Darriwilian (Middle Ordovician) conodont biostratigraphy in NW Estonia

Olle Hints, Viive Viira and Jaak Nõlvak

Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia; Olle.Hints@gi.ee, Viive.Viira@gi.ee, Jaak.Nolvak@gi.ee

Abstract. Darriwilian conodonts have been studied in numerous sections of Baltoscandia, but few data are available from the classical outcrop area in northern Estonia. In this paper we report the succession of Darriwilian conodonts and chitinozoans from the bed-by-bed sampled Uuga and Osmussaar cliffs, NW Estonia. Standard Baltoscandian conodont and chitinozoan zones and subzones were identified from the topmost Volkhov to Uhaku regional stages. The global Dapingian–Darriwilian boundary coincides with the Volkhov–Kunda boundary in NW Estonia. The Kunda Stage is represented by its middle or upper part only, and the Aseri Stage is probably missing in both sections studied. The lowermost part of the Lasnamägi Stage with the conodont *Yangtzeplacognathus foliaceus* is also very condensed. The rest of the Lasnamägi and Uhaku stages, corresponding to the main part of the *Pygodus serra* conodont Zone, is well represented and can be correlated across Estonia and Sweden. Subtle regional variations in this interval indicate very uniform depositional conditions over wide areas of the Baltoscandian palaeobasin. Our results suggest that the *Y. foliaceus* Subzone in Estonia needs further assessment. Stratigraphically well-constrained *Y. protoramosus* appears to be more common than previously thought, and is thus a valuable regional subzonal index. The integrated conodont and chitinozoan scale provides more than 20 biostratigraphically important levels for local and regional correlations, probably approaching temporal resolution in the order of 0.1 Ma for the late Darriwilian.

Key words: conodonts, chitinozoans, high-resolution biostratigraphy, Darriwilian, NW Estonia, Baltoscandia.

INTRODUCTION

Well-preserved and fossiliferous carbonate rocks of Darriwilian age, Middle Ordovician, are widespread in Baltoscandia and widely utilized locally as building material. Divided into the uppermost Volkhov, Kunda, Aseri, Lasnamägi and Uhaku regional stages, they bear evidence of rapid diversification of many groups of organisms (Hints et al. 2010 and references therein). Nowadays mostly microfossils are used to date and correlate these strata, whereas conodonts and chitinozoans are especially useful. The standard North Atlantic conodont biozonation (Bergström 1971), widely used in Baltoscandia and elsewhere, is based on several successive zones and subzones, some of which have clearly evolutionary significance (Bergström 1983; Zhang 1998). Darriwilian conodont zones and subzones have been identified in numerous sections in Scandinavia and Estonia. In recent years new information has been obtained particularly from drill cores (Bergström et al. 2011; Männik & Viira 2012, and references therein). However, very few data are still available from the classical outcrop area of northern Estonia, which serves as the standard for many Baltic regional stages. Therefore the original concept of regional stages has become difficult to follow. Furthermore, in drill cores the sampling density and sample size often limit the temporal resolution and complicate detailed comparison of biozonations based on different fossil groups.

Recently Tammekänd et al. (2010) analysed the succession of Darriwilian chitinozoans from bed-by-bed samples at the Uuga Cliff, Pakri Peninsula, NW Estonia. This enabled biostratigraphic dating of Darriwilian strata and highlighted problems of regional stratigraphy. A large collection of conodonts was also obtained from the same set of samples, which forms the basis of our present study. Previously Lower Ordovician conodonts from the same section have been reported by Löfgren et al. (2005). In addition, Mellgren et al. (2012) published Darriwilian conodonts from Osmussaar Island, NW Estonia, ca 40 km west of the Uuga Cliff. This motivated us to re-study a series of old samples from the Osmussaar Cliff and to extend the succession of Mellgren et al. (2012) into the Lasnamägi and Uhaku regional stages.

This contribution aims to (1) biostratigraphically characterize two Darriwilian reference sections in NW Estonia, (2) analyse mutual distribution of conodonts and chitinozoans, (3) test and refine regional correlation criteria, (4) assess temporal resolution of palaeontological time scales and (5) compare the conodont succession in NW Estonia with previously studied sections elsewhere in Estonia and Sweden.

GEOLOGICAL SETTING AND STRATIGRAPHY

The Darriwilian succession of northern Estonia is represented by cool-water carbonate deposits that formed in shallow shelf settings, the North Estonian Confacies, of the Baltoscandian palaeobasin (Fig. 1; see Männil 1966; Jaanusson 1976; Nestor & Einasto 1997). According to recent correlation schemes, the Darriwilian corresponds to the topmost Volkhov, Kunda, Aseri, Lasnamägi and Uhaku stages (Nõlvak et al. 2006; Bergström et al. 2009; Cooper & Sadler 2012). As a full characterization of regional stages and formations is provided elsewhere (Orviku 1940, 1960; Männil 1966; Rõõmusoks 1970; Hints 1997; Meidla 1997), the sequence is only briefly described below.

The thickness of Darriwilian strata in NW Estonia is about 10 m, of which 7 m is exposed and sampled at the Uuga and Osmussaar cliffs. The Volkhov Stage is represented by glauconitic limestones of the Toila Formation, only the topmost part of which was studied here.

The 0.5–1.1 m thick Kunda Stage is represented by sandy limestones to calcareous sandstones of the Pakri Formation, which is distributed in NW Estonia only and includes the so-called Osmussaar Breccia (see Suuroja et al. 2003). The breccia is characterized by specific sedimentary structures, occurrence of chromite grains (Alwmark et al. 2010) and at least partly mixed fossil associations (Tinn et al. 2010). All these features point to an impact-related event in Kunda time (see also discussion by Alwmark et al. 2010 and Mellgren et al. 2012).

A thin limestone layer rich in quartz sand and phosphatic ooids (0.1–0.2 m in the studied sections), representing the Kandle Formation, lies on top of the Pakri Formation. On Osmussaar this unit has been assigned either to the Aseri Stage (Orviku 1940; Rõõmusoks 1970; Hints 1997) or Lasnamägi Stage (Männil & Rõõmusoks 1984; Mellgren et al. 2012).

The Väo Formation (5.1 m in the Uuga Cliff section) is composed of relatively pure limestones (wacke- to packstones), subdivided into the Rebala, Pae and Kostivere members. The dolomitic Pae Member is well defined at the Uuga Cliff (Tammekänd et al. 2010, fig. 2), but on Osmussaar similar dolomitization has not occurred and recognition of the three members remains tentative. The Lasnamägi–Uhaku stage boundary falls
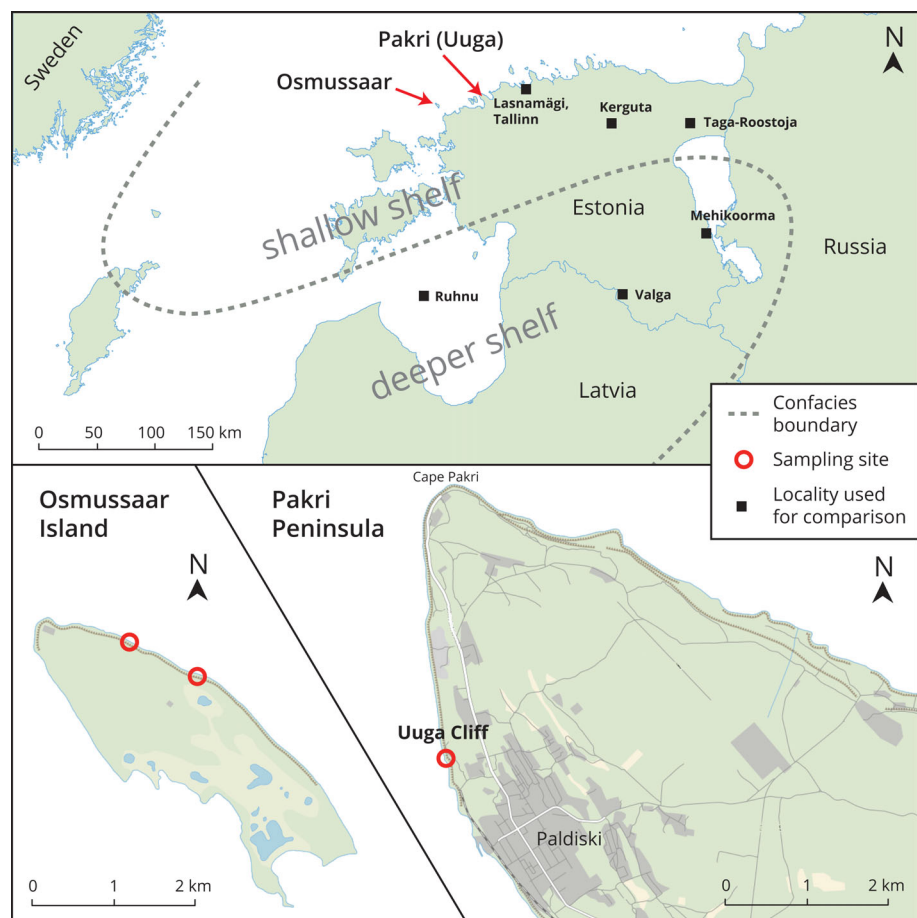

Fig. 1. Locality map, showing sampling sites on Osmussaar Island, the Pakri Peninsula and other sections, where Darriwilian conodonts have recently been studied and are compared here.

within the Väo Formation and is defined by the appearance of the graptolite *Gymnograptus linnarssoni* and the conodont *Baltoplacognathus robustus* (Männil 1976; Männil & Meidla 1994). Numerous impregnated and commonly bioturbated discontinuity surfaces are found throughout the Väo Formation. Several individual beds and surfaces (described in detail from the Pakri Peninsula by Einasto & Rähni 2005) can be traced over wide areas in northern Estonia, denoting a very flat sea floor and uniform depositional conditions (Jaanusson 1976).

