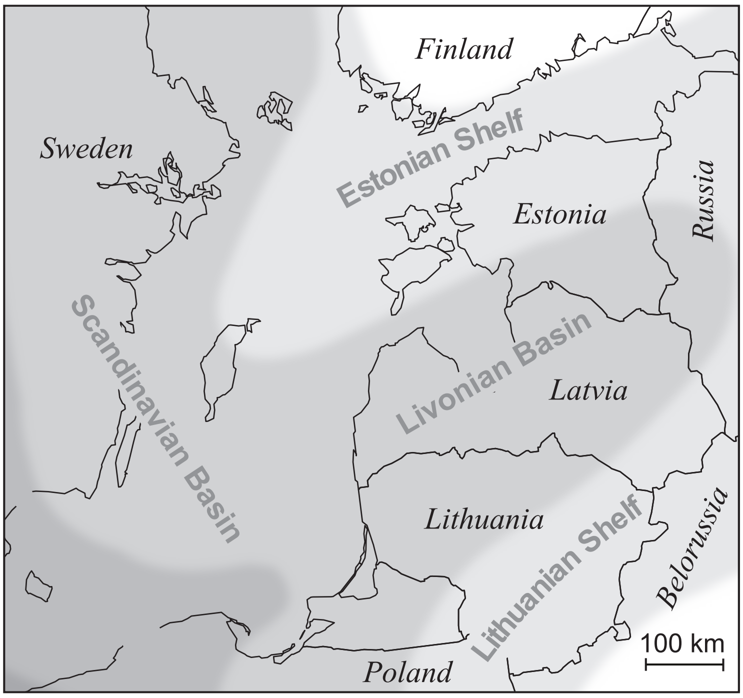


Fig. 1. Post-Tremadocian Ordovician facies zonation.

The total thickness of the Ordovician in Estonia varies from 70 to 180 m, being greatest in central and eastern Estonia and considerably less in the outcrop area, as well as in the southwestern mainland of Estonia.

Several correlation problems still persist in the Ordovician of Estonia, due to marked biofacies differences between northern and southern Estonia. In part, they are discussed also in a recent monographic overview of Estonian geology (see Heinsalu & Viira 1997, Meidla 1997, Hints 1997, Hints & Meidla 1997 in Raukas & Teedumäe 1997). During the last years the application of the stable carbon isotopic zonation (Ainsaar *et al.* 2010) has opened new opportunities to solve still persisting problems in regional stratigraphy.

The term "Stage", first employed by Bekker (1921), has become the principal category in the chronostratigraphic classification of the Ordovician System in Estonia. 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 introduced for Estonia by Bassler (1911). A number of regional series and subseries for the Ordovician System in Estonia and neighbouring Russia were brought into use by Schmidt (1881) and several subsequent authors. Raymond (1916) applied the traditional American three-fold subdivision of the Ordovician System to 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 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 & Meidla 1994 and Nõlvak *et al.* 2006 for a summary), but they are very rarely used today and the well-established framework of the Ordovician System has in fact replaced the regional suprastadial units in publications. The modern three-fold classification of the Ordovician System (IUGS 2013) was first used for the Estonian succession by Webby (1998) and is presented here in detail (Fig. 2).

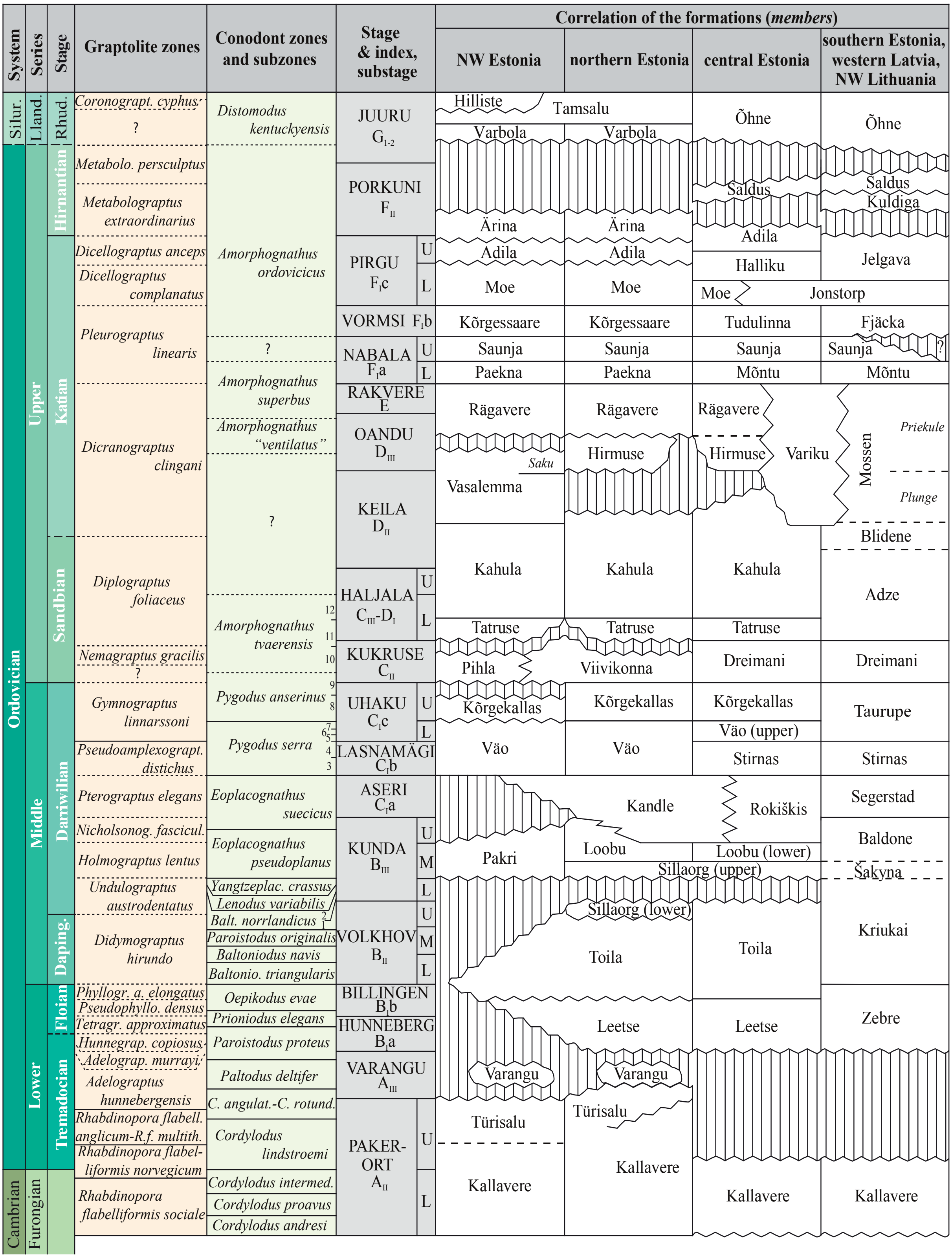


Figure 2. Ordovician stratigraphy of Estonia. Graptolite zonation according to Kaljo & Vingissaar, 1969, Kaljo *et al.*, 1986, Männil, 1976, Resheniya..., 1987, Männil & Meidla, 1994, Nõlvak *et al.*, 2006, conodont zones according to Kaljo *et al.*, 1986, Meidla, 1997 and Männik in Nõlvak *et al.*, 2006. 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; subzones of the *Pygodus anserinus* Zone: 8 – *Sagittodontia kielcensis* Subzone, 9 – *Amorphognathus inaequalis* Subzone; subzones of the *Amorphognathus tvaerensis* Zone: 10 – *Baltoniodus variabilis* Subzone, 11 – *Baltoniodus gerdae* Subzone, 12 – *Baltoniodus alobatus* Subzone.

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 Stage in Estonia turned out to be necessary. According to conodont data, the systemic boundary in the northern Estonian sections lies a few metres higher than previously suggested, i.e. in the middle of the Pakerort Stage, within the Kallavere Formation (Puura & Viira 1999). The lower boundary of the Silurian System has traditionally been drawn at the base of the Juuru Stage. The most recent results on the stable carbon isotopic chemostratigraphy disagree with this viewpoint and emphasize that the evidence behind this traditional solution is not convincing, arguing for a higher position of this boundary in the regional succession, within the Juuru Stage.

Main features of the chronostratigraphic (stage) classification of the Ordovician System were outlined already by Männil (1966). Only minor changes in stage nomenclature have been made in the later decades: the Ceratopyge Stage has been renamed the Varangu Stage (Männil 1990), the Latorp Stage replaced by the Hunneberg and Billingen stages (Hints *et al.* 1993) and a new unit, the Haljala Stage, has merged the former Idavere and Jõhvi Stages (following Jaanusson 1995 and Nõlvak 1997) that were difficult to distinguish outside northwestern Estonia. Hints & 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 Stage that also marks a faunal change in the succession. However, as stratigraphic hiatuses on the stage boundaries are very common in northern Estonia (and all remarkable faunal changes are usually related to hiatuses), wide usage of this concept for the stage boundaries in this area still seems rather complicated.

Graptolites are rare in the carbonate succession of Estonia. The Scandinavian graptolite zones are usually adopted for the correlation charts, although their correlation to the local succession is mainly based on indirect evidence as the local graptolite record is well resolved in some intervals only (the intervals of the Pakerort–Varangu and Uhaku–Kukruse stages (Kaljo & Kivimägi 1970, 1976; Kaljo *et al.* 1986; Männil 1966, 1976, 1987; Nõlvak *et al.* 2006; Fig. 2). Conodont zonation, however, has been elaborated in detail and is of very high resolution for the Lower and Middle Ordovician (see Fig. 2).

The elaboration of lithostratigraphic classification of the Ordovician rocks was initiated by Orviku (1940), who proposed the lithostratigraphic subdivision for the upper Middle Ordovician. This approach was widely accepted by subsequent authors and led to description of a very substantial number of formations and members and 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 & 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 & Meidla 1994). The correlation chart in Fig. 2 contains some recent improvements compared to this publication, the most recent ones being introduced by Ainsaar & Meidla (2001) and Nõlvak *et al.* (2006). Some more modifications of the Ordovician correlation charts for Estonia have been published by Hints *et al.* (1993) and Nõlvak (1997). The composition and textures of the Ordovician carbonate rocks and main differences between the confacies belts were summarized by Põlma (1982 and references therein).

The monographic studies on the Ordovician palaeontology started already in the 19th century. After the comprehensive review on 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 have been 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 monograph *Geology and mineral resources of Estonia* (Raukas & Teedumäe 1997; http://sarv.gi.ee/geology/).

References

Ainsaar, L. & Meidla, T., 2001. Facies and stratigraphy of the middle Caradoc mixed siliciclastic-carbonate sediments in eastern Baltoscandia. *Proceedings of the Estonian Academy of Sciences. Geology*, 50, 5–23.

Ainsaar, L., Meidla, T. & Martma, T., 2004. The Middle Caradoc facies and faunal turnover in the Late Ordovician Baltoscandian palaeobasin. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 210, 119–133.

Ainsaar, L., Kaljo, D., Martma, T., Meidla, T., Männik, P., Nõlvak, J. & Tinn, O., 2010. Middle and Upper Ordovician carbon isotope chemostratigraphy in Baltoscandia: A correlation standard and clues to environmental history. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 294, 3–4, 189–201.

Bassler, R. F., 1911. *The Early Palaeozoic Bryozoa of the Baltic Provinces*. Smithsonian Institute. US National Museum Bulletin, 77, 1–382.

Bekker, H., 1921. The Kuckers Stage of the Ordovician Rocks of NE Estonia. *Acta et Commentationes Universitatis Tartuensis*, A2, 81–84.

Eichwald, E., 1825. *Geognostico-zoologicae per Ingriam marisque Baltici provincias nec non de trilobitis observationes*. Casani, 58 pp.

Engelhardt, M., 1820. *Darstellung aus dem Felsgebäude Russlands. Erste Lieferung. Geognostischer Umriss von Finland*. Berlin, 44 pp.

Heinsalu, H. & Viira V., 1997. Pakerort Stage. Varangu Stage. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and Mineral Resources of Estonia.* Estonian Academy Publishers, Tallinn, 52–58.

Hints, L., 1997. Aseri Stage. Lasnamägi Stage. Uhaku Stage. Haljala Stage. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and Mineral Resources of Estonia*. Estonian Academy Publishers, Tallinn, 66–74.

Hints, L. & Meidla, T., 1997. Keila Stage. Oandu Stage. Rakvere Stage. Nabala Stage. Vormsi Stage. Pirgu Stage. Porkuni Stage. *In:* Raukas, A. & Teedumäe, A.(eds). *Geology and Mineral Resources of Estonia.* Estonian Academy Publishers, Tallinn, 74–88.

Hints, L., Meidla, T., Gailite, L.-I. & Sarv, L. (comp.), 1993: *Catalogue of Ordovician Stratigraphical Units and Stratotypes of Estonia and Latvia*. Institute of Geology, Estonian Academy of Sciences, Tallinn, 62 pp.

Hints, O. & Nõlvak, J., 1999. Proposal for the lower boundary-stratotype of the Keila Regional Stage (Upper Ordovician). *Proceedings of the Estonian Academy of Sciences. Geology*, 48, 158–169.

IUGS 2013. *International stratigraphic chart*. IUGS International Commision of Stratigraphy, http://www.stratigraphy.org/index.php/ics-chart-timescale.

Jaanusson, V., 1960. Graptoloids from the Ontikan and Viruan (Ordovician) limestones of Estonia and Sweden. *The Bulletin of the Geological Institutions of the University of Uppsala*, 38, 289–366.

Jaanusson, V., 1976. Faunal dynamics in the Middle Ordovician (Viruan) of Baltoscandia. *In:* Bassett, M. G. (ed.). *The Ordovician System*. Proceedings of a Palaeontological Association Symposium, Birmingham, September 1974. University of Wales Press, Cardiff, 301–326.

Jaanusson, V., 1995. Confacies differenciation and upper Middle Ordovician correlation in the Baltoscandian basin. *Proceedings of the Estonian Academy of Sciences. Geology*, 44, 73–86.

Kaljo, D., Borovko, N., Heinsalu, H., Khazanovich, K., Mens, K., Popov, L., Sergeyeva, S., Sobolevskaya, R. & Viira, V., 1986. The Cambrian–Ordovician boundary in the Baltic–Ladoga clint area (North Estonia and Leningrad Region, USSR). *Proceedings of the Academy of Sciences of Estonian SSR. Geology*, 35, 3, 97–108.

Kaljo, D., Hints, L., Hints, O. Martma, T. & Nõlvak, J., 1999. Carbon isotope excursions and coeval environmental and biotic changes in the late Caradoc and Ashgill of Estonia. *Acta Universitatis Carolinae Geologica*, 43, 507–510.

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

Kaljo, D. & Kivimägi, E., 1970. On the distribution of graptolites in the *Dictyonema* shale of Estonia and on the uncontemporaneity of its different facies. *Eesti NSV Teaduste Akadeemia Toimetised. Keemia, Geoloogia*, 19, 4, 334–341. [in Russian, with English summary]

Kaljo, D. & Kivimägi, E., 1976. Zonal stratigraphy of the Estonian Tremadocian. *In:* Kaljo, D. L. & Koren T. N. (eds). *Graptolites and stratigraphy*. Academy of Sciences of Estonian SSR, Institute of Geology, Tallinn, 56–63. [in Russian with English summary].

Kaljo, D., Rõõmusoks, A. & Männil, R., 1958. On the series of the Baltic Ordovician and their significance. *Eesti NSV Teaduste Akadeemia Toimetised. Tehniliste ja Füüsikalis-Matemaatiliste Teaduste Seeria*, 7, 71–74. [in Russian with English summary].

Kaljo, D. & Vingisaar, P., 1969. On the sequence of the Raikküla Stage in southernmost Estonia. *Eesti NSV Teaduste Akadeemia Toimetised. Keemia, Geoloogia*, 18, 3, 270–277. [in Russian with English summary].

Männil, R., 1966. *Evolution of the Baltic Basin during the Ordovician*. Valgus, Tallinn, 200 pp. [in Russian with English summary].

Männil, R., 1976. Distribution of graptoloids in the Ordovician carbonate rocks of the East Baltic area. *In:* Kaljo, D. L. & Koren T. N. (eds). *Graptolites and stratigraphy*. Academy of Sciences of Estonian SSR, Institute of Geology, Tallinn, 105–118. [in Russian with English summary].

Männil, R., 1990. The Ordovician of Estonia. *In:* Kaljo, D. & Nestor, H. (eds). *Field Meeting Estonia 1990. An Excursion Guidebook*. Estonian Academy of Sciences, Tallinn, 11–20.

Männil, R. & Meidla, T., 1994. The Ordovician System of the East European Platform (Estonia, Latvia, Lithuania, Byelorussia, parts of Russia, the Ukraine and Moldova). *In:* Webby, B.D.R., Ross, R.J. & Zhen, Yong Y. (eds). *The Ordovician System of the East European Platform and Tuva (Southeastern Russia): Correlation Charts and Explanatory Notes*. IUGS Publication, 28, A, 1–52.

Männil, R. & Rõõmusoks, A., 1984. The revision of the lithostratigraphic subdivision of the Ordovician of North Estonia. *In:* Männil, R. & Mens, K. (eds). *Stratigraphy of the Lower Palaeozoic rocks in the East Baltic*. Institute of Geology, Academy of Sciences of the Estonian SSR, Tallinn, 52–62. [in Russian with English summary].

Männil, R., Põlma, L. & Hints, L., 1968. Stratigraphy of the Viruan and Harjuan deposits (Ordovician) in the central East Baltic. *In:* Grigelis, A. (ed.). *Stratigraphy of the Lower Paleozoic and Correlation with Other Regions*. Mintis, Vilnius, 81–110. [in Russian with English summary].

Meidla, T., 1996. Late Ordovician Ostracodes of Estonia. *Fossilia Baltica*, 2, 222 pp.

Meidla, T., 1997. Hunneberg Stage. Billingen Stage. Volkhov Stage. Kunda Stage. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and Mineral Resources of Estonia*. Estonian Academy Publishers, Tallinn, 58–65.

Nestor, H. & Einasto, R., 1997: Ordovician and Silurian carbonate sedimentation basin. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and Mineral Resources of Estonia*. Estonian Academy Publishers, Tallinn, 192–204.

Nõlvak, N., 1997. Ordovician. Introduction. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and Mineral Resources of Estonia*. Estonian Academy Publishers, Tallinn, 52–55.

Nõlvak, J., Hints, O. & Männik, P., 2006. Ordovician timescale in Estonia: recent developments. *Proceedings of the Estonian Academy of Sciences. Geology* 55, 95-108.

Öpik, A., 1930. *Brachiopoda Protremata der estländischen ordovizischen Kukruse-Stufe*. Tartu Ülikooli Geoloogia Instituudi Toimetised 20, 261 pp.

Öpik, A., 1934. *Über Klitamboniten*. *Acta et Commentationes Universitatis Tartuensis*, A 26, 5, 1–239.

Orviku, K., 1940. Lithologie der Tallinna-serie (Ordovizium, Estland). *Acta et Commentationes Universitatis Tartuensis*, A 36, 1–216.

Põlma, L., 1982. *Comparative Lithology of the Ordovician Carbonate Rocks in the Northern and Middle East Baltic*. Valgus, Tallinn, 164 pp. [in Russian with English summary].

Puura, L & Viira, V., 1999. Chronostratigraphy of the Cambrian-Ordovician boundary beds in Baltoscandia. *Acta Universitatis Carolinae Geologica*, 43, 5–8.

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

Raymond, P.E., 1916. The correlation of the Ordovician strata of the Baltic basin with those of North America. *In:* Raymond, P.E. & Twenhofel, W. (eds). *Expedition to the Baltic provinces of Russia and Scandinavia, 1914.* Bulletin of the Museum of Comparative Zoology at Harvard College, 56, 179–286.

Remane, J., 2003. Chronostratigraphic correlations: their importance for the definition of geochronologic units. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 196, 7–18.

Resheniya... 1965. *Resolution of the joint discussion on establishing an unitary Precambrian and Palaeozoic scheme for the Russian Platform, 1962*. VSEGEI, Leningrad, 79 pp. [in Russian].

Resheniya... 1978. *Resolution of inter-regional stratigraphic discussion on establishing an unitary stratigraphic scheme for the East Baltic region, 1976*. Lithuanian NIGRI, Leningrad, 86 pp. [in Russian].

Resheniya... 1987. *Resolution of the joint stratigraphic discussion on the Ordovician and Silurian of the East European Platform, 1984*. VSEGEI, Leningrad, 114 pp. [in Russian].

Rõõmusoks, A., 1983. *Eesti aluspõhja geoloogia*. Valgus, Tallinn, 224 pp. [in Estonian].

Rõõmusoks, A., Puura, V, Raukas, A. & Mark-Kurik, E., 1997. History of geological research. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and Mineral Resources of Estonia*. Estonian Academy Publishers, Tallinn.,15–26.

Schmidt, F., 1858. *Untersuchungen über die Silurische Formation von Ehstland, Nord-Livland und Oesel*. Archiv für die Naturkunde Liv- Ehst- and Kurlands, ser. 1, 2, Dorpat, 248 pp.

Schmidt, F., 1881. *Revision der ostbaltischen silurischen Trilobiten nebst geognostischer Übersicht des ostbaltischen Silurgebiets*. Abt. 1. Mémoires de l'Academie Impériale des Sciences de St. Petersburg, ser. 7, 30, 1, 238 pp.

Strangways, W. T. H. F., 1821. Geological sketch of the environs of Petersburg. *Transactions of the Geological Society of London*, 5, 392–458.

Tinn, O., 2002. Early ostracode evolution and palaeoenvironmental application in the Ordovician of Baltoscandia. *Dissertationes Geologicae Universitatis Tartuensis 13*, 145 pp.

Tinn, O. and Meidla, T., 2001. Middle Ordovician ostracods from the Lanna and Holen Limestones, south-central Sweden. *GFF*, 123, 129–136.

Tuuling, I., 1998. Shipborne geophysical study of an Ordovician–Silurian carbonate platform, Faro Hiiumaa area, northeastern Baltic Sea. *Meddelanden fran Stockholms Universitets Institution for Geologi och Geokemi*, 301, 21 pp.

Tuuling, I. and Flodén, T., 2013. Silurian reefs off Saaremaa and their extension towards Gotland, central Baltic Sea. *Geological Magazine*, 150, 5, 923-936.

Webby, B.D., 1998. Steps towards a global standard for Ordovician stratigraphy. *Newsletters on Stratigraphy*, 36, 1–33.

The Silurian System in Estonia

Peep Männik

Institute of Geology at Tallinn University of Technology, Estonia

During the Ordovician and Silurian, from the late Tremadocian to the end of the Přidoli, the territory of present-day Estonia was part of the northern flank of a shallow cratonic sea in the western Baltica continent. In the earlier stages of development this sea extended from Norway to the Volga region, and from the Finnish to the Belarussian–Mazurian Precambrian massif. During the final stages of development the basin was restricted to the Baltic Syneclise in the East Baltic area and North Poland (Nestor & Einasto 1997). In the Silurian the Baltica continent was located in equatorial latitudes and drifted gradually northwards (Melchin *et al.* 2004). The Baltic Palaeobasin was characterized by a wide range of tropical shelf environments with accumulation of various calcareous deposits and occurrence of rich and diverse biotas.

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

Based on the distinctly expressed lateral (facies) changes of Silurian rocks, the Mid-Estonian and South-Estonian confacies belts have been distinguished (Kaljo 1977). Various limestones and dolomites, rich in shelly faunas, dominate the Mid-Estonian Confacies Belt. 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 the mainland of Estonia the Silurian succession is less complete and its upper part has undergone extensive dolomitization. The South-Estonian Confacies Belt consists mostly of marl- and mudstones with deeper-water shelly fauna and graptolites. These rocks are covered by Devonian strata and are accessible in core sections only.

Study of rocks of Silurian age in Estonia started in the early 19th century (Engelhardt & Ulprecht 1830). The first stratigraphical classification of the Silurian rocks in Estonia was worked out by Schmidt (1858, 1881, 1892) and several of his units (including their notation: G, H, J, etc.) are still in use. Bekker (1922, 1925) and Luha (1930, 1933, 1946) established the present nomenclature of the Silurian regional chronostratigraphical units – regional stages. Before the 1940s geological studies in Estonia were mainly based on natural outcrops and on a number of small quarries located in the outcrop area. From the late 1940s until the collapse of the Soviet system extensive drilling projects were carried out in Estonia by the nowadays Geological Survey of Estonia. The studies based on very rich core material resulted in considerable improvement of the knowledge about the geology and stratigraphy of the region. Particularly active Silurian studies started in Estonia in the late 1950s–earlier 1960s. During the following decades all aspects of the Silurian succession were studied and the results summarized in several monographs (*e.g.* Jürgenson 1966; Kaljo 1970, 1977; Kaljo & Klaamann 1986).

The regional stratigraphical scheme has been revised and updated many times during the long history of Silurian studies in Estonia. Lithostratigraphical units still in use have been 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 has been published in the unified regional stratigraphical schemes (Resheniya… 1978; Resheniya… 1987) and in some later papers (Nestor 1995, 1997; Hints 2008).

The Silurian succession in Estonia consists of ten regional stages (Nestor 1997). However, due to sporadic distribution of macrofauna, the stage boundaries were defined as levels corresponding to certain sedimentological changes in the succession. Up till now the boundaries are not adequately constrained

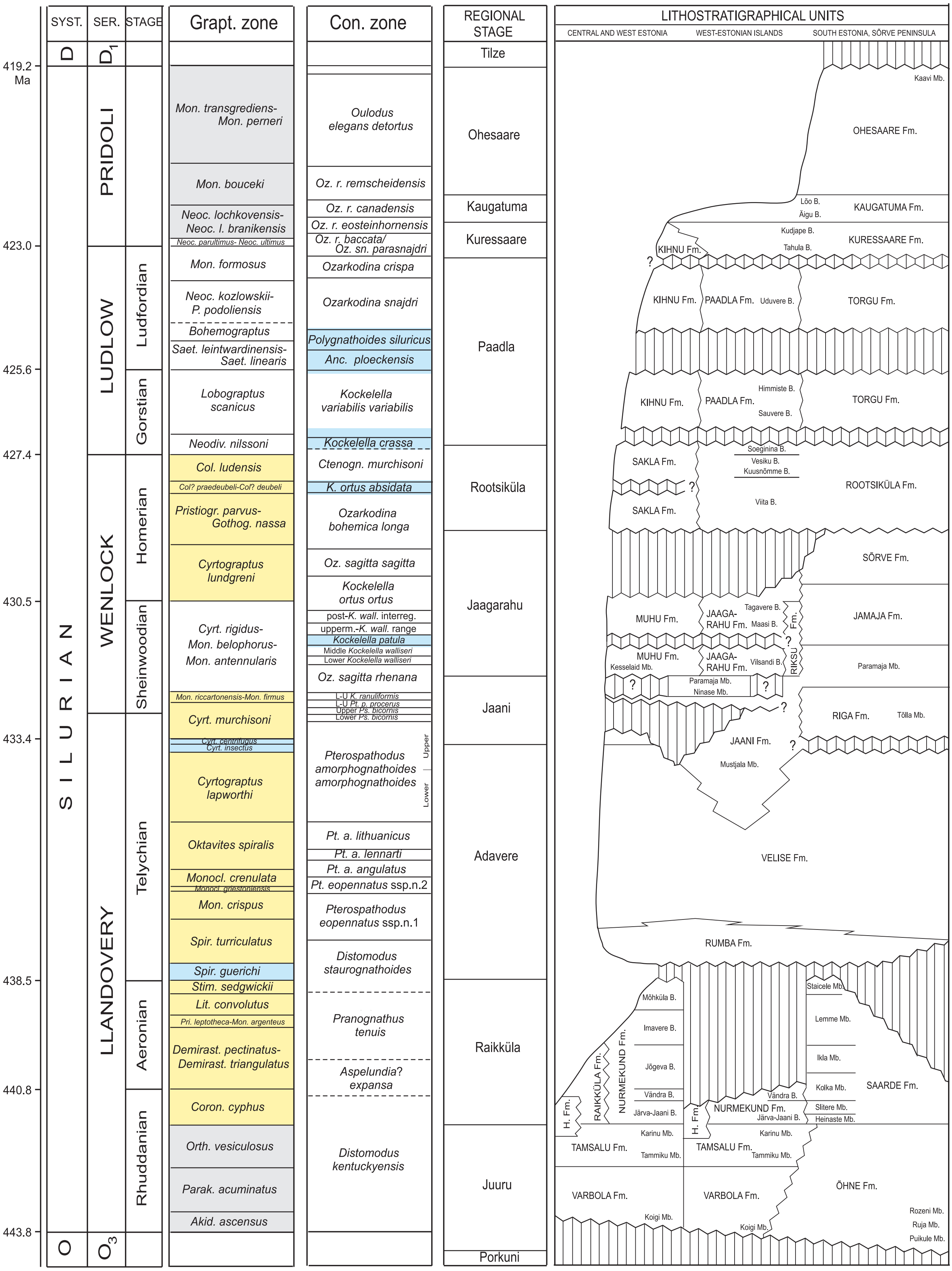


Figure 1. Silurian stratigraphical scheme of Estonia. Modified from Nestor (1997). The global Silurian time scale according to Melchin et al. (2012). Colour in the column of grptolite zones: yellow – zones reliably correlated (based on co-occurrences of graptolites, conodonts and chitinozoans) with Estonian succession; white – some indirect correlation available; grey – no information. Graptolite and conodont zones marked with blue colour – more or less well proved gaps in Estonian succession.

biostratigraphically. Based on the lithological composition of strata, the stages are subdivided into formations. Separate sets of formations have been established within the confacies belts. Traditionally, a formation has been dealt as a topostratigraphical unit: it was defined mainly by lithological composition but its lower and upper boundaries were drawn based on biostratigraphical data and considered to be isochronous (hence, horizontal boundaries of formations in published stratigraphical schemes). This has caused some confusion and resulted in the revision of several formation boundaries from publication to publication (*e.g.* the lower boundary of the Jaani Formation in the Viki core section: Nestor, H. 1990; Nestor, V. 1994; Põldvere 2010). In the last years some investigators have preferred to keep the lithostratigraphical (formations) and chronostratigraphical units clearly separated but the former concept is still popular among others.

Many intervals of the Silurian succession possess distinct cyclicity, particularly in the more shallow-water Mid-Estonian Confacies Belt. In such cases a cyclostratigraphical unit, the so-called beds consisting of alternating types of rocks with a certain trend of succession, has been distinguished and treated as a subdivision of a formation. In some cases formations can be subdivided in more detail, into members.

The correlation of the succession of Silurian regional stages in Estonia with the global chronostratigraphical standard has been considered reasonably reliable and has stayed almost unchanged in the last decades. New data, however, have revealed several problems and a need for the restudy/revision of the scheme. The revision of the scheme is in progress and a partly modified scheme is provided in Fig. 1. Brief comments on main recent developments in the Silurian stratigraphy in Estonia and problems still waiting to be resolved are provided below.

Correlation of regional stages with the international graptolite standard

Due to rare occurrence of graptolites in the Silurian strata in Estonia, the correlation of some regional stages with the standard graptolite succession has been, and still is, highly problematic. The situation has improved considerably in the last decades as a result of detailed palaeontological and biostratigraphical studies of core sections from SW Estonia and western Latvia where graptolites, conodonts and chitinozoans co-occur (Loydell *et al.* 1998, 2003, 2010). Most of the Llandovery and Wenlock graptolite biozones (marked with yellow colour in Fig. 1) can now be traced reliably into the sections formed in shallow-water environments in Estonia. Combined biostratigraphical and chemostratigraphical ($\delta^{13}C$, K-bentonites) studies have resulted in more reliable dating of strata and in improved correlation of sections in the region (Kiipli *et al.* 2012; Märss & Männik 2013; Männik *et al.* 2014). However, the dating of some other intervals (particularly in the Rhuddanian and Přidoli; grey intervals in Fig. 1) is still problematic.

The Ordovician–Silurian boundary

The Ordovician–Silurian boundary in Estonia has been considered to coincide with the boundary between the Porkuni and Juuru stages, with the base of the Varbola (Central Estonia) and Õhne (South Estonia) formations. This conclusion is based on the occurrence of Hirnantian trilobites and brachiopods in the Kuldiga and Saldus formations of the Porkuni Stage and records of *Stricklandia lens prima* Williams from the lowermost beds of the Varbola Formation of the Juuru Stage (Kaljo *et al.* 1988). In all sections the boundary is marked by a gap and a sharp change in lithology. Recent $\delta^{13}C$ data suggest that in some parts of the basin the strata (lithologically) considered as the lowermost Juuru Stage might be, in reality, of late Hirnantian age (Ainsaar *et al.* 2011).

The Velise–Jaani (formations), Adavere–Jaani (stages) and Llandovery–Wenlock boundaries

In the stratigraphical schemes cited above the boundary between the Velise and Jaani formations has always been drawn as coinciding with the boundary between the Adavere and Jaani stages, and both of these boundaries have been correlated with the Llandovery–Wenlock boundary. It is known now that the Llandovery–Wenlock boundary (as defined in its type section at Leasows) lies close to Datum 2 of the Ireviken Event (close to the boundary between the Upper *Pseudooneotodus bicornis* and the lower *Pterospathodus pennatus procerus* conodont zones (CZ), in the upper part of the *Cyrtograptus murchisoni* graptolite Zone (GZ): Jeppsson 1997; Männik 2007a), the boundary between the Adavere and Jaani stages in the Upper *Pt. amorphognathoides* conodont Subzone (Männik 2007b), and, based on the latest data from the type section of the Mustjala Member (lower Jaani Formation), the boundary between the Velise and Jaani formations lies in the *Pt. amorphognathoides lithuanicus* CZ. In Fig. 1, the lower boundary of the Mustjala Member is drawn based on published data from different sections in Estonia. In western mainland Estonia and the islands in the Muhu Straight the Llandovery–Wenlock boundary interval is characterized by a gap. The strata corresponding to the Ireviken Event are evidently completely missing in some sections (Männik *et al.* 2014). However, this gap has not been recognized in the distal, graptolite-bearing environments. Instead, a gap corresponding to the *Cyrtograptus insectus* and *Cyrt. centrifugus* GZs was recognized there (Loydell *et al.* 2003). If present in proximal environments, duration of the last gap is evidently below biostratigraphical resolution available at the moment.

The revisions of the scheme discussed above are biostratigraphically well founded and the results are published. What follows below is based on preliminary analysis of available data. Additional studies are needed to prove the correctness of proposed conclusions.

Boundary between the Jaani and Jaagarahu stages

In practise, this boundary has been based on sedimentological considerations and drawn at the contact between the Jaani and Jaagarahu (in western Saaremaa) and Jaani and Muhu formations (in eastern Saaremaa and western mainland Estonia; Nestor 1997). The appearance of reefal rocks has been considered to be most characteristic of the lowermost Jaagarahu Stage. Again, biostratigraphically the boundary was poorly constrained. In reality, for over a decade it has been well known that, lithologically, the (upper) Jaani, Jaagarahu and Muhu formations are complicated, and due to the lack of adequate biostratigraphical data the real temporal relationship of different lithologies (members) in these formations is problematic (Perens 1995). Moreover, reefal rocks are now known to appear in the Ninase Member already. Analysis of conodont distribution in the transitional interval between the Jaani and Jaagarahu stages provides some possibilities for solving this problem. The appearance of *Ozarkodina sagitta rhenana* (Walliser) was recorded in the lower Ninase Formation in the Panga section (this guide: p. 186, Fig. 1), in the lowermost Muhu Formation in the Pulli and Salevere sections (this guide: p. 184, Fig. 1; Einasto & Männik 1991) and in the lowermost Jaagarahu Formation in the Jaagarahu core section (Männik, unpubl. data). This suggests two possibilities. (1) The lower Muhu Formation, and the lower Jaagarahu Formation in NW Saaremaa, are older than the Jaagarahu Formation in the Panga section and correlate with the upper Jaani Formation in that section. (2) The strata of the upper Jaani Formation with *Oz. s. rhenana* exposed in the Panga section are missing (correspond to gaps) in NW and eastern Saaremaa (e.g. in the Pulli section) and western mainland Estonia. A possible third explanation, ecologically restricted distribution of *Oz. s. rhenana*, seems unrealistic: as is known from Gotland (L. Jeppsson pers. comm.; P. Männik, pers. observations) *Oz. s. rhenana* is equally common in the NE part (in the proximal carbonate environments) as well as in the SE part (in the distal carbonate-terrigenous environments) of the island. Also, *Oz. s. rhenana* occurs in the argillaceous marlstones of the upper Riga Formation (upper Tõlla Member) in the Ohesaare core section in SE Saaremaa (P. Männik, unpubl. data). In Fig. 1, following the traditional concept of the stage boundary, the bases of the Muhu and Jaagarahu formations are tentatively drawn as corresponding to the base of the Jaagarahu Stage and as separated by a gap from the Jaani Formation.