The Kõrgekallas Formation is represented by slightly more argillaceous limestones above the so-called six-fold discontinuity surface (Orviku 1940; Rõõmusoks 1970; Einasto & Rähni 2005). The lower part of the Kõrgekallas Formation is exposed and has been sampled in the Uuga Cliff, whereas the Osmussaar Cliff exhibits only the uppermost part of the Väo Formation.

MATERIAL AND METHODS

This study is based on 143 samples collected mostly bed-by-bed from the NW Estonian coastal cliffs on the Pakri Peninsula and Osmussaar Island. The Uuga Cliff section (Pakri Peninsula) was sampled in 2006 by Olle Hints and Jaak Nõlvak (Fig. 2; samples OM6-1 to OM6-62 from the Kandle to Kõrgekallas formations; chitinozoan data were published by Tammekänd et al. 2010). Subsequently conodonts were studied from the same residues and additional samples were collected from the Toila and Pakri formations (OM11-1 to OM11-4; Fig. 2). The Osmussaar section is a composite of two sampling sites (Fig. 1) from where nearly 77 samples were collected already in 1971 by Ralf Männil and Lembit Põlma (Fig. 3; samples M-5850 to M-5916). Stratigraphically the studied part of the Osmussaar Cliff is limited to the Kandle and Väo formations.

Conodonts, chitinozoans and other acid-resistant microfossils (scolecodonts and graptolites) were extracted from ca 0.3 to 2 kg limestone samples using ca 10% acetic acid. The residues were cleaned from clay either by decanting or 0.05 mm sieve. Microfossils were hand-picked from the residues and stored in standard micro-fossil cavity slides (conodonts) or in glycerine preparations (chitinozoans, scolecodonts). The Osmussaar samples, processed in the 1970s, were picked for conodonts only selectively, with emphasis on biostratigraphically important species. Conodonts were identified by Viive Viira and Olle Hints, and chitinozoans by Jaak Nõlvak. For a few graptolite finds unpublished identifications by Ralf Männil were used. Selected conodonts from the more complete Uuga Cliff were imaged with a Zeiss EVO MA15 scanning electron microscope.

The research was conducted at the Institute of Geology at Tallinn University of Technology (abbreviated as GIT), where the samples, residues and all recovered specimens are deposited. For the figured specimens the collection number 654 is allocated. More information on individual samples and specimens can be obtained from the on-line catalogue at http://sarv.gi.ee.

RESULTS AND DISCUSSION
Conodont biostratigraphy

Conodonts are generally very well preserved and abundant in the Darriwilian strata of the Uuga and Osmussaar cliffs (with the exception of the Pakri and Kandle formations). The conodont colour alteration index (CAI) is estimated to be 1, indicating burial temperatures well below 100 °C (Epstein et al. 1977). The taxonomic composition of the Darriwilian conodont fauna is similar to that of previously studied sections of Estonia. The assemblages are commonly dominated by species of *Baltoniodus*, *Semiacontiodus* and *Panderodus*. A particular feature of the studied sections seems to be the low abundance of *Protopanderodus* and absence of *Costiconus* (= *Walliserodus*). Biostratigraphically important species were found throughout the succession, enabling the standard North Atlantic conodont zones and subzones (Bergström 1971; Nõlvak et al. 2006) from the *Paroistodus originalis* to *Pygodus serra* zones (tentatively to the *P. anserinus* Zone) to be followed. The most useful correlative levels are provided by the successive subzones of the *P. serra* Zone, which include one to three evolutionary lineages of polyplacognathids (Bergström 1971, 1983; Dzik 1978; Zhang 1998). The genus level classification of that group of platform conodonts is still under discussion and different generic names have been used by different authors. Herein we follow Zhang (1998), who divided *Eoplacognathus sensu lato* into *Eoplacognathus*, *Baltoplacognathus* and *Yangtzeplacognathus*. The distribution of individual taxa in the Uuga and Osmussaar sections is shown in Figs 2 and 3 and selected conodont taxa are illustrated in Figs 4–6. The succession of conodonts with emphasis on stratigraphically useful taxa is characterized below.