The uppermost Paadla Stage and the age of the Kuressaare Stage

Traditionally, the Kuressaare Stage has been indirectly correlated with the upper part of the Ludlow Series, with the *Monograptus formosus* GZ (Nestor 1997). However, conodont data do not fit with this dating. The *Ozarkodina crispa* CZ, roughly corresponding to the *M. formosus* GZ, is the uppermost one in the Ludlow (Corradini & Serpagli 1999; Cramer *et al.* 2011). According to Viira (1999), in Estonia *Oz. crispa* appears in the upper Paadla Stage, traditionally correlated with the strata older than the *M. formosus* GZ (Nestor 1997), and occurs also in the (lower) Kuressaare Stage. Such distribution of *Oz. crispa* indicates that, most probably, the upper part of the Paadla Stage corresponds to the lower *M. formosus* GZ and that the Kuressaare Stage (at least its upper part) is of Přidoli age.

Gaps in the upper part of the succession

Several conodont zones have not been recognized and evidently correspond to gaps in Estonia (indicated with blue colour in Fig. 1). However, their location in the succession as shown in the scheme is provisional. At present not enough data are available to locate them precisely, *i.e.* to tell between/in which beds they occur.

References

Ainsaar, L., Truumees, J. & Meidla, T., 2011. Carbon isotope chemostratigraphy of the Ordovicina/Silurian boundary beds in central Estonia: new data from drillcores in the Pandivere area. *The Eighth Baltic Stratigraphica Conference, 28 August–1 September 2011*, *Latvia. Abstracts*, 10.

Bekker, H., 1922. Ülevaade Eesti ordoviitsiumi ja siluri kohta käivatest uurimustest. *Loodus*, 4, 217–224. [in Estonian].

Bekker, H.,1925. Lühike ülevaade Eesti geoloogiast (Eozoiline ja Paleozoiline ladekond). Rmt.: *Eesti Loodus*, Tartu, 31-61. [in Estonian].

Corradini, C. & Serpagli, E., 1999. A Silurian conodont biozonation from late Llandovery to end Přidoli in Sardinia (Italy). *Bollettino della Società Paleontologica Italiana*, 37, 255–273.

Cramer, B. D., Brett, C. E., Melchin, J. M., Männik, P., Kleffner, M. A., McLaughlin, P. I., Loydell, D. K., Munnecke, A., Jeppsson, L., Corradini, C., Brunton, F. R. & Saltzman, M. R., 2011. Revised correlation of Silurian Provincial Series of North America with global and regional chronostratigraphic units and $\delta^{13}C_{carb}$ chemostratigraphy. *Lethaia*, 44, 185-202.

Einasto, R. & Männik, P., 1991. Stop 2.5: Salumägi at Salevere. *In:* Puura, V., Kalm, V. & Puura, I. (eds). *Geology and mineral resources of Estonia: Excursion guide*. Tallinn, 51–53.

Engelhardt, M. & Ulprecht, E., 1830. Umriss der Felsstructures Estlands und Livlands. *Arch. Miner. (Karsten)*, 2, 94–112.

Hints, O., 2008. The Silurian System in Estonia. *In:* Hints, O., Ainsaar, L., Männik, P. & Meidla, T. (eds). *The Seventh Baltic Stratigraphical Conference. Abstracts and field guide.* Tallinn, 113–114.

Jeppsson, L., 1997. A new latest Telychian, Sheinwoodian and Early Homerian (Early Silurian) standard conodont zonation. *Transactions of the Royal Society of Edinburgh. Earth Sciences*, 88, 91–114.

Jürgenson, E., 1966. *Lithology of Llandoverian beds in Estonia*. ENSV TA, Tallinn, 65 pp.

Kaljo, D., 1977. Structural and facial subdivisions on the East Baltic Silurian basin. *In:* Kaljo, D. (ed.). *Facies and fauna of the Baltic Silurian*. Tallinn, 6–13. [in Russian].

Kaljo, D., Nestor, H. & Põlma, L., 1988. East Baltic Region. *Bull. British Museum (Nat. Hist.), Geol.,* Ser. 43, 85–91.

Kaljo, D. (ed.), 1970. *The Silurian of Estonia*. Valgus, Tallinn, 343 pp. [in Russian].

Kaljo, D. (ed.), 1977. *Facies and fauna of the Baltic Silurian.* Tallinn, 286 pp. [in Russian].

Kaljo, D. & Klaamann, E. (eds), 1986. *Theory and practice of ecostratigraphy*. Valgus, Tallinn, 294 pp. [in Russian].

Kiipli, T., Kallaste, T. & Nestor, V., 2012. Correlation of upper Llandovery–lower Wenlock bentonites in the När (Gotland, Sweden) and Ventspils (Latvia) drill cores: role of volcanic ash clouds and shelf sea currents in determining areal distribution of bentonite. *Estonian Journal of Earth Sciences*, 61, 295–306.

Loydell, D. K., Kaljo, D. & Männik, P., 1998. Integrated biostratigraphy of the lower Silurian of the Ohesaare core, Saaremaa, Estonia. *Geological Magazine*, 135, 769–783.

Loydell, D. K., Männik, P. & Nestor, V., 2003. Integrated biostratigraphy of the lower Silurian of the Aizpute-41 core, Latvia. *Geological Magazine*, 140, 205–229.

Loydell, D. K., Nestor, V. & Männik, P., 2010. Integrated biostratigraphy of the lower Silurian of the Kolka-54 core, Latvia. Geological Magazine, 147, 253–280.

Luha, A., 1930. Über Ergebnisse stratigraphischer Untersuchungen im Gebiete der Saaremaa- (Ösel-) Schichten in eesti (Unterösel und Eurypterusschichten). *Acta et Comm. Univ. Tartuensis*, A 18, 1–18.

Luha, A., 1933. Eesti geoloogiline koostis. Rmt.: *Eesti Entsüklopeedia*, 2, 528–535. [in Estonian].

Luha, A.,1946. *Eesti NSV maavarad. Rakendusgeoloogiline kokkuvõtlik ülevaade*. Teaduslik Kirjandus, Tartu, 176 lk. [in Estonian].

Melchin, M. J., Cooper, R. A. & Sadler, P. M., 2004. The Silurian Period. *In:* Gradstein, F. M., Ogg, J. G. & Smith, A. G. (eds). *A Geological Time Scale 2004.* Cambridge University Press, 188–201.

Männik, P., 2007a. Some comments on the Telychian–early Sheinwoodian conodont faunas, events and stratigraphy. *Acta Palaeontologica Sinica*, 46 (Suppl.), 305–310.

Männik, P., 2007b. An updated Telychian (Late Llandovery, Silurian) conodont zonation based on Baltic faunas. *Lethaia*, 40, 45–60.

Männik, P., Põldvere, A., Nestor, V., Kallaste, T., Kiipli, T. & Martma, T., 2014. The Llandovery–Wenlock boundary interval in the west-central continental Estonia: an example from the Suigu (S-3) core section. *Estonian Journal of Earth Sciences*, 63, 1–17.

Märss, T. & Männik, P., 2013. Revision of Silurian vertebrate biozones and their correlation with the conodont succession. Estonian Journal of Earth Sciences, 62, 181–204.

Melchin, M. J., Sadler, P. M. & Cramer, B. D., 2012. The Silurian Period. *In:* Gradstein, F. M., Ogg, J. G., Schmitz, M. D. & Ogg, G. M. (eds). *The Geologic Time Scale 2012*, vol. 1. Elsevier, 525–558.

Nestor, H., 1990. Locality 9:1. Silurian sequences at Särghaua field station. *In:* Kaljo, D. & Nestor, E. (eds). *Field Meeting, Estonia 1990. An Excursion Guidebook*. Estonian Academy of Sciences, Tallinn, Estonia, 184–186.

Nestor, H., 1995. Comments on the modernized Silurian correlation chart of Estonia and Latvia. *Geologija*, 17, 88–95.

Nestor, H., 1997. Silurian. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 89–106.

Nestor, H. & Einasto, R., 1997. Ordovician and Silurian carbonate sedimentation basin. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 192–204.

Nestor, H., Einasto, R., Männik, P. & Nestor, V., 2003. Correlation of some lower-middle Llandovery reference sections in central and southern Estonia and sedimentation cycles of lime muds. *Proceedings of the Estonian Academy of Sciences, Geology*, 52, 3–27.

Perens, H., 1995. Transition beds of Jaani and Jaagarahu regional stages on Saaremaa Island. *Bulletin of the Geological Survey of Estonia*, 5/1, 12–19.

Põldvere, A. (ed.), 2010. *Viki drill core*. *Estonian Geological Sections,* 10, 56 pp.

Resheniya... 1978. *Resolution of inter-regional stratigraphic discussion on establishing an unitary stratigraphic scheme for the East Baltic region, 1976*. Lithuanian NIGRI, Leningrad, 86 pp. [in Russian].

Resheniya... 1987. *Resolution of the joint stratigraphic discussion on the Ordovician and Silurian of the East European Platform, 1984*. VSEGEI, Leningrad, 114 pp. [in Russian].

Schmidt, F., 1858. *Untersuchungen über die Silurische Formation von Ehstland, Nord-Livland und Oesel*. Archiv für die Naturkunde Liv- Ehst- and Kurlands, ser. 1, 2, Dorpat, 248 pp.

Schmidt, F., 1881. *Revision der ostbaltischen silurischen Trilobiten nebst geognostischer Übersicht des ostbaltischen Silurgebiets*. Abt. 1. Mémoires de l'Academie Impériale des Sciences de St. Petersburg, ser. 7, 30, 1, 238 pp.

Schmidt, F., 1892. Einige Bemerkungen über das baltische Obersilur in Verlassung der Arbeit des Prof. W. Dames über die Schichtenfolge der Silurgebildungen Gotlands. *Bull. Acad. Sci. St. Petersb.,* Nouv. Ser. 2, 34, 381–400.

Viira, V., 1999. Late Silurian conodont biostratigraphy in the northern East Baltic. *Bollettino della Società Paleontologica Italiana*, 37, 299–310.

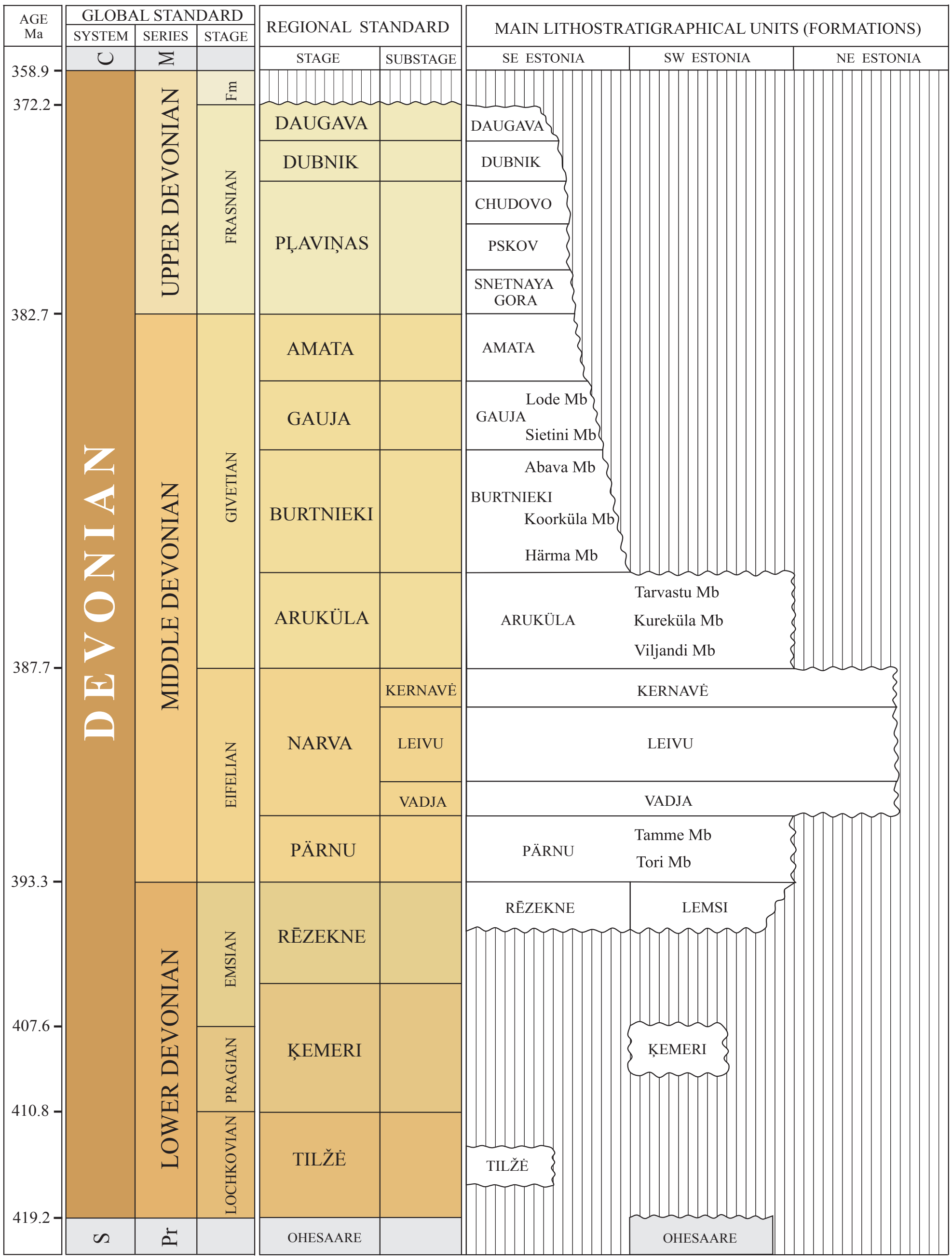
The Devonian System in Estonia

Anne Põldvere
Geological Survey of Estonia

The Devonian rocks form the youngest part of Estonian bedrock. 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, 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)

Figure 1. Devonian stratigraphy of Estonia.



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 fine-gained 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, silt- and 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 cross-bedded 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 clay-cemented 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).

References

Kleesment, A., 1997. Devonian sedimentation basin. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 205–208.

Kuršs, V. M., 1992. *Devonskoe terrigennoe osadkonakoplenie na Glavnom devonskom pole [Deposition of the terrigenous sediments of Devonian in the Central Devonian Field]*. Zinatne, Riga, 208 pp. [in Russian].

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

Pre-conference excursion: *Ordovician of Estonia*

Stop A1: Pakerort and Uuga cliffs on the Pakri Peninsula

Olle Hints
Institute of Geology at Tallinn University of Technology, Estonia

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 (or North Estonian 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 have been well known and studied since the 1840s and the up to 24 m high Pakerort cliff is nowadays an important geotourism site in Estonia.

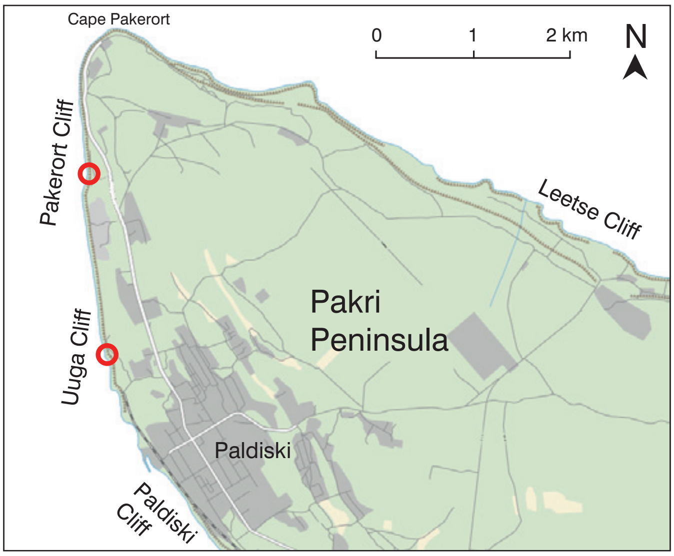


Figure 1. Sketch map of the Pakri Peninsula, NW Estonia, showing location of Uuga and Pakerort cliffs.

The western coast of the Pakri Peninsula constitutes a nearly continuous outcrop subdivided into the Paldiski, Uuga and Pakerort cliffs (Fig. 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 (Photo 1). in the north is the etymon for the Pakerort Regional Stage and provides an opportunity to study lower Cambrian (Series 2) to Tremadocian strata. The Floian to Darriwilian succession is best accessible at the Uuga cliff (Photo 2). close to the town of Paldiski.

Photo 1. Pakerort cliff, Pakri Peninsula, NW Estonia (photo O. Hints).

The composite section on the Pakri Peninsula is characterized below (Fig. 2), based on the descriptions by and data of Mens et al. (1996, 1999), Nemliher & Puura (1996), Hints *et al.* (2013), Löfgren *et al.* (2005), Põldsaar & Ainsaar (2013), Tammekänd *et al.* (2010), Einasto & Rähni (2005) and Mens & Puura (1996) and 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).

Photo 2. Uuga cliff, Pakri Peninsula, NW Estonia (photo O. Hints).

(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 conspicuous basal conglomerate (Photo 3). This conglomerate comprises (1) loose cobbles and boulders of the Tiskre Formation, up to ca 40 cm in diameter, and (2) dark-coloured flat bebbles and cobbles cemented with pyrite, apatite and carbonates (Nemliher & Puura 1996). The upper part of the Kallavere Formation (Suurjõgi Member) is represented by cross-bedded sandstones and a strongly pyritized sandstone layer on the top. The formation contains scattered debris of lingulate brachiopods, mostly belonging to the genus *Ungula* (Nemliher & Puura 1996).

Photo 3. Basal conglomerate between the lower Cambrian Tiskre Formation and upper Cambrian Kallavere Formation (photo O. Hints).

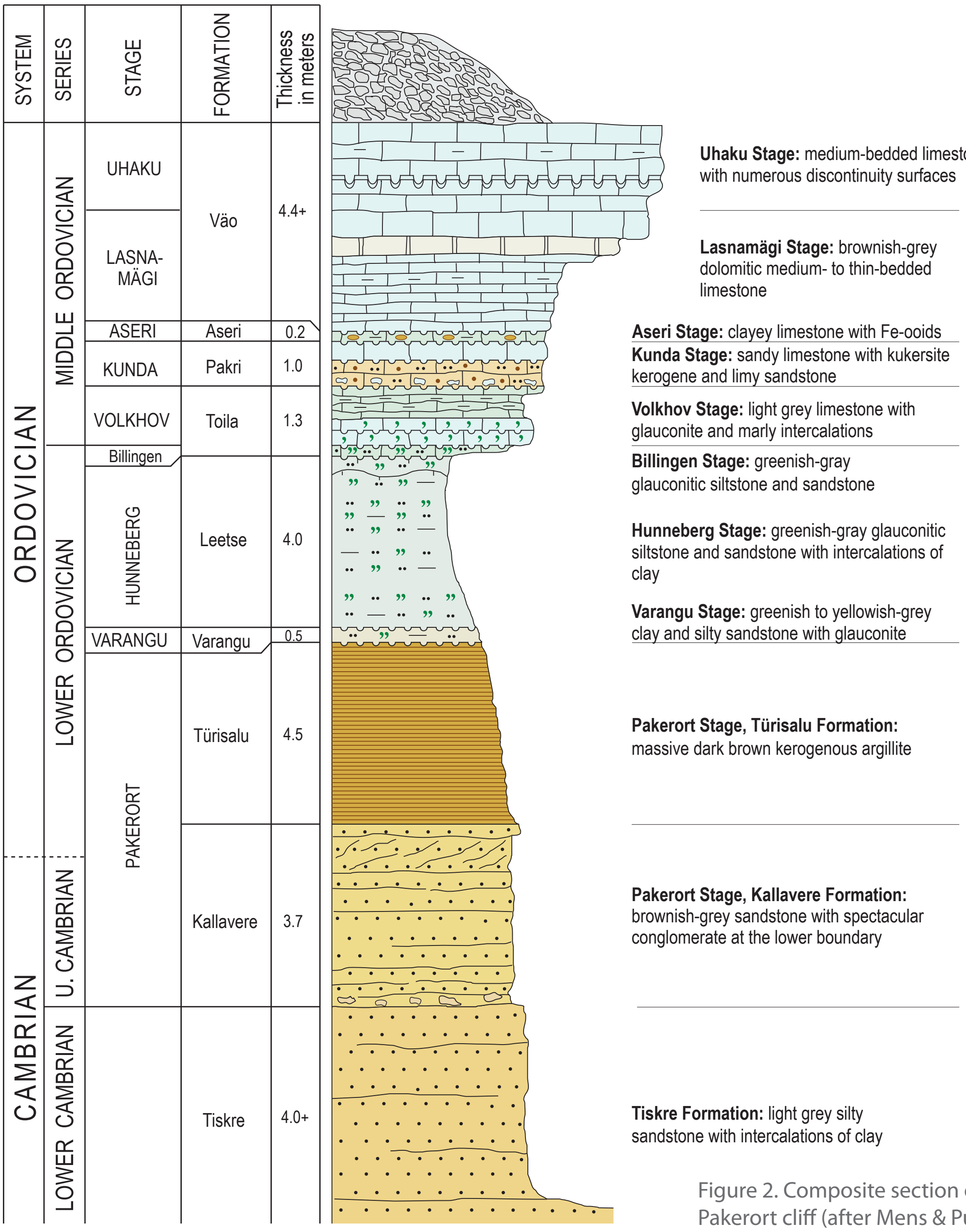


Figure 2. Composite section of the Pakerort cliff (after Mens & Puura 1996).

Conodont and acritarch evidence suggests 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 & 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 draw it at the base of the cross-bedded sandstones of the Suurjõgi Member.

(3) The Türisalu Formation (4.5 m, Pakerort Regional Stage, Tremadocian) consists of homogenous dark brown kerogenous argillite (previously known as the "Dictyonema Shale") containing graptolites *Rhabdinopora flabelliformis flabelliformis* and *Rhabdinopora flabelliformis* cf. *desmograptoides* in Pakri sections (Mens et al. 1996). The formation is characterized 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.* 2013 and references therein), it has been suggested that dynamic sedimentation events, rather than slow net sedimentation, may have 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, and 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 underlying Toila Formation is gradual, characterized 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. This surface indicates a regional hiatus and 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 Stage are insufficiently known on the Pakri Peninsula, but the top of the formation seems to fall into the *Paroistodus originalis* Zone (Fig. 3; Hints *et al.* 2012). This suggests that the upper part of the Volkov Stage corresponds to a gap in NW Estonia.

(7) The Pakri Formation (ca 1.0 m, Kunda Stage, Darriwilian) is composed of sandy limestone to limy sandstone (up to ca 80% quartzose sand according to Põldsaar & Ainsaar 2013). 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, sand volcanoes) that indicate large-scale liquefaction and fluidization of the unconsolidated and water-saturated sediments, probably by a large earthquake (Põldsaar & Ainsaar 2013). 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.

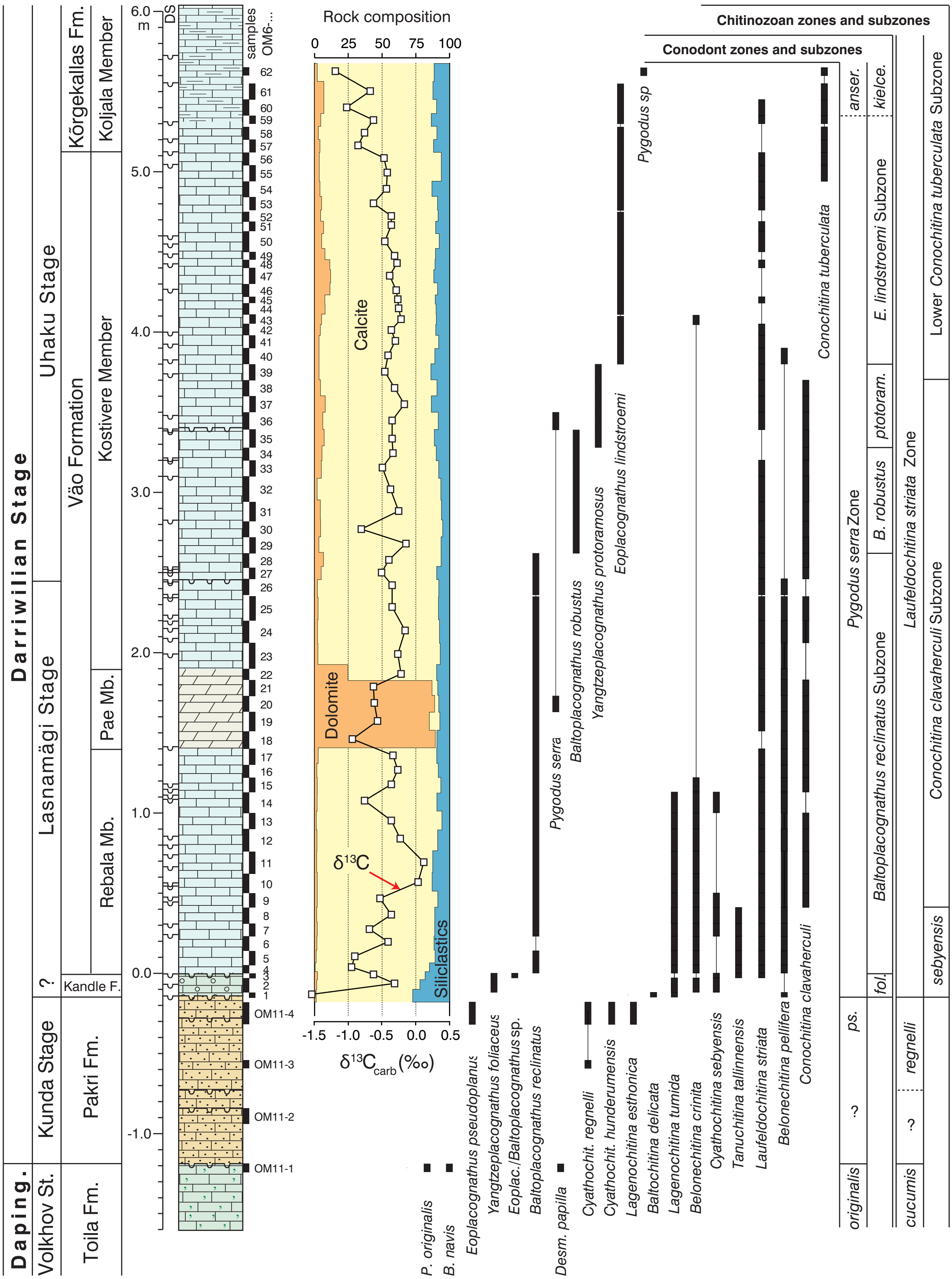


Figure 3. Rock composition and distribution of selected conodonts and chitinozoans in the Darriwilian strata of the Uuga cliff. For full range charts and discussion see Tammekänd *et al.* (2010) and Hints *et al.* (2012).

(8) The Kandle Formation (ca 0.1 m, =Aseri Formation in some previous publications; Aseri/Lasnamägi 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 lower Lasnamägi age. If this is true, the Aseri Stage may be entirely missing in some parts of the Pakri Peninsula and in other places in NW Estonia (Hints *et al.* 2012).

(9) The Väo Formation (ca 5.1 m, Lasnamägi and Uhaku stages, Darriwilian) is represented by grey thin- to medium-bedded limestones (wacke- to packstones), a discrete layer of dolomite (Pae Member) and numerous phosphatic and pyritic discontinuity surfaces. The formation is well dated by conodont and chitinozoan biostratigraphy, the most useful being subzones of the *Pygodus serra* conodont Zone. The base of the Uhaku Stage is regionally 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 useful 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 mined and utilized in northern Estonia. Many of the individual layers are specifically named by local quarrymen and some of these layers can be recognized over hundreds of kilometres (Einasto & 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.

References

Alwmark, C., Schmitz, B. & Kirsimäe, K., 2010. The mid-Ordovician Osmussaar breccia in Estonia linked to the disruption of the L-chondrite parent body in the asteroid belt. *Geological Society of America Bulletin*, 122, 1039–1046.

Einasto, R. & Rähni, A., 2005. The scanned and digitized core of Lasnamägi building limestone from the Pakri Peninsula. *Keskkonnatehnika*, 7, 66–71. [in Estonian].

Hints, O., Viira, V. & Nõlvak, J., 2012. Darriwilian (Middle Ordovician) conodont biostratigraphy in NW Estonia. *Estonian Journal of Earth Sciences*, 61, 210–226.

Hints, R., Hade, S., Soesoo, A. & Voolma, M., 2014. Depositional framework of the East Baltic Tremadocian black shale revisited. *GFF*. doi: 10.1080/11035897.2013.866978

Löfgren, A., Viira, V. & Mens, K., 2005. Conodont biostratigraphy and sedimentary history in the upper Tremadoc at Uuga, Cape Pakri, NW Estonia. *GFF*, 127, 283–293.

Mens, K. & Puura, I., 1996. Pakri Peninsula. *In:* The *Third Baltic Stratigraphical Conference. Abstracts and Field Guide*. Tartu, p. 88–92.

Mens, K., Heinsalu, H., Jegonjan, K., Kurvits, T., Puura, I. & Viira, V., 1996. Cambrian-Ordovician boundary beds in the Pakri Cape section, NW Estonia. *Proceedings of the Estonian Academy of Sciences. Geology*, 45, 9–21.

Mens, K., Paalits, I. & Puura, I., 1999. Biostratigraphic dating of pebbles from the Upper Cambrian conglomerates in Estonia. *Proceedings of the Estonian Academy of Sciences. Geology*, 48, 140–157.

Nemliher, J. & Puura, I., 1996. Upper Cambrian basal conglomerate of the Kallavere Formation on the Pakri Peninsula, NW Estonia. *Proceedings of the Estonian Academy of Sciences. Geology*, 45, 1–8.

Orviku, K. 1940. Lithologie der Tallinna-serie (Ordovizium, Estland) I. *Acta et Commentationes Universitatis Tartuensis* A, 36, 1, 1–216.

Põldsaar, K. & Ainsaar, L., 2013 (in press). Extensive soft-sediment deformation structures in the early Darriwilian (Middle Ordovician) shallow marine siliciclastic sediments formed on the Baltoscandian carbonate ramp, northwestern Estonia. *Marine Geology*. doi:10.1016/j.margeo.2013.08.012.

Puura, I. & Viira, V., 1999. Chronostratigraphy of the Cambrian–Ordovician boundary beds in Baltoscandia. *Acta Univ. Carolinae Geol.*, 43, 5–8.

Tammekänd, M., Hints, O. & Nõlvak, J., 2010. Chitinozoan dynamics and biostratigraphy in the Väo Formation (Darriwilian) of the Uuga Cliff, Pakri Peninsula, NW Estonia. *Estonian Journal of Earth Sciences*, 59, 25–36.

Stop A2: Vasalemma (Nordkalk) quarry

Björn Kröger[1], Linda Hints[2], Oliver Lehnert[3] and Toomas Post[4]
[1]*Finnish Museum of Natural History, University of Helsinki, Finland*
[2]*Institute of Geology at Tallinn University of Technology, Estonia*
[3]*Friedrich-Alexander Universität Erlangen-Nürnberg, Erlangen, Bavaria, Germany*
[4]*Nordkalk AS*

The large quarry east of the Vasalemma settlement, c. 40 km southwest of Tallinn, is currently one of the most important outcrops of the early Katian reefs and their flank facies [Vasalemma Formation (Fm)] (Photo 1) and the lateral time equivalents of the Kahula Fm of the Keila Stage (St). In some areas the range of the section comprises marly and silty sediments in restricted thickness (Oandu St) and the yellowish, micritic limestones of the Rägavere Fm at the top (Tõrevere Member?).

Photo 1. Vasalemma quarry – view at the eastern wall with reefs (photo H. Bauert).

Based on the combined core and outcrop data a reef-growth zone can be reconstructed as a narrow band that stretches nearly in a NE/SW direction by three areas of high reef concentration. The reefs are highly concentrated in the Rummu area in the west, the Vasalemma area in the centre and the Tuula area in the east (Fig. 1). Within this narrow band the reefs occur as patches with a maximum thickness of c. 15 m and diameters of up to 50 m, surrounded by massive echinoderm grainstones.

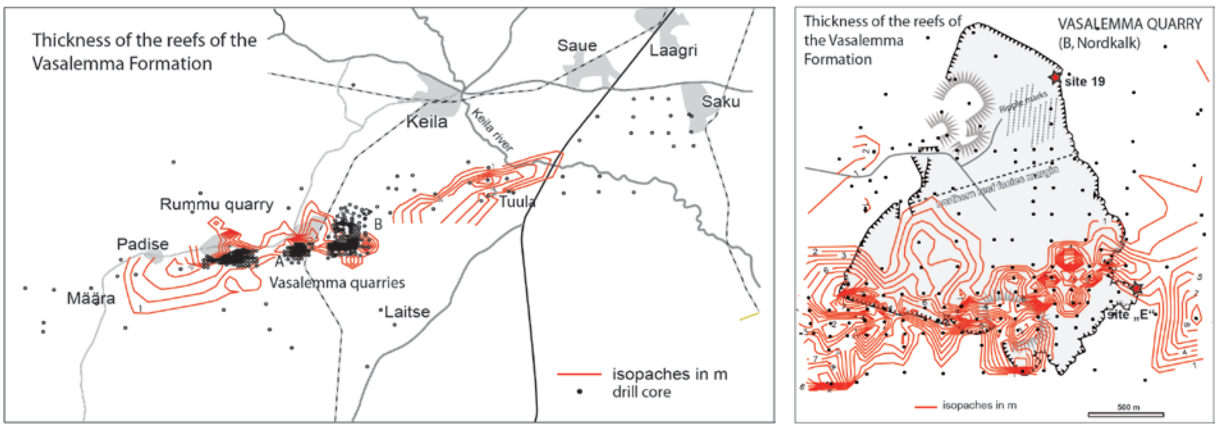


Figure 1. Thickness distribution of the reefs of the Vasalemma Formation (latest Katian) of the Rummu, Vasalemma (A, B – Vasalemma-Nordkalk quarry) and Tuula areas. Black dots mark wells used for the map constructions. Contours and isopaches are based on bilinear spline interpolation (see Kröger *et al.* in press for details) of drill core data only.

Stratigraphy

The cystoid limestones (= echinoderm grainstones) of the Vasalemma Fm have been quarried for centuries and are known in the region as "marble of Vasalemma". The limestones were first described and named in a stratigraphical context by Eichwald (1854) and Schmidt (1881). The names "Hemicosmitenkalk" (Eichwald 1854) or "cystoid limestone" (Männil 1960) refer to the rock-building abundance of echinoderm (mainly *Hemicosmites*, Rhombifera) intraclasts. The reefs are composed of a variety of wacke-, rud- and bafflestones with intercalated marl and silt layers. Together, the echinoderm grainstones and the reefs form the "Wasalemm'sche Schicht" of Schmidt (1881). In the current stratigraphical use it corresponds to the Vasalemma Fm (*e.g.* Rõõmusoks 1970; Männil & Rõõmusoks 1984), which spans the uppermost Keila St in the Rummu, Vasalemma and Tuula area (Fig. 2). In the easternmost parts, in the area of Saku, the Vasalemma Fm includes some reefs and the Saku Member (Mb), which reaches into the Oandu St (Ainsaar & Meidla 2001; Hints & Miidel 2008).

The Vasalemma reef bodies were for the first time explicitly mentioned by Raymont (1916) in a general review of the Estonian Ordovician but the first macroscopic description and illustrations of cross sections of some reef bodies were published by Männil (1960). In his description Männil termed the reefs "bryozoan-microbial bioherms" and interpreted their core facies as composed of "aphanitic" (= massive, micritic) limestones. In conference field guides (*e.g.* Hints 1996) the reefs have been classified as "mud" mounds, following Männil's original description of the core facies as "aphanitic". This mud mound paradigm held until Rozhnov (2004) emphasized the importance of echinoderms, especially the edrioasteroid *Cyathocystis* and the rhombiferid *Hemicosmites*, as framebuilders for the Vasalemma bioherms. Rozhnov (2004) also mentioned that echinoderms are not the only skeletal animals that contributed to the growth of the Vasalemma reefs.

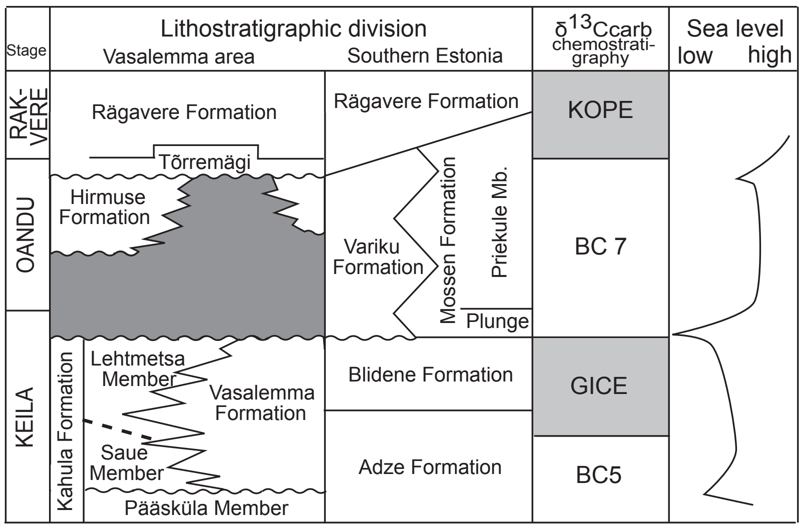


Figure 2. Lithostratigraphic division of selected late Sandbian – early Katian sediments of Baltica. Dark grey, hiatus; light grey, positive δ¹³C isotope excursion. Note the exclusively late Keila age of the Vasalemma Formation in the Vasalemma area. Tõrremägi and Plunge are members. GICE – Guttenberg Excursion, KOPE – Rakvere Excursion.

Despite a long and intensive history of research, the boundary of the Keila and Oandu regional stages never could explicitly be drawn within or in relation to the Vasalemma Fm. Recently the $\delta^{13}C$ chemostratigraphy (Kröger *et al.* in press) was used to highlight that problem.

The Keila/Oandu boundary interval is marked by a prominent $\delta^{13}C$ positive excursion, the Guttenberg Isotopic Carbon Excursion (GICE), which can be recognized in numerous sections throughout Baltica (*e.g.* Ainsaar *et al.* 2010; Bergström *et al.* 2012), Laurentia (*e.g.* Bergström *et al.* 2010b) and elsewhere in the world (*e.g.* Bergström *et al.* 2010a). In the Vasalemma quarry carbon isotopes have been studied in two places in the northeastern (outcrop 19) and southeastern parts (outcrop E) (Fig. 1). The new data demonstrate that in this quarry the Saue and Lehtmetsa members of the Kahula Fm (site 19) and the Vasalemma Fm (site E) belong to the rising limb of the GICE (Fig. 3), which commonly characterizes the late Keila age strata (Fig. 4). The higher $\delta^{13}C$ values in locality E, in comparison with locality 19, allow us to suppose that in the first site the topmost Vasalemma Fm is younger than in site 19. That is supported, for example, by the occurrence of the brachiopod *Rostricellula* (*Rhynchotrema* in Oraspõld 1956) in site E (Fig. 3).

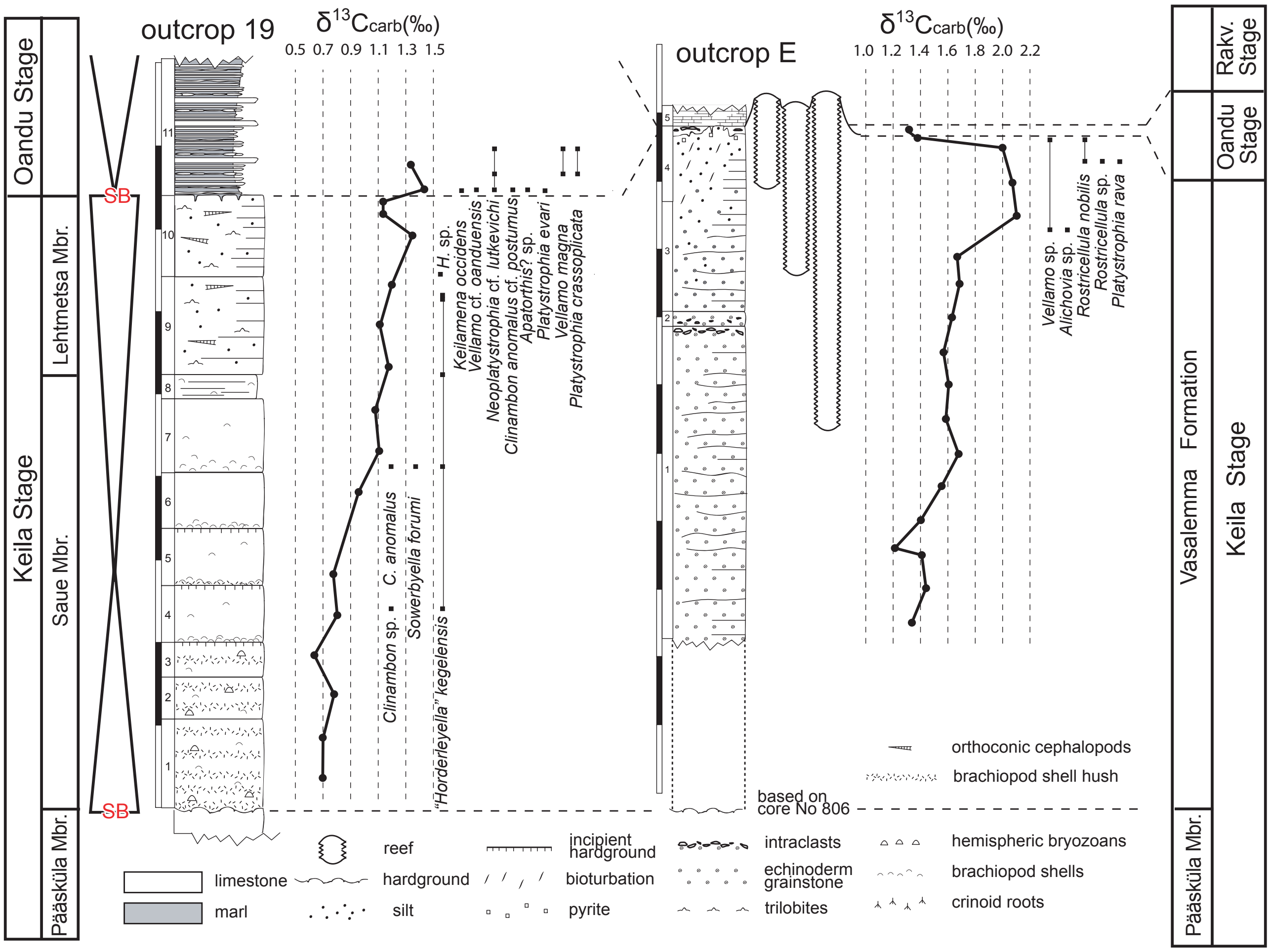


Figure 3. Lithology, macrofauna, $\delta^{13}C$ chemostratigraphy, and sequence stratigraphic interpretation of two sections at the eastern wall of the Vasalemma Nordkalk quarry. SB, Sequence boundary. $\delta^{13}C_{carb}$ data from bulk samples (Kröger *et al.* in press). Rakv., Rakvere Stage.

Lateral transition from the biodetritic, partly argillaceous to silty wackestones of the Saue and Lehtmetsa members (Põlma *et al.* 1988) of the Kahula Fm to the Vasalemma Fm is exposed on the eastern wall of the quarry.

The base and the top of the Vasalemma Fm are diachronous. Combined drill core and outcrop data indicate that in the southern part of the quarry the base is either at the prominent hardground on the top of the Pääsküla Mb of the Kahula Fm or less than a few metres above, within the overlying Saue Mb of the same formation. The top Pääsküla Mb forms the bottom of the northeastern part of the quarry and exposes a ripple surface. The ripple-marks have a mean wavelength of c. 0.4 m (Ripple indexes: RI=10.7, RSI=1.3) and a 10°NE/190°SW direction (Hints & Miidel 2008).

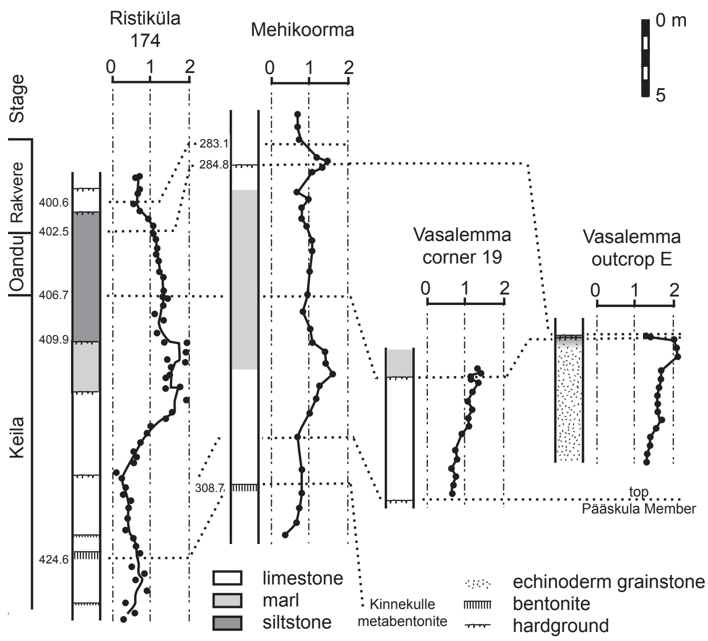


Figure 4. Correlation and carbon isotope curves of the early Katia sections in Estonia (Ristiküla from Ainsaar *et al.* 1999; Mehikoorma from Martma 2005; Vasalemma from Kröger *et al.* in press).

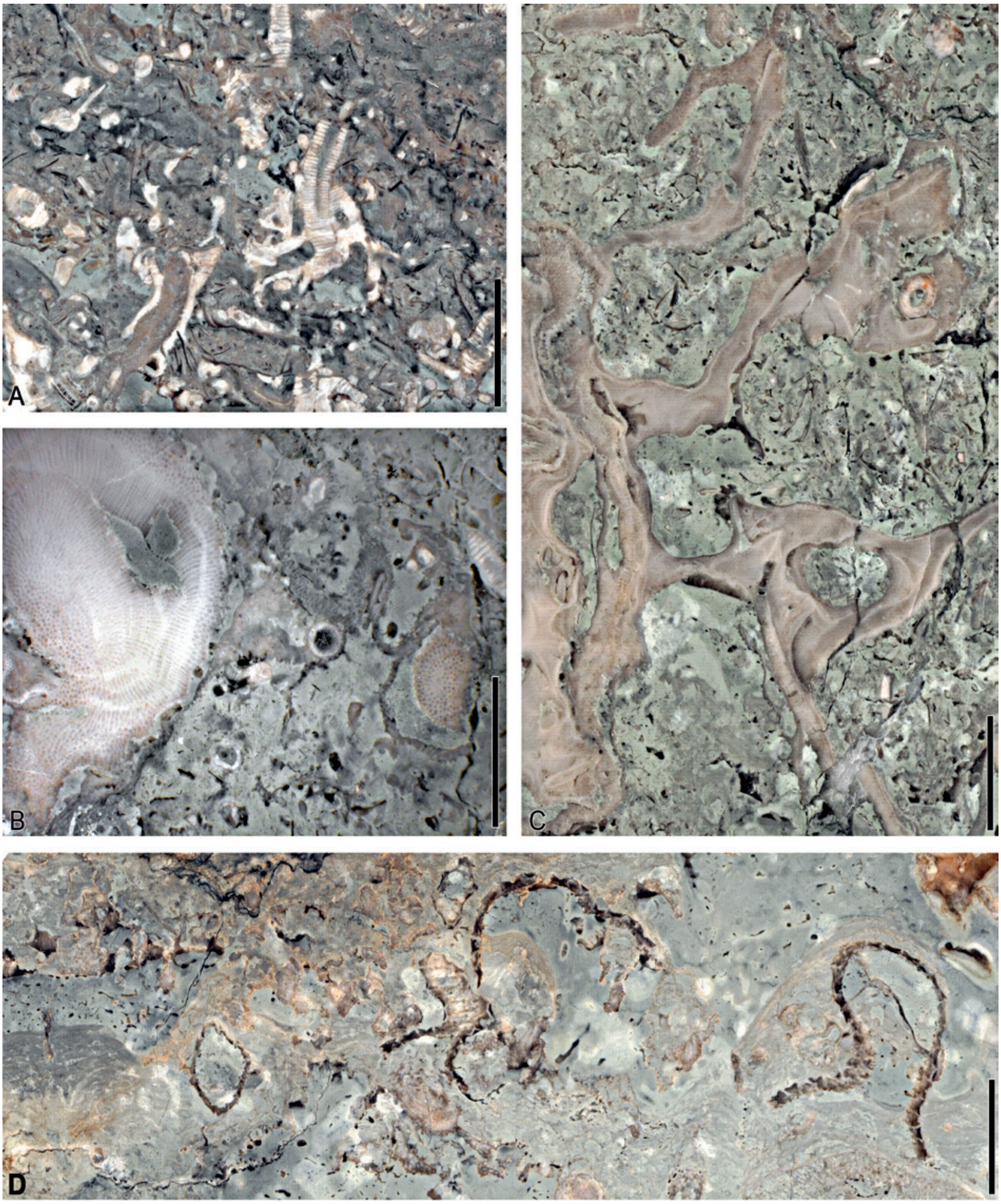


Photo 2. Polished slabs of reef limestone from the Vasalemma Formation, earliest Katian, outcrop E, Vasalemma Nordkalk quarry. **A.** Network of roots of *Hemicosmites* sp. overgrown by incrusting bryozoans. **B.** Bryozoan framestone with domal and incrusting forms. **C.** Network of dendroid bryozoan, partly overgrown with incrusting bryozoans, note birdseyes structures in sediment matrix. **D.** Slab with receptaculites and domal microbial interbeds, note also concentration of spicules in mudstone area (e.g. extreme left of picture), that is interpreted as small synsedimentary filled cavity. Scale 10 mm.

An erosional hardground with pyrite impregnation and bioerosion caps the Vasalemma Fm. In some places dense cornulitid infestation of the hardground surface is remarkable. Locally the hardground is covered by a conglomerate with highly rounded, pyrite-impregnated clasts from the Vasalemma Fm. Macrofauna and chemostratigraphy indicate Oandu age for this conglomerate. In other places the hardground is directly covered by the yellowish micritic limestones of the Tõrremägi Mb of the Rägavere Fm.

Reef growth zone and composition

In the southern part of the Vasalemma (Nordkalk) quarry more than 60 reefs are exposed on the quarry floor and on the quarry walls (Fig. 1). The data of 241 core sections from the quarry area show that this part of the quarry represents one of the centres of very high reef concentration. A band of abundant, thick (maximum 15 m), and sometimes more than 50 m wide reefs runs in a nearly E/W direction through the southern part of the Vasalemma quarry (Kröger *et al.* in press). The space between the reefs is filled with layered beds of echinoderm grainstone with a thickness of up to 15 m. The data of the core sections reveal a highly variable pattern of thickness distribution throughout the quarry area with a general decreasing trend towards the north (Fig. 1).

The reef growth started above the top hardground of the Pääsküla Member. This surface can be used as an approximation of the sea bottom topography of the reef development. This level provides the basis for an altitudinal map, which reflects the general tectonic southward-dipping trend of the sediments in northern Estonia (see Kröger *et al.* in press for method). The Vasalemma quarry is positioned in a platform-like region that was situated at the southern margin of a depression with a NNW/SSE direction. The basinward direction of this platform must have been towards the NE. In direction to the SW probably a local elevation was positioned, which is marked by an elongated narrow region of non-deposition of late Keila–Oandu sediments (see Ainsaar *et al.* 2004).

Our sedimentological studies (Kröger *et al.* in press) confirm that the reefs are composed of a partly complicated mosaic of framebuilders, binders and bafflers, of masses of massive micritic limestones and of filled caves and cravices. Generally, four facies types can be distinguished within the reefs:

1. A bryozoan framestone – bindstone with dendroid cystoporid bryozoans (such as *Vasalemmapora* Pushkin) (Photo 2B, C) and more commonly with incrusting cystoporid bryozoans. The incrusting forms (not formally described yet) act as sediment binders in the interspaces and caverns between bafflers.

2. An echinoderm framestone – bindstone. Large parts of the reef bodies were built by dense networks of *Hemicosmites*-roots acting as main sediment bafflers (Photo 2A). Locally, especially higher in the Vasalemma Formation, patches of reefs are built by the balanid-like skeletons of *Cyathocysthis*.

3. A receptaculite–bryozoan–microbial framestone. *Receptaculites*, described as *Receptaculites poelmi*, are locally very abundant, forming the frames of significant parts of the reef bodies (Photo 2D). The interspaces between the receptaculite-skeletons are often formed by layered microbial bindstones, which contain significant numbers of sponge spicules.

4. A tabulate bafflestone. This type occurs exclusively at the stratigraphically highest parts of reef limestones and at the flanks of the stratigraphically highest reefs. It is composed of large bodies of *Lyopora tulaensis*.

The reefs, additionally, contain a rich, yet undescribed, fauna of cephalopods, other molluscs, trilobites and brachiopods, which are often concentrated in so-called “pockets”, synsedimentary crevices and caves. Rugose corals are represented by several species in the Vasalemma Fm.

Macrofossils other than echinoderm fragments are relatively rare within the echinoderm grainstone. Remarkable are levels with decimetre-size colonies of the tabulate coral *Eofletcheria orvikui* and domal skeletons of the chaetetid sponge *Solenopora*.

The macrofauna of the Vasalemma Formation strongly contrasts with the brachiopod-dominated fauna of the contemporaneous beds of the Saue and Lehtmetsa members of the Kahula Fm. The brachiopods (*Estlandia pyron silicificata*, *Bassettella alata*, *Saukrodictya* sp., *“Horderleyella” kegelensis*, *Apatorthis* sp.) occur mainly in the argillaceous interlayers in the lower half of the Vasalemma Fm. The species of genera *Sowerbyella* (*Sowerbyella*), *Strophomena* (*Keilamena*), *Clinambon* and also *Vellamo* represent the most common brachiopods in the Saue and Lehtmetsa members.

Mining of Vasalemma limestone

Limestone excavation in Estonia is documented already from the 13th century, when western crusaders invaded Estonia and started to build castles, churches, etc. The Harjumaa region is well known for ancient limestone buildings, the most important of which is the Padise monastery built of Vasalemma Limestone. Limestone usage continued through centuries and Vasalemma Limestone was even transported with ships to Germany. Many limestone quarries are located in the Vasalemma region. The more recent Vasalemma quarry history started during the first Republic of Estonia, when a small quarry was opened in 1931. During the Soviet period the limestone was mainly used as raw material for railway building, and also for other sectors such as cement industry. In the 1980s a total of six crushing lines were running; the last one was demolished in 2011. Currently the quarrying area in Vasalemma is over 340 hectares. When the reserves are fully quarried the area will be recultivated and the quarry will be the second largest artificial lake in Estonia.

Since 1996 the large Vasalemma quarry has been operated by Nordkalk AS, which produces not only for the domestic market, but also for export. During the best years of Nordkalk AS a total of one million tons of Vasalemma limestone was produced per year. In 2007 the Nordkalk AS invested for a new mobile crushing and screening line, which replaced the existing lines. Currently Nordkalk AS uses additional contractors for the crushing and screening, but the company is ready to invest for a new crushing line if annual volumes increase. Nordkalk AS has plans to make investments for a washing unit, which will increase our raw material utilization and then so-called stone-sand will be produced.

At the domestic market the main customers are engaged in the road industry, but Vasalemma limestone is also used for the cement industry. The export markets of Vasalemma Nordkalk AS are currently oriented to Finland. There the limestone is further ground and purified by the Talvivaara Mining Company. Vasalemma Limestone is also used in the desulphurization process of coal plants and producing fodders. Furthermore, Nordkalk AS has a long history with the sugar industry, where limestone is used for the carbonization process, which will remove impurities from sugar juice before crystallization.

Taking into account that Vasalemma Limestone has a long history as building stone, Nordkalk AS started a cooperation with one of the Estonian companies, who is adding value to raw material and making so-called finishing stone. In this way Nordkalk AS is part of the process of making Estonian limestone more known and used. Limestone has been very important for Estonian industry and Nordkalk AS is proud to be part of that.

References

Ainsaar, L., Kaljo, D., Martma, T., Meidla, T., Männik, P., Nõlvak, J. & Tinn, O., 2010. Middle and Upper Ordovician carbon isotope chemostratigraphy in Baltoscandia: A correlation standard and clues to environmental history. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 294, 3–4, 189–201.

Ainsaar, L. & Meidla, T., 2001. Facies and stratigraphy of the middle Caradoc mixed siliciclastic-carbonate sediments in eastern Baltoscandia. *Proceedings of the Estonian Academy of Sciences. Geology*, 50, 5–23.

Ainsaar, L., Meidla, T. & Martma, T., 1999. Evidence for a widespread carbon isotopic event associated with late Middle Ordovician sedimentological and faunal changes in Estonia. *Geological Magazine*, 136, 1, 49–62.

Ainsaar, L., Meidla, T. & Martma, T., 2004. The Middle Caradoc facies and faunal turnover in the Late Ordovician Baltoscandian paleobasin. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 210, 119–133.

Bergström, S. M., Lehnert, O., Calner, M. & Joachimski, M. M., 2012. A new upper Middle Ordovician–Lower Silurian drillcore standard succession from Borenshult in Östergötland, southern Sweden: 2. Significance of $\delta^{13}C$ chemostratigraphy. *GFF*, 134, 1, 39–63.

Bergström, S. M., Agematsu, S. & Schmitz, B., 2010a. Global Upper Ordovician correlation by means of $\delta^{13}C$ chemostratigraphy: implications of the discovery of the Guttenberg δ1[3]C excursion (GICE) in Malaysia. *Geological Magazine*, 147, 641–651.

Bergström, S. M., Schmitz, B., Saltzman, M. R. & Huff, W. D., 2010b. The Upper Ordovician Guttenberg $d^{13}C$ excursion (GICE) in North America and Baltoscandia: occurrence, chronostratigraphic significance, and paleoenvironmental relationships. *Geological Society of America Special Paper*, 466, 37–67.

Eichwald, E., 1854. Die Grauwackenschichten von Liev- und Ehstland. *Bulletin de la Societe Imperiale des Naturalistes de Moscou*. 27, 1, 1–111.

PRE-CONFERENCE EXCURSION

Hints, L., 1996. Vasalemma quarry. *In:* Meidla, T., Puura, I., Nemliher, J., Raukas, A. & Saarse, L. (eds). *The Third Baltic Stratigraphical Conference. Abstracts. Field Guidet.* Tartu University Press, Tartu, 93–96.

Hints, L. & Miidel, A., 2008. Ripple marks as indicators of Late Ordovician sedimentary environments in Northwest Estonia. *Estonian Journal of Earth Sciences,* 57, 11–22.

Kröger, B., Hints, L. & Lehnert, O. (*in press*), Age, facies and geometry of the Katian (Upper Ordovician) pelmatozoan-bryozoan-receptaculite reefs of the Vasalemma Formation, north Estonia. [submitted to "*Facies*", March 2014]

Männil, R., 1960. The stratigraphy of the Oandu ("Vasalemma") Stage. *Trudy Instituta Geologii Akademii Nauk Estonskoj SSR*, 5, 89–122. [in Russian with English summary].

Männil, R. M. & Rõõmusoks, A., 1984. A revision of the lithostratigraphic subdivision of the Ordovician of North Estonia. *In:* Männil, R. M. & Mens, K. A. (eds). *Stratigrafiya drevnepaleozojskikh otlozhenii Pribaltiki*. ENSV TA Geoloogia Instituut, Tallinn, 52–62. [in Russian].

Martma, T., 2005. Ordovician carbon isotopes. *In:* Põldvere, A. (ed). *Mehikoorma (421) drill core. Estonian Geological Sections, Bulletin 6,* 25–27.

Oraspõld, A., 1956. New brachiopods from the Jõhvi, Keila and Vasalemma stages. *ENSV TA Geoloogia Instituudi Uurimuse*d, I, 41–67. [in Russian].

Põlma, L., Sarv, L. & Hints, L., 1988. *Lithology and fauna of the Caradoc Series type sections in North Estonia*. Valgus, Tallinn, 101 pp. [in Russian with English summary].

Raymond, P. E., 1916. The correlation of the Ordovician strata of the Baltic Basin with those of Eastern North America. *Bulletin of the Museum of Comparative Zoology at Harvard College*, 7, 3, 179–286.

Rõõmusoks, A., 1970. Stratigraphy of the Viruan Series (Middle Ordovician) in Northern Estonia. Valgus Publishers, Tallinn, 346 pp. [in Russian].

Rozhnov, S. V., 2004. Echinoderms of the bioherms of the Baltic Ordovician basin: comparison of the coldwater (Volkhovian) and tropical (Keila) communities. *In:* Hints, O. & Ainsaar, L. (eds). *WOGOGOB 2004, Conference materials*, 86–87.

Schmidt, F., 1881. Revision der ostabaltischen silurischen Trilobiten nebst geognostischer Übersicht des ostbaltischen Silurgebiets. Abt. I. Phacopiden, Cheiruriden und Encrinuriden. *Memoires de L'Academie Imperiale des Sciences de St. Petersburg*, 7, 30, 1–238.

Stop A3: Ristna coastal outcrop

***Tõnu Meidla*[1], *Vincent Perrier*[2] *and Leho Ainsaar*[1]**

[1]*Department of Geology, University of Tartu, Estonia*
[2]*Department of Geology, University of Leicester, UK*

The Ristna cliff (Photo 1) is located 60 km WSW of Tallinn, on the eastern coast of the Ristna headland (59°16′22.39″N, 23°4′2.6″E). The limestone beds containing rich and diverse fossil fauna crop out along the eastern coast of the headland. The length of the exposure is over 300 m but the actual situation is very much dependent on the movement of loose sediment and algal masses, as well as on the water level, as some of the exposed strata are accessible near or even below the water level.

Photo 1. View to the southern part of the Ristna cliff (photo T. Meidla).

The exposed strata comprise the middle part of the Kurtna Member of the Kahula Formation. The total thickness of the exposed strata reaches 3.5 m (Hints *et al.* 1990).

The southern part of the outcrop exposes light yellowish-grey thin-bedded argillaceous limestone in a thickness of approximately 1.4 m (Hints *et al.* 1990). Further to the north, the escarpment is slowly gaining a height up to 2 m and a K-bentonite bed appears in the lower part of the section. The description at that location (from the base; see also Photo 2; coordinates indicated above) is as follows:

Photo 2. The lower-middle parts of the Ristna section (photo T. Meidla).

0.75 m – greenish- to yellowish-grey slightly argillaceous limestone (wackestone). The content of skeletal material decreases in the upper part and some silicification may occur in the upper 0.15 – 0.2 m of the interval. Accumulations of echinoderm columnals and fragments (*Ristnacrinus marinus* Öpik – Hints *et al.* 1990) may occur on bedding planes.

0.06 m – yellowish-grey hard K-bentonite with rare tiny biotite flakes, exposed in a deep abrasional niche. The layer is mainly composed of K-feldspar and a mixture of illite and smectite. Calcite, the main component of the over- and underlying rocks, is almost absent in these levels (Perrier et al. 2012; see also Fig. 2). The unit contains silicified bryozoan and crinoidal fragments and rare brachiopods *Sowerbyella (Sowerbyella) trivia* (Rõõmusoks) and *Horderleyella*? *kegelensis* (Alichova) (Hints *et al.* 1990).

1.2 m – light grey limestone (wackestone) intercalated with slightly dolomitic calcareous marl. Dolomitic intervals show a slightly elevated concentration of very fine dispersed quartz (Perrier *et al.* 2012; see Fig. 2).

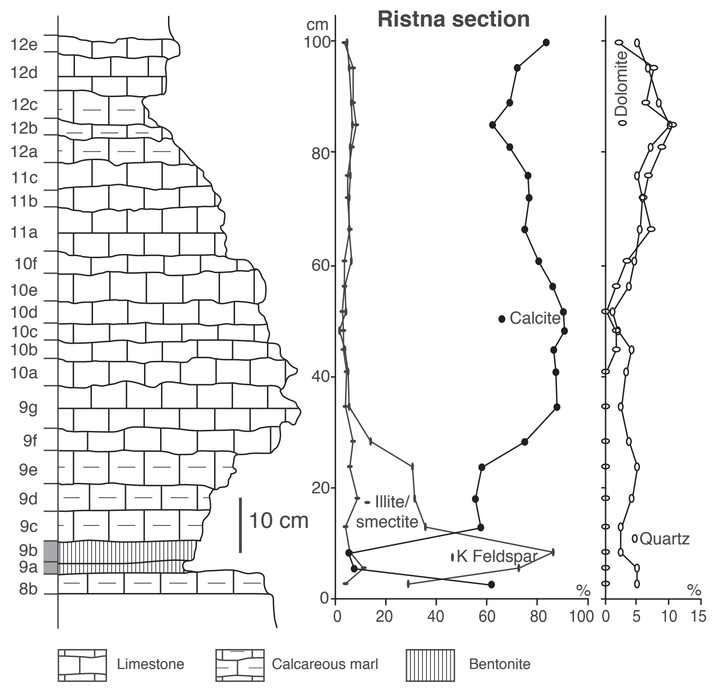


Figure 1. Rock composition in the middle part of the Ristna section (Perrier *et al.* 2012, Fig. 1.5).

The K-bentonite layer in the section has been produced as a result of one of the very numerous (about 150 in total, Perrier *et al.* 2012) volcanic episodes recorded in the Baltoscandian sedimentary succession. In older papers the particular layer was designated as the "metabentonite bed e" (Jürgenson 1958 and subsequent papers). Recently the term "Grimstorp K-bentonite" was introduced for the same layer (Bergström *et al.* 1995). The altered material of volcanic origin was deposited in sea water, strongly affected by subsequent compaction (3–4 times, Huff *et al.* 1996). This bed is located about 6 m above the Kinnekulle K-bentonite (term introduced by Bergström *et al.* 1995) at Ristna. This inter-bentonite interval is only 2–4 m thick in most of North Estonia and its thickness is further reduced in South Estonia (1–2 m) and western islands (below 1 m) (Perrier *et al.* 2012).

The section is richly fossiliferous, containing both macro- and microfauna. It is an ideal section to study environmental impacts of the Ordovician ash falls and the subsequent recovery of benthic communities. The pilot study carried out in the interval of the Kinnekulle K-bentonite (Hints *et al.* 2003) showed that ostracods are the most sensitive components among the benthic groups. The comparative investigation of ostracod response to the volcanic events of different magnitude (Perrier *et al.* 2012) revealed a very rich and diverse ostracod assemblage in the Ristna section (see Fig. 3) and demonstrated a distinct disturbance interval of about 15 cm where the abundance, species richness and diversity are clearly affected. The ash falls of different magnitude seem to cause impacts of different scale, as the influence of the larger Kinnekulle ash fall could be recorded in an interval of 25 cm (Perrier *et al.* 2012). It is interesting that the estimated ostracod recovery period was much longer in the Ordovician than the recovery of benthic foraminifers in modern oceans. The reasons for this discrepancy are not very clear yet.

Figure 2. Ostracod distribution and changes in ostracod abundance, species richness and diversity in the Ristna section (compiled from Perrier *et al.* 2012, figures 6 and 3). Width of the bars represents relative frequency (%) of the species. Light gray represents the Grimstorp Bentonite. Samples 1–8 and 13 from Hints *et al.* (1990). 1 – *Hemiaechminoides* cf. *arvus*; 2 – *Rectella* sp.; 3 – *Pedomphalella egregia* (Sarv); 4 – *Rectella* ex. gr. *romboformis* Neckaja; 5 – *Tvaerenella longa* longa (Sarv); 6 – *Sigmoopsis rostrata* (Krause, 1892); 7 – *Braderupia asymmetrica* (Neckaja); 8 – *Krauselloides* sp.; 9 – *Bolbina major* (Krause); 10 – *Polyceratella aluverensis* Sarv; 11 – *Tetrada harpa/krausei*; 12 – *Medianella* aff. *longa* (Stumbur); 13 – *Airina amabilis* (Neckaja); 14 – *Scrobisylthis reticulatus* (Sarv); 15 – *Oepikella canaliculata* (Krause); 16 – *Oepikium* sp.; 17 – *Sigmobolbina variolaris*? (Bonnema); 18 – *Circulinella nuda* (Neckaja); 19 – *Longiscula parrectis*? (Neckaja); 20 – *Leperditella prima* Sarv; 21 – *Pentagona* sp.; 22 – *Ctenonotella bidens* (Krause); 23 – *Easchmidtella fragosa* (Neckaja); 24 – *Snaidar radians* (Krause); 25 – *Homeokiesowia frigida* (Sarv); 26 – *Tetrada grandis* (Sarv); 27 – *Cryptophyllus*?; 28 – *Bolbina ornata* (Krause); 29 – *Hemeaschimdtella* sp.; 30 – *Vogdesella* sp.; 31 – *Platybolbina temperata* Sarv; 32 – *Circulina fimbriata* Neckaja; 33 – *Kiesowia scopulosa* Sarv; 34 – *Sigmoopsis cornuta* (Krause); 35 – *Pseudoancora* sp.; 36 – *Unisulcopleura* sp.; 37 – *Bolbina* sp.; 38 – *Euprimites* (*Bichilina*) *prima* Sarv; 39 – *Disparigonya voigti* Schallreuter; 40 – *Rectella inequalis*? Neckaja; 41 – *Carinobolbina carinata* (Sarv); 42 – *Fallaticella bulbata*? Schallreuter; 43 – *Circulina*? *paulis* Neckaja; 44 – *Hillmeria maeandrica* Schallreuter; 45 – *Ceratobolbina allikuensis* (Sarv); and 46 – *Rakverella spinosa* Öpik.

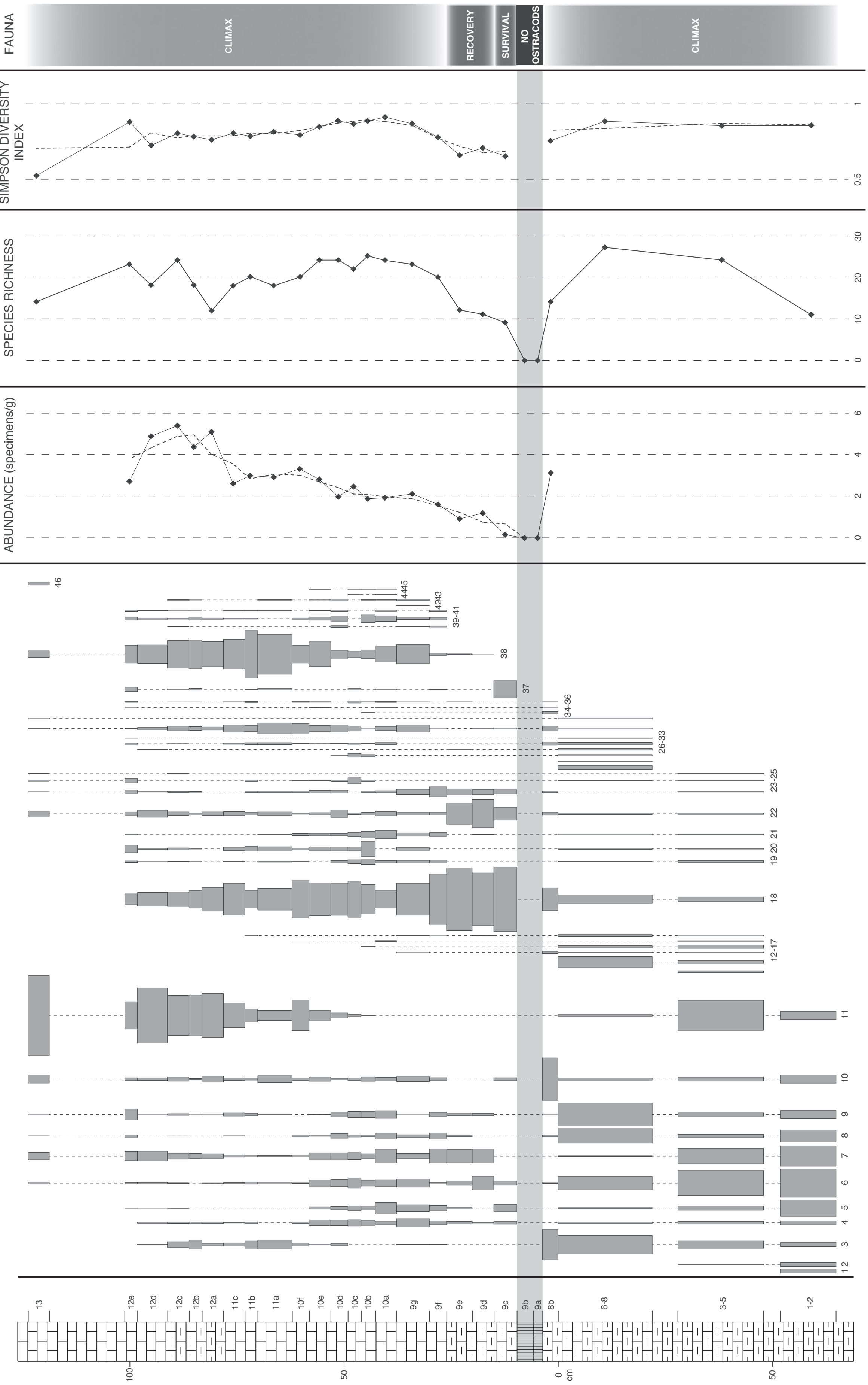


Figure 2. *See description on a previous page.*

Chitinozoan distribution is relatively uniform throughout the section and supports the Keila age of the exposed strata (J. Nõlvak in Hints *et al.* 1990, Fig. 30). The barren interval recorded below the bentonite bed is likely due to preservational reasons.