The Toila Formation is represented by a single sample from the Uuga Cliff (OM11-1). The most abundant species in this sample are *Baltoniodus navis* (Lindström) and *Microzarkodina flabellum* Lindström. The occurrence of *Paroistodus originalis* together with *Triangulodus brevibasis* (Sergeeva) indicates the **Paroistodus originalis Zone** (Löfgren 1995), which corresponds to the middle part of the Volkhov Stage (Nõlvak et al. 2006; Männik & Viira 2012) and the upper part of the Dapingian (Cooper & Sadler 2012). The absence of *Baltoniodus*
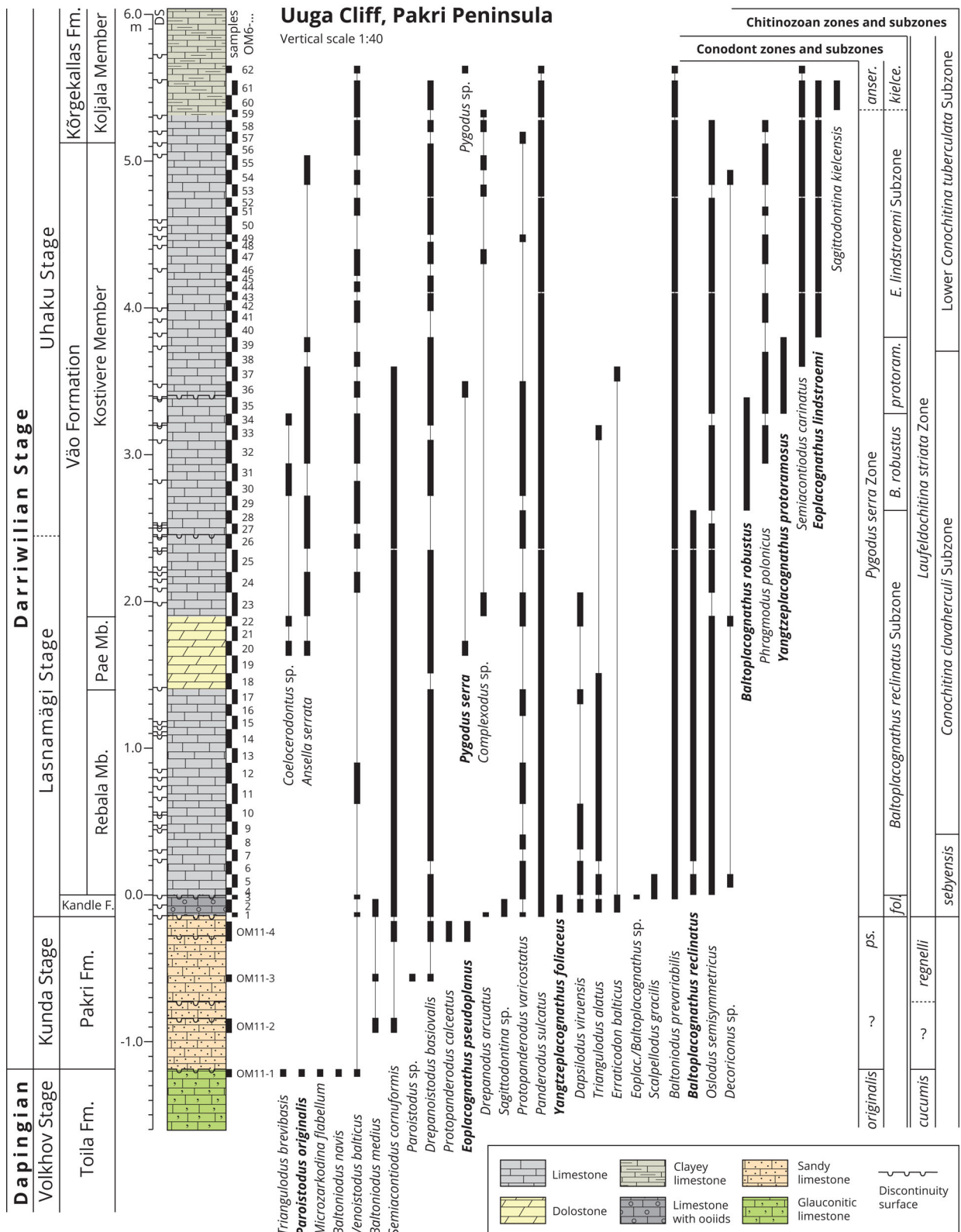
Fig. 2. Distribution of conodonts in the Uuga Cliff section. For a full range chart of chitinozoans, general rock composition and stable carbon isotope record from the same samples see Tammekänd et al. (2010). DS, discontinuity surface; *ps.*, *E. pseudoplanus* Zone; *fol.*, *Y. foliaceus* Subzone; *protoram.*, *Y. protoramosus* Subzone; *anser.*, *P. anserinus* Zone; *kielce.*, *S. kielcensis* Subzone.
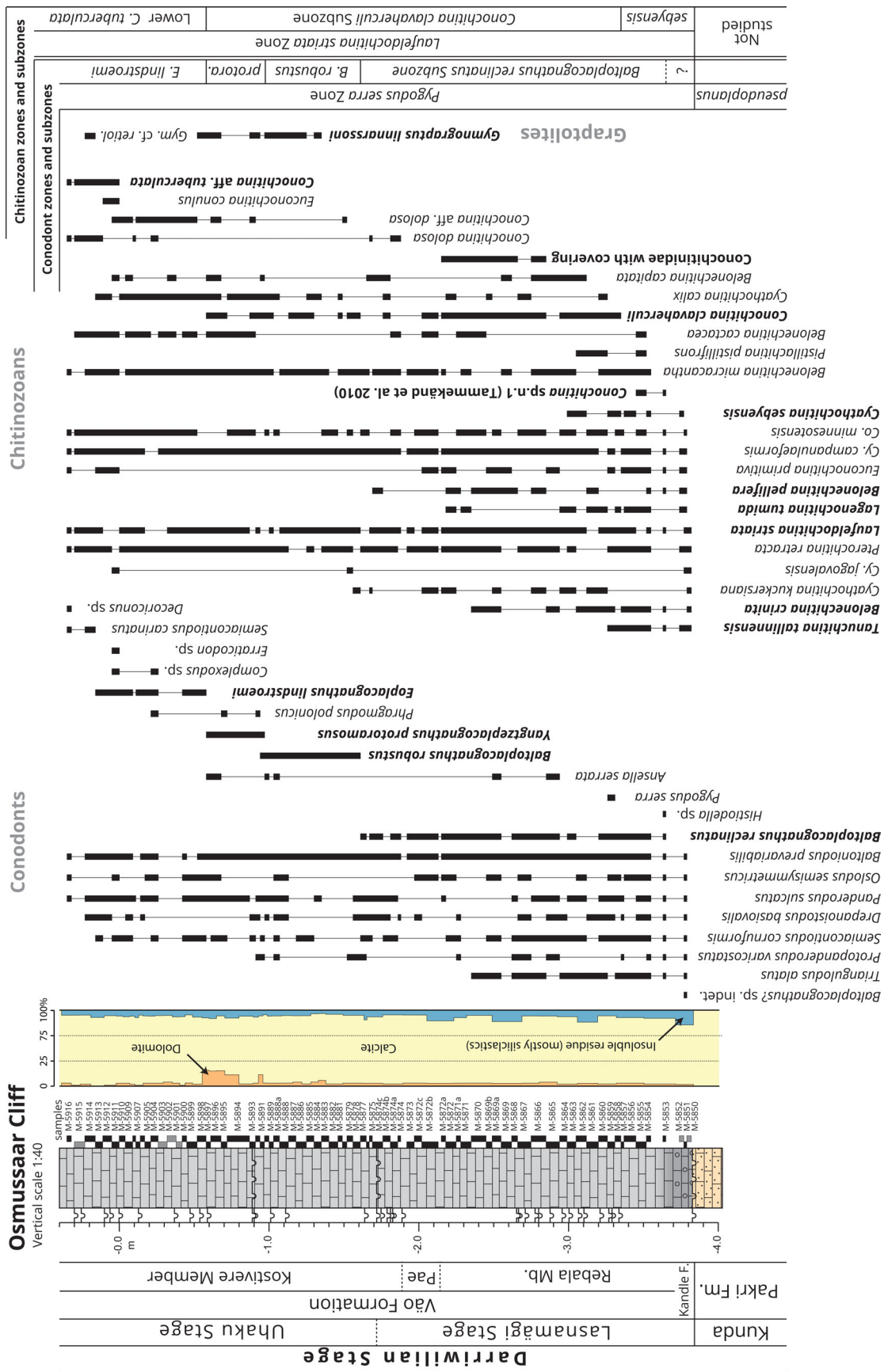
Fig. 3. Distribution of selected conodonts, chitinozoans and graptolites in the Osmussaar Cliff section. All species of *Desmochitina* and *Rhabdochitina* are omitted. For lithological legend see Fig. 2. The rock composition is shown after unpublished carbonate and insoluble residue analyses by Lembit Põlma from the 1970s. Due to the lack of a stratigraphically constrained dolomitic layer, distinction of the Pae Member is tentative. *Protora.*, *Y. protoramosus* Subzone; *Gym.* cf. *retiol.*, *Gymnograptus* cf. *retioloides*; *Cy.*, *Cyathochitina*.
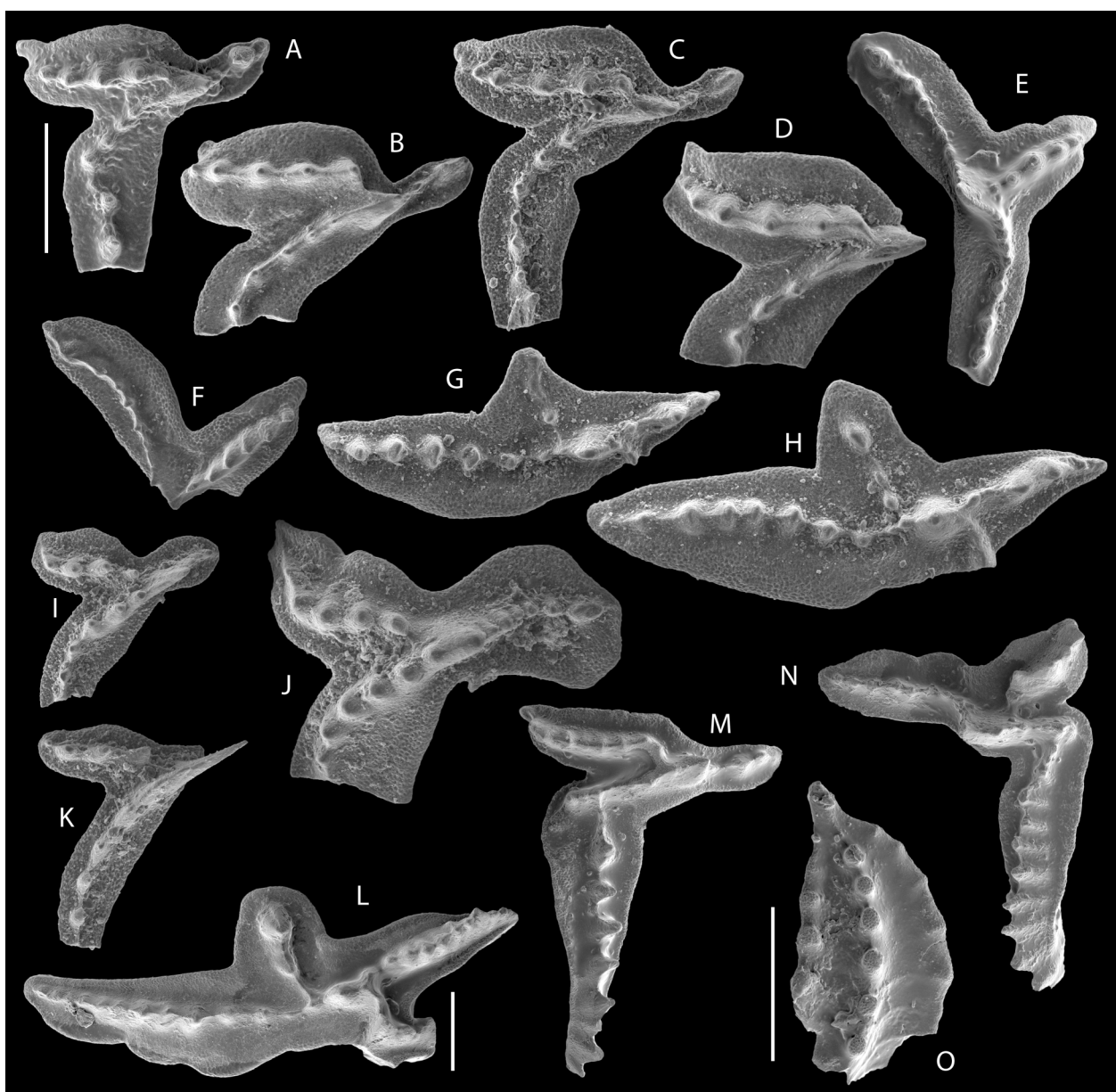
Fig. 4. Selected Darriwilian conodonts from the Uuga Cliff section. A scale bar corresponds to 0.2 mm and applies to all consecutive illustrations until the next scale bar appears. **A–H**, *Yangtzeplacognathus foliaceus* (Fåhraeus); A, C–E, G, H, from sample OM6-3, basal Lasnamägi Stage; B, F, from sample OM6-2, basal Lasnamägi Stage; A, sinistral Pb element GIT 654-1; B, sinistral Pb element GIT 654-2; C, sinistral Pb element GIT 654-3; D, sinistral Pb element GIT 654-4; E, dextral Pb element GIT 654-5; F, dextral Pb element GIT 654-6; G, dextral Pa element GIT 654-7; H, dextral Pa element GIT 654-8. **I–K**, *Eoplacognathus*? sp., all from sample OM6-3, basal Lasnamägi Stage; I, sinistral Pb element GIT 654-9; J, sinistral Pb element GIT 654-10; K, sinistral Pb element GIT 654-11. **L–N**, *Yangtzeplacognathus protoramosus* (Chen et al.), from sample OM6-36, Uhaku Stage; L, dextral Pa element GIT 654-12; M, sinistral Pb element GIT 654-13; N, dextral Pb element GIT 654-14. **O**, *Pygodus serra* (Hadding), Pa element GIT 654-15, from sample OM6-20, Lasnamägi Stage.