The composition of the macrofossil assemblage in the Ristna section was summarized by Rõõmusoks (1970) and supplementary data were provided by L. Hints (in Hints *et al.* 1990) and Rõõmusoks (1998). The upper part of the section (above the bentonite) contains *Estlandia pyron silcificata* Öpik, *Porambonites ventricosus* Kutorga, *Clinambon anomalus anomalus* (Schlotheim), *Asaphus* (*Neoasaphus*) *nieszkowskii* Schmidt, *Toxochasmops (Schmidtops*) *maximus* (Schmidt) and *Ristnacrinus marinus*. The lower part of the section contains also *Saucrodictya* sp., *Platystrophia* ex gr. *dentata dentata* (Pander), *Babanicrinus* cf. *kegelensis* (Yeltyschewa) and *Baltocrinus hrevicaensis* (Yeltyschewa).

References

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

Hints, L., Meidla, T. & Nõlvak, J., 1990. Locality 2:4, Ristna cliff. *In:* Kaljo, D., Nestor, H. (eds.). *Field Meeting, Estonia 1990. An Excursion Guidebook*. Estonian Academy of Science, Tallinn, 136–138.

Hints, O., Hints, L., Meidla, T. & Sohar, K., 2003. Biotic effects of the Ordovician Kinnekulle ash-fall recorded in northern Estonia. *Bulletin of the Geological Society of Denmark*, 50, 115–123.

Huff, W.D., Kolata, D.R., Bergström, S.M. & Zhang, Y.-S., 1996. Large-magnitude Middle Ordovician volcanic ash falls in North America and Europe: dimensions, emplacement and post-emplacement characteristics. *Journal of Volcanology and Geothermal Research*, 73, 285–301.

Jürgenson, E., 1958. Metabentonites of the Estonian SSR. *Proceedings of the Institute of Geology*, 2, 73–85. [in Russian].

Perrier, V., Meidla, T., Tinn, O. & Ainsaar, L., 2012. Biotic response to explosive volcanism: Ostracod recovery after Ordovician ash-falls. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 365, 166–183.

Rõõmusoks, A., 1970. Stratigraphy of the Viruan Series (Middle Ordovician) in Northern Estonia. Valgus Publishers, Tallinn, 346 pp. [in Russian].

Rõõmusoks, A., 1998. Trilobites of the genus *Toxochasmops* from the Ordovician of Estonia. *Proceedings of the Academy of Sciences of Estonia. Geology*, 47, 1, 173–194.

Stop A4: Sutlema quarry

Tõnu Meidla and Leho Ainsaar

Department of Geology, University of Tartu, Estonia

The new Sutlema quarry is located 29 km south of Tallinn, 7.8 km west of Kohila, in the Rapla County (59°10′29″N, 24°37′13″E). References to the old quarries in the vicinity are known already from the historical sources.

The quarry is of irregular shape and measures about 500 m in W–E and 250 m in N–S directions. Its depth reaches mostly 2–3 m but a deep excavation in the eastern central part of the quarry adds about 4 m to the section. This excavation is partly flooded in wet season.

The quarry exposes the boundary strata of the Nabala and Vormsi stages (middle–upper Katian). The description presented here (see Fig. 1) is based on the combined section in the main (eastern) part of the quarry, which is represented in two escarpments (Photo 1), at a distance of about 90 m. The top of the lower escarpment (Photo 2) nearly coincides with the base of the upper escarpment that comprises the outer boundary of the quarry (Photo 3).

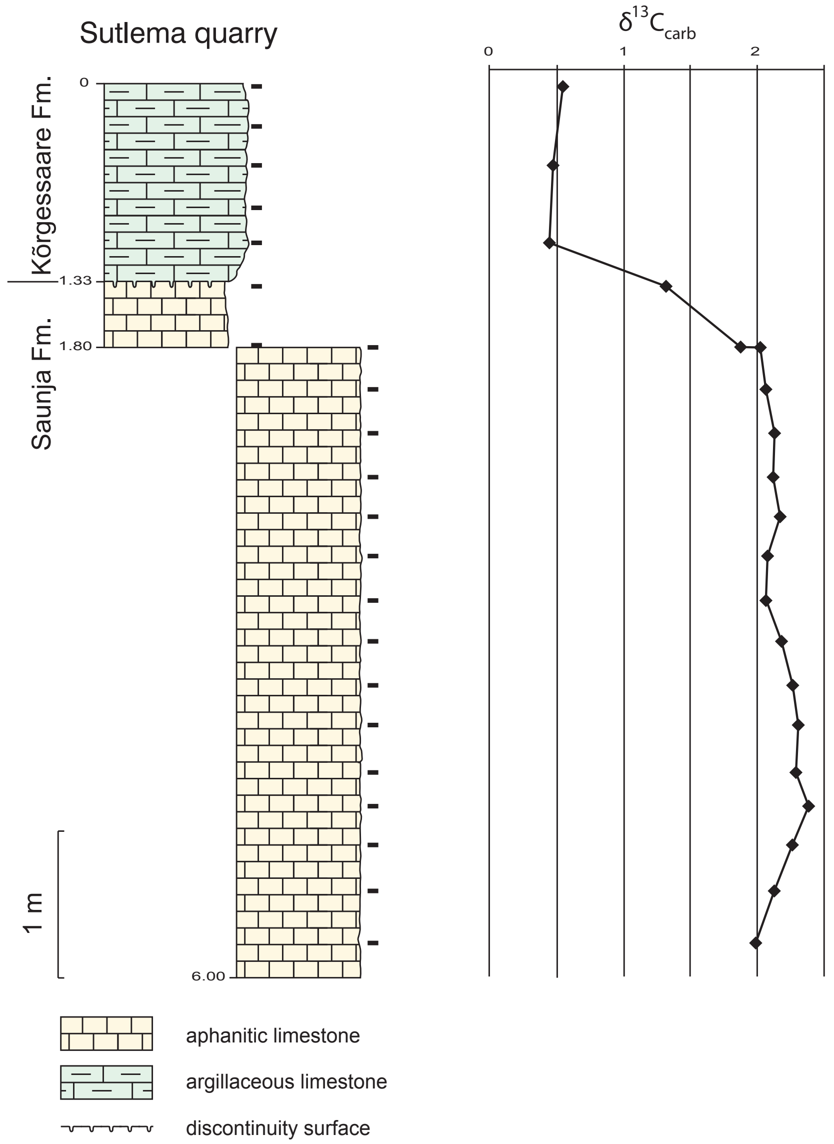


Figure 1. Lithology and δ13C values in the Sutlema section, exposing the lowermost part of the Kõrgessaare Formation (Vormsi Stage) and upper part of the Saunja Formation (Nabala Stage). Distance between the upper and lower parts of the section is about 90 m.

Kõrgessaare Formation (main part of the upper escarpment):
1.33 m – brownish to bluish-grey weakly argillaceous limestone (wackestone), mostly medium-bedded, seminodular, with thin wavy interbeds of calcareous marl. The rocks are moderately fossiliferous, containing tabulate corals, gastropods, rhynchonelliformean brachiopods, fragmentary orthogonic cephalopods, rare linguliformean brachiopods and other fossils.

The lower boundary of this unit represents an uneven discontinuity surface that marks a sharp change in the rock composition.

Saunja Formation (the lowermost part of the upper escarpment and the lower escarpment):
4.67 m + – yellowish to bluish-grey cryptocrystalline (aphanitic) limestone (mudstone), thick-bedded, with occasional spots and marks of fine dispersed pyrite. Fossils are very rare.

Photo 1 (left). Sutlema quarry, the upper escarpment and upper part of the lower escarpment. Width of the plateau between them is about 90 m.

Photo 2 (lower left). The lower escarpment in the Sutlema quarry – the aphanitic limestones of the Saunja Formation.

Photo 3 (down). The upper escarpment in the Sutlema quarry – the limestones of the Kõrgessaare Formation. The below the formational boundary at the base of escarpment, the topmost Saunja Formation could be excavated (all photos T. Meidla).

The transition from pure mudstones to moderately argillaceous wackestones has been historically considered the lower boundary of the Vormsi Stage, although in the first order it represents a facies boundary. Substantial differences are observed in macrofauna, as the upper unit is richly fossiliferous compared to the lower one.

The stable isotopic curve (Fig. 1) shows a characteristic change in $\delta^{13}C_{carb}$ values. Higher values, up to 2.39‰, are recorded in the lower part of the succession, in the cryptocrystalline pure limestones of the Saunja Formation. This high of the curve comprises the Saunja Excursion (Ainsaar *et al.* 2010), earlier also termed the 2nd late Caradoc Excursion (Kaljo *et al.* 2007). In terms of stable carbon isotopic zonation (Ainsaar *et al.* 2010), this part of the curve represents Zone BC10, whilst the upper 1.3 m of the section is attributed to Zone BC11 (Vormsi Stage) that is known to show quite variable $\delta^{13}C$ values (*e.g.* in the Männamaa section, Ainsaar & Meidla 2008). The Saunja Excursion seems to be tied to specific lithologies and may be obscure or fairly absent in the areas where cryptocrystalline limestones are absent (*e.g.* the Fjäcka section in Sweden, Ainsaar *et al.* 2010). The Saunja Excursion has been correlated with the Waynesville Excursion in North America (Bergström *et al.* 2012).

References

Ainsaar, L., Kaljo, D., Martma, T., Meidla, T., Männik, P., Nõlvak, J. & Tinn, O., 2010. Middle and Upper Ordovician carbon isotope chemostratigraphy in Baltoscandia: A correlation standard and clues to environmental history. Palaeogeography, Palaeoclimatology, Palaeoecology, 294, 189–201.

Ainsaar, L. & Meidla, T., 2008. Ordovician carbon isotopes. *In:* Põldvere, A. (ed). *Männamaa (F-367) drill core. Estonian Geological Sections*, Bulletin 9. Geological Survey of Estonia, Tallinn, 27–29.

Bergström, S. M., Eriksson, M. E., Young, S. A. & Widmark, E.-M. 2012. Conodont biostratigraphy, and $\delta^{13}C$ and $\delta^{34}S$ isotope chemostratigraphy, of the uppermost Ordovician and Lower Silurian at Osmundsberget, Dalarna, Sweden. *GFF*, 134, 4, 251–272.

Kaljo, D., Martma, T. & Saadre, T., 2007. Post-Hunnebergian Ordovician carbon isotope trend in Baltoscandia, its environmental implications and some similarities with that of Nevada. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 245, 138–155.

Stop A5: Väo quarry

Heikki Bauert[1], Rein Einasto[2] and Jaak Nõlvak[1]
[1]Institute of Geology at Tallinn University of Technology, Estonia
[2]TTK University of Applied Sciences, Estonia

The large, ca 3 sq km in an area, active Väo limestone quarry is located in the eastern suburb of Tallinn where limestone mining and crushing into limestone aggregate is operated by two companies – Paekivitoodete Tehas OÜ and Väo Paas OÜ.

The southern quarry wall (59°25´43.49″N, 24°53´34.12″E) exposes an excellent over 12 m thick succession of Middle Ordovician cool-water carbonates (Photo 1). The section spans carbonate rocks of the upper Volkhov, Kunda, Aseri, Lasnamägi and lower to middle part of the Uhaku regional stages, being coeval with most of the Darriwilian Global Stage.

The following description of the Väo quarry section (Fig. 1, Photo 2) is based on an exploratory drillcore Väo No. 4, drilled ca 200 m south of the quarry limit:

Volkhov Stage, Toila Formation
16.85–17.85+ m – light greenish-grey biomicritic, glauconitic limestone, microcrystalline with distinctive dark grey marlstone layers (2–4 cm in thick).

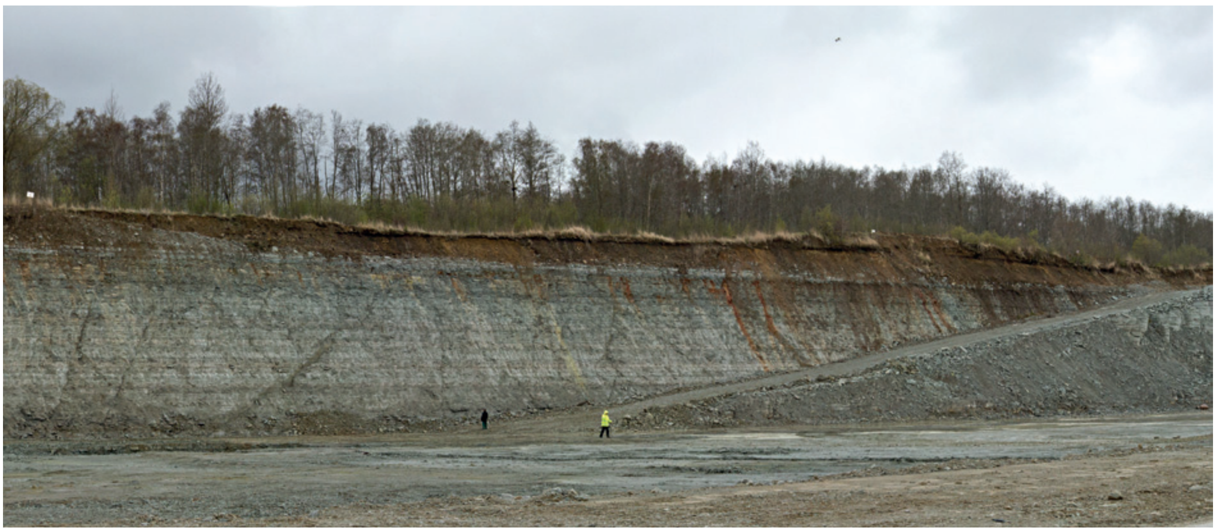
Kunda Stage, Loobu Formation
16.25–16.85 m – grey biomicritic limestone, finely crystalline massive bed with numerous phosphatic dicontinuity surfaces. The lower 10 cm interval is more argillaceous and contains ferriferous ooids. Orthocone cephalopod conchs are observed. The lower boundary is marked by a discontinuity surface.

Aseri Stage, Kandle Formation
15.50–16.25 m – grey with rusty-looking spots or yellowish-grey biomicritic limestone with abundant ferriferous ooids in the upper and lower parts. The middle 15 cm is grey calcilutic limestone, topped by a distinctive hardground with a thin pyritic veneer. The lower boundary is represented by a conspicuous pyritic hardground.

Lasnamägi Stage, Väo Formation, Rebala Member
14.60–15.50 m – light grey finely crystalline, massive dolostone. The lower boundary is drawn by the appearance of ferriferous ooids.

13.15–14.60 m – light grey finely crystalline biomicritic limestone, slightly dolomitized with thin marly films.

Photo 1. Southern quarry wall of the Väo quarry, exposing succession of Darriwilian carbonate rocks (photo H. Bauert).



Lasnamägi Stage, Väo Formation, Pae Member

12.70–13.15 m – grey finely crystalline, massive dolostone. The lower boundary is transitional.

Lasnamägi–Uhaku stages, Väo Formation, Kostivere Member

6.35–12.70 m – light grey finely crystalline biomicritic limestone with rare marly films. Several weakly developed discontinuity surfaces with faint phosphatic or pyritic impregnation can be observed throughout the interval. However, a conspicuous double hardground with deep, narrow pockets occurs at a depth of 9.90 m. This "2x discontinuity surface" is considered as a specific lithostratigraphic marker level in NW Estonia. The lower boundary marks a change in lithologies.

Uhaku Stage, Kõrgekallas Formation

2.7–6.35 m – greenish-grey finely crystalline biomicritic argillaceous limestone. Kukersite organic matter is recorded in marly beds at depths of 2.7 and 3.2 m. A distinctive, well-developed pyritic hardground

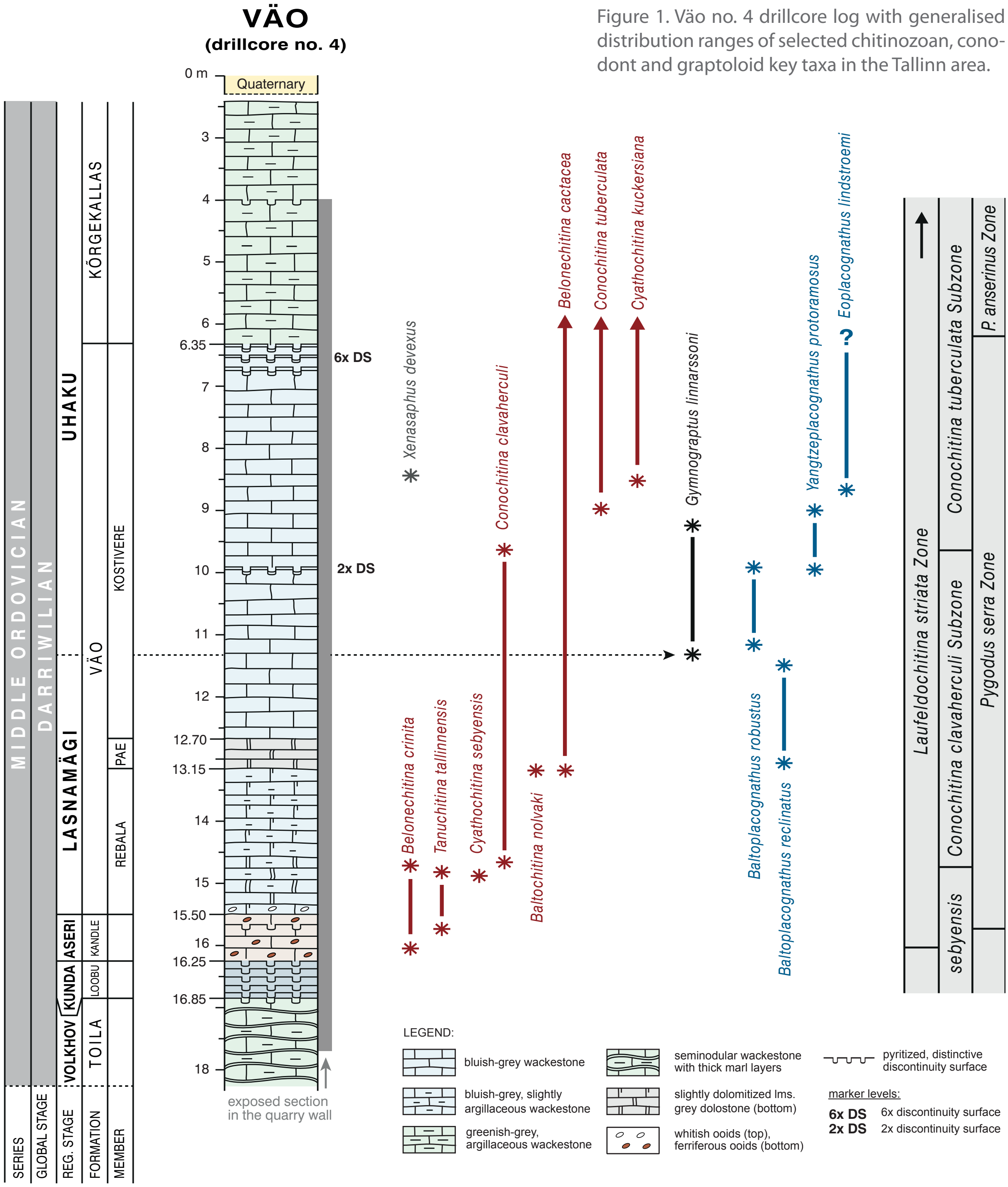


Figure 1. Väo no. 4 drillcore log with generalised distribution ranges of selected chitinozoan, conodont and graptoloid key taxa in the Tallinn area.

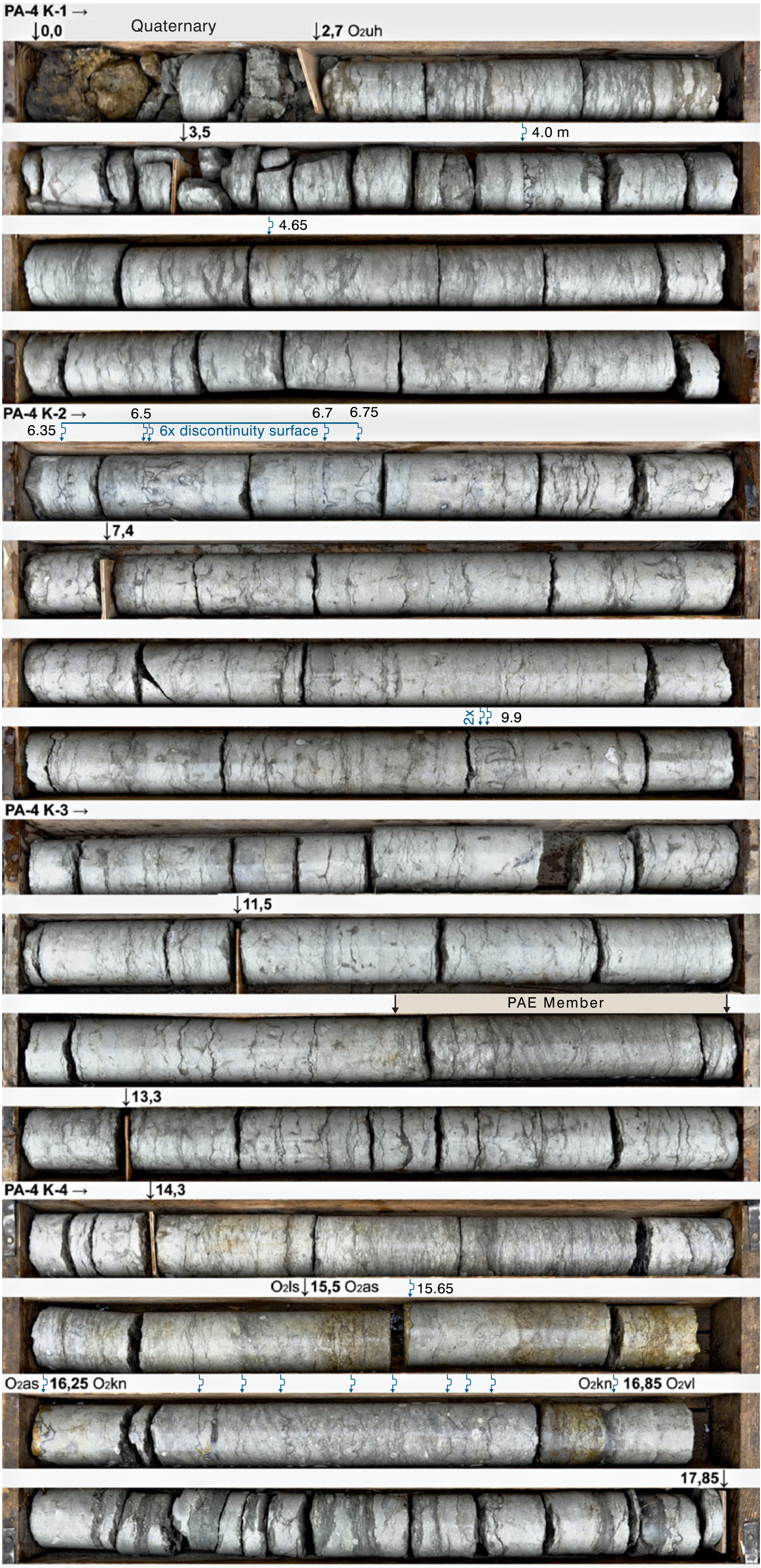


Photo 2. Väo no. 4 drillcore photolog (courtesy of Steiger OÜ).

is observed at a depth 4.0 m – the same hardground is recognizable within the uppermost beds of the quarry wall section as well. The lower boundary is drawn on top of a set of well-developed pyritic hardgrounds, which forms a well-known lithostratigraphic marker level ("6x discontinuity surface") for tracing the boundary of the Väo and Kõrgekallas formations in NW Estonia.

Key faunas of the Lasnamägi – Uhaku succession

The carbonate rocks of the Lasnamägi–Uhaku succession crop out only within a narrow latitudinal belt in northern Estonia, therefore the use of macrofaunas for biostratigraphic correlation purposes in the Palaeobaltic basin is areally confined to northern Estonia only. In contrast, some microfossils, particularly conodonts and chitinozoans have shown a great prospective for correlating Darriwilian rocks both in outcrops and drill cores all over the Palaeobaltic basin. A generalized distribution of the key faunas in the Lasnamägi–Uhaku succession of the Tallinn area (based on Männil 1976 and unpublished data by J. Nõlvak) is shown in Fig. 1.

Although graptolites are very rare in carbonate rocks, the appearance of *Gymnograptus linnarssoni* (Moberg) has proved to be a reliable indicator for tracing the boundary of the Lasnamägi and Uhaku stages in the Tallinn area (Männil 1976) as well as in NW Estonia (Uuga cliff at Cape Pakri: Tammekänd *et al*. 2010, Fig. 5; Osmussaare cliff: Hints *et al.* 2012, Fig. 3). Apart from Estonian sections, *G. linnarssoni* has been found in the Vikarby section (Siljan district, Sweden) as well as in the Aizpute and Kandava-25 drill cores in western Latvia (Männil 1976, Figs 2, 3).

Besides *G. linnarssoni*, conodonts offer a complementary tool for tracing the Lasnamägi–Uhaku boundary. The level of the LAD of *Baltoplacognathus reclinatus* (Fåhreus) with the FAD of *Baltoplacognathus robustus* (Bergström) has shown great biostratigraphic potential for establishing this boundary in southern Estonia as well (in the Tartu-453 core). The other short-ranged, biostratigraphically useful conodonts seem to be *Yangtzeplacognathus protoramosus* (Cheng, Cheng & Zhang) and *Eoplacognathus lindstroemi* Hamar (Männik & Viira 2012).

No chitinozoans are known to be indicative of the Lasnamägi–Uhaku boundary, however, several short-ranged key species (*Belonechitina crinita* (Grahn), *Tanuchitina tallinnensis* Grahn, *Cyathochitina sebyensis* Grahn, *Conochitina clavaherculi* Eisenack, *Baltochitina nolvaki* Paris & Grahn) can be confidently used for correlation purposes. The FAD and range data of *Belonechitina cactacea* (Eisenack), *Conochitina tuberculata* Eisenack and *Cyathochitina kuckersiana* (Eisenack) make them biostratigraphically useful as well.

References

Hints, O., Viira, V., & Nõlvak, J., 2012. Darriwilian (Middle Ordovician) conodont biostratigraphy in NW Estonia. *Estonian Journal of Earth Sciences*, 61, 210–226.

Männik, P., & Viira, V., 2012. Ordovician conodont diversity in the northern Baltic. *Estonian Journal of Earth Sciences*, 61, 1–14.

Männil, R., 1976. Distribution of graptoloids in the Ordovician carbonate rocks of the East Baltic area. *In:* Kaljo, D. L. & Koren T. N. (eds). *Graptolites and stratigraphy*. Academy of Sciences of Estonian SSR, Institute of Geology, Tallinn, 105–118. [in Russian with English summary].

Tammekänd, M., Hints, O. & Nõlvak, J. 2010. Chitinozoan dynamics and biostratigraphy in the Väo Formation (Darriwilian) of the Uuga Cliff, Pakri Peninsula, NW Estonia. *Estonian Journal of Earth Sciences*, 59, 25–36.

Stop A6: Arbavere field station

Anne Põldvere

Geological Survey of Estonia

The Arbavere field station of the Geological Survey of Estonia is located in northern Estonia, ca 70 km east of Tallinn. The field station was founded in 1972, in the course of the mapping of Precambrian crystalline rocks. Geologists understood very fast that this place was logistically perfect for field works and drill core storage. In 1975, old farmhouses were bought and in the next years drill core depositories and accommodation were set up. The field station was in active usage for thirty years but financial support to the station decreased substantially during the last decade. In 2010, the Geological Survey of Estonia obtained relief from the Environmental Investment Centre for the restoration of depositories' roofs and intended to develop the Arbavere Drill Core Research Centre here.

Today, 4500 core boxes are stored at the Arbavere field station. They contain drill cores of Precambrian crystalline rocks and of Cambrian, Ordovician and Silurian sedimentary rocks from the northern part of Estonia. Estonia's longest (815.2 m) drill core, Soovälja (K – 1), is deposited here as well. The Soovälja borehole was drilled during geological mapping in the area of the Kärdla impact structure in 1990.

The Soovälja (K – 1) and Männamaa (F – 367) drill cores will be demonstrated during the excursion. The sections expose sediments that are characteristic of the NW part of the East European Platform. The deposition took place in the marginal area of a shallow sea that recorded environmental changes caused by drift of the Baltica Palaeocontinent from higher southern latitudes towards the equator.

The Soovälja drill hole is located on the northern coast and the Männamaa drill hole in the central part of Hiiumaa Island. The Soovälja core section penetrates Upper Ordovician post-impact sedimentary rocks with 27 registered K-bentonite beds (at 24.0 – 301.2 m), a polymict impact breccia complex (at 301.2 – 522.8 m), strongly brecciated crystalline basement (at 522.8 – 588.5 m) and a part of the Palaeoproterozoic subcrater fractured basement down to 815.2 m. The crater structure of Sandbian age (about 455 million years ago) has been documented in detail from 60 closely spaced drill holes.

The Männamaa drill core penetrates the Silurian and Ordovician carbonate rocks (respectively at 29.0 – 46.5 m and 46.5 – 183.0 m), the Cambrian succession of clayey siltstones and quartz sandstones (at 183.0 – 298.0 m) and the Palaeoproterozoic migmatized gneisses and migmatite granites (298.0 – 358.3 m). The Kärdla impact event is marked here by a well-preserved interbed at 164.8 – 164.9 m where microbedded siltstones are intercalated by carbonate and clay.

The data on the Soovälja and Männamaa drill cores were published in the series *The Estonian Geological Sections*, in 2002 and 2008, respectively. The volumes are a result of long-term collaboration between specialists from Estonia and other countries.

Located in a peaceful pine forest near the Loobu River, the Arbavere field station is not far from the significant places of Estonian natural heritage: the North Estonian Klint, the Lahemaa National Park and several nature reserve areas (Viitna, Ohepalu, Kõrvemaa) with eskers, erratic boulders and karst. The nearest quarries of the Baltic Oil Shale Basin in northeastern Estonia are about 25 km away. Several hotels and hostels, as well as objects of cultural history (*e.g.* the Palmse, Sagadi and Vihula manors) are located in the vicinity.

Stop A7: Aluvere quarry

Leho Ainsaar and Tõnu Meidla

Department of Geology, University of Tartu, Estonia

In the abandoned Aluvere quarry near Rakvere, south of the Tallinn–Narva road (59°22´48″N, 26°24´20.8″E), the limestone succession of the Kahula Formation, Haljala Stage (Sandbian), is exposed. Here we see three lowermost members of the Kahula Formation: argillaceous limestone of the Vasavere Member with distinct thin claystone and K-bentonite layers, rhythmically intercalating limestone and argillaceous limestone of the Aluvere Member, and argillaceous limestone and marl of the Pagari Member. The Kahula Formation is overlying limestones of the Tatruse Formation, Haljala Stage, which are nowadays almost completely covered in the quarry.

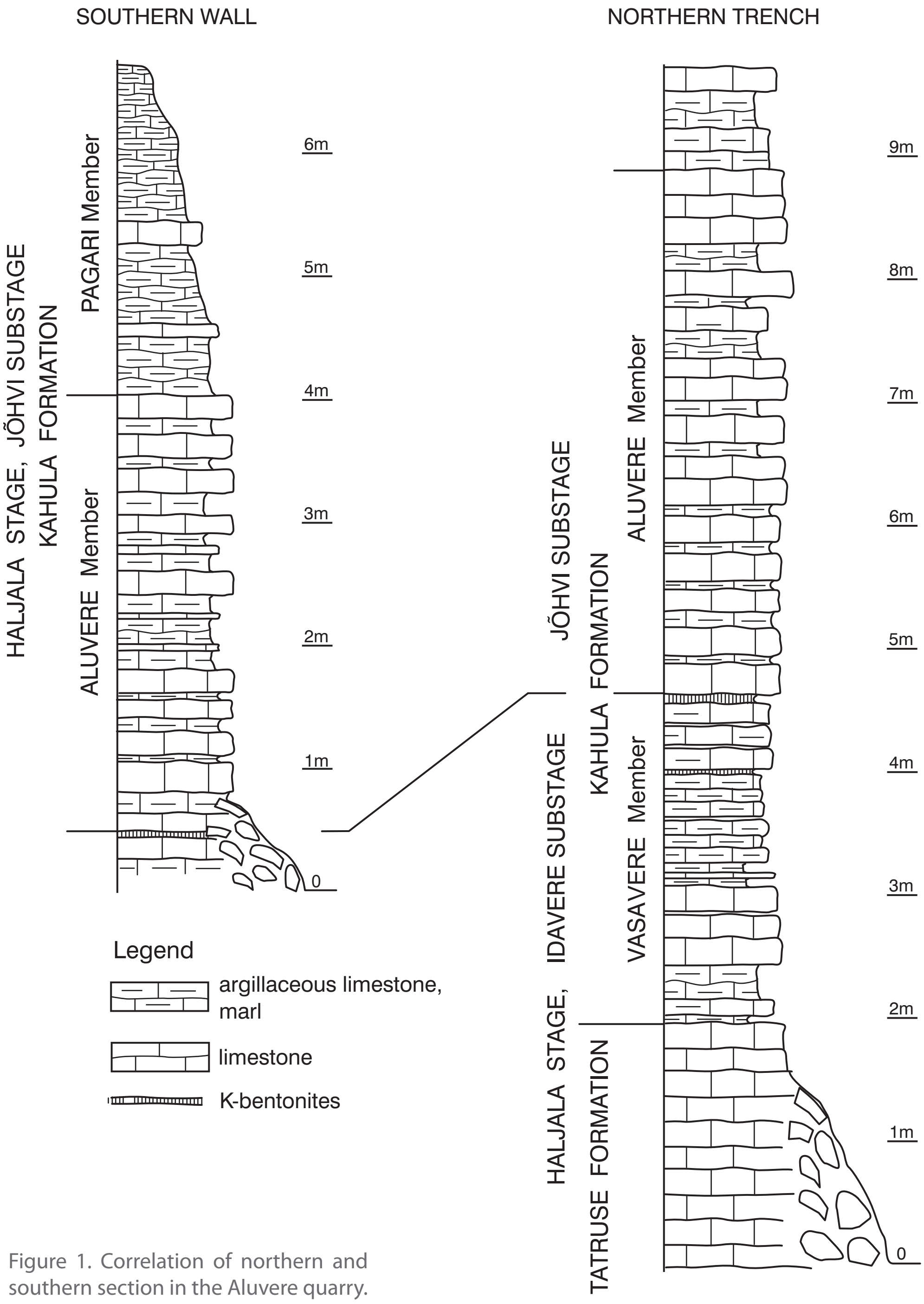


Figure 1. Correlation of northern and southern section in the Aluvere quarry.