norrlandicus and *Lenodus antivariabilis* also suggests that the respective zones, and the upper part of the Volkhov Stage, are missing in NW Estonia. The Dapingian–Darriwilian boundary thus coincides with the Volkhov–Kunda boundary in the study area.

The Pakri Formation, studied in the Uuga Cliff, yielded mainly broken and worn conodonts of the genera *Scolopodus*, *Paltodus*, *Acodus* and *Cordylodus* (note that they are excluded from Fig. 2). These genera are typical of the Hunneberg and Billingen stages of

Fig. 5. Selected Darriwilian conodonts from the Uuga Cliff section. A scale bar corresponds to 0.2 mm and applies to all consecutive illustrations until the next scale bar appears. **A–C**, *Baltoplacognathus reclinatus* (Fåhraeus), from sample OM6-14, Lasnamägi Stage; A, sinistral Pb element GIT 654-16; B, dextral Pb element GIT 654-17; C, dextral Pa element GIT 654-18. **D–F**, *Baltoplacognathus robustus* (Bergström), Uhaku Stage; D, dextral Pa element GIT 654-19, from sample OM6-29; E, sinistral Pb element GIT 654-20, from sample OM6-31; F, dextral Pb element GIT 654-21, from sample OM6-31. **G–I**, *Eoplacognathus lindstroemi* (Hamar), Uhaku Stage; G, sinistral Pb element GIT 654-22, from sample OM6-43; H, dextral Pb element GIT 654-23, from sample OM6-47; I, dextral Pa element GIT 654-24, from sample OM6-48. **J**, **K**, *Baltoniodus prevariabilis* (Fåhraeus), from sample OM6-53, Uhaku Stage; J, sinistral Pb element GIT 654-25; K, dextral Pa element GIT 654-26. **L**, *Eoplacognathus pseudoplanus* (Viira), Pb element GIT 654-27, from sample OM11-4, Kunda Stage. **M**, *Complexodus* sp. Pb element GIT 654-28, from sample OM6-53, Uhaku Stage.

Baltoscandia and thus indicate reworking from older sediments. Additionally rare and similarly poorly preserved specimens of *Semiacontiodus cornuformis* (Sergeeva), *Drepanoistodus basiovalis* (Sergeeva) and *Protopanderodus* cf. *calceatus* Bagnoli & Stouge, typical of the Kunda Stage, were identified. Only the topmost

sample from the Pakri Formation (OM11-4) contains a specimen of *Eoplacognathus* cf. *pseudoplanus* (Viira), suggesting the presence of the **E. pseudoplanus Zone**. Mellgren et al. (2012) also reported *E. pseudoplanus* from the uppermost Kunda beds (interpreted as the Loobu Formation by them) on Osmussaar. The lower
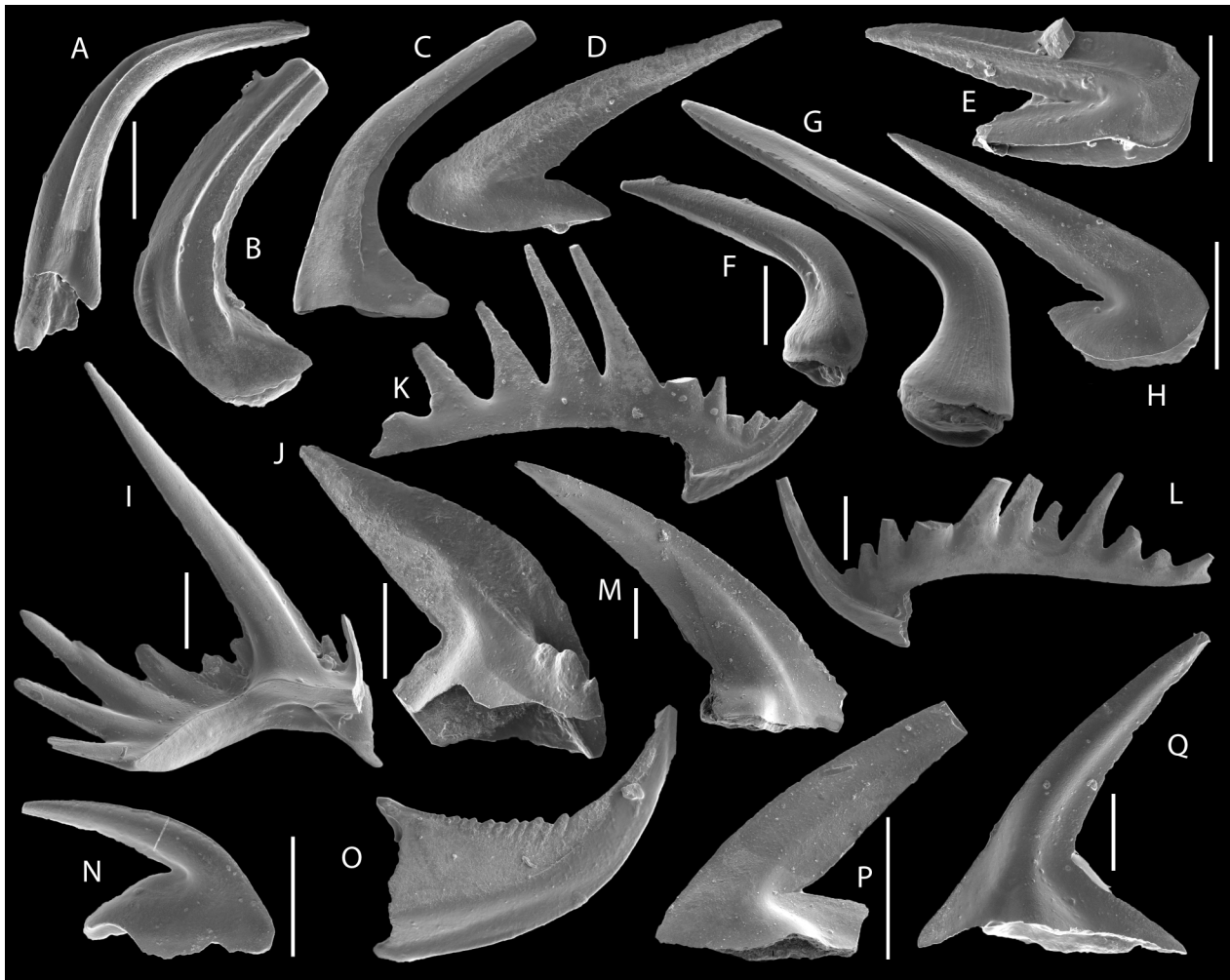
Fig. 6. Selected Darriwilian conodonts from the Uuga Cliff section. A scale bar corresponds to 0.2 mm and applies to all consecutive illustrations until the next scale bar appears. **A**, *Panderodus sulcatus* (Fåhraeus), S element GIT 654-29, from sample OM6-24, Lasnamägi Stage. **B**, *Protopanderodus varicostatus* (Sweet & Bergström). S element GIT 654-30, from sample OM6-28, Lasnamägi Stage. **C**, **D**, *Oslodus semisymmetricus* (Hamar), from sample OM6-12, Lasnamägi Stage; C, S element GIT 654-31; D, M element GIT 654-32. **E**, *Venoistodus balticus* Löfgren, M element GIT 654-33, from sample OM6-29, Uhaku Stage. **F**, **G**, *Semiacontiodus cornuformis* (Sergeeva), from sample OM6-16, Lasnamägi Stage; F, Sa element GIT 654-34; G, S element GIT 654-35. **H**, *Drepanoistodus basiovalis* (Sergeeva), M element GIT 654-36, from sample OM6-14, Lasnamägi Stage. **I**, *Erraticodon balticus* (Dzik), P element GIT 654-37, from sample OM6-3, Lasnamägi Stage. **J–L**, **P**, *Phragmodus polonicus* Dzik, from sample OM6-42, Uhaku Stage; J, Pb element GIT 654-38; K, S element GIT 654-39; L, S element GIT 654-40; P, M element GIT 654-41. **M**, **Q**, *Triangulodus alatus* Dzik, from sample OM6-16, Lasnamägi Stage; M, M element GIT 654-42; Q, P? element GIT 654-43. **N**, **O**, *Ansella serrata* (Dzik), from sample OM6-33, Uhaku Stage; N, M element GIT 654-44; O, S element GIT 654-45.