Photo 1. Section at northern trench of the Aluvere quarry (photo T. Meidla).

Photo 2. Southern wall of the Aluvere quarry (photo T. Meidla).

In the northern part of the quarry, in an old railway cut, the Vasavere and Aluvere members are exposed. This section is well studied and repeatedly treated in publications (Rõõmusoks 1970; Põlma *et al.* 1988). Rõõmusoks (1970) documented the limestone succession in the northern trench in a thickness of 9.5 m but only about 7 m is still visible (Photo 1). Two thin (2–4 cm) K-bentonite beds, cropping out in the middle part of this wall, belong to the Grefsen K-bentonite complex (Bergström *et al.* 1995). The upper bed is considered as the boundary between the Idavere (below) and Jõhvi substages (previously referred to as stages) of the Haljala Stage.

In the southern wall of the quarry, 550 m away from the northern trench, 6 m of the section can be studied, representing the Aluvere and Pagari members (Photo 2). The limestone can be classified as wackestone to packstone with varying content (10–25%) of siliciclastic mud. The siliciclastics content varies rhythmically, forming 10–20 cm thick cycles that are clearly observable in the weathered walls of the quarry. A thin K-bentonite bed has been discovered in the lowermost part of this section, about 0.5 m above the quarry floor. This bed is very likely equivalent to the uppermost bentonite layer in the northern trench.

Rhythmically bedded argillaceous wackestones–packstones of the Haljala Stage have been deposited in temperate climate open marine conditions on the upper shelf or ramp (Nestor & Einasto 1997). The abundance and high diversity of benthic shelly fauna refers to the depositional environment at a moderate depth, probably within the photic zone. The Aluvere quarry has been a well-known fossil site since the beginning of the 20th century (Rõõmusoks 1970). More than 150 species of macrofossils have been reported from the locality, with brachiopods, bryozoans and various microfossils being abundant and diverse. Most common macrofossils are e.g. *Porambonites (Equirostra) baueri* Noetling, *Platystrophia lynx lynx* (Eichwald), *Clinambon anomalus* (Schlotheim), *Estlandia pyron silicificata* Öpik, *"Chasmops" wenjukowi* Schmidt, *Pyritonema subulare* (Roemer), *Diplotrypa petropolitana petropolitana* (Nicholson), *Tettragonis murchisoni* (Eichwald), *Conichnus conicus* Männil (for the extended lists see Rõõmusoks 1970 and Põlma *et al.* 1988). Silicification of fossils may occur in the southern section: the fossils may be completely or partly replaced or encrusted by bright white very fine-grained mass of SiO_2.

References

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

Nestor, H. & Einasto, R., 1997: Ordovician and Silurian carbonate sedimentation basin. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and Mineral Resources of Estonia*. Estonian Academyt Publishers, Tallinn, 192–204.

Põlma, L., Sarv, L. & Hints, L., 1988. *Lithology and Fauna of the Caradoc Series Type Sections in North Estonia*. Valgus, Tallinn, 101 pp. [in Russian with English summary].

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

Stop A8: Saka – Ontika Klint

Olle Hints

Institute of Geology at Tallinn University of Technology, Estonia

The Baltic Klint is one of the most extensive outcrops of Lower Palaeozoic rocks in the world. This nearly 1200 km long escarpment emerges at the western coast of Öland Island, Sweden, and extends through the Baltic Sea and North Estonia up to Lake Ladoga in Northwest Russia. The Saka – Ontika section represents the highest and most scenic part of the Baltic Klint. It reaches 56 m above sea level at the Ontika cliff, exposing the geological history of Baltica from the early Cambrian to Middle Ordovician. Based on unpublished descriptions by K. Mens and E. Pirrus, and Heinsalu *et al.* (1991) and Mägi (1990), the composite succession of the Saka – Ontika Klint (Fig. 1) contains the following main units.

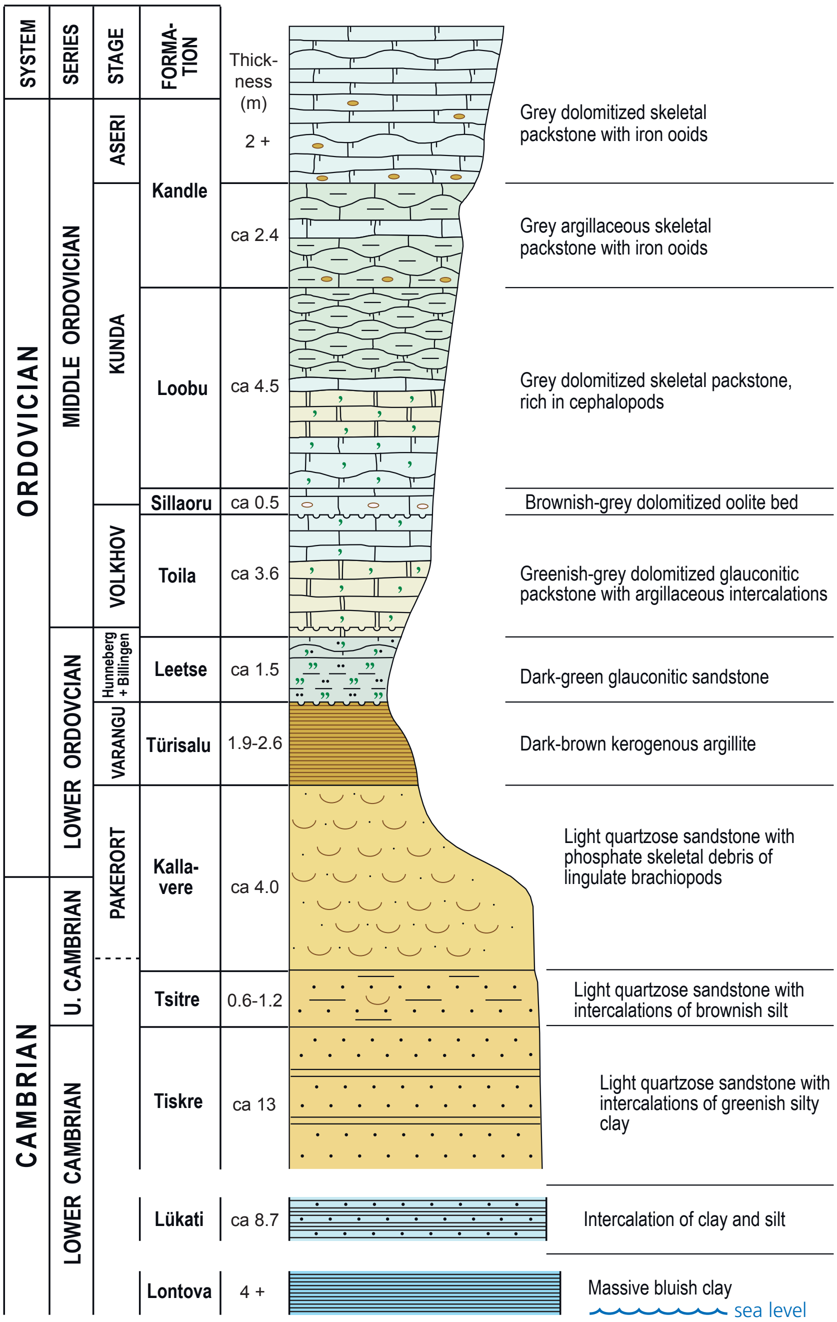


Figure 1. Composite section of the Saka – Ontika Klint, combined from Mens & Pirrus (unpublished data), Heinsalu *et al.* (1991), Mägi (1990), and Tinn (2004).

The lower Cambrian is represented by more than 25 m of bluish clays and siltstones of the Lontova and Lükati formations and silty sandstones of the Tiskre Formation, which are only partly exposed. The so-called Blue Clay of the Lontova Formation corresponds to the pre-trilobitic Cambrian and contains pyritic trace fossils, shells of *Platysolenites* and rare small shelly fossils (*Aldanella kunda*). The Lontova Formation has retained properties of clays, such as plasticity, which is extremely rare for deposits of similar age worldwide, suggesting a very low burial depth and lack of thermal overprinting on the entire Palaeozoic succession of Estonia.

The Furongian (upper Cambrian) contains ca 5 m of sandstones of the Tsitre and Kallavere formations, the latter being rich in lingulate shell fragments. Conodont biozonation (Heinsalu *et al.* 1991) allows tracing the Cambrian–Ordovician boundary at the appearance of *Cordylodus lindstromi* within the lower part of the Kallavere Formation.

The Lower Ordovician is represented by dark brown argillite of the Türisalu Formation (1.9–2.6 m). It is thinner and younger in the Saka–Ontika Klint than on the Pakri Peninsula (Stop A1), corresponding to the Varangu Regional Stage, Tremadocian, and its sedimentary fabrics indicate more proximal settings in the palaeobasin. The glauconitic sandstone of the Leetse Formation (1.5 m) is also notably thinner compared to the NW Estonian succession, but based on conodont data, stratigraphically more complete (Viira *et al.* 2006). The Tremadocian–Floian boundary falls into the Leetse Formation.

The base of **the Middle Ordovician** is traced at the conspicuous discontinuity surface within the lower part of ca 3.6 m thick glauconite-rich limestone of the Toila Formation. The base of the Darriwilian is tentatively drawn at the boundary of the Volkhov and Kunda regional stages, awaiting further detailed biostratigraphic studies. The Darriwilian strata (ca 9 m) are represented by dolomitized ooilitic and glauconitic limestones of the Sillaoru, Loobu and Kandle formations that are rich in cephalopods, trilobites, brachiopods and other shelly faunas.

Individual parts of this succession can be accessed in several places in the Saka–Ontika area:

The Valaste waterfall section (Photo 1) is one of the most picturesque sites on the North Estonian Klint and the best place to get a full overview of the geological succession. Unfortunately, the visitor platform was closed recently for safety reasons, making the spot somewhat less attractive.

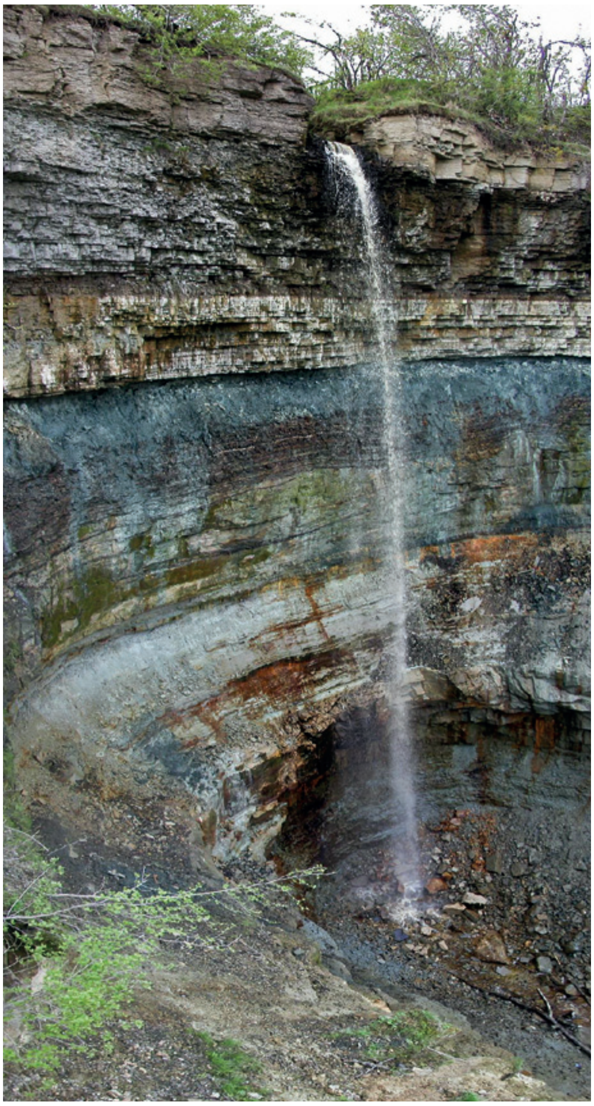


Photo 1. Lower Cambrian to Middle Ordovician succession at the Valaste waterfall section, Saka–Ontika Klint, NE Estonia (photo O. Hints).

The Saka trench section provides the best opportunities to study the Ordovician succession, especially Middle Ordovician limestones. This outcrop was cut into the limestone plateau for a sewerage pipe from the nearby town of Kohtla-Järve.

Cambrian sandstones and clays, and to some extent Ordovician strata, can be accessed or observed near **the Saka Manor** (Saka Hotel), where a short nature trail takes visitors up and down the otherwise steep cliff.

References

Mägi, S., 1990. Locality 4:2. Ontika klint. *In:* Kaljo, D. and Nestor, H. (eds). *Field meeting, Estonia 1990. An Excursion Guidebook*. Institute of Geology, Estonian Academy of Sciences, Tallinn, 148–153.

Tinn, O., 2004. Stop 10. Valaste waterfall. *In:* Hints, O. and Ainsaar, L. (eds). *WOGOGOB-2004*. 8th Meeting on the Working Group on the Ordovician Geology of Baltoscandia May 13–18, 2004, Tallinn and Tartu, Estonia. Tartu, University Press, 137–138.

Heinsalu, H., Kurvits, T. & Oja, T., 1991. Lithological-mineralogical characteristics of the stratotypical section of the Rannu Member (Cm_3 – O_1klR) at Saka II, North-East Estonia. *Proceedings of the Estonian Academy of Sciences. Geology*, 40, 1–7.

Viira,V., Mens, K. & Nemliher, J., 2006. Lower Ordovician Leetse Formation in the North Estonian Klint area. *Proceedings of the Estonian Academy of Sciences. Geology*, 55, 156–174.

Stop A9: Põhja-Kiviõli kukersite open-pit mine

Heikki Bauert and Jaak Nõlvak

Institute of Geology at Tallinn University of Technology, Estonia

The Põhja-Kiviõli kukersite open-pit mine (owned by a private company Kiviõli Keemiatööstuse OÜ) is located along the northern edge of the central part of the Estonia oil shale deposit. The open-pit section (59°21´52″N, 26°52´30″E) exposes the lower part of the Kukruse Stage and the uppermost Uhaku Stage.

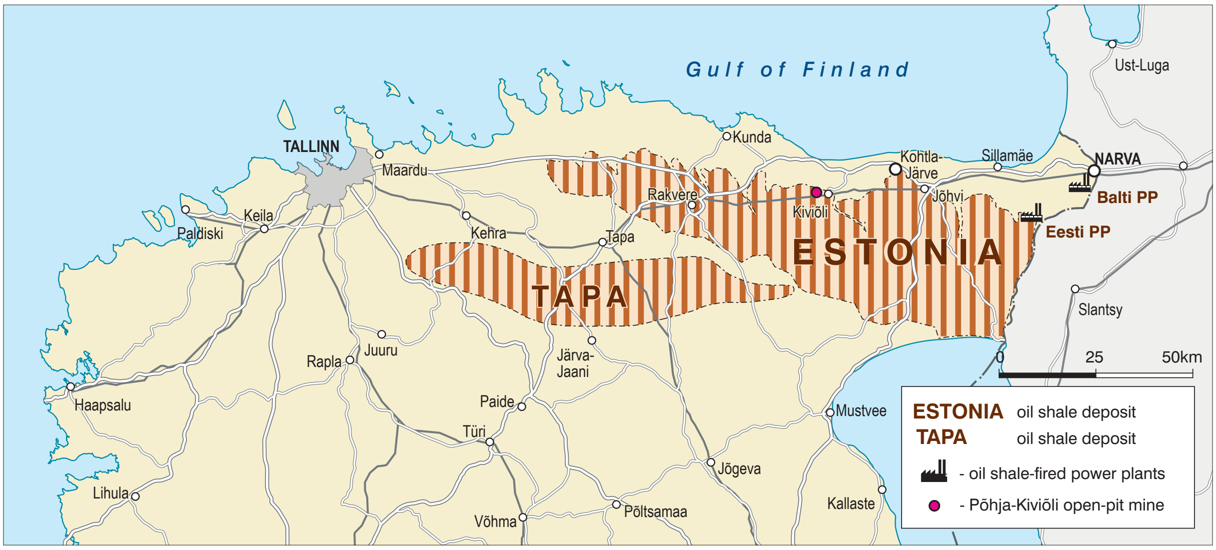


Figure 1. Kukersite oil shale deposits in Estonia.

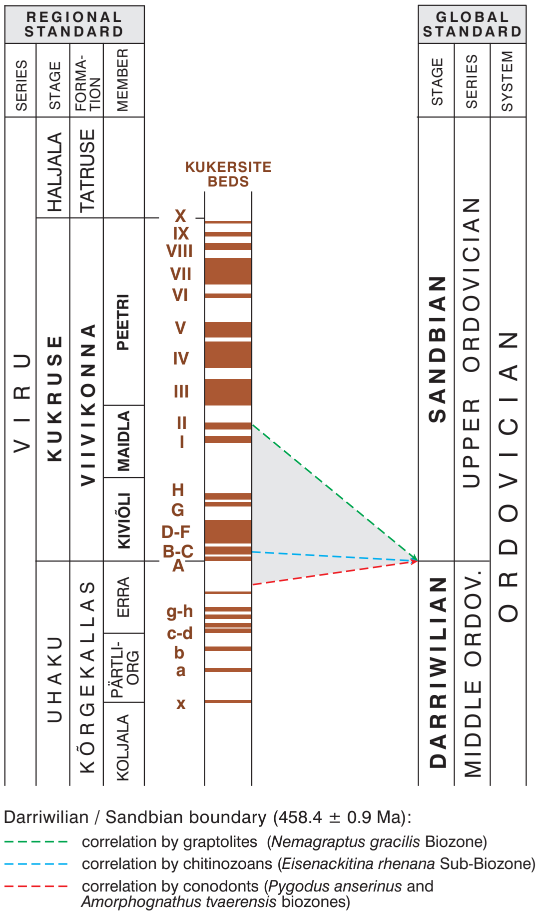


Figure 2. Stratigraphic chart of the Kukruse Stage, showing levels of main indexed kukersite beds and correlation between global and regional time scales (after Fig. 2 in Hints, O. *et al.* 2007).

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 Late Middle Ordovician to Early Late Ordovician time span (Fig. 2).

The kukersite oil shale beds 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 as A–F_2 are feasible for mining and are currently mined in three open-pits (Narva, Põhja-Kiviõli, Ubja) and two underground mines (Estonia, Ojamaa).

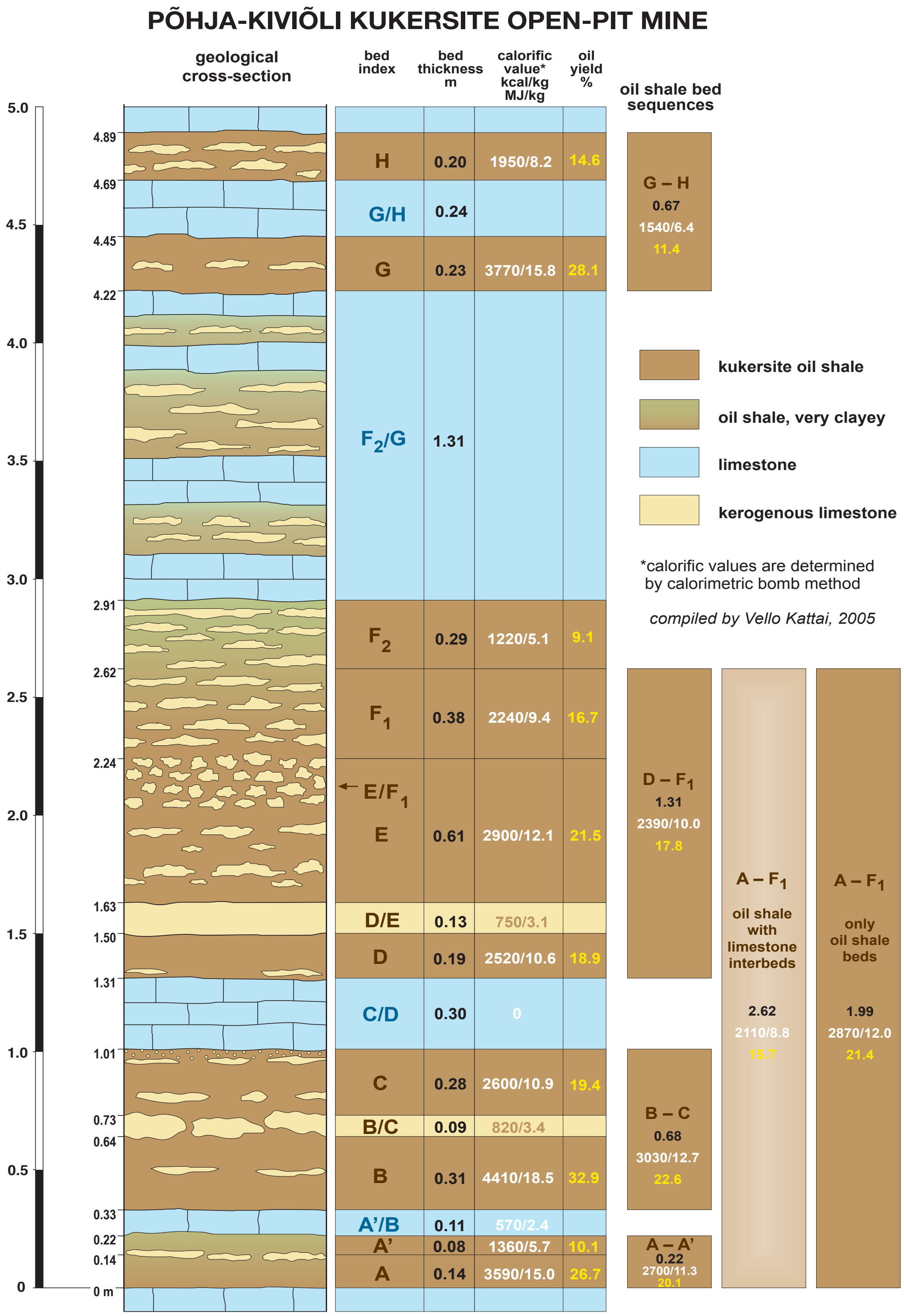


Figure 3. Main characteristics of kukersite oil shale beds in the Põhja-Kiviõli quarry

The main characteristics of individual kukersite beds in the Põhja-Kiviõli open-pit are shown in Fig. 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; Table 1). Rock-Eval pyrolysis analyses (Dyni *et al.* 1989; Foster *et al.* 1989) indicate that kukersite oil shales have a significant hydrocarbon potential (S_1 & S_2 = 300–350; S_1 – kg of hydrocarbons (extractable) per tonne rock; S_2 – kg of hydrocarbons (kerogen pyrolysate) per tonne rock) and are characterized by a high hydrogen index (HI = 675–960; mg hydrocarbons (S_2) 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: 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).

The matrix minerals in Estonian kukersite oil shale beds and interbedded more or less argillaceous limestones (Bauert & Kattai 1997; Fig. 213) include mainly low-Mg calcite (usually > 50%, but less in kukersite beds), dolomite (usually less than 15%) and siliciclastic minerals. The XRD analyses and thin section studies have revealed that the siliciclastics are mostly composed of silt-sized quartz and illite, while feldspars and chlorite occur in subordinate amounts. Besides, kukersite oil shale contains a few percentages of authigenic pyrite.

Origin of the kukersite OM

Major kukersite-type OM accumulations have been recorded in the Upper Uhaku to Kukruse age rocks (Kõrgekallas to 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 Rakvere stages (uppermost Sandbian to Katian). Based on the dominant OM type, the kukersite OM 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).

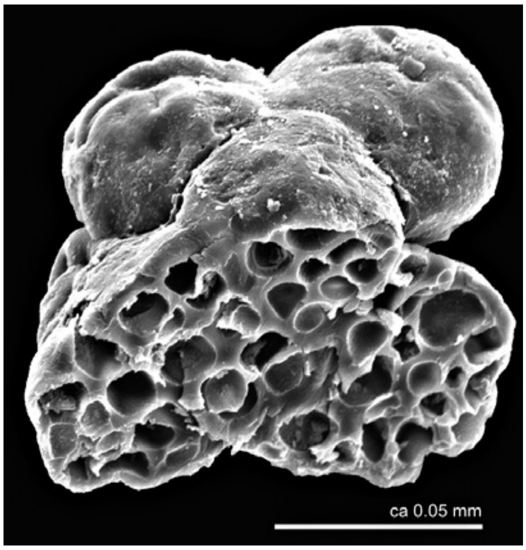


Photo 1. *Gloeocapsomorpha prisca* SEM image (photo J. Nõlvak)

The algal structure of kukersite was recognized by a Russian botanist M. Zalessky already in 1917. 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 as *Gloeocapsomorpha prisca*. Viewed under the light microscope, the microfossils are bright yellow in colour. The individual colonies are spherical to oval in outline and range in size from 10 to 40 µm (Photo 1). 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 OM

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

1. A major kukersite OM deposition occurred during a regression of the Kukruse sea southwards. The regression is suggested by a 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 well traceable for over 250 km in the west–east direction (Bauert & Kattai 1997; Figs 204, 205).

2. The kukersite OM deposited along the northern margin of the shallow carbonate shelf, bordering the Finnish lowland in the north (Fig. 4).

3. A great number of hardgrounds, either with thin pyritic impregnation veneer or without any impregnation, have been recorded in the Uhaku – Kukruse succession. Most of them 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

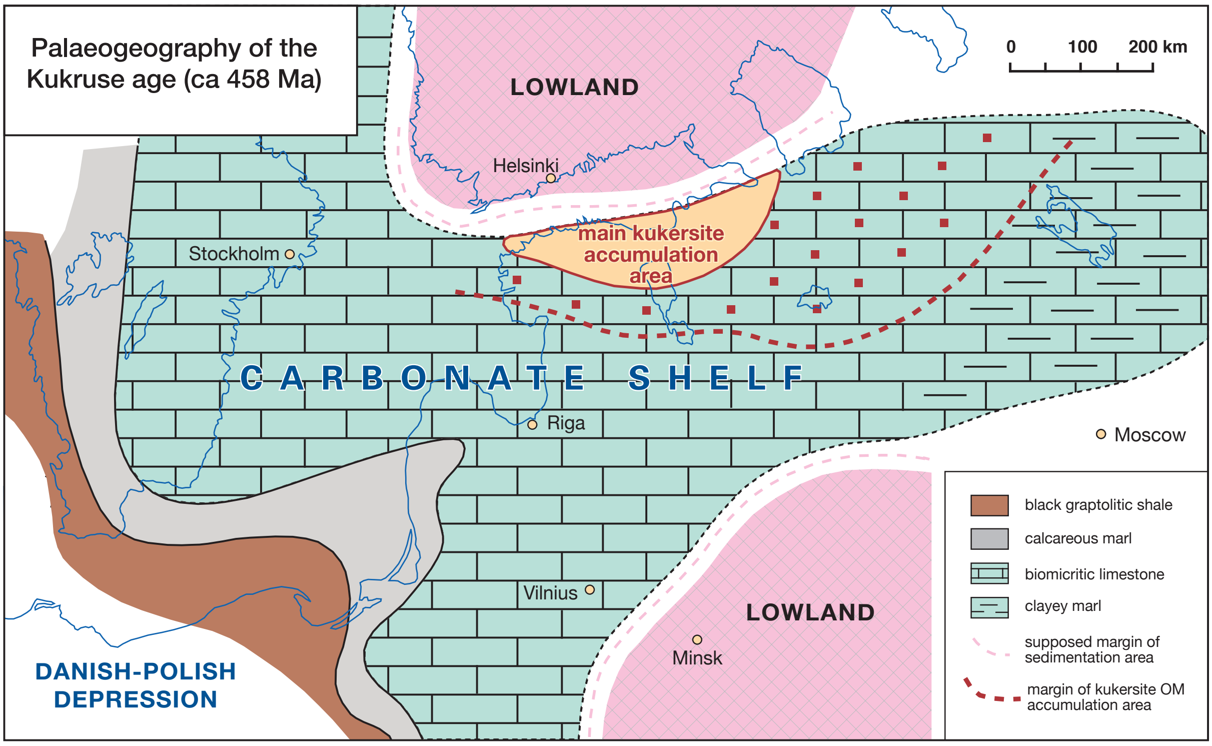


Figure 4. Palaeogeographic scheme of the Paleobaltic basin in Kukruse age

1989). One such surface is observed on top of kukersite bed III and is traceable in an area of 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) 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 OM deposition could be a sink-down of rather inert cyanobacterial OM directly from algal blooms.

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. 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 (Photo 2). It should be pointed out that contrary to most of the other organic-rich rocks, no anoxia is recorded during the accumulation of kukersite OM, as indicated by flourishing bottom life, the abundance of trace fossils and relative scarcity of authigenic pyrite.

Photo 2. Delicate bryozoan *Pseudohornera bifida* Eichwald on the bedding plane of the kukersite oil shale bed B (photo H. Bauert).

Kukruse Stage and the base of the global Sandbian Stage (base of the Upper Ordovician)

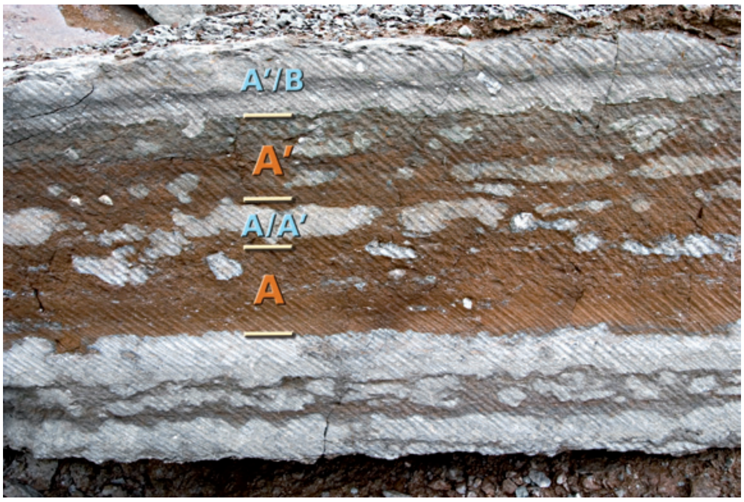


Photo 3. Close-up of the kukersite bed A which base marks the boundary of the Uhaku/Kukruse regional stages and the Darriwilian/Sandbian global stages (photo H. Bauert).

The Fågelsång section in Scania, southern Sweden, has been chosen as a 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 is given by Hints et al. 2007 (Fig. 1).

Graptoloids are rare and only occasionally found in shallow shelf carbonate successions, 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 so far been recorded from the outcrop area of the Kukruse 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 kukersite 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; Fig. 6), 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.

Certain chitinozoan species, particularly *Eisenackitina rhenana* and *Conochitina savalaensis* (Nõlvak & Bauert in press), have proven to be reliable indicators for correlating the base of the Kukruse Stage throughout Estonia. Both chitinozoans appear close to the base of 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 as well.

References

Bauert, H., 1989. Discontinuity surfaces of possible microkarst origin in the Viivikonna Formation (Kukruse Stage, Middle Ordovician), Estonia. *Proceedings of the Academy of Sciences of the Estonian SSR. Geology*, 38, 2, 77–82.

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

Bekker, H., 1921. The Kuckers stage of the Ordovician rocks of NE Estonia. *Acta et Commentationes Universitatis Dorpatensis*, A2, 81–84.

Bergström, S. M., Finney, S. C., Chen, X., Pålsson, C., Wang, Z. H. & Grahn, Y., 2000. A proposed global boundary stratotype for the base of the Upper Series of the Ordovician System: The Fågelsång section, Scania, southern Sweden. *Episodes*, 23, 2, 102–109.

Burns, D. A., 1982. A transmission electron microscope comparison of modern *Botryococcus braunii* with some microfossils previously referred to that species. *Revista Española de Micropaleontología*, 14, 1165–1185.

Cook, A. C. & Sherwood, N. R., 1991. Classification of oil shales, coals and other organic-rich rocks. *Organic Geochemistry*, 17, 2, 211–222.

Derenne, S., Largeau, C., Casadevall, E., Sinninghe Damsté, J. S., Tegelaar, E. W. & De Leeuw, J. W., 1990. Characterization of Estonian Kukersite by spectroscopy and pyrolysis: evidence for abundant alkyl phenolic moieties in an Ordovician, marine, type II/I kerogen. Organic Geochemistry, 16, 4, 873–888.

Dyni, J. R., 2006. Geology and resources of some world oil-shale deposits. *U.S. Geological Survey Scientific Investigations Report 2005–5294*, 42 pp.

Foster, C. B., Reed, J. D. & Wicander, R., 1989. *Gloeocapsomorpha prisca* Zalessky, 1917: A new study: Part I: Taxonomy, geochemistry, and paleoecology. *Geobios*, 22, 6, 735–759.

Foster, C. B., Wicander, R., & Reed, J. D., 1990. *Gloeocapsomorpha prisca* Zalessky, 1917: A new study: Part II: Origin of kukersite, a new interpretation. Geobios, 23, 2, 133–140.

Hints, O., Nõlvak, J., & Viira, V., 2007. Age of Estonian kukersite oil shale – Middle or Late Ordovician?. *Oil Shale*, 24, 4, 527–533.

Kattai, V. & Bauert, H., 2007. The mineral resources of Estonia: kukersite oil shale. *In:* Põldvere, A. & Bauert, H. (eds). *Excursion Guidebook. 15th Meeting of the Association of European Geological Societies, 16–20 September 2007, Tallinn, Estonia*, 12–19.

Kõrts, A., 1992. Ordovician oil shale of Estonia – origin and palaeoecological characteristics. *In:* Webby, B.D. & Laurie, J.R. (eds). *Global Perspectives on Ordovician Geology.* Balkema, Rotterdam, 445–454.

Nõlvak, J. & Goldman, D., 2007. Biostratigraphy and taxonomy of three-dimensionally preserved nemagraptids from the Middle and Upper Ordovician of Baltoscandia. Journal Paleontology, 81, 2, 254–260.

Põldvere, A., 2006 (ed.). Kerguta (565) drill core. *Estonian Geological Sections, Bulletin 7*. Geological Survey of Estonia, Tallinn, 43 pp.

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

Vandenbroucke, T., 2004. Chitinozoan biostratigraphy of the Upper Ordovician Fågelsång GSSP, Scania, southern Sweden. *Review of Palaeobotany and Palynology*, 130, 1, 217–239.

Wilson, M. A. & Palmer, T. J., 1992. *Hardgrounds and hardground faunas*. University of Wales, Aberystwyth, 131 pp.

Stop A10: Porkuni quarry

Linda Hints and Peep Männik

Institute of Geology at Tallinn University of Technology, Estonia

The Porkuni quarry (old 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 dolomite as a specific type of rock. A few years later Schmidt (1858) established the Borkholm'che Schicht comprising four different lithologies, which according to the modern nomenclature, correspond to the Porkuni Stage: to the Röa, Vohilaid, Siuge and Tõrevere members of the Ärina Formation. The uppermost part of the formation, 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 where dolomitized limestone rich in quartz sand is 1.38 m thick (Kaljo *et al.* 2008b).

The Ärina Formation in the Porkuni quarry consists of shallowing-upward lithologies: crinoidal dolomite (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 1, 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).