boundary of the zone cannot be identified in either section, but most likely the entire Pakri Formation corresponds to the *E. pseudoplanus* Zone in the study area.

The lowermost sample from the Kandle Formation in the Uuga Cliff section (OM6-1) contains no zonal species, but *Panderodus sulcatus* (Fåhraeus) and *Sagittodontina* sp. indicate the *Eoplacognathus suecicus* Zone or younger strata. The next samples (OM6-2 and OM6-3) yield characteristic elements of *Yangtzeplacognathus foliaceus*

(Fåhraeus), the index species of the **Y. foliaceus Subzone** of the **Pygodus serra Zone**. *Pygodus serra* is very rare in both sections and was identified in only three samples from the Väo Formation (Figs 2, 3). Interestingly, sample OM6-3 also contained a few conodont elements that resemble *E. suecicus* and *Baltoplacognathus reclinatus* (Fig. 4I–K). It is possible that other polyplacognathid species co-occur with *Y. foliaceus* or the specimens in question indicate reworking from under- or overlying

beds, but no firm conclusions can be drawn due to the limited number of specimens currently available. Lithologically similar strata of the Osmussaar Cliff contained no diagnostic taxa in our sample (M-5851). Mellgren et al. (2012) identified *Y. foliaceus* (= *Eoplacognathus foliaceus*) from approximately the same level at Osmussaar (sample Est09-OS3), however, their illustrated specimens (Mellgren et al. 2012, fig. 6C, G, Q) are rather different from typical *Y. foliaceus*, which are found at Uuga (Fig. 4A–H). Regardless of that, the *Y. foliaceus* Subzone, if present, is very thin in NW Estonia. The oolithic limestone of the Kandle Formation appears to be of Lasnamägi rather than Aseri age in the studied sections, confirming the interpretation of Männil & Rõõmusoks (1984) and Mellgren et al. (2012), but disagreeing with, e.g., Orviku (1940), Rõõmusoks (1970) and Hints (1997).

The first specimens of *Baltoplacognathus reclinatus* (Fåhraeus) appear in the Väo Formation, marking the base of the succeeding **B. reclinatus Subzone**. Characteristic specimens of this species are found in samples OM6-4 to OM6-24 at the Uuga Cliff and M-5854 to M-5860 at the Osmussaar Cliff. Samples from OM6-25 to OM6-28 from the Uuga Cliff contain few and/or fragmentary specimens, some of which appear to be intermediate between *B. reclinatus* and the morphologically closely connected successor species *B. robustus*. A similar unclear interval is observed in the Osmussaar succession from samples M-5865 to M-5874a. In this study the base of the **Baltoplacognathus robustus Subzone** is drawn at the level where the first typical mature Pb elements of the index species appear (sample OM6-29 at Uuga and M-5877 on Osmussaar). This level is slightly above the marked discontinuity surface within the so-called 'Raudsüda' bed (the lithological boundary criterion for the Uhaku Stage). The entire *B. robustus* Subzone is 0.65–0.8 m thick in the studied sections.

The base of the **Yangtzeplacognathus protoramosus Subzone** is drawn at the first appearance of the nominal species. It is significant that the oldest specimens of *Y. protoramosus* co-occur with the youngest recorded specimens of *B. robustus* in just one sample in both sections (OM6-35 and M-5891). Possibly these samples span across a sharp zonal boundary and/or the boundary interval is time-averaged. A more plausible explanation is that the two species represent separate evolutionary lineages as suggested by Zhang (1998) and hence their mutual occurrence would be expected. In any case the lower and upper boundaries of the *Y. protoramosus* Subzone are sharp in both sections and no interval of morphological transition could be observed. The *Y. protoramosus* Subzone is 0.4–0.5 m thick in the studied sections and embraces a distinct lithological marker (the so-called double discontinuity surface) in its lower part (Figs 2, 3).

The **Eoplacognathus lindstroemi Subzone** occurs in both sections just above the *Y. protoramosus* Subzone and no range overlap of the nominal species was recorded. At the Uuga Cliff, *E. lindstroemi* was identified in successive samples from OM6-40 to OM6-61, being most abundant in samples OM6-46 and OM6-47. The upper boundary of the subzone is defined by the appearance of *Pygodus anserinus*, which has not been found in the studied sections. However, the uppermost part of the Uuga Cliff section yielded rare specimens of *Sagittodontina kielcensis* (Dzik), which are used here to tentatively draw the base of the **Pygodus anserinus Zone** and its lower **S. kielcensis Subzone**. The succession studied on Osmussaar ends within the middle part of the *E. lindstroemi* Subzone in the uppermost part of the Väo Formation.

In addition to the above-mentioned index species, few other taxa are stratigraphically useful and worth mentioning. For example, *Triangulodus alatus* Dzik is characteristic of the lower part of the Väo Formation in both sections (Figs 2, 3). *Ansella serrata* Fåhraeus & Hunter is typical of the middle part of the Väo Formation. Due to relative rarity of this species, however, its range ends are at slightly different levels in the Uuga and Osmussaar sections. Another relatively rare species, *Phragmodus polonicus* Dzik, originally described from the Moijcza section of Poland (Dzik 1978), appears in the middle of the *B. robustus* Subzone (Uuga Cliff) or just above it (Osmussaar Cliff). In other Estonian sections *P. polonicus* has previously been identified only in the Kukruse Stage, in the basal part of the *Amorphognathus tvaerensis* Zone (Viira et al. 2006a). Conodont biostratigraphy in the Uuga and Osmussaar sections is summarized in Fig. 7.

Ma	GS	Reg. Stage	Formation	Conodont zone / subz.		
– 460	Darriwilian	**Uhaku**	Kõrgekallas Fm.	*P. a.*	*S. kielcensis*	
			Väo Fm.	*P. serra*	*E. lindstroemi* *Y. protoramosus* *B. robustus* *B. reclinatus* *Y. foliaceus*	
– 462		**Lasnamägi**				
		Aseri				
– 464		**Kunda**	Pakri Fm.	*E. pseudoplanus*		
– 466						
467.3	Daping.	**Volkhov**				
– 468			Toila Fm.	*P. originalis*		

Fig. 7. Summary of conodont biostratigraphy in NW Estonian sections. Note that the precise temporal content of indicated gaps remains hypothetical. Regular time scale and correlation with regional stages are based on the latest international geological time scale (Cooper & Sadler 2012). GS, Global stage; *P. a.*, *Pygodus anserinus*.

218

Notes on chitinozoans and graptolites

The succession of chitinozoans at the Uuga Cliff was published by Tammekänd et al. (2010). Additional samples (OM11-1 to OM11-4) revealed the presence of the *Conochitina cucumis* and *Cyathochitina regnelli* zones, which correspond to the Volkhov and Kunda stages, respectively (Fig. 2; for a full range chart see Tammekänd et al. 2010, fig. 5). Chitinozoan data from the Osmussaar Cliff are unpublished and comments are included here. The preservation of material is good to excellent, similar to that at the Uuga Cliff (see Tammekänd et al. 2010). Altogether 36 species have been identified. The distribution of selected species with reference to the Baltoscandian chitinozoan zonation (Nõlvak & Grahn 1993; Nõlvak et al. 2006) is shown in Fig. 3.

The entire succession studied corresponds to the **Laufeldochitina striata Zone**, with the nominal species occurring throughout the section. The formal subzone boundaries are defined by the appearance of *Conochitina clavaherculi* Eisenack, which marks the top of the **Cyathochitina sebyensis Subzone** and the base of the **C. clavaherculi Subzone** in the lower part of the Väo Formation. The disappearance of *C. clavaherculi* in the upper part of the Väo Formation defines the base of the succeeding **Lower Conochitina tuberculata Subzone**.

Tammekänd et al. (2010) additionally distinguished several informal, but biostratigraphically useful levels at the Uuga Cliff. Most of these were also identified in the Osmussaar succession, with the exception of *Baltochitina delicata* Nõlvak (= *Baltochitina* sp. n. 1 in Tammekänd et al. 2010) and *Desmochitina grandicolla* Eisenack. The disappearance of *Tanuchitina tallinnensis* Grahn, *Belonechitina crinita* Grahn, *Cyathochitina sebyensis* Grahn and *Belonechitina pellifera* (Eisenack) in the lower part of the Väo Formation is followed on Osmussaar in the same sequence as at Uuga. *Lagenochitina tumida* Umnova ranges slightly higher in the Osmussaar section, whereas the stratigraphically restricted forms of *Conochitina* with specific soft brownish covering range slightly lower than at Uuga. In the middle and upper parts of the Väo Formation, the first abundant occurrence of *Belonechitina cactacea* (Eisenack) and *Conochitina* aff. *dolosa* Eisenack, and the appearance of *Conochitina* aff. *tuberculata* Eisenack are recorded in the same order in both sections. The occurrence of *C.* aff. *tuberculata* in the topmost 0.3 m of the Osmussaar Cliff section suggests that there most of the Väo Formation is present.

Two species of graptolites recovered from the Osmussaar Cliff are of special interest. *Gymnograptus linnarssoni* (Moberg) was identified in a number of samples within the *B. robustus* and *Y. protoramosus* zones and the basal part of the *E. lindstroemi* Zone

(Fig. 3). This species is used to define and correlate the base of the Uhaku Stage (Männil 1976; Männil & Meidla 1994), but in many sections, for example at the Uuga Cliff, it has not been recovered or occurs sporadically. The occurrence in the Osmussaar Cliff section, even if not representing the full range of the species in Baltoscandia, enables integration with conodont and chitinozoan zonations. The conodont succession suggests that the single find of *G. linnarssoni* at the Uuga Cliff (Tammekänd et al. 2010, fig. 5) represents most likely the middle part of its range. Another useful graptolite, *Gymnograptus* cf. *retioloides* Wiman, is recorded in two samples (M-5914, M-5915; identification by Ralf Männil) near the top of the Osmussaar Cliff slightly above the appearance of *Conochitina* aff. *tuberculata*, with the same order of occurrence and position as at the Uuga Cliff.

Integrated biozonation and correlation of the Uuga and Osmussaar sections

Correlation of the Uuga and Osmussaar sections based on integrated conodont and chitinozoan biostratigraphy is shown in Fig. 8. Nearly 20 correlative levels can be recognized in the Väo Formation (Lasnamägi and lower Uhaku stages) and both sections display a markedly similar sequence of events, with no cross-correlations between chitinozoan and conodont data. A scatter-plot representation of the correlation is presented in Fig. 9, showing that the chitinozoans seem to have slightly higher dispersion (i.e. variation between the sections).

Multiple options for correlation are evident only in the lowermost part of the succession, where *Yangtzeplacognathus foliaceus* and chitinozoans *Baltochitina delicata* and *Desmochitina grandicolla* indicate a more complete section at Uuga, whereas the appearance of *Baltoplacognathus reclinatus* and *Conochitina* sp. n. 1 of Tammekänd et al. (2010) allow of slightly different interpretation (Fig. 8). This discrepancy cannot be resolved without additional sampling efforts. Other conodont subzone boundaries correspond quite well with chitinozoan levels. For instance, *Baltoplacognathus robustus* appears 10–20 cm above the disappearance of *Belonechitina pellifera* and *E. lindstroemi* appears very close to the LAD of *Conochitina clavaherculi* (Fig. 8) in both sections. The latter level in the Osmussaar Cliff section coincides also with the LAD of *Gymnograptus linnarssoni*.

Both chitinozoans and conodonts show that the age-equivalent strata from the base of the Lasnamägi Stage to the uppermost common marker level (FAD of *Conochitina* aff. *tuberculata*) are about 1 m thicker at the Uuga Cliff. This agrees well with lithological and macrofossil data, and follows the westward thinning of
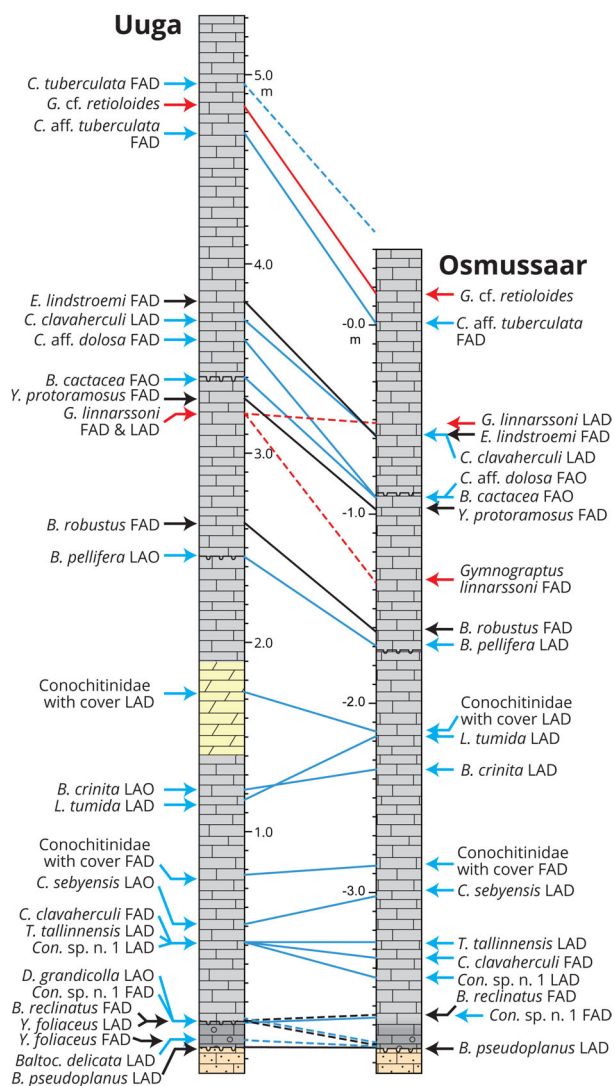
Fig. 8. Correlation of conodont and chitinozoan bioevents between the Uuga and Osmussaar cliff sections. FAD, first appearance datum; LAD, last appearance datum; LAO, last abundant occurrence; FAO, first abundant occurrence. These notations are used in case of single specimens outside the main continuous range. See further explanation in the text. The LAD of *Eoplacognathus pseudoplanus* at Osmussaar is based on data of Mellgren et al. (2012). *Baltoc*, *Baltochitina*.

Fig. 9. Scatter-plot graphical representation of the correlation between the Uuga and Osmussaar cliff sections. The line of correlation was fitted empirically.

ca 1.4 m at Uuga, but only 0.75 m at Osmussaar. This interval contains a number of discontinuity surfaces including the one used as a lithological marker for the lower boundary of the Uhaku Stage in northern Estonia (Einasto et al. 1996; Einasto 2002). As the *B. robustus* Subzone is of nearly equal thickness in both sections, the missing strata are probably on account of the topmost Lasnamägi Stage rather than the basal Uhaku Stage. Whether there is just one gap, or a set of smaller ones, remains beyond the current biostratigraphical resolution. The *Y. protoramosus* Subzone and common part of the *E. lindstroemi* Subzone are only slightly thinner in the Osmussaar section.

Regional comparison of conodont biozonation

As shown above, the conodont distribution patterns in both studied sections are very similar and provide a good basis for characterization of the NW Estonian Darriwilian succession. However, it is also of interest to explore how our new data compare with those available from other parts of Estonia as well as Scandinavia. A comparison of the thicknesses of conodont zones and subzones in selected sections is further discussed below and illustrated in Table 1.

Only two earlier studies of the northern Estonian outcrop area can be used for comparison (Männil 1986; Viira et al. 2001), both from sections at Lasnamägi, Tallinn. Männil (1986, fig. 2.1.1) provided generalized ranges of upper Darriwilian index species from *Y. foliaceus* to *E. lindstroemi*. Viira et al. (2001), on the other hand, included material from the lower Darriwilian, up to the *Y. foliaceus* Zone. The combined section at Lasnamägi appears to be more complete, especially in the Kunda to

the Darriwilian succession in northern Estonia (e.g., Orviku 1940; Hints 1997).