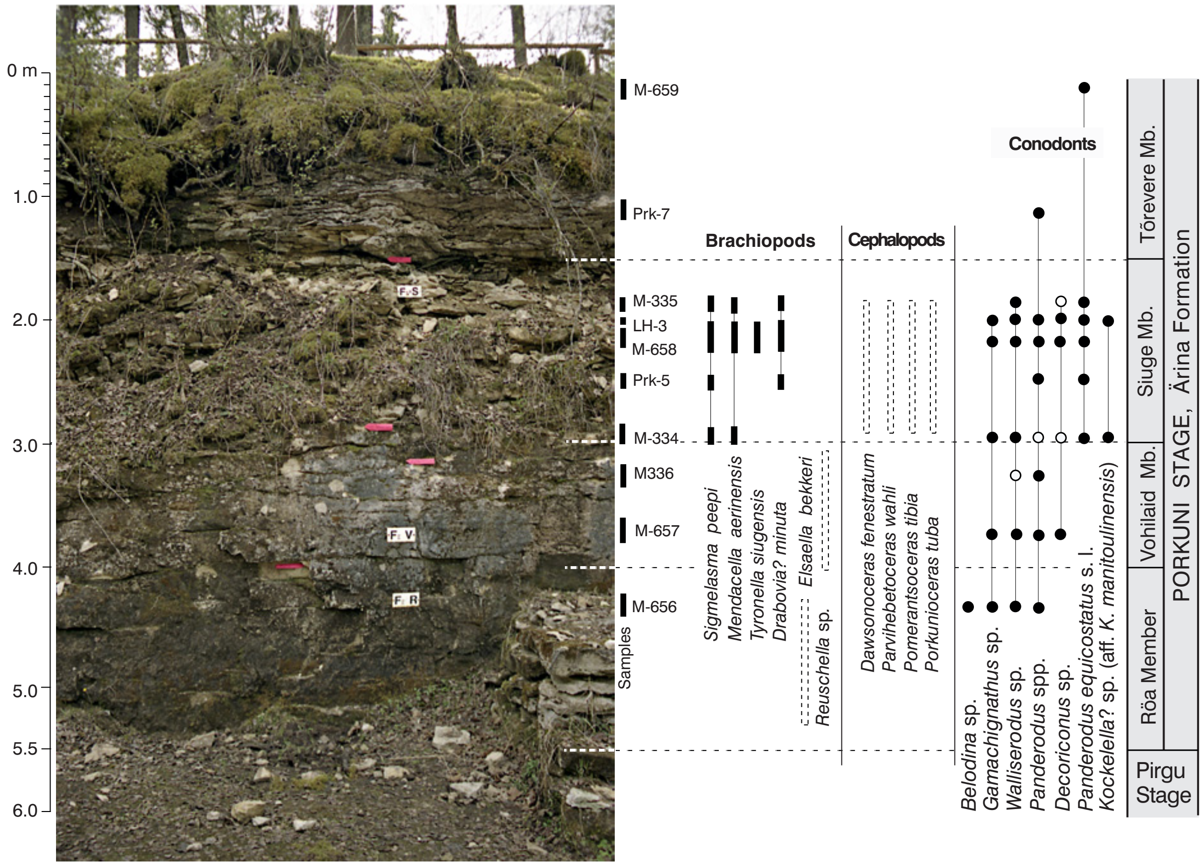


Figure 1. Section of the Porkuni Regional Stage in the type section of the Porkuni quarry (Hints *et al.* 2000). Red lines mark the boundary levels between the Röa (**R**) and Vohilaid (**V**) members (see Fig. 2), transitional interval between the Vohilaid and Siuge (**S**) members and the boundary between the Siuge and Tõrevere (**T**) members. Distribution of macrofossils by Hints 2012 and Gröger 2007.

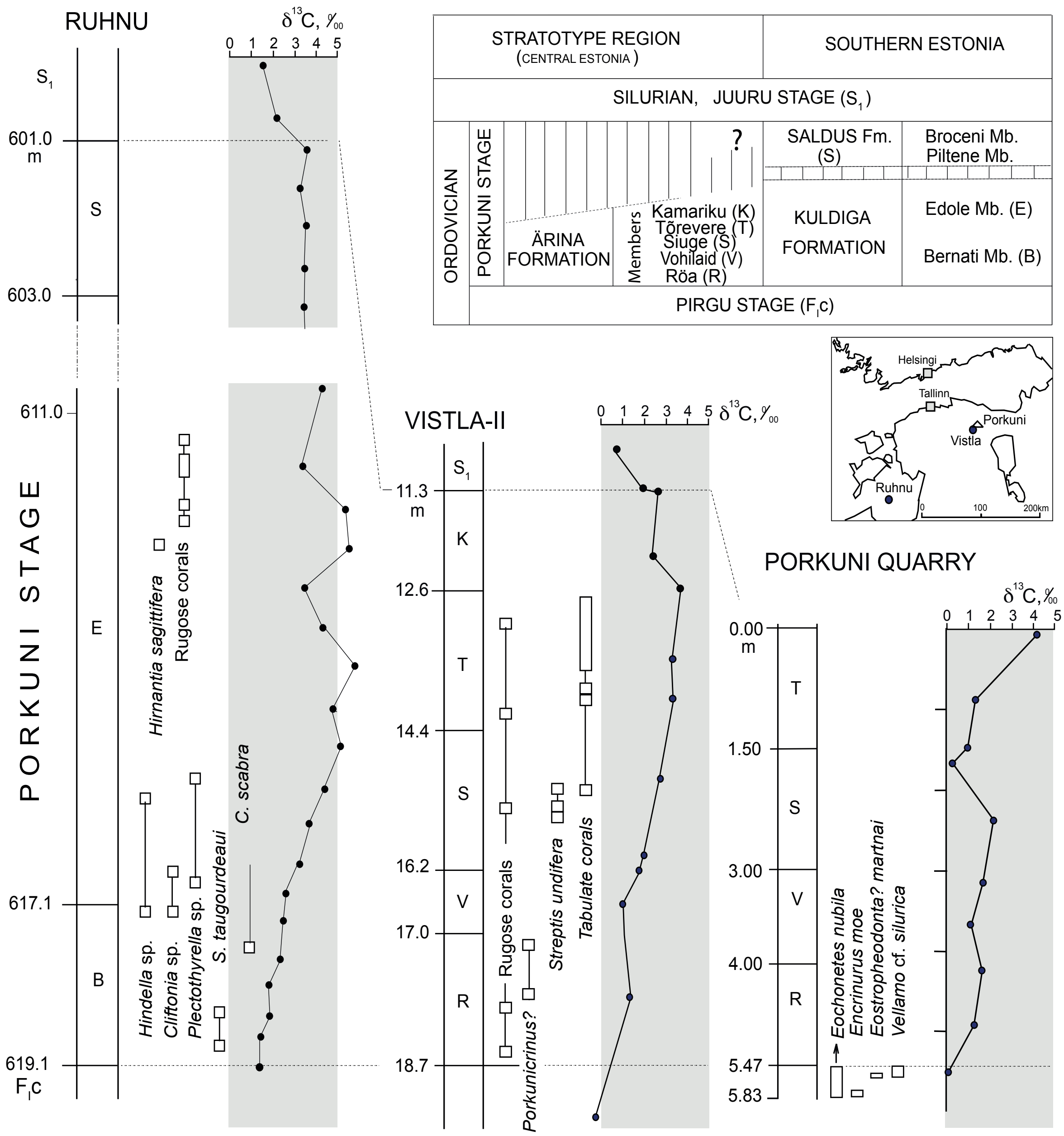


Figure 2. The carbon isotope curves and distribution of some fossils in the Ruhnu and Vistla-II drill cores, and in the Porkuni quarry (by Hints *et al.* 2000).

Based on the occurrence of *Hirnantia* brachiopod fauna (Rong & Harper 1988) in the Porkuni Regional Stage 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 Ordovician sections. The results of carbon isotope studies as well 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. 2). In the most complete sections in western Latvia this interval correlates roughly with the strata characterized by the *Hindella–Cliftonia* and *Dalmanella testudinaria* associations and yielding also the trilobite *Mucronaspis mucronata* (Hints *et al.* 2010). The late Hirnantian deposits are missing in the stratotype area of the Porkuni Stage,

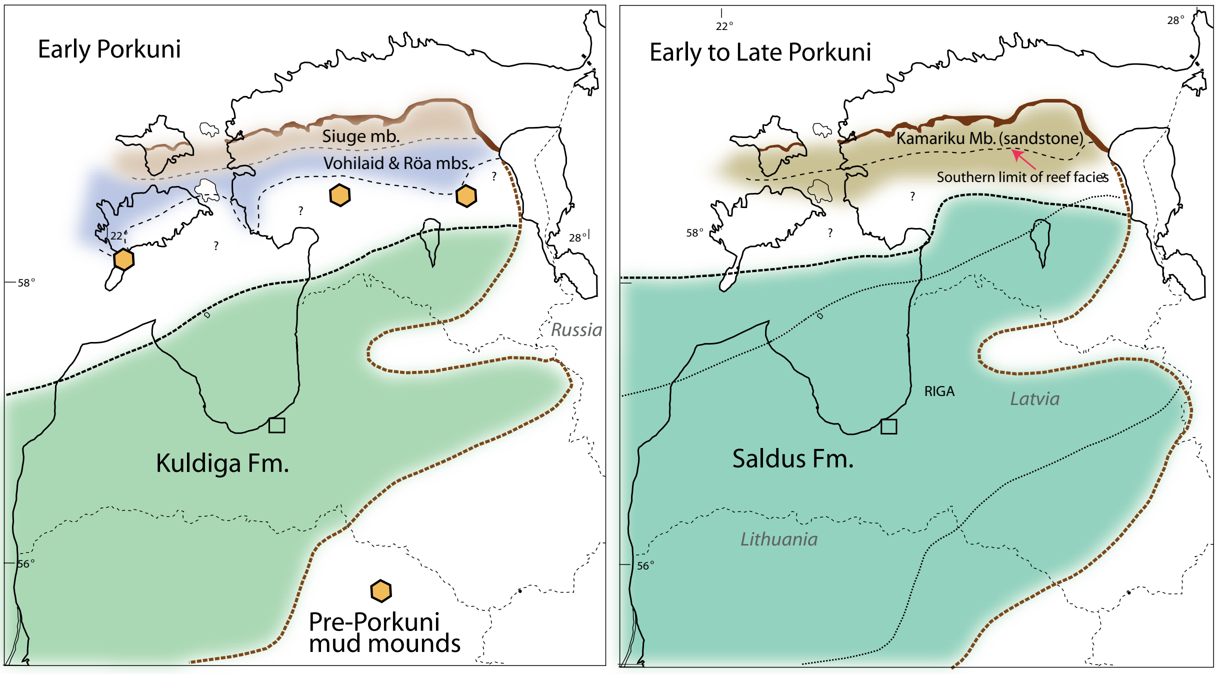


Figure 3. Distribution of the formations and members of the Porkuni Regional Stage (modified from Oraspõld 1975).

evidently due to the glacioeustatic sea-level drop. The stratigraphically incomplete sections occur also 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 considerd to be genetically related to the Ärina Formation and correlated with the upper part of the Kuldiga Formation (Fig. 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 of the Porkuni quarry section

Description of the Porkuni section is available in guidebooks of previous geological excursions (Hints & Oraspõld 2004; Kaljo *et al.* 2008b). Results of detailed study of the section were published by Hints *et al.* (2000; see http://www.kirj.ee/earthsciences/). Additional data about the section and faunas can be found in Oraspõld (1975), Kaljo e*t al.* (2001), Kröger (2007).

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 [*Holacanthia tubula* (Dybowski), *Strombodes middendorfi* (Dybowski)], and stromatoporoids (*Clathrodictyon gregale* Nestor, *Ecclimadictyon koigiense* Nestor). Brachiopods are relatively rare. Skeletal fragments of echinoderms and bryozoans form an essential part in the composition 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*, *Sclerophyllum sokolovi* Reiman, *Streptis undifera* (Schmidt), *Leptaean (L.) acuteplicata*

Figure 4. Fossils from the Porkuni quarry, Upper Ordovician, Porkuni Regional Stage.
All photos of specimens from the geological database sarv.gi.ee. Scale for all specimens – 1 cm.
1. Tabulate coral: *Halysites* cf. *catenularius* (Linnaeus, 1967), TUG 860-1666.
2. Bivalvia: *Ambonychia orvikui* Isakar, 1991, TUG 3-30.
3. Rugose coral: *Calostylis concavifundatus* Reiman, 1958; GIT 406-572.
4. Cephalopoda: *Strandoceras orvikui* Kröger, 2007, TUG 1227-28.
5.Trilobite: *Proetus*? *ramisulcatus* Niezkowski, 1857 TUG 1589-840.
6. Rugose coral: *Calostylis concavifundatua* Reimer, 1958, TUG 1589-406.
7.Tabulate coral: *Porkunites amalloides* Dybowski, 1873, GIT 406-584.
8. Brachiopoda: *Leptaena (Leptaena) acuteplicata* (Schmidt, 1908) TUG 72-164.
9. Trilobite: *Platylichas vultuosus* Öpik, 1937, TUG 1085-58.
10. Gastropoda: *Trochonema panderi* Koken, 1896, GIT 404-360.
11. Rostroconchis: *Hyppocardia* sp. TUG 2-149.
12. Brachiopoda: *Streptis undifera* (Schmidt, 1858), GIT 626-64.
13. Brachiopoda: *Pirgumena* (=?*Eostropheodonta*) cf. *martnai* Rõõmusoks, 2004, TUG 2-189.
14. Contact of the Röa dolomites with the grainstones of the Vohilaid Member, GIT 242-8.

(Schmidt)] there occur several fossils known only from the Siuge Member, e.g. brachiopods *Sigmelasma peepi* Hints and *Tyronella siugensis* Hints, and several species of 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 which 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 gradually. The Vohilaid Member comprises a diverse association of rugose and tabulate corals, bryozoans and brachiopods. The oldest reefs in the Porkuni section appear close to the lower boundary of the member. A large 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 dolomite. 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 dolomite, 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. However, it lies just below the quarry floor and was accessed after some digging in 2000.

The Porkuni quarry section has repeatedly been sampled for conodonts. Samples up to 20 kg in weight have been processed. As elsewhere in the uppermost Ordovician strata in Central Estonia, conodonts are very rare (and poorly preserved) also in the Porkuni section and species are difficult to identify. The faunas are mostly characterized by *Gamachignathus* sp., *Walliserodus* sp. and *Panderodus* spp. 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 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, and brachiopods, part of which were recently described in two papers (Hints 2012, Hints *et al.* 2013). Examples of Porkuni fossils are presented on Fig. 4.

Massive homogenous dolomite of the Röa Member has been used as building and carving material for a long time. Its earliest known use dates back to the 15th century. The Porkuni fortress 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 fortress is preserved. Now an exhibition of the Estonian national stone "paas" (in Estonian) is exposed in that tower. The term "paas" means both the limestone and dolomite used widely in buildings and as raw material in different industries in Estonia.

References

Ainsaar, L., Kaljo, D., Martma, T., Meidla, T., Männik, P., Nõlvak, J. & Tinn, O., 2010. Middle and Upper Ordovician carbon isotope chemostratigraphy in Baltoscandia: a correlation standard and clues to environmental history. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 294, 189–201.

Ainsaar, L., Truumees, J. & Meidla, T., 2011. Carbon isotope chemostratigraphy of the Ordovician/Silurian boundary beds in central Estonia: new data from drillcores in the Pandivere area. *In:* Lukševičs, E., Stinkulis, Ģ. & Vasiļkova, J. (eds). *The Eighth Baltic stratigraphical conference. Abstracts*. Riga, 10.

Bergström, S. M., Saltzman, M. M. & Schmitz, B., 2006. First record of the Hirnantian (Upper Ordovician) $\delta^{13}C$ excursion in the North American Midcontinent and its regional implications. *Geological Magazine*, 143, 657–678.

Bergström, S. M., Chen, X., Gutierrez-Marco, J. C., Dronov, A., 2009. The new chronostratigraphic classification of the Ordovician System and its relation to major regional series and stages and to $\delta^{13}C$ chemostratigraphy. *Lethaia*, 42, 97–107.

Brenchley, P. J., Marshall, J. D., Carden, G. A. F., Robertson, D. B. R., Long, D. G. F., Meidla, T., Hints, L. & Anderson, T., 1994. Bathymetric and isotopic evidence for a short-lived Late Ordovician glaciation in greenhouse period. *Geology*, 22, 295–298.

Eichwald, E., 1854. Die Grauwackenschichten von Liv- und Estland. *Bull. Soc. Nat. Moscou*, 27, 1, 1–111.

Hints, L., Oraspõld, A. & Kaljo, D., 2000. Stratoptype of the Porkuni Stage with comments on the Röa Member (Uppermost Ordovician, Estonia). Proceedings of the Estonian Academy of Sciences. *Geology*, 49, 3, 177–199.

Hints, L., Hints, O., Kaljo, D., Kiipli, T., Männik, P., Nõlvak, J. & Pärnaste, H., 2010. Hirnantian (latest Ordovician) bio- and chemostratigraphy of the Stirnas-18 core, western Latvia. *Estonian Journal of Earth Sciences*, 59, 1, 1–24.

Hints, L., 2012. New Hirnantian orthide brachiopods from the type section of the Porkuni Stage (Porkuni quarry, northeastern Estonia). *Estonian Journal of Earth Sciences* 61, 4, 227–241.

Hints, L., Popov, L. & Holmer, L. E., 2013. Morphology, ontogeny and affinities of the Hirnantian triplesiid brachiopods *Streptis undifera* from Baltoscandia. *Palaeontology*, 1–10.

Hints, L. & Oraspõld, A., 2004. Stop 6. Porkuni quarry. *In:* Hints, O. & Ainsaar, L. (eds). *WOGOGOB-2004 Conference Materials Abstracts and Field Guidebook*. Tartu, 127–128.

Hints, O., Martma, T., Männik, P., Põldvere, A., Shen, Y. & Viira, V., 2014. New data on Ordovician stable isotope record and conodont biostratigraphy from the Viki reference drill core, Saaremaa Island, western Estonia. *GFF*, 136, 100–104.

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

Kaljo, D., Hints, L., Martma, T., Nõlvak, J. & Oraspõld, A., 2004. Late Ordovician carbon isotope trend in Estonia, its signigicance in stratigraphy and environmetal analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 210, 165–185.

Kaljo, D., Hints, L., Männik, P. & Nõlvak, J., 2008a. The succession of Hirnantian events based on data from Baltica: brachiopods, chitinozoans, conodonts, and carbon isotopes. *Estonian Journal of Earth Sciences*, 57 (4), 197–218.

Kaljo, D., Einasto, R. & Hints, L., 2008b. Stop B2: Ordovician-Silurian boundary in Estonia: localities at Porkuni and Neitla. *In:* Hints, O., Ainsaar, L., Männik, P. & Meidla, T. (eds). *The Seventh Baltic Stratigraphical Conference. Abstracts & Field guide*. Tartu, 100–104.

Kröger, B., 2007. Concentrations of juvenile and small adult cephalopods in the Hirnantian cherts (Late Ordovician) of Porkuni, Estonia. *Acta Palaeontologica Polonica*, 52, 3, 591–608.

Oraspõld, A., 1975. On the lithology of the Porkuni Stage in Estonia. *In: Töid Geoloogia alalt VII*. Acta Comment. Univ. Tartuensis, 359, 33–75 (in Russian).

Põldvere, A., 2010. Viki drill core. *Estonian geological sections*, Bulletin 10, 56 p.

Rong Jia-yu & Harper, D.A.T., 1988. A global synthesis of latest Ordovician Hirnantian brachiopod faunas. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, 79, 383–402.

Schmidt, F., 1858. Untersuchungen über die silurische Formation von Estland, Nord-Livland und Oesel. *Arch. Naturk. Liv-, Est- und Kurl*., Ser I, Bd.2, Lief.

Schmitz, B. & Bergström, S. M., 2007. Chemostratigraphy in the Swedish Upper Ordovician: Regional significance of the Hirnantian ð^{13}C excursion (HICE) in the Boda Limestone of the Siljan region. *GFF*, 129, 133–140.

Post-conference excursion: *Silurian of Estonia*

Stop B1: Kalana quarry

***Leho Ainsaar*[1]*, Oive Tinn*[1]*, Peep Männik*[2] *and Tõnu Meidla*[1]**

[1]*Department of Geology, University of Tartu, Estonia*
[2]*Institute of Geology at Tallinn University of Technology, Estonia*

In the Kalana (Otisaare) quarry (Photo 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 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 in the eastern side of the quarry.

The main (lower) part of the Jõgeva Beds (thickness over 8 m) is dominated by 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, dolomitized limestone which contain abundant noncalcified algal and rarer distinctive early land plant remains. 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 represented by a series of beds of pure hard light grey cross-bedded fine-grained grainstone in a thickness of 1–4 m. Historically, this rock is known as a good building limestone (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 dolomitized greenish-grey argillaceous micritic limestone. The exposed thickness of these beds increases in westwards, where an increase in carbonate content is visible upwards in the succession.

Photo 1. An overview of the Kalana quarry (photo H. Bauert).

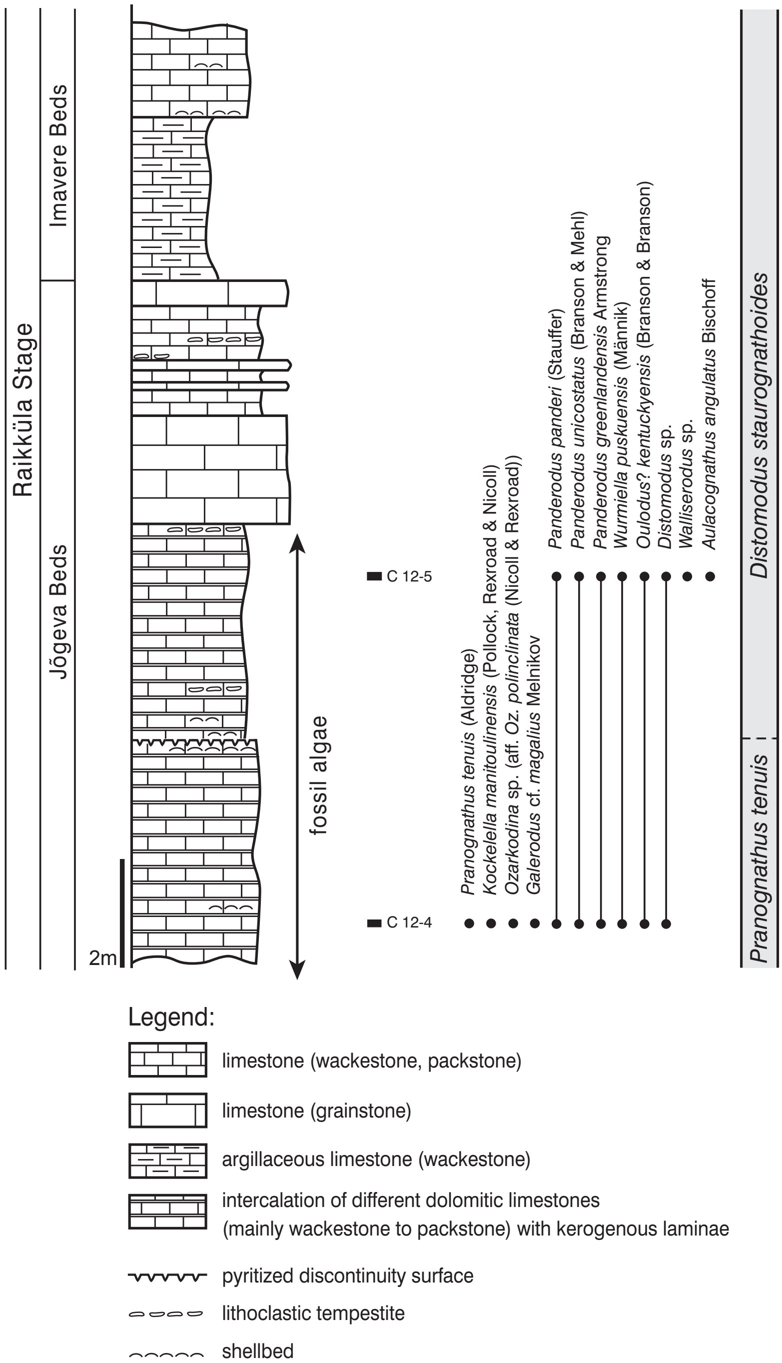


Fig. 1. Section of the Kalana quarry, combined from eastern and western parts of the quarry.

The Jõgeva and Imavere beds have been considered to be of early and middle Aeronian age, respectively (Nestor 1997). The sample processed for conodonts from the lowermost Jõgeva Beds yielded numerous specimens of *Pranognathus tenuis* (Aldridge) indicating the *Pr. tenuis* conodont Zone for this level. *Pranograptus 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 (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 *Pr. tenuis* seems to occur in the upper Aeronian, in the *Lituigraptus convolutus* 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* Bischofft, known from the uppermost Aeronian *Stimulograptus sedgwickii* graptolite Zone in Australia (Bischoff 1986). *Pranograptus tenuis* is missing in this sample. Hence, when comparing with data from elsewhere, both samples seem to indicate a younger age for the Jõgeva Beds than other data from the northern Baltic area. One explanation for this discrepancy might be that as *Pr. tenuis* and *Aul. angulatus* are both known from very few regions/sections only, they actually appear earlier than believed so far. However, problems in regional stratigraphy cannot be excluded as well.

Recent investigations have revealed a high diversity of noncalcareous algal fossils of exceptional preservation in the Kalana section. About dozen morphological groups (species) of algae have been distinguished (see Fig. 2), showing a considerably higher diversity than documented from the Cambro-Silurian strata up to now. The most abundant in this flora is *Leveilleites hartnageli*, a species indistinguishable from that described from the Hirnantian strata of Canada. This indicates a wide distribution of the species and its long temporal range in the Iapetus Ocean. Based on distinctive architecture of its thallus and the position of the reproductive structures, *L. hartnageli* was assigned to the Division Rhodophyta.

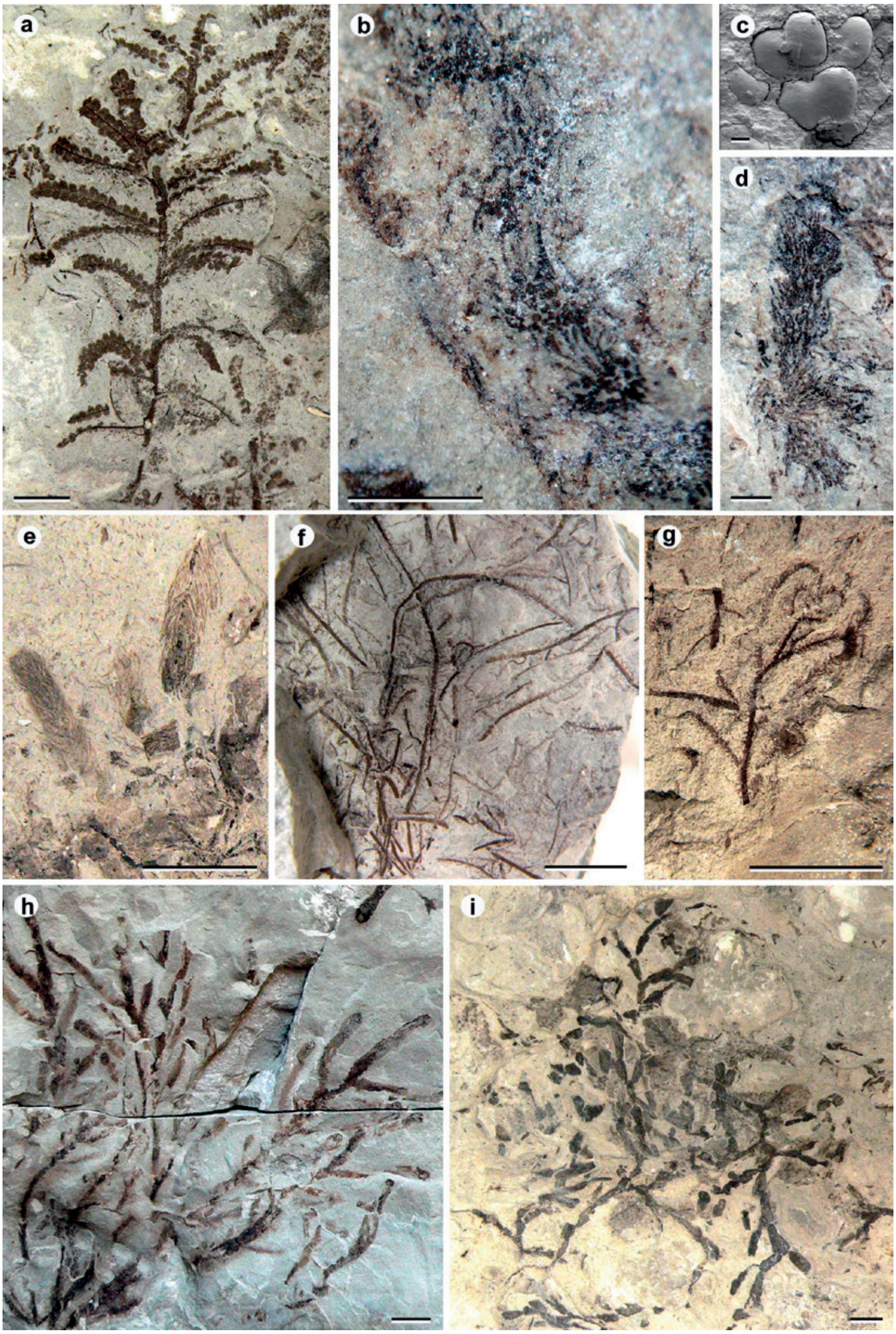


Figure 2. Algal fossils from Kalana, Estonia, of Aeronian (Llandovery, Silurian) age (Tinn *et al.* 2009; Fig. 2).
a. *Leveilleites hartnageli,* scale 1 cm, (Tartu University Natural History Museum specimen number TUG 1269-1).
b. alga with tapelike thallus, scale 1 mm (TUG 1269-2).
c. SEM picture of organic-walled reproductive structures, scale 20 µm (TUG 1269-3)
d. *Meduseagraptus* sp., scale 1 mm (TUG 1269-4)
e. *Chaetocladus* sp. scale 1cm (TUG 1269-5)
f. *Inopinatella* sp., scale 1 cm (TUG 1269-6)
g. an early growth phase of *L. hartnageli*, scale 1 cm (TUG 1269-7)
h. noncalcified alga, scale 1 cm (TUG 1269-8)
i. *Paleocympolia silurica*, scale 1 cm (TUG 1269-9)

Many algal fossils in Kalana are evidently representatives of the Order Dasycladales of green algae, of an extant group of large unicells generally dominated by calcareous forms and having a long and highly diverse geological history. The dasyclade flora in Kalana includes *Paleocymopolia silurica* (a species with serially segmented dichotomously branching noncalcified thallus), *Medusaegraptus mirabilis*, *Chaetocladus* sp., *Inopinatella* sp. and several other yet undescribed species. A very recent, but perhaps one the most exciting discoveries in Kalana are the remains of primitive land plants, preserved as coalified fossils. A number of them have naked sterile axes of different length and preservation, but there are also axes with microphylls, fertile axes with lateral sporangia and disconnected sporangial spikes. The latter two types have also revealed *in situ* spores.

In addition to common Silurian skeletal fossils, also finely preserved specimens of soft-bodied annelids and almost complete specimens of stalked crinoids with fine pinnules attached to slender brachials on calyces have been found. Considering the composition of the rocks and the succession of different lithologies in the section, the plant-containing layers evidently accumulated in the restricted shelf environment. It is possible that vast marine areas were protected from normal wave action by shoal belts, later on covering the study area as well. In this environment organic material probably preserved due to local anoxia in quiet water depressions. Occasional tempestites present suggest that heavy storms sometimes reached and disturbed also this area. Terrestrial plant remains might have been transported into the shelf by rivers and redeposited by storms, although no obvious connection between tempestites and plant-containing laminae has been observed.

References

Bischoff, G. C. O., 1986. Early and middle Silurian conodonts from midwestern New South Wales. *Courier Forschungsinstitut Senckenberg*, 89, 336 pp.

Cramer, B. D., Brett, C. E., Melchin, J. M., Männik, P., Kleffner, M. A., McLaughlin, P. I., Loydell, D. K., Munnecke, A., Jeppsson, L., Corradini, C., Brunton, F. R. & Saltzman, M. R., 2011. Revised correlation of Silurian Provincial Series of North America with global and regional chronostratigraphic units and $\delta^{13}C_{carb}$ chemostratigraphy. *Lethaia*, 44, 185–202.

Nestor, H., 1997. Silurian. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 89–106.

Nestor, H., Einasto, R., Männik, P. & Nestor, V., 2003. Correlation of some lower-middle Llandovery reference sections in central and southern Estonia and sedimentation cycles of lime muds. *Proceedings of the Estonian Academy of Sciences, Geology*, 52, 3–27.

Perens, H., 1992. Raikküla Regional Stage (Llandovery) and its lithostratigraphy in the outcrop area. *Bulletin of the Geological Survey of Estonia*, 2/1, 27–31. [in Estonian with English summary]

Tinn, O., Meidla, T., Ainsaar, L. & Pani, T., 2009. Thallophytic algal flora from a new Silurian Lagerstätte. *Estonian Journal of Earth Sciences*, 58, 1, 38–42.

Stop B2: Eivere quarry

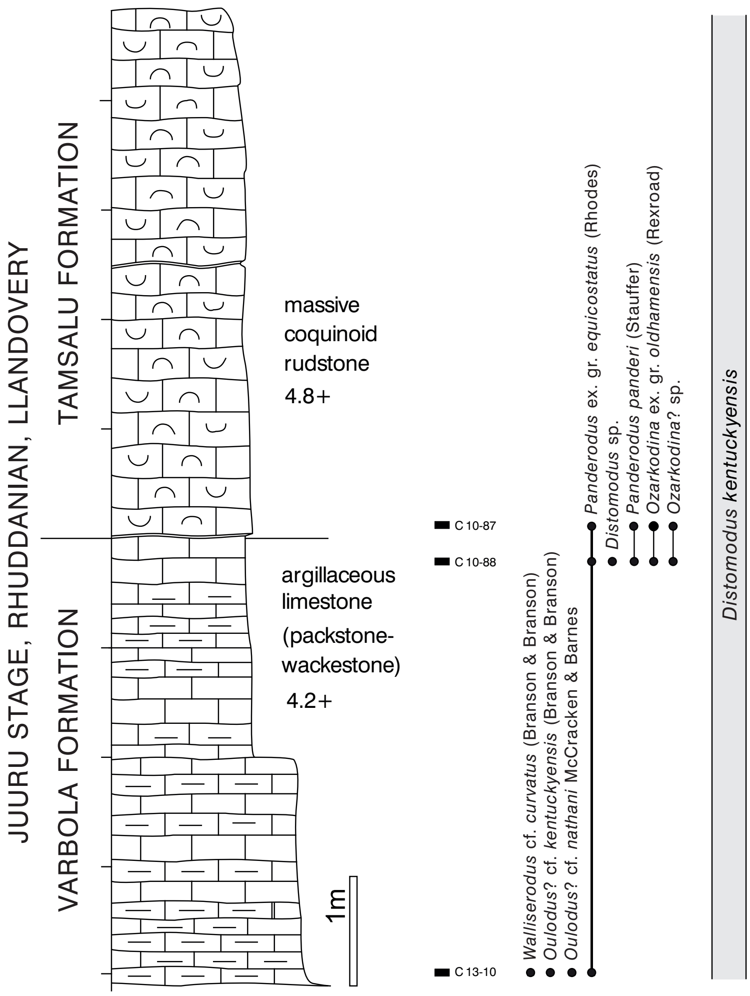
***Leho Ainsaar*[1], *Peep Männik*[2] and *Tõnu Meidla*[1]**

[1] *Department of Geology, University of Tartu, Estonia*

[2] *Institute of Geology at Tallinn University of Technology, Estonia*

In Central Estonia the Juuru Regional Stage includes two lithologically distinctive units, the Varbola and Tamsalu formations. These beds comprise roughly the lower and middle parts of the Rhuddanian Stage, while according to the newest isotope chemostratigraphic data, the lowermost Varbola Formation may be Hirnantian in age. The Eivere quarry (58°58´35.94˝N, 25°34´28.51˝E, Photo 1) exposes both the fossil-rich limestone of the Varbola Formation and the coquina limestone of the Tamsalu Formation. The Eivere quarry is relatively small (about 300 m x 200 m) and the rocks are exposed in several escarpments. The upper part of the section is best exposed at the entrance, while the lowermost part is accessible in the northern part of the quarry.

Photo 1. Eivere quarry (photo P. Männik).



In the lower part of the section slightly argillaceous, nodular packstones of the upper Varbola Formation containing lenses of bioclastic limestone are exposed in a thickness of 4.2 m. The upper part of the section consists of massive 4.8 m thick coquinoid rudstone of *Borealis borealis borealis* (Tammiku Member of the Tamsalu Formation, Photo 2) (Fig. 1). The rock is composed of complete and fragmental valves of *B. borealis borealis* (Eichwald). Interestingly, in the coquina *B. borealis borealis* is represented almost exclusively by ventral valves. The valves of *B. borealis borealis* may comprise up to 64% of the rock in the Tammiku Member (Jürgenson 1966). The matrix consists of pellets and rounded skeletal fragments in sparry calcite. The bedding planes are usually marked by stylolites, with occasional thin marl coatings. The coquina contains rare stromatoporoids.

Figure 1. Combined section of the Eivere quarry and distribution of conodonts.

Photo 2. Limestone of the Tamsalu Formation – *the Borealis borealis borealis* coquina (photo P. Männik).

The limestones of the Varbola Formation represent open marine tropical carbonate shelf sediments, deposited after the end-Ordovician post-glaciation flooding. The shell bank of the Tamsalu Formation was deposited in a shallow-water high-energy environment, in the shoal belt of the Silurian Baltoscandian Sea. The *B. borealis borealis* coquina accumulated in an about 30 km wide zone extending up to 200 km from east to west in Central Estonia. The thickness of the *Borealis* bank is up to 13.5 m (Nestor 1997). These strata, lying over the argillaceous limestones (wackestones) of the Varbola Formation that comprises the lower part of the Juuru Stage, about 10–20 m above the Ordovician–Silurian boundary, reflect the first Silurian shallowing in the Baltoscandian Palaeobasin. The distribution of the massive *Borealis* bank, resistant to erosion, has shaped the bedrock core of the Pandivere Upland in east-central Estonia.

Although macrofossils are common and taxonomically variable in the Varbola Formation (*e.g.* Kaljo 1970), conodonts are rare and represented by poor faunas in the Eivere section, as elsewhere in Central Estonia. Three samples were processed for conodonts from this section. All of them were productive. The assemblage recovered is characteristic of the *Distomodus kentuckyensis* conodont Zone.

The *Borealis*-bank limestone is very clean in the Pandivere area and contains only minor amounts of dolomite (1–10%) and siliciclastic (clay; usually <2%) material (Jürgenson 1966). For over a century the rock has been used for lime production in this region. In Eivere the rock is quarried for limestone aggregate production.

References

Jürgenson, E., 1966. Lithology of the Llandoverian beds in Estonia. *Institute of Geology, Academy of Sciences of the Estonian SSR*, Tallinn, 68 pp. [in Russian with English summary].

Kaljo, D. (ed.), 1970. *The Silurian of Estonia*. Valgus, Tallinn, 343 pp. [in Russian].

Nestor, H., 1997. Silurian. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and Mineral Resources of Estonia*. Estonian Academy Publishers, Tallinn, 89–106.

Stop B3: Päri outcrop

Olle Hints

Institute of Geology at Tallinn University of Technology, Estonia

A shallow disused Päri quarry (58°50′25.65″N, 24°02′34.04″E) is located on a flat limestone hillock, ca 5.5 km SW of Kullamaa village, 1 km W of the Tallinn–Virtsu road (Photo 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 3.9 m.

Photo 1. Overview of the Päri quarry (photo O. Hints).

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 species, in particular corals and stromatoporoids, and the only outcrop of the Osmundsberg bentonite in the East Baltic.

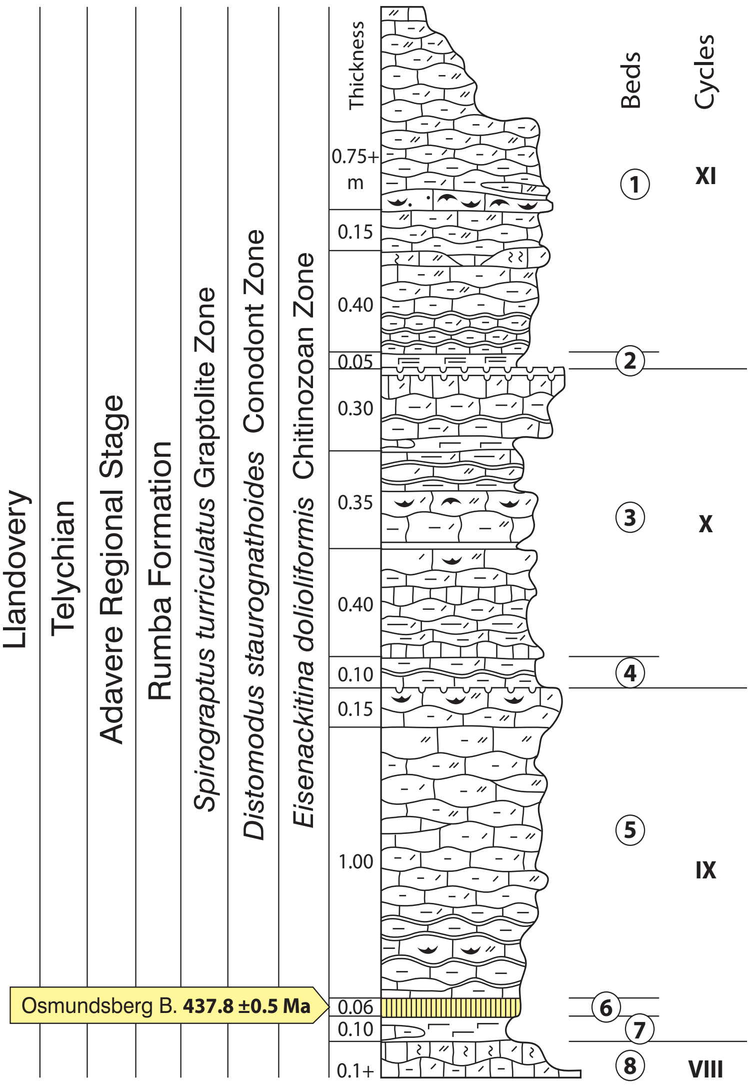


Figure 1. Succession of argillaceous limestones in the Päri quarry. Lithology from Kaljo & Einasto (1990), age of the Osmundsberg bentonite according to Bergström *et al.* (2008), stratigraphy combined from different sources.

According to Kaljo & Einasto (1990), the succession of the deepest part of the quarry is described as follows (from the top; see Fig. 1, Photo 2; note that starting from the middle of bed 5, the section is commonly filled with debris):

(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.

(5) 1.15 m – greenish-grey, irregularly nodular, argillaceous skeletal limestone (packstone) with lenses of skeletal grainstone (*Pentamerus*-coquinas). Upper 15 cm contains purer limestone with a pyritic discontinuity surface 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. 1). Usually a cycle begins with a thin marlstone layer, while upwards the clay content decreases and grainstone or coquinoid rudstone lenses appear; each cycle ends with a distinct discontinuity surface (Kaljo & Einasto 1990).

Photo 2. Deepest part of the quarry; small hammer in the lower part points to the 6-cm thick the Osmundsberg bentonite, partly under water (photo O. Hints).

The lower part of the Päri section includes a ca 6 cm thick bioturbated K-feldspar-rich bentonite layer. This is the thickest Silurian volcanogenic layer in Estonia, previously referred to as the "O"-bentonite (Kiipli *et al.* 2006 and references therein). Now it is 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. 2), whereas the thickness map indicates a 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 in the carbonate content of burrows within the bed (Kiipli 2008). The U–Pb dating of the Osmundsberg bentonite from the type locality in Sweden provided a radiometric age of 437.8 ± 0.5 Ma (Bergström *et al.* 2008).

The Päri quarry is rich in shelly faunas, as generally typical of the Rumba Formation. The Rumba Formation as well as the Päri section show an abundant occurrence of *Pentamerus oblongus* (Photo 3). Other brachiopods, tabulate corals (*Paleofavosites*, *Catenipora*, *Aulopora*, *Placocoenites*, *Subalveolites*, *Propora*) and stromatoporoids (*Clathrodictyon*) are common, and rugosans (*Calostylis*), gastropods (*Hormotoma*), cephalopods, echinoderms and trilobites (*Calymene*, *Encrinurus*) may also be found.

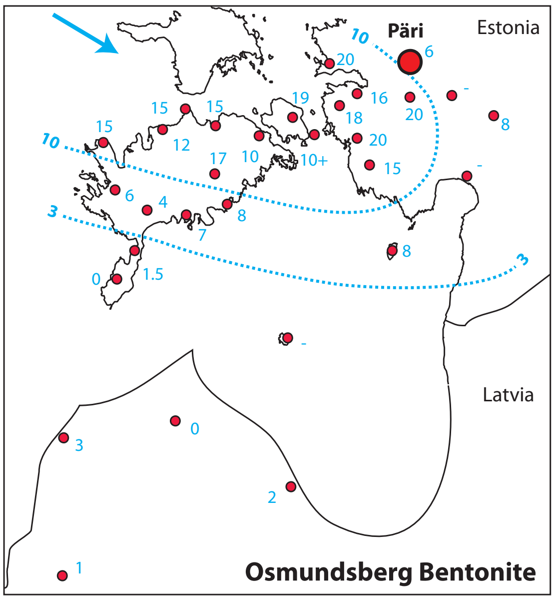


Figure 2. Thickness distribution of the Osmundsberg bentonite in East Baltic (after Kiipli *et al.* 2006).


Photo 3. Erosional surface with cut shells of *Pentamerus oblongus* in the Päri quarry (photo O. Hints).

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) and *Eisenackitina dolioliformis* chitinozoan Zone. Recent data by conodonts suggest *Distomodus staurognathoides* conodont Zone for the section (P. Männik pers. comm. 2014).

References

Bergström, S. M., Huff, W. D. & Kolata, D. R., 1998. The Lower Silurian Osmundsberg K-bentonite. Part I: stratigraphic position , distribution , and palaeogeographic significance. *Geological Magazine*, 135, 1–13.

Kiipli, E., Kiipli, T. & Kallaste, T., 2006. Identification of the O-bentonite in the deep shelf sections with implication on stratigraphy and lithofacies, East Baltic Silurian. *GFF*, 128, 255–260.

Kiipli, T., Orlova, K., Kiipli, E. & Kallaste, T., 2008. Use of immobile trace elements for the correlation of Telychian bentonites on Saaremaa Island, Estonia, and mapping of volcanic ash clouds. *Estonian Journal of Earth Sciences*, 57, 39–52.

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

Einasto, R., Nestor, H., Kala, E. & Kajak, K., 1972. Correlation of the Upper Llandoverian sections in West Estonia. *Proceedings of the Academy of Sciences of the Estonian SSR. Chemistry and Geology*, 21, 333–343. [in Russian].

Kiipli, T., 2008. Excursion A: Ordovician and Silurian bentonites of Estonia. *In:* Hints, O., Ainsaar, L., Meidla, T. & Männik, P. (eds). *The Seventh Baltic Stratigraphical Conference. Abstracts & Field Guide.* The Geological Society of Estonia, Tallinn, 83–92.

Nestor, H., 1993. *Catalogue of Silurian stratigraphical units and stratotypes in Estonia and Latvia*. Institute of Geology, Estonian Academy of Sciences, Tallinn, 23 pp.

Bergström, S. M., Toprak, F. Ö., Huff, W. D. & Mundil, R., 2008. Implications of a new, biostratigraphically well- controlled, radio-isotopic age for the lower Telychian Stage of the Llandovery Series (Lower Silurian, Sweden). *Episodes*, 31, 309–314.

Stop B4: Pulli cliff

Peep Männik[1], Tõnu Meidla[2] and Viiu Nestor[1]
[1]*Institute of Geology at Tallinn University of Technology, Estonia*
[2]*Department of Geology, University of Tartu, Estonia*

The Pulli (=Oiu) cliff is located in the northeastern corner of Saaremaa, about 10 km northwest of the Orissaare settlement (58°36′52″N, 22°57′20″E). The outcrop was first described by Schmidt (1858) as the Ojo cliff. Jürgenson & Nestor (1990) suggested that the boundary between the Jaani and Jaagarahu stages is exposed in this section. However, this conclusion was based mainly on sedimentological reconstructions, because the Jaagarahu age of the upper part of the section was not proved biostratigraphically. Micropalaeontological data seem to suggest Jaani age also for the upper part of the section (see below). In the Pulli section dolomitic marlstones of the Paramaja Member (Jaani Formation) and stratified vuggy and massive reefal (mud-mound) dolomites of the Kesselaid Member (Muhu Formation) are exposed. These two lithologies (members) are separated by a distinct strongly wavy contact.

Photo 1. View at the Pulli cliff (photo H. Bauert).

Description of the section

(from the top; modified from Jürgenson & Nestor 1990):

Kesselaid Member, Jaagarahu (?) Stage.

The upper part of the section (thickness up to 2 m) includes upward-expanding dolomitized mud-mounds. They consist of fine- to microcrystalline vuggy dolomite with irregular structure and contain small irregular pockets of greenish argillaceous marlstone and brownish-grey dolomite.

Mud-mounds are underlain and laterally replaced by bluish- to greenish-grey medium-bedded fine-crystalline dolomite (thickness up to 1 m) with relict texture of coarse-grained bioclastic grainstone, thin discontinuous argillaceous partings and abundant vugs of various sizes. The vugs were formed by dissolution of calcitic shells of brachiopods, rugose corals, pelmatozoans and bryozoans. At the base of the Kesselaid dolomites there is an intensely impregnated rusty discontinuity surface.

Paramaja Member, Jaani Stage.

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

Trilobites *Encrinurus punctatus* (Wahlenberg) and *Calymene blumenbachii* Brongniart have been identified from the marlstones of the Paramaja Member. Two samples processed for conodonts, one

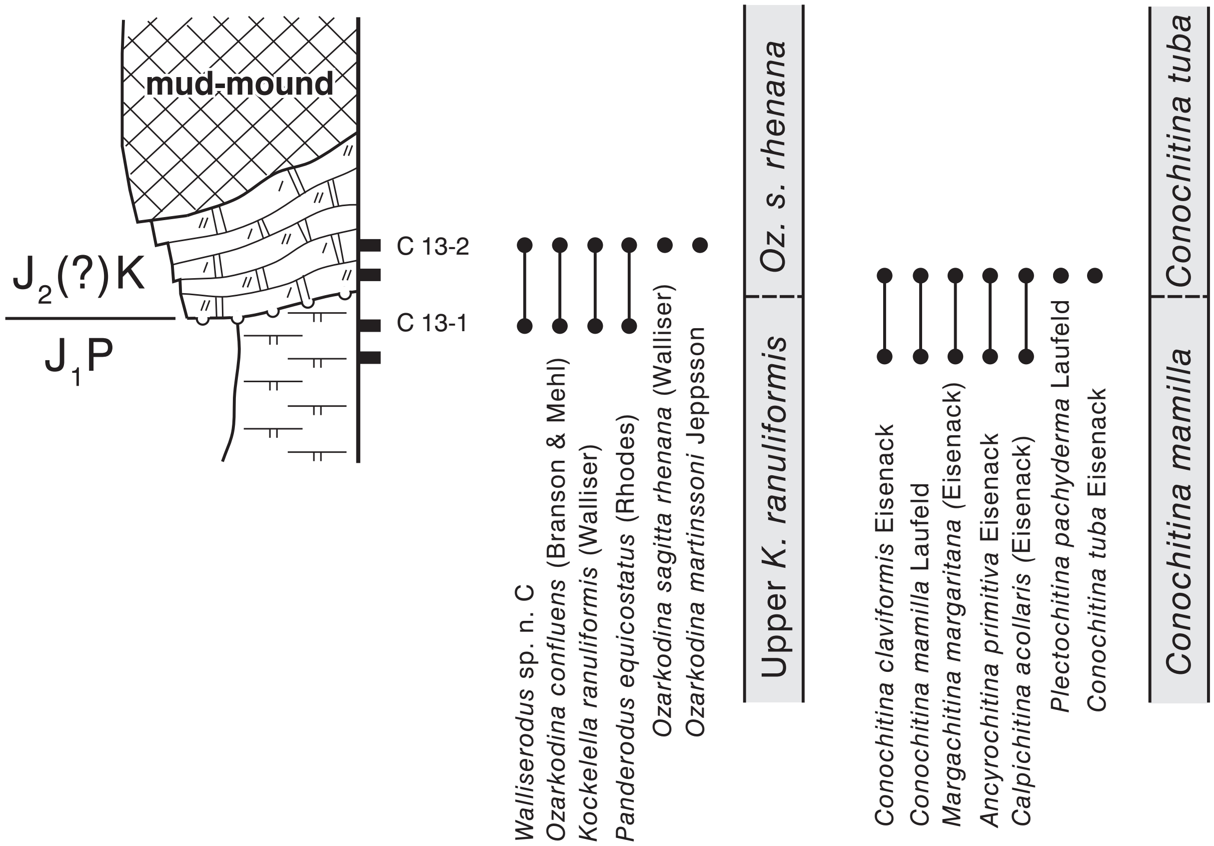


Figure 1. The Pulli Cliff section. From left to right: regional stratigraphy, lithology (see legend on page 202); location of micropalaeontological samples; sample numbers; distribution of conodonts; conodont zones; distribution of chitinozoans; chitinozoan zones. Black dots – reliable identifications, white dots – problematic identifications (cf., ?). Abbreviations: **J**$_1$ – Jaani Stage; **J**$_2$ – Jaagarahu Stage; **P** – Paramaja Member; **K** – Kesselaid Member.

from the topmost Paramaja 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 probably indicate that the boundary between the Upper *Kockelella ranuliformis* (Walliser) and *O. s. rhenana* conodont zones lies close to the contact between the Paramaja and Kesselaid members (Fig. 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. As both zonal boundaries are known to occur in the upper Jaani Stage (Nestor 1994; Viira & Männik 1997), it is probable that the upper part of the Pulli section (reefal rocks of the Kesselaid Member) is also of Jaani age. However, it cannot be excluded that the gap at the boundary between the Paramaja and Kesselaid members has considerable duration in the region and the Kesselaid Member is really of Jaagarahu age, as both the *O. s. rhenana* and *C. tuba* zones correlate with the upper Jaani and lower Jaagarahu stages.

References

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

Nestor, V., 1994. *Early Silurian chitinozoans of Estonia and North Latvia*. Academia 4. Estonian Academy Publisher, Tallinn, 163 pp.

Schmidt, F., 1858. Untersuchungen über die Silurische Formation von Ehstland, Nord-Livland und Oesel. *Arch. Naturk. Liv.-, Ehst- und Kurl*., ser. 1, 2, 1, Dorpat, 1–248.

Viira, V. & Männik, P. 1997. Conodonts. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 241–247.

Stop B5: Panga cliff

Peep Männik and Viiu Nestor
Institute of Geology at Tallinn University of Technology, Estonia

The Panga cliff is located just east of Küdema Bay, close to Võhma village in northern Saaremaa (coordinates of its eastern end 58°34′12″N, 22°17′49″E). The cliff has two main escarpments, one below and the other one above sea level. These escarpments are separated by a shallow water plateau several hundreds metres wide. 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 from north to south for about 3 km, curving along the sea. The escarpment below sea level was sampled in 1982 by archaeologists from the Estonian Maritime Museum but the section was never described. However, the samples available show that the succession consists of dolomitized marlstone and dolomitic argillaceous limestone of Telychian age (upper Adavere and lower Jaani stages). The cliff above sea level exposes dolomitized marlstone, argillaceous dolomitic limestone and dolomite of the Jaani and Jaagarahu stages (Photo 1). The upper part of the cliff is very difficult to reach. It can be studied in a smaller escarpment located farther inland. Here, porous dolomite of the Vilsandi Beds (Jaagarahu Stage) containing small bioherms crop out (Photo 2).

As a prominent landform and scientifically important natural object, the Panga cliff (also known as the Mustjala cliff) is under state protection.

Photo 1. The main escarpment of the Panga cliff (photo P. Männik).

Photo 2. The uppermost part of the Panga section in a small escarpment (photo P. Männik).

<u>Description of the section</u> (from base to top; modified from Rubel & Einasto 1990).

Mustjala Member, upper Adavere–lower Jaani stages.

(1) 10+ m (underwater part of the cliff) – based on the samples taken from every metre, it consists of grey bioturbated dolomitic marlstone containing unsorted bioclastic debris but also nodules and interbeds of dolomitized argillaceous bioclastic limestone (mudstone and wackestone).

(2) 0.6 m – grey unsorted bioclastic argillaceous dolomite (mudstone).

(3) 1.0 m – bioturbated argillaceous bioclastic dolomite (mainly mudstone), with 1–3 cm thick interbeds of dolomitic marlstone.

(4) 1.8 m – dolomitized bioclastic marlstone with nodules and up to 5 cm thick interbeds of fine-grained argillaceous bioclastic dolomite (wackestone–packstone). The upper contact is erosional. Stromatoporoids, tabulate and rugose corals, brachiopods, trilobites and ostracods occur in this interval.

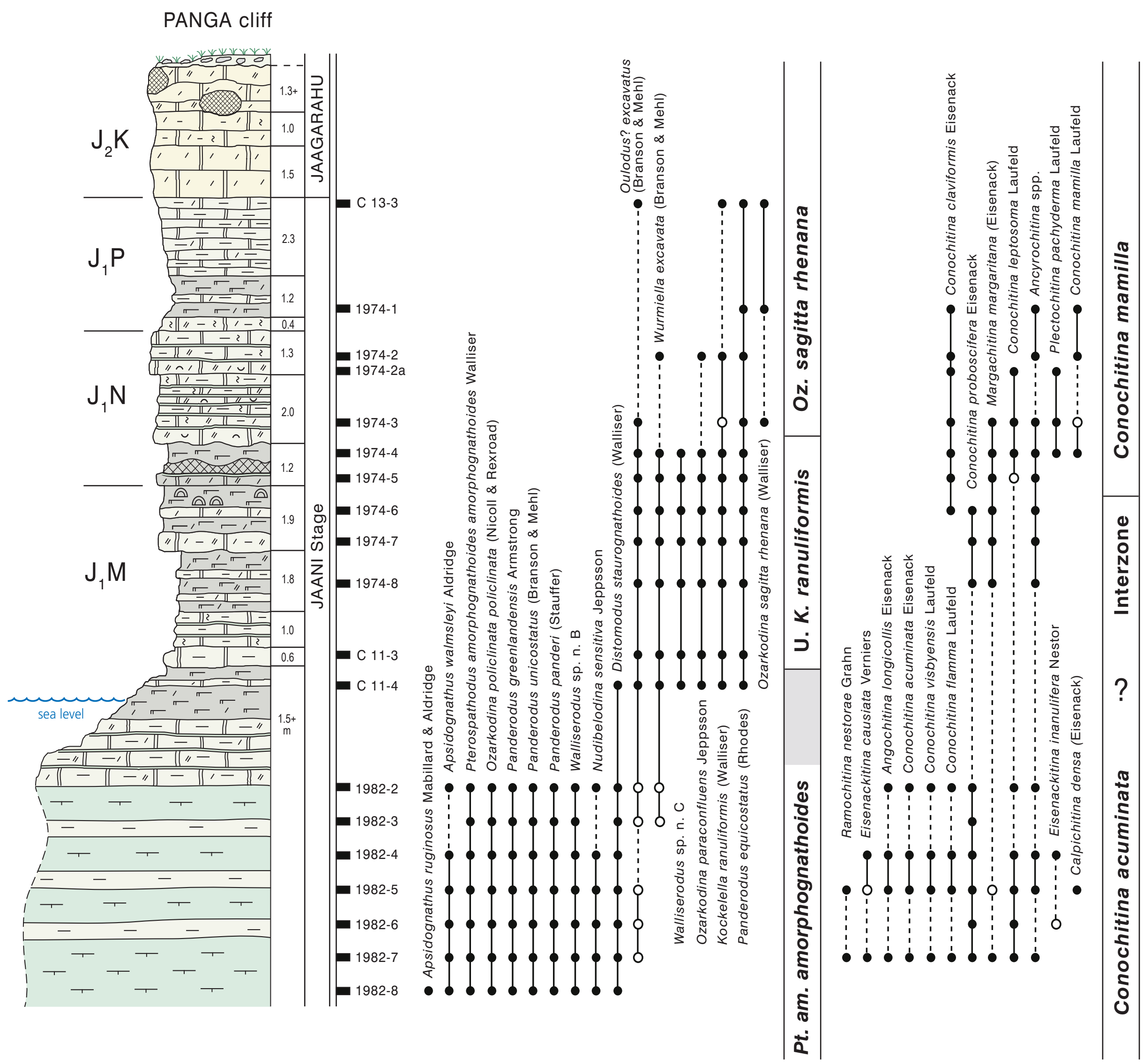


Figure 1. The Panga Cliff section (modified from Rubel & Einasto 1990). From left to right: lithology (see legend on page 202) with bed numbers to right of the log; thickness of beds (m); location of micropalaeontological samples; sample numbers; distribution of conodonts; conodont zones; distribution of chitinozoans; chitinozoan zones. Black dots – reliable identifications, white dots – problematic identifications (cf., ?). Abbreviations: **J**$_1$ – Jaani Stage; **J**$_2$ – Jaagarahu Stage; **M** – Mustjala Member; **N** – Ninase Member; **P** – Paramaja Member; **K** – Kesselaid Formation.

(5) 1.9 m – lower 0.4 m of the bed consists of unsorted argillaceous bioclastic or fine-grained dolomite (packstone) yielding stromatoporoids, tabulate corals, brachiopods and trilobites; upper 1.5 m is bioturbated argillaceous bioclastic dolomite (wackestone–packstone) with up to 5 cm thick interbeds of argillaceous dolomitic marlstone. Small, up to 35 cm high bioherms, formed mainly by stromatoporoids but including also some tabulate corals, are present.

Ninase Member, Jaani Stage.

(6) 1.2 m – analogous to bed 5: the lowermost 0.35 m consists of bioclastic dolostone (packstone–grainstone) dominated by crinoid and brachiopod fragments. The middle part of the bed contains bryozoan bioherms (1.3 m x 1.2 m), the upper part consists of greenish-grey dolomitic marlstone.

(7) 2.0 m – interbedding of coquinoid biomorphic to bioclastic dolomite (packstone–grainstone), argillaceous dolomite (wackestone–packstone) and dolomitic marlstone. In bioclastic material fragments of brachiopods and crinoids are dominating.

(8) 1.3 m – similar to bed 7 but less argillaceous. Dolomitized packstone and grainstone are more common. Brachiopods, gastropods, trilobites and ostracods have been found.

Paramaja Member, Jaani Stage.

(9) 0.4 m – bioturbated argillaceous bioclastic dolomite (wackestone–packstone).

(10) 1.2 m – dolomitic marlstone with scarce bioclastic material (mainly ostracods) and interbeds of argillaceous bioclastic dolomite (wackestone–packstone).

(11) 2.3 m – grey thin-bedded highly argillaceous dolomite (wackestone) with scarce fine bioclastic material (brachiopods, ostracods, trilobites).

Jaagarahu Formation

(12) 1.5 m – thick-bedded bioclastic dolomite (packstone and grainstone). Bioclastic material is dominated(?) by crinoid fragments.

(13) 1.0 m – slightly argillaceous bioturbated dolomite (wackestone) with unevenly distributed bioclastic material (fragments of crinoids were recognized).

(14) 1.3 m – porous dolomite (packstone–grainstone) with small bioherms. Crinoid fragments, stromatoporoids, tabulate corals and probable calcareous algae have been reported.

Fauna

The section, particularly some levels in its lower part (Mustjala Member), is rich in various macrofossils. From the Mustjala Member stromatoporoids *Densastroma pexisum* (Yavorsky), *Eostromatopora impexa* (Nestor), *Oslodictyon suevicum* (Nicholson), *Petridiostroma simplex* (Nestor) and tabulate corals *Catenipora panga* Klaamann, *C. quadrata* (Fischer-Benzon), *Halysites senior* Klaamann, *Subalveolites sokolovi* Klaamann, *Syringolites kunthianus* (Lindström), *Syringopora novella* Klaamann, *Thecia tenuicula* Klaamann have been identified. In the loose material at the coast stromatoporoids supposedly of Adavere age (*Clathrodictyon variolare* (Rozen), *C. delicatulum* Nestor and *Oslodictyon suevicum* (Nicholson) have been found. The brachiopods *Atrypa* (*Atrypa*) *reticularis* (Linnaeus), *Dalejina hybrida* (J. de C. Sowerby), *Dolerorthis rustica* (J. de C. Sowerby), *Estonirhynchia estonica* Schmidt, *Microsphaeridiorhynchus nucula* (J. de C. Sowerby), *Stegerhynchus borealis* Buch, *Leptaena* sp., *Resserella* sp. and *Whitfieldella* sp. are known to occur in all members of the Jaani Stage. The loose material of the Ninase Member has yielded trilobites *Calymene blumenbachi* (Brongniart) and *Proetus concinnus osiliensis* Schmidt.

The *Pterospathodus amorphognathoides amorphognathoides*, Upper *Kockelella ranuliformis* and *Ozarkodina sagitta rhenana* conodont zones are recognized (Fig. 1). Based on the data available, the Ireviken Event (and the Llandovery–Wenlock boundary) in the Panga section lies in the unsampled strata of the shallow-water plateau between the escarpments below and above sea level (grey interval in Fig. 1). However, Datum 8 of the event (and the boundary between the Lower and Upper *Kockelella ranuliformis* conodont zones) is exposed just above the sea level, in the basal part of the second escarpment. Recognition of the *Conochitina acuminata* chitinozoan Zone in the lower part of the underwater escarpment suggests that the corresponding beds belong to the Adavere Stage.

References

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

Stop B6: Abula cliff

Peep Männik
Institute of Geology at Tallinn University of Technology, Estonia

The Abula cliff (Photo 1) is located on the eastern coast of Tagalaht Bay, 3 km north of the Mustjala–Veere road (coordinates of its southern end 58°27′7″N, 22°6′50″E). The topmost lagoonal dolomitic marlstone of the Vilsandi Beds (at the base of the section) and the basal part of the Maasi Beds, middle Jaagarahu Stage, are exposed in the cliff (Fig. 1). Luha (1934) referred to these rocks as Kurevere Limestone.

Description of the section
(from top to base; modified from Rubel & Einasto 1990):

(1) 0.4+ m – bioclastic wackestone–packstone rich in stromatoporoids, and with lenses of bioclastic marlstone (thickness 0.1 m) in the lower part. A distinct discontinuity surface occurs at the base of the bed.

(2) 0.7 m – light grey wavy-bedded pelletal limestone (grainstone) with several discontinuity surfaces in the upper 15–20 cm and common stromatoporoids. The middle part of the bed contains accumulations of brachiopod shells.

Photo 1. View at the Abula cliff (photo H. Bauert).

(3) 0.6 m – light yellowish-grey fine-nodular pelletal limestone (packstone–grainstone) with stromatoporoids, tabulate corals (*Favosites mirandus* Sokolov is the commonest), ostracods and calcareous algae. The lowermost 0.1 m of the bed contains thin interbeds of marlstone, the uppermost 0.2 m comprises irregularly nodular skeletal wackestone with 0.15 m thick and 1.5 m long lenses of bioclastic grainstone. Large *Megalomus*-type shells are found.

(4) 0.10–0.15 m – grey fine-grained pelletal limestone (packstone).

(5) 0.5 m – yellowish-grey fine-nodular pelletal and bioclastic, slightly argillaceous limestone (wackestone–packstone). Brachiopods are common, tabulate corals are rare. The basal 10–15 cm of the bed is more argillaceous; a discontinuity surface occurs at the base.

(6) 0.2 m – thin-bedded bioclastic (ostracod) packstone with 1–2 cm thick interbeds of calcareous marlstone.

(7) 0.5 m – yellowish-grey wavy-bedded pelletal limestone (wackestone–packstone) containing large ostracods and gastropods. A 3 cm thick ostracod grainstone layer with small oncoids occurs at the base.

(8) 0.2 m (exposed on the sea bottom, accessible when sea level is low) – greenish-grey calcareous dolomitic marlstone with 1–2 cm thick lenses and interbeds of fine-grained bioclastic and pelletal packstone. Large ostracods and *Eurypterus* fragments are found.

Stromatoporoids *Clathrodictyon kudriavzevi* Riabinin, *Vikingia tenuis* (Nestor), *Ecclimadictyon macrotuberculatum* (Riabinin), and tabulate corals *Thecia confluens* (Eichwald) and *Favosites mirandus* Sokolov have been identified in the Abula section.

The samples processed for conodonts have yielded poor faunas dominated by *Ozarkodina conflues* (Branson & Mehl). Taxa specific to a particular conodont zone have not been found but based on earlier

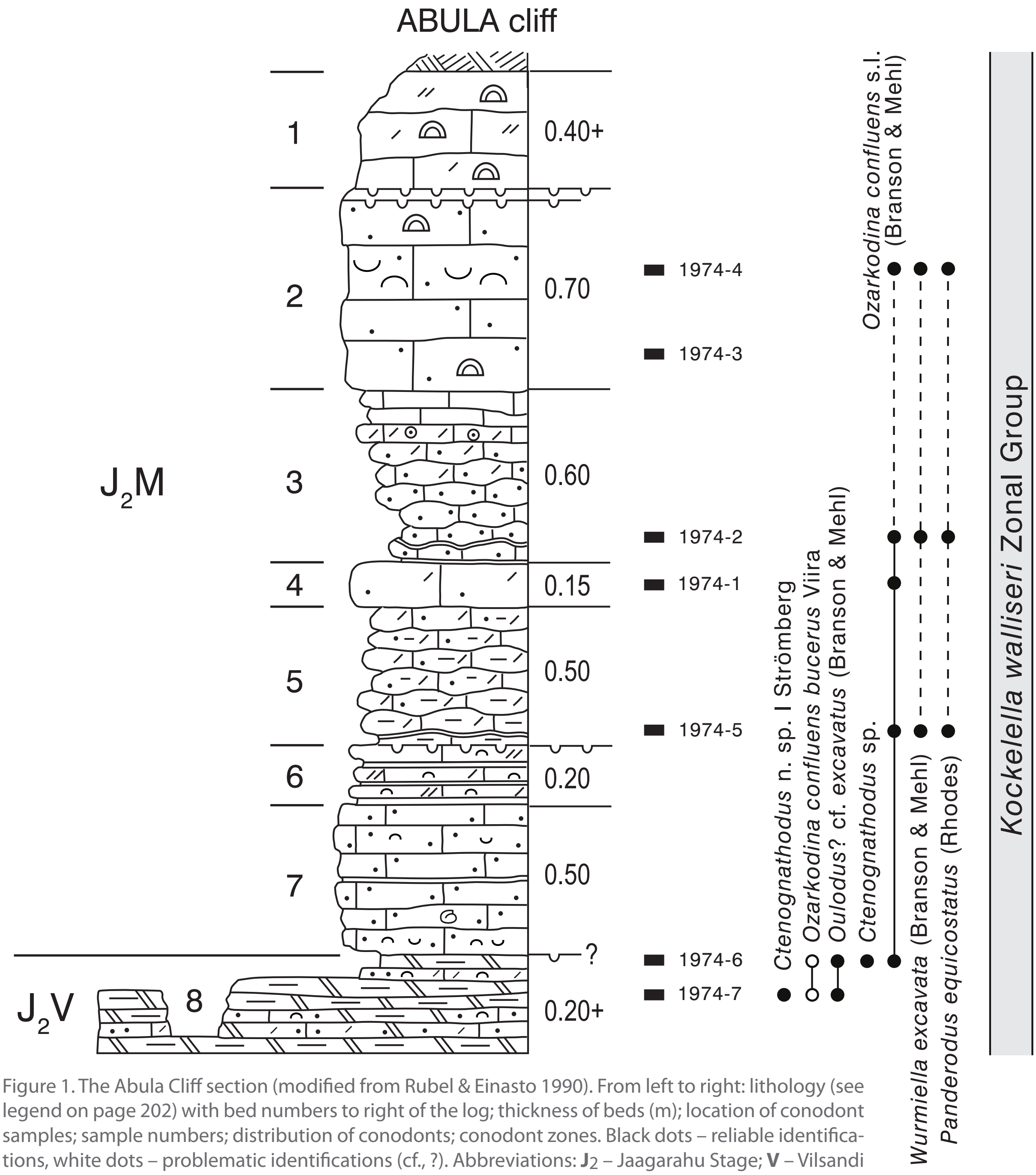


Figure 1. The Abula Cliff section (modified from Rubel & Einasto 1990). From left to right: lithology (see legend on page 202) with bed numbers to right of the log; thickness of beds (m); location of conodont samples; sample numbers; distribution of conodonts; conodont zones. Black dots – reliable identifications, white dots – problematic identifications (cf., ?). Abbreviations: **J**$_2$ – Jaagarahu Stage; **V** – Vilsandi Beds; **M** – Maasi Beds.

general comparison of distributions of conodonts on Gotland (Sweden) and in Estonia (Jeppsson *et al.* 1994), most probably that the Abula section correlates with an interval in the (lower) *Kockelella walliseri* Zonal Group *sensu* Jeppsson (1997).

References:

Jeppsson, L., 1997. A new latest Telychian, Sheinwoodian and Early Homerian (Early Silurian) standard conodont zonation. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, 88, 91–114.

Jeppsson, L., Viira, V. & Männik, P., 1994. Conodont-based correlations between Estonia and Gotland. *Geological Magazine*, 131, 201–218.