Integrated conodont and chitinozoan data show that the difference in thickness is not distributed equally across the sequence. The lower part of the Väo Formation (Rebala Member), correlated by the LAD or *Belonechitina crinita*, is of nearly the same thickness in both sections, if not slightly thicker at Osmussaar. In contrast, the interval between the LAD of *Belonechitina crinita* and FAD of *Baltoplacognathus robustus* is
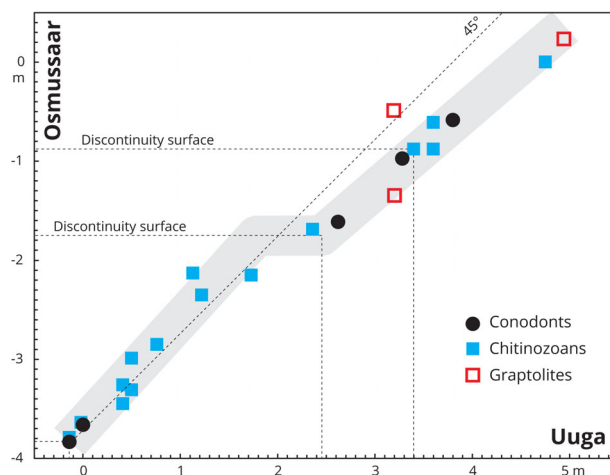
Table 1. Comparison of thicknesses of conodont zones and subzones in the studied sections and localities in Estonia and Sweden. The data come from the following sources: Kerguta core (Viira et al. 2006b), Taga-Roostoja core (Viira & Männik 1999), Mehikoorma core (Männik & Viira 2005), Valga core (Männik 2001) and Ruhnu core (Männik 2003). The Lasnamägi section is compilation from an outcrop (Viira et al. 2001) and the unpublished Lasnamägi 198 drill core. Swedish data from Bergström (2007) and Bergström et al. (2011). For locality map see Fig. 1. Note that the *Y. protoramosus* Subzone in the Taga-Roostoja section was corrected by restudying the original collection. In the Valga core, a sample with questionably identified *Y. protoramosus* is omitted. See further explanation in text

Conodont zone/subzone	NW Estonia		Northern Estonia			Southern Estonia			Sweden	
	Osmussaar	Uuga	Lasnamägi	Kerguta	Taga-Roostoja	Mehikoorma	Valga	Ruhnu	Kårgärde	Smedsby Gård
P. serra Zone — *E. lindstroemi* (range)	1.0+	1.8?	?	1.0+	2.2	3.6	0.2	3.0	3.0+	~6.0
Y. protoramosus Subz.	0.4	0.5	0.7+	0.3	1.1	1.1	1.5?	1.0	~0.5	0.7
B. robustus Subzone	0.7	0.7	?	1.6	2.2	2.2	1.1	3.0	<2.0	1.5
B. reclinatus Subzone	2.2	2.6	?	2.2	1.1	2.6	3.3+	2.8+	4.0	1.6+
Y. foliaceus Subzone	0.0	0.1	?	0.0?	1.0	1.5	–	–	2.0	–
E. suecicus Zone	0.0	0.0	0.7	4.2?	4.5	3.0	–	–	5.0	–
E. pseudoplanus Zone	0.5?	1.1?	2.0	3.6?	4.4	6.8	–	–	–	–
Y. crassus Zone	–	0.0	?	0.9	0.0?	0.0?	–	–	–	–
B. variabilis Zone	–	0.0	0.2	0.8	2.4	0.0?	–	–	–	–
B. norrlandicus Zone	–	0.0	0.3	1.5	0.7	4.0	–	–	–	–

Aseri interval, where the *Baltoniodus norrlandicus* and *Eoplacognathus suecicus* zones are well defined. In the Lasnamägi and Uhaku stages (i.e. *Pygodus serra* Zone), the same successive index taxa have been observed both in NW Estonia and the Tallinn area. These include the short-ranging *Y. protoramosus*, which was first recorded in Estonia by Männil (1986) under an informal name *Eoplacognathus bergstroemi*. As in NW Estonia, the zonal index *P. serra* is very rare in the Tallinn area.

A notable difference between our data and earlier studies in the Tallinn area concern the *Y. foliaceus* Subzone. Viira et al. (2001) listed this taxon from their uppermost sample (Mä95-51), defining the base of the corresponding subzone. However, these authors illustrated a sinistral Pb element (Viira et al. 2001, fig. 8U), which diverges considerably from the typical specimens of Viira (1974, pl. 8:10–11) and those from the Uuga Cliff (Fig. 4). According to Männil (1986, fig. 2.1.1), the *Y. foliaceus* Subzone extends to the top of the Pae Member in Tallinn, which strongly disagrees with our data from the Uuga Cliff. Although the Pae Member may be diachronous and the Väo Formation is more complete in the Tallinn area, a number of common chitinozoan species in the lower part of the Väo Formation suggest a different explanation; it is likely that different taxonomic concepts of *Y. foliaceus* have been applied.

Viira (1974, fig. 8) has nevertheless shown that the *Y. foliaceus* Subzone is present in the Tallinn area, but its boundaries obviously need re-evaluation. Since the original collection of Männil (1986) cannot be located at present, this problem can only be resolved by re-sampling the Lasnamägi type section.

The conodont succession in other parts of Estonia has recently been studied in the Kerguta (Viira et al. 2006b), Taga-Roostoja (Viira & Männik 1999), Mehikoorma (Männik & Viira 2005), Valga (Männik 2001) and Ruhnu cores (Männik 2003). Additionally, Viira (2011) showed the distribution of Darriwilian conodonts in a number of core sections in southern Estonia and adjacent Russia. In summary, the pre-*serra* Darriwilian strata are notably thicker and more complete in most of these sections (Table 1). For instance, the lower Darriwilian conodont succession from the *B. norrlandicus* to *E. suecicus* zones is ca 20 m thick in the Mehikoorma core in SE Estonia (Männik & Viira 2005). This interval corresponds to about 1 m at the Uuga Cliff, represented by the *E. pseudoplanus* Zone only.

In contrast, the *P. serra* Zone is much less variable across Estonia. All five subzones identified in NW Estonia have been recognized in other sections in similar or only slightly thicker units (Table 1), suggesting that unlike in the early Darriwilian, the depositional conditions were

very uniform during Lasnamägi and early Uhaku times in the Estonian area. It is worth mentioning that only in the Ruhnu core, which probably represents the deepest shelf settings in the Estonian area, *P. serra* and *P. anserinus* were relatively common, just as they are in Swedish sections (Bergström 2007; Bergström et al. 2011).

We discuss here only two more recently published sections of Sweden: the Smedsby Gård core, Östergötland, southern Sweden (Bergström et al. 2011) and the Kårgärde outcrop, Siljan area, south-central Sweden (Bergström 2007). The latter is especially important, being the reference section for the *E. suecicus* and *P. serra* zones and the *Y. foliaceus*, *B. reclinatus*, *B. robustus* and *E. lindstroemi* subzones (Bergström 1971, 2007).

The *E. suecicus* Zone and *Y. foliaceus* Subzone are relatively thick at Kårgärde, 5 and 2 m, respectively, and correspond to a gap in the NW Estonian succession. The *B. reclinatus* and *B. robustus* subzones are thicker at Kårgärde (4 and 2 m, respectively), but otherwise directly comparable to those in NW Estonia. Interestingly, the ca 0.5 m range of *Y. protoramosus* is reported to overlap entirely with the *E. lindstroemi* Subzone (Bergström 2007; but note a confusion regarding this identification: *Y. protoramosus* is mentioned in the text on p. 32, but fig. 6 lists the range of *Eoplacognathus jiangeensis* instead). This is not surprising as *Y. protoramosus* likely represents a different evolutionary lineage from *E. lindstroemi* (Zhang 1998). However, this is in contrast to the pattern at the Uuga and Osmussaar cliffs and elsewhere in Estonia. Further study is needed to see if any other sections display a similar overlap of ranges of these species. Until then, in most sections, the short range of *Y. protoramosus* could be used as a stratigraphically well-constrained regional subzone. The *E. lindstroemi* Subzone in its type section is approximately 2 m thick, which is only slightly more than recorded here at the Uuga Cliff.

The succession in the Smedsby Gård core starts in the Furudal Limestone, corresponding to the *P. serra* and *P. anserinus* zones. These index species are common throughout their ranges. Only the upper part of the *B. reclinatus* Subzone is represented there and is 1.6 m thick. The full *B. robustus* Subzone in Smedsby Gård is about twice as thick as in NW Estonia. Bergström et al. (2011) also identified *Y. protoramosus* just above *B. robustus*, but included it in the *E. lindstroemi* Subzone.

In summary, our data confirm that the lower Darriwilian succession in NW Estonia is stratigraphically incomplete, with missing biozones and reduced thickness in the Kunda–Aseri interval. However, during the *Pygodus serra* Zone, remarkably uniform depositional conditions prevailed all over the Baltoscandian area, with only minor changes in sequence thickness and without major hiatuses. There the studied sections in NW Estonia can be directly compared with those elsewhere in Estonia and Sweden.

Updates to the integrated biostratigraphical scheme and comments on stage boundaries

The new high-resolution data from the Uuga and Osmussaar cliffs allow updates to the current correlation scheme between conodont and chitinozoan biozonations summarized by Nõlvak et al. (2006). The new scheme, as well as levels that remain uncertain at present, are shown in Fig. 10.