Luha, A., 1934. Saaremaa pinnaehitus ja aluspõhi. *Eesti Maateaduslik, majanduslik ja ajalooline kirjeldus, VI – Saaremaa*. Eesti Kirjanduse Selts, Tartu, 4–22. [in Estonian].

Rubel, M. & Einasto, R., 1990. Locality 6:2. Abula cliff. *In:* Kaljo, D. & Nestor, E. (eds). *Field Meeting, Estonia 1990. An Excursion Guidebook*. Estonian Academy of Sciences, Tallinn, Estonia, 165–166.

Stop B7: Suuriku and Undva cliffs

Tõnu Meidla[1], Oive Tinn[1], Peep Männik[2] and Rein Einasto[3]

[1]*Department of Geology, University of Tartu, Estonia*
[2]*Institute of Geology at Tallinn University of Technology, Estonia*
[3]*TTK University of Applied Sciences, Estonia*

The Suuriku and Undva cliffs are located in northwestern Saaremaa. In both sections approximately the same stratigraphical interval, representing the uppermost Mustjala and lower Ninase members of the Jaani Formation, is exposed. Transition from the marls of the Mustjala Member to the grainstones of the Ninase Member, from the open shelf mudstones to shoal pre-reef grainstones, marks a remarkable shallowing event in the palaeobasin (Nestor & Einasto 1997). The same interval is exposed also in the lower part of the Panga section (in this guidebook).

Both sections have been studied repeatedly (see references). Descriptions of the sections below are mainly based on data by T. Meidla, O. Tinn and R. Einasto (field studies in 2002).

Suuriku cliff

The Suuriku cliff (Photo 1) is an about 950 m long escarpment along the northern coast of the Tagamõisa Peninsula, NW Saaremaa (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). This is the second highest cliff in Saaremaa Island. Its maximum height reaches 8 m. The escarpment is actively abraded and some intervals of it are unstable. Heaps of limestone debris and blocks below the escarpment point at recent collapses.

Photo 1. Suuriku cliff (photo T. Meidla).

Six subunits are distinguished in the succession, the lowermost one representing the Mustjala Member and the other ones the overlying Ninase Member.

<u>**Description of the section**</u>
(58°30´28.48″N, 22°0´1.76″E; from the base; see also Fig. 1):

I (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;

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

III (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;

IV (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;

V (1.7 – 3 m) – thick-bedded oncoidal grainstone, grading into argillaceous wackestone to packstone rich in brachiopods;

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

Thicknesses of the subunits vary slightly in different parts of the cliff (see Fig. 2).

Near the eastern end of the cliff, lense-like bryozoan reefs occur in the upper part of the escarpment. Bryozoans *Ceramopora* and *Lioclema* as the main reef builders, but also branching tabulates, stromatoporoids and echinoderms, as well as ostracods and brachiopods in the clay lenses between the bryozoan encrustations are present (Aaloe & Einasto 1970; Rubel *et al.* 1991). The trilobite *Encrinurus punctatus* (Wahlenberg) has been recorded (Männil 1978).

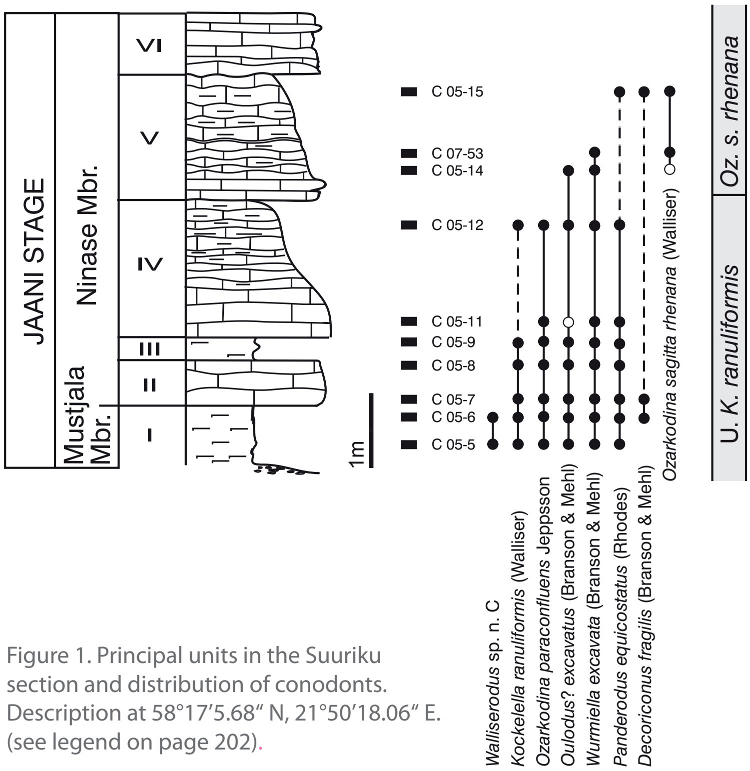


Figure 1. Principal units in the Suuriku section and distribution of conodonts. Description at 58°17'5.68" N, 21°50'18.06" E. (see legend on page 202).

Rubel *et al.* (1991) identified 34 brachiopod species in this section. Of the more common species, *Eoplectodonta (Eoplectodonta) duvalii* (Davidson) and *Visbyella visbyensis* (Lindström) are restricted to the 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 II–IV), being accompanied by *Atrypa reticularis* (Linnaeus) in this interval. The diversity of brachiopods decreases upwards in the section. *Dolerorthis 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 (intervals V–VI).

Klaamann (1961) identified eight tabulate species representing the genera *Palaeofavosites*, *Mesofavosites*, *Syringolites*, *Thamnapora*?, *Subalveolites*, *Halysites* and *Propora* in this section. According to Sarv (1968), beyrichiacean ostracods *Beyrichia (B.) halliana* Martinsson, *Beyrichia (B.) suurikuensis* Sarv, *Craspedobolbina (Mitrobeyrichia) unculifera* Martinsson, *Clavofabella juvenca* Sarv are common. *Beyrichia (B.) bicuspis* Kiesow, appearing in the Ninase Formation, is abundant.

The Upper *Kockelella ranuliformis* and *Ozarkodina sagitta rhenana* conodont zones (CZ) are recognized in the Suuriku section (Fig. 1). Samples from the Upper *K. ranuliformis* CZ are dominated by *Panderodus equicostatus* (Rhodes) and *Wurmiella excavata* (Branson & Mehl), those from the *Oz. s. rhenana* CZ (the lowermost sample excluded) are largely dominated by *Oz. s. rhenana* (Walliser) (over 80% of specimens). According to L. Jeppsson (pers. comm.), strong domination of *Oz. s. sagitta* and lack of *Oz. paraconfluens* Jeppsson characterize Subzone 1 of the *Oz. s. rhenana* CZ. This fauna suggests a correlation of the uppermost part of the Suuriku section with the lower Tofta Formation on Gotland (Jeppsson et al. 2006).

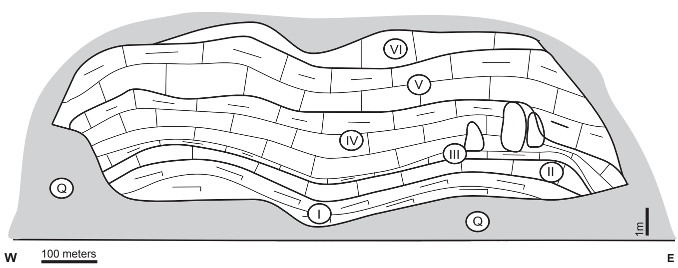


Figure 2. Profile of the Suuriku cliff. The principal units distinguished in the succession are shown in the figure 1 and described in the text (see legend on page 202).

Undva cliff

The Undva cliff (Photo 2) is located about 4 km west of the Suuriku cliff. The cliff is about 400 m long. Its western end lies at 58°30´58.07″N and 58°30´58.07″E, eastern end at 58°30´58.46″N and 21°55´20.96″E. The low escarpment (up to 3 m) is actively abraded and may be partly covered by loose debris, mostly coarse limestone pebbles. Three subunits are described in the succession, the lowermost one comprising the Mustjala Member, the two overlying ones representing the lowermost Ninase Member.

Photo 2. Undva cliff (photo P. Männik).

Description of the section

(58°31´0.91″N, 21°55´5.88″E; from the base; see also Fig. 3):

I (0.6–1.5 m) – calcareous marl with interbeds of crinoidal packstone;

II (0.4–0.7 m) – cross-bedded crinoidal grainstone with few stylolites; the upper surface represents a weakly pyritized discontinuity surface; small bioherms occur in the upper part of the interval;

III (0.2–0.3 m) – crinoidal packstone to grainstone with abundant brachiopods and bryozoans, grading into bioturbated wackestone to packstone.

Thicknesses of the subunits are quite variable. The western part of the section exposes mostly the Ninase Member, whilst the eastern part offers better access to the Mustjala Member (see Fig. 4).

The section is relatively rich in tabulate corals. Klaamann (1961) identified here ten tabulate species of the genera *Thecia*, *Mesofavosites*, *Syringolites*, *Thamnapora*?, *Subalveolites*, *Catenipora*, *Halysites* and *Propora*. The trilobite *Encrinurus punctatus* (Wahlenberg) was recorded by Männil (1978). Relatively well-preserved thecae of crinoidean echinoderms

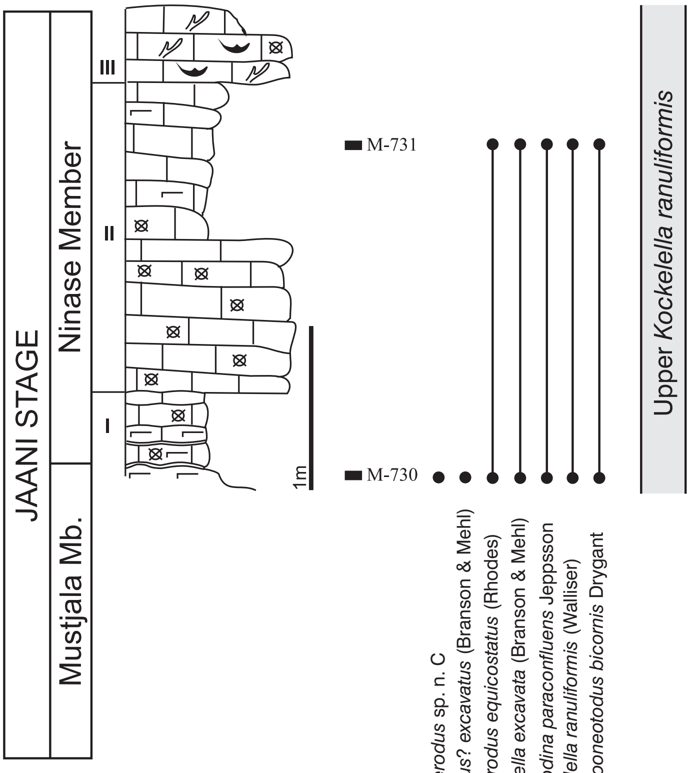


Figure 3. Principal units in the Undva section and distribution of conodonts. Description at 58°17'5.68" N, 21°50'18.06" E (see legend on page 202).

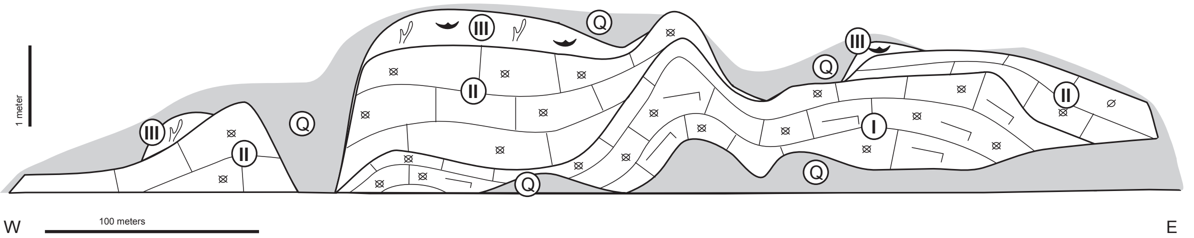


Figure 4. Profile of the Undva cliff. The principal units distinguished in the succession are shown in the Figure 3 and described in the text (see legend on page 202).

Pereichocrinus laevis? (Angelin), *Calliocrinus* sp. and several species of *Eucalyptocrinites* (including *E. regularis* (Hisinger)) may occasionally be found (Ausich *et al.* 2012, 2014, in press). Beyrichiacean ostracods are represented by abundant *Craspedobolbina (Mitrobeyrichia) unculifera* Martinsson (Sarv 1968).

Two samples processed for conodonts, one from the Mustjala and the other from the Ninase Member, yielded faunas indicating the lowermost Sheinwoodian Upper *Kockelella ranuliformis* Zone (Fig. 3).

References

Aaloe, A. & Einasto, R., 1970. Biohermal limestones. *In:* Kaljo, D. (ed). *The Silurian of Estonia*. Valgus, Tallinn, 41-46. [in Russian].

Ausich, W. I., Wilson, M. A. & Vinn, O., 2012. Crinoids from the Silurian of Western Estonia. *Acta Palaeontologica Polonica*, 57, 613–631.

Ausich, W. I., Wilson, M. A. & Vinn, O., 2014. Wenlock and Pridoli (Silurian) crinoids from Saaremaa, western Estonia (phylum Echinodermata). *Journal of Paleontology* [in press].

Jeppsson, L., Eriksson, M. E. & Calner, M., 2006. A latest Llandovery to latest Ludlow high-resolution biostratigraphy based on the Silurian of Gotland – a summary. *GFF*, 128, 109–114.

Klaamann, E., 1961. The Wenlockian Tabulata and Heliolitida of Estonia. *Geoloogia Instituudi Uurimused*, 6, Tallinn, 69-112.

Männil, R., 1978. Wenlockian trilobites of the *Encrinurus punctatus* species-group of the East Baltic. *Eesti NSV Teaduste Akadeemia Toimetised. Geoloogia,* 27, 3, 108–115.

Nestor, H. & Einasto, R., 1997. Ordovician and Silurian carbonate sedimentation basin. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 192–204.

Rubel, M., Brazauskas, A., Musteikis, P. & Puura, I., 1991. Distribution of Wenlock brachiopods in the Suuriku section, Estonia. *Proc. Acad. Sci. Geology*, 40, 2, 61–73. [in Russian].

Sarv, L., 1968. Ostracode families Craspedobolbinidae, Beyrichiidae and Primitiopsidae in the Silurian of Estonia. Valgus, Tallinn, 104 pp. [in Russian].

Stop B8: Soeginina cliff

Tõnu Meidla[1], Oive Tinn[1] and Peep Männik[2]

[1]*Department of Geology, University of Tartu, Estonia*

[2]*Institute of Geology at Tallinn University of Technology, Estonia*

Photo 1. Soeginina cliff (photo P. Männik).

The Soeginina cliff (Photo 1) is located in western Saaremaa, in the southern part of the Vilsandi National Park. In this section the upper Vesiku, Anikaitse and Soeginina beds of the Rootsiküla Formation are exposed.

The Soeginina cliff is an about 1000 m long escarpment along the western coast of Saaremaa (coordinates of the terminal points: northeast – 58°17´20.22˝N, 21°50´30.05˝E; southwest – 58°16´55.96˝N and 21°49´54.73˝E). Its maximum height reaches almost 4 m. The escarpment is actively abraded by the sea and some collapses may occur from time to time.

Description of the section

(58°17´5.68˝N, 21°50´18.06E; from the base; modified from Viira & Einasto 2003; see also Fig. 1):

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* dolomite with spots of fine disperse pyrite. Lamination is only locally preserved. 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 & Einasto (2003) described this interval as the Anikaitse Beds (in Fig. 2 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 varigrained 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 most shallow 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.

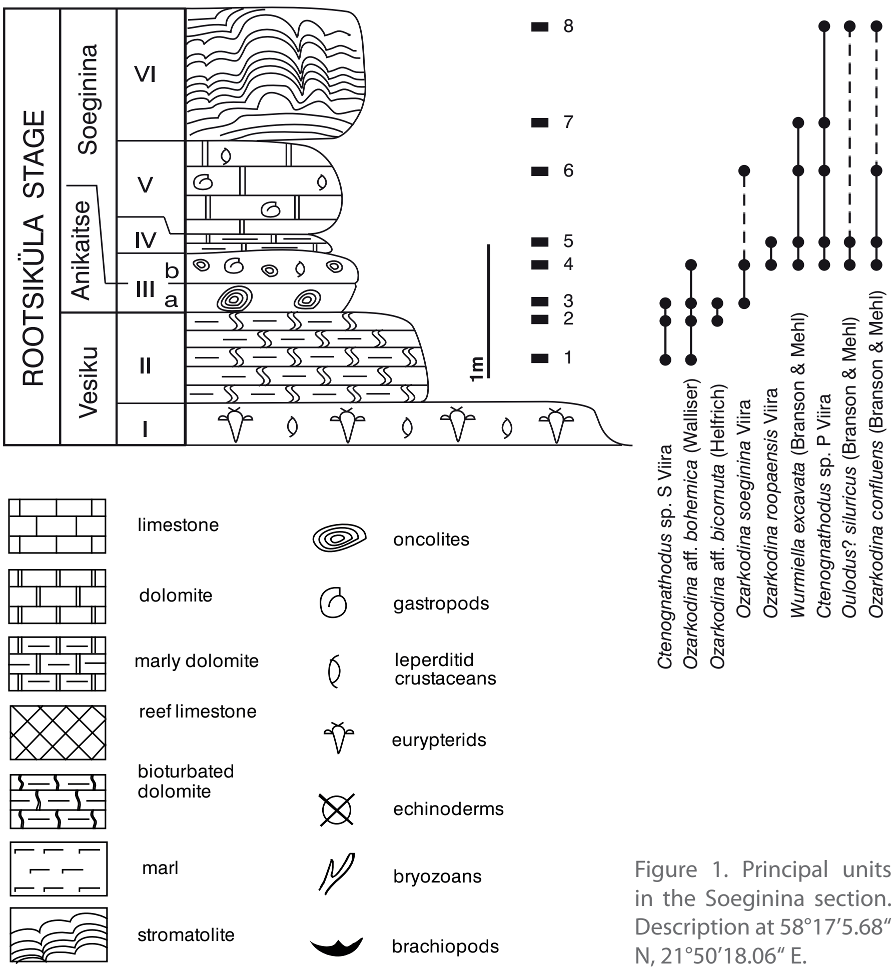
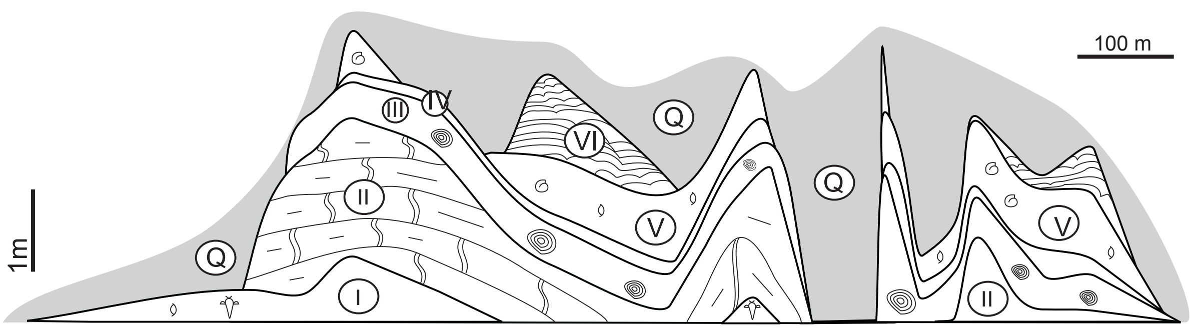


Figure 1. Principal units in the Soeginina section. Description at 58°17’5.68“ N, 21°50’18.06“ E.

Due to rare occurrences of age-diagnostic fauna in the Rootsiküla Stage its age has been debated for long time and its correlation with the global stratigraphical scheme 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 gobal topmost Wenlock zone, in the Viita Beds in the Ohesaare core section 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.

The Soeginina section is palaeontologically poorly characterised. The lower part of the succession contains fragments of *Eurypterus remipes tetragonophthalmus* Fischer 1839. Complete specimens are extremely rare. Oncoids in the middle part of succession are often formed around coralline alga *Solenopora* sp. and contain also cyanobacterial fragments (genus *Bevocastria* – Kõrts, 1991). Moulds

Figure 2. Profile of the Soeginina cliff.
The principal units distinguished in the succession are shown in the Fig. 1 and described in the text.



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) and *Paralogania martinssoni* (Gross) in this section. According to Viira & Einasto (2003) conodonts in the Vesiku and Anikaitse Beds are dominated by *Ctenognathodus* sp. S Viira, 2003 (occurs in this interval only), also *Ozarkodina* aff. *bohemic*a (Walliser) is quite common. In the lowermost Soeginina Beds, in the unit IIIb (Fig. 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 appearance of *O. confluens* and *W. excavata* in the lowermost Soeginina Beds suggests some improvement in environmental conditions.

References

Kaljo, D. (ed.), 1970. *The Silurian of Estonia*. Valgus, Tallinn, 343 pp. [in Russian].

Kõrts, A., 1991. Distribution of calcareous algae, oncolites and stromatolites in Wenlock-Ludlow boundary beds in Estonia. *Proceedings of the Estonian Academy of Sciences. Geology*, 40, 2, 43–49.

Märss, T., 1986. Silurian vertebrates of Estonia and West Latvia. *Fossilia Baltica*, 1. Valgus, Tallinn, 1–104. [in Russian].

Märss, T & Männik, P., 2013. Revision of Silurian vertebrate biozones and their correlation with the conodont succession. *Estonian Journal of Earth Sciences*, 62, 4, 181–204.

Nestor, H., 1997. Silurian. *In:* Raukas, A. & Teedumäe, A. (eds). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 99–104.

Nestor, V., 2007. Chitinozoans in the Wenlock–Ludlow boundary beds of the East Baltic. *Estonian Journal of Earth Sciences*, 56, 2, 109–128.

Viira, V. & Einasto, R., 2003. Wenlock–Ludlow boundary beds and conodonts of Saaremaa Island, Estonia. *Proceedings of the Estonian Academy of Sciences. Geology*, 52, 213–238.

Stop B9: Kaarma quarry

Leho Ainsaar

Department of Geology, University of Tartu, Estonia

The Kaarma quarry is located 12 km north of the town of Kuressaare, next to the Uduvere–Saia road (58°20´17″N, 22°28´30″E). An interval of lagoonal microlaminated argillaceous dolomites of the Paadla Formation (Paadla Regional Stage, Ludlow) is exposed in this quarry.

According to Einasto (1990, 2008), the exposed section can be divided into three parts with a total of eight distinctive beds. The upper part (Bed 1) is yellowish-grey vuggy massive secondary dolomite 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 main, middle part of the section (Beds 2–7) comprises the typical wavy microlaminated argillaceous "Kaarma dolomite" with distinct irregular lamination and microcycles. The total thickness of the Kaarma lagoonal dolomite is up to 3.8 m in the Kaarma quarry. A bed of argillaceous dolomite (Bed 5) is subdividing the lower massive blocks of this rock. The Kaarma dolomite is very poor in fossils. Moulds of gastropods, bivalves and leperditids are found at only some levels. The microlaminated structure of dolomite is disturbed by distinct bioturbation, showing limited life activity in this saline lagoonal environment. Rare thin intervals with dissolved traces of shelly fossils may be formed by occasional storm events. The dolomite contains about 14–22% insoluble residue, mainly siliciclastic clay and silt with authigenic pyrite admixture (Einasto 1962).

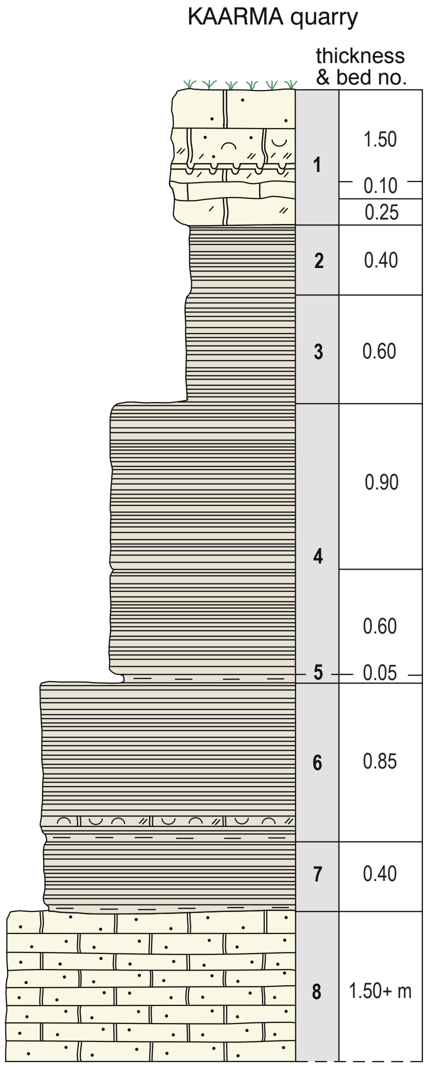


Figure 1. Kaarma quarry section (Einasto 1990).

The basal part of the section (Bed 8) is randomly visible on the quarry floor. It is represented by brownish-grey medium-bedded dolomite, which originally might have been pelletal limestone (Einasto 1990).

According to Einasto (1990), the Kaarma lagoonal dolomite represents the upper part of a mesocyclite, tentatively attributed to the junction of the Sauvere and Himmiste beds of the Paadla Stage. The dolomite can be well processed and is weather-resistant, therefore it has been widely used as a building and carving stone since the medieval times. The examples include the Kuressaare castle, many churches and manor houses in Saaremaa, as well as modern buildings and monuments over the country (Perens 2012).

References

Einasto, R., 1962. The correlation of the most important sections of the Kaarma stage. *Eesti NSV Teaduste Akadeemia Geoloogia Instituudi Uurimused*, 10, 221-241. [in Russian with English summary].

Einasto, R., 1990. Kaarma quarry. *In:* Kaljo, D. and Nestor, H. (eds). *Field Meeting, Estonia 1990. An Excursion Guidebook*. Institute of Geology, Estonian Academy of Sciences, Tallinn, p. 173.

Einasto, R., 2008. Kaarma quarry. *In:* Hints, O., Ainsaar, L., Männik, P. and Meidla, T. (eds). *The Seventh Baltic Stratigraphical Conference. Abstracts and Field Guide.* Geological Society of Estonia, Tallinn, p. 132.

Perens, H., 2012. *Looduskivi Eesti ehitistes*. Eesti Geoloogiakeskus, Tallinn, 168 pp. [in Estonian].

Stop B10: Kaugatuma & Lõo coastal outcrops

Olev Vinn

Department of Geology, University of Tartu, Estonia

Kaugatuma cliff

The Kaugatuma cliff (after Einasto 1990) is an about 2.5 m high outcrop (Photo 1) on the western coast of the Sõrve Peninsula, a few kilometres south from its northern neck and about 100 m from the coastline (58°7´22″N, 22°11´36″E). 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. 1):

Photo 1. Kaugatuma cliff (photo H. Bauert).

0.5+ m – greenish-grey nodular argillaceous wackestone, mostly 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 sorting degree. Some bedding plains show erosion marks. Large colonies of *Syringopora blanda* (about 30 cm in diameter) are found. The layer was formed in normal marine forereef conditions.

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

Palaeontologically the most interesting part of the Kaugatuma section 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. This part of the Kaugatuma outcrop is about 0.5–0.6 m high and about 60–70 m long. The section is represented by yellow-grey coarse-grained wavy-bedded crinoidal limestones which were formed in very active hydrodynamic conditions and contain 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 (*Enallocrinus* sp.; Photo 2),

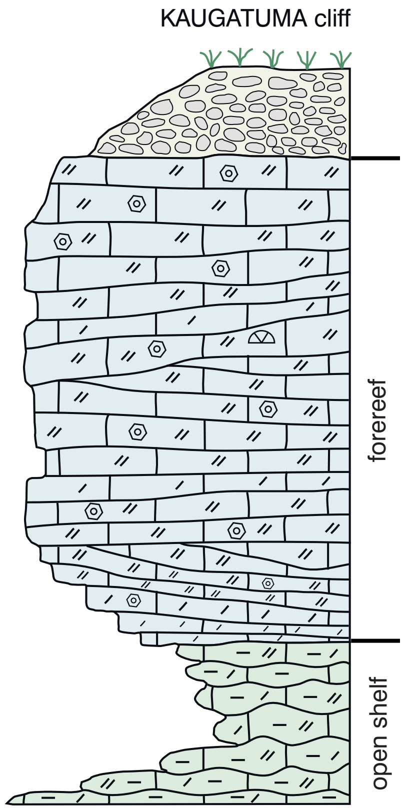


Figure 1. Kaugatuma cliff section. Modified after Einasto (1990).

Photo 2. Kaugatuma beach. Argillaceous limestone layer containing *in situ* buried fossils (photo O. Vinn).

also *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

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 from 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 Stage. 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*. In addition to these unbroken tabulate corals, which are preserved in the growth position, there occur many other corals, brachiopods, ostracods and also fish scales.

Kaugatuma cape (after Einasto 1990)

Large east–west directed well-preserved Silurian ripple marks are exposed on a 200 m long seashore between the Kaugatuma and Lõo cliffs (Photo 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), height up to 10 cm. Under the uneven discontinuity surface that forms the base of this ripple mark bed, up to 10 cm of dark grey unsorted skeletal packstone is exposed.

Photo 3. Ripple marks at the Kaugatuma cape (photo P. Männik).

References

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

Leito, T. & Märss, T., 2003. *Saaremaa pangad (Cliffs of Saaremaa Island)*. Tartu, Eesti Loodusfoto.

Stop B11: Ohesaare cliff

Tiiu Märss and Heldur Nestor
Institute of Geology at Tallinn University of Technology, Estonia

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 (58°0´2″N, 22°1´10″E). 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.

Photo 1. Ohesaare cliff (photo H. Bauert).

The lower beds of the Ohesaare Stage, the highest stage in the Silurian of Estonia, are exposed here. This outcrop serves as a stratotype of the Ohesaare Stage 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 in the entire Baltic area. The carbonate rocks exposed here contain a rich association of different fossils including fishes, molluscs, 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.

<u>Description of the section</u>:
The section is characterized by the intercalation of thin-bedded limestones and marlstones. The intervals containing relatively few or 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 packstones) in the middle part of the section but biosparitic (skeletal grainstones) 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 found also 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

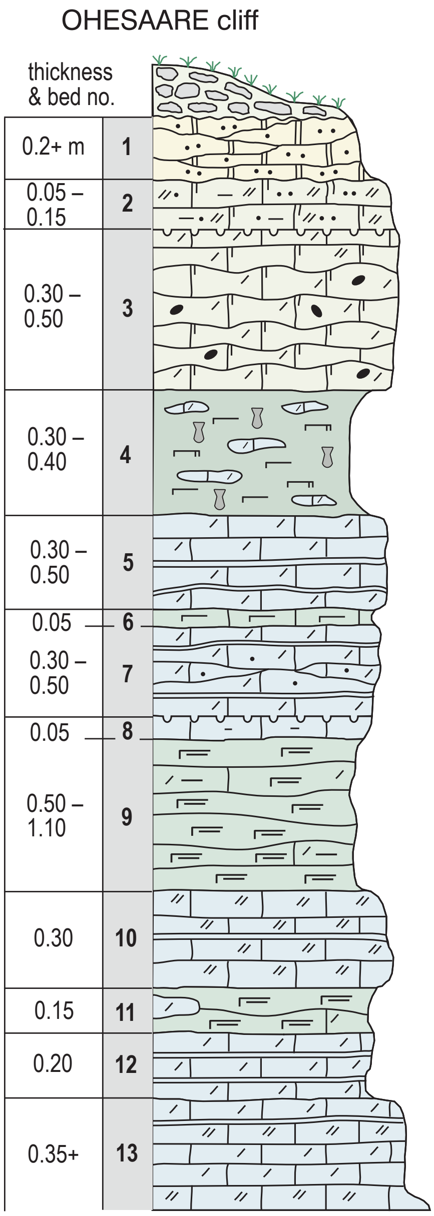


Figure 1. Ohesaare cliff section.

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, containing abundant shells of *Grammysia obliqua* buried in 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 which is 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.

The Ohesaare cliff is characterized by a rich and diverse shelly fauna. The most abundant macrofossils are brachiopods represented by *Delthyris magna*, *D. elevata*, *Homoeospira baylei*, *Morinorhynchus orbignyi*, *Isorthis ovalis*, *Dalejina hybrida*, *Shaleria (Janiomya) ornatella*, *Collarothyris collaris*. Common are also bryozoans *Fistulipora tenuilamellata*, *F. aculeata*, *Eridotrypa parvulipora*, *Trematopora porosa* and others, and bivalves *Grammysia obliqua*, *Cardiola interrupta*, *Palaeopecten danbyi*, *Modiolopsis complanata* and others. Trilobites are most often represented by *Calymene conspicua*, *C. soervensis* and *Acaste dayiana*. Corals occur at certain levels in the middle part of the section and are represented by long-ranging species. The middle part of the section (beds 5 – 10) has yielded also tentaculites *Tentaculites scalaris* (Schlotheim) and *Lowchidium inaequale* Eichwald. The association of microfossils (particularly ostracods) is very diverse and rich.

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, form bonebeds in several levels of the section.

The content of terrigenous material is high, probably due to intense influx of fine siliciclastic material into the basin at the final stage of its development.

References

Nestor, H., 1990. Locality 7:4 Ohesaare cliff. *In:* Kaljo, D. & Nestor, H. (eds). *Field meeting, Estonia 1990. An Excursion Guidebook*. Institute of Geology, Estonian Academy of Sciences, Tallinn, 175–178.

LEGEND for figures

LIMESTONES:

- limestone
- argillaceous limestone
- dolomitic limestone
- silty limestone (top) sandy limestone (bottom)
- coarse skeletal grainstone
- unsorted skeletal packstone
- fine skeletal grainstone
- fine-grained skeletal wackestone
- bioclastic floatstone
- lithoclastic skeletal rudstone
- oolitic grainstone (top) and packstone (bottom)
- pelletal grainstone (top) and packstone (bottom)
- coquinoid rudstone (top) and floatstone (bottom)
- boundstone) (reef limestone)
- aphanitic limestone

BEDDING STRUCTURES:

- horizontal bedding
- horizontal lamination
- limestone/marlstone interbedding (ratio ~1:1)
- wavy bedding
- cross-bedding
- nodular lms. with thin clayey partings
- nodular lms. with clayey intercalations
- seminodular limestone
- marlstone with limestone nodules
- hardground
- ripple marks
- mudcracks

SANDSTONES:

- sandstone
- calcitic sandstone
- dolomitic sandstone

DOLOMITES:

- dolomite
- argillaceous dolomite
- calcitic dolomite
- silty dolomite (top) sandy dolomite(bottom)
- vuggy (porous) dolomite
- bioturbated argillaceous dolomite
- *Eurypterus*-dolomite
- cryptolaminated argillaceous dolomite
- reef-dolomite
- breccia-dolomite

MARLSTONES:

- marlstone
- calcareous marlstone
- argillaceous marlstone
- dolomitic marlstone
- dolomitic, argillaceous marlstone

DOMERITES:

- domerite
- calcareous domerite
- argillaceous domerite
- calcitic domerite
- calcitic, argillaceous domerite

ARGILLACEOUS ROCKS:

- clay
- mudstone
- argillite (top) shale (bottom)
- calcitic mudstone
- dolomitic mudstone

SILTSTONES:

- siltstone
- calcitic siltstone
- dolomitic siltstone

MINERALOGICAL & LITHOLOGICAL characteristics:

- pyrite crystals
- pyrite mottles
- pyrite skeletal debris
- pyrite burrows
- pyrite pebbles
- phosphatic pebbles
- calcitic ooids
- phosphatic ooids
- goethitic ooids
- glauconite
- silicification
- bitumen
- kerogen
- K-bentonite layer (thin)
- K-bentonite layer (thick)
- red-coloured rocks

FOSSILS:

- oncolites
- sponges
- stromatoporoids
- tabulate corals
- bryozoans
- brachiopods
- gastropods
- bivalves (pelecypods)
- trilobites
- ostracods
- eurypterids
- pelmatozoans
- horizontal burrows
- vertical burrows

4th Annual Meeting of IGCP 591

The Early to Middle Paleozoic Revolution

Estonia, 10-19 June 2014