In the previous compilation (Nõlvak et al. 2006), the *Y. foliaceus* Subzone was considered to overlap with the *Conochitina clavaherculi* Subzone to some extent. According to our data, it seems more likely that *B. reclinatus* appeared slightly earlier than *C. clavaherculi* and consequently the *Y. foliaceus* Subzone must entirely fall within the *Cyathochitina sebyensis* Subzone. Second, the LAD of *C. clavaherculi* virtually coincides with the LAD of *Y. protoramosus* and FAD of *E. lindstroemi* in both sections studied, as well as in the Lasnamägi section in Tallinn (Männil 1986). Thus it would be more appropriate to correlate the base of the *E. lindstroemi* Subzone with the base of the Lower *C. tuberculata* Subzone (see discussion on the definition of the latter subzone in Tammekänd et al. 2010). Previously the *Y. protoramosus* Subzone was considered to correspond to the Lower *C. tuberculata* Subzone (Nõlvak et al. 2006).

GS	Reg. Stage	Gr	Conodont zone / subz.		Chitinozoan zone / subz.	
Darriwilian	Uhaku	*Gymnogr. jinnarssoni* / *P. serra*	*Pyg. anser.*	*S. kielcensis*	*L. striata*	Lower *C. tuberculata*
				E. lindstroemi		
				Y. protoramosus		*C. clavaherculi*
				B. robustus		
	Lasnamägi			*B. reclinatus*		
				Y. foliaceus		*C. sebyensis*
	Aseri		*E. suecicus*		not defined	
	Kunda		*E. pseudoplanus*		*C. regnelli*	

Fig. 10. Updated correlation between conodont and chitinozoan biozonations and Baltic regional stages. Note that exact correspondence between the lower and upper boundaries of the Aseri Stage and conodont biozones awaits further high-resolution data from the type sections. GS, Global stage; Gr, graptolites; *Pyg. anser.*, *Pygodus anserinus*.

The Aseri, Lasnamägi and Uhaku stages were introduced based on lithological and macrofossil evidence, with type sections located in northern Estonia (Orviku 1940, 1960; Rõõmusoks 1970). Outside the stratotype area conodonts are nowadays among the most commonly used fossil groups for tracing boundaries of these stages in Baltoscandia (e.g., Bergström 1983; Zhang & Sturkell 1998; Zhang 1999; Löfgren & Zhang 2003). However, the exact correspondence between the original stage concepts and stratotypes and conodont (and chitinozoan) biozonation has remained poorly known. Thus at present the lower boundaries of the Aseri and Lasnamägi stages can only tentatively be correlated with the *E. suecicus* and *P. serra* zones (Fig. 10).

The lower boundary of the Uhaku Stage is drawn by the appearance of *Gymnograptus linnarssoni* and *B. robustus* (Männil & Meidla 1994). In the Tallinn area this boundary coincides with a discontinuity surface within a bed locally known as 'Raudsüda' (Einasto et al. 1996). As hitherto only a generalized faunal log of the Lasnamägi section is available to characterize this level (Männil 1986, fig. 2.1.1), our study provides valuable additional data. In both the Uuga and Osmussaar sections the lithological marker appears to coincide with the LAD of *Belonechitina pellifera* (Fig. 7). Confidently identified *B. robustus* appears 10–20 cm above this level, followed by *G. linnarssoni* 0.35 cm above the same discontinuity surface on Osmussaar. All these markers can be considered virtually coincident for regional correlations, providing multiple options for identifying the base of the Uhaku Stage in Baltoscandia. In northern Estonia, however, conodonts and chitinozoans appear to be more useful than the relatively rare graptolite faunas.

Temporal resolution of Darriwilian biostratigraphy

Bergström et al. (2011) provided an interesting discussion on the geochronologic resolution of conodont biostratigraphy as well as on net accumulation rates in the Baltic Ordovician. Using time scales of Cooper & Sadler (2004), Webby et al. (2004) and Sadler et al. (2009), they estimated the duration of Uhaku conodont subzones to be on average less than 0.5 Ma. Following a similar approach, we focus here on the *P. serra* Zone. According to Cooper & Sadler (2004), the *P. serra* Zone corresponds to about 1.2 Ma. Webby et al. (2004), as well as the latest Geologic Time Scale (Cooper & Sadler 2012), infer about 2 Ma. Based on these time scales, it would at present be reasonable to assume that the temporal range of the *P. serra* Zone was most likely somewhere between 1.0 and 2.5 Ma.

The five subzones recognized in our study would therefore represent on average 0.2–0.5 Ma, which is

close to the estimation by Bergström et al. (2011). Some of the individual subzones, especially the *Y. protoramosus* Subzone, are relatively thinner across Baltoscandia, and their temporal content is likely smaller. Moreover, when using well-constrained conodont zonal boundaries and adding the chitinozoan correlative levels, biostratigraphic resolution below 0.1 Ma could probably be achieved. This is similar to what has been demonstrated by Cramer et al. (2010) from the Llandovery–Wenlock boundary interval.

Bergström et al. (2011) also estimated net accumulation rates for the late Darriwilian of Baltoscandia, suggesting extremely low values of 3–4 mm ka^{-1}. In the Uuga section the entire *P. serra* Zone is roughly 5.5 m thick, inferring a similar net accumulation rate of 2.2–5.5 mm ka^{-1} (based on the above mentioned duration of the *P. serra* Zone). Indeed, the deposition has most likely been episodic rather than continuous and single beds may have been formed rather quickly, as mentioned also by Bergström et al. (2011). The duration of periods of non-deposition remains mostly beyond biostratigraphic resolution, but at least some gaps can be traced by quantitative microfossil data, as shown by Tammekänd et al. (2010) and by comparing adjacent sections as done in this study.

CONCLUDING REMARKS

The data set from the Uuga and Osmussaar cliff sections is among the most detailed ones for Darriwilian conodont and chitinozoan distributions hitherto available. Altogether, more than 20 biostratigraphically important levels were recognized, probably approaching temporal resolution of 0.1 Ma in the upper Darriwilian. Some lithological marker horizons fit perfectly with the biostratigraphical data and indicate potential for future improvements in the temporal framework at least in northern Estonia.

The base of the Darriwilian coincides with the regional Volkhov–Kunda boundary in the study area, and the Aseri Stage is most probably missing in both the Uuga and Osmussaar sections. The lowermost part of the Lasnamägi Stage, corresponding to the *Y. foliaceus* Subzone, is also very condensed or missing in NE Estonia. The rest of the Lasnamägi and Uhaku stages is well dated by successive conodont subzones of the *Pygodus serra* Zone, which can be identified all over Estonia and Sweden. The zonal species *P. serra* and *P. anserinus* are too rare in most of the Estonian sections to be used for high-resolution biostratigraphy.

Our data and regional comparison suggest that *Y. protoramosus* is more common than previously thought, has a short range and is stratigraphically well-constrained in Estonia and Sweden. Thus, unlike

Bergström et al. (2011), we consider it a valuable regional subzonal index. Our results also suggest that some previous identifications of the *Y. foliaceus* Subzone in Estonia are contradictory and this unit awaits further assessment.

The results point to the need for obtaining new high-resolution data from the historical stratotype sections of the Aseri, Lasnamägi and Uhaku stages, to reconcile the original stage concepts with the current biostratigraphic resolution available in Baltoscandia.

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Darriwili lademe (Kesk-Ordoviitsium) konodontide biostratigraafia Loode-Eestis

Olle Hints, Viive Viira ja Jaak Nõlvak

Darriwili lademe konodondid on Baltoskandias üldiselt hästi tuntud, kuid klassikalise Põhja-Eesti avamuse kohta on andmestik seni väga puudulik. Käesolevas töös on detailselt analüüsitud konodontide ja kitiinikute levikut Loode-Eestis Uuga ning Osmussaare pangal. Standardse Põhja-Atlandi konodontide biotsonaalse skaala abil dateeriti läbi-lõiked Volhovi lademe ülaosast kuni Uhaku lademeni. Selgus, et Darriwili globaallademe piir langeb Loode-Eestis kokku Volhovi-Kunda lademe piiriga, Kunda lade on kondenseeritud ja Aseri lade uuritud läbilõigetes tõenäoliselt puudub. Ka Lasnamäe lademe alumine osa, mis vastab *Yangtzeplacognathus foliaceus*'e alamtsoonile, on konden-seeritud. Ülejäänud osa Lasnamäe ja Uhaku lademest on seevastu hästi esindatud ning konodontide liigestuse alusel hästi rööbistatav Eesti ja Rootsi läbilõigetega. Selle intervalli ruumiline pidevus näitab Balti paleobasseinis ulatus-likul alal levinud ühetaolisi tingimusi. Töö tulemused viitavad vajadusele revideerida varasemaid *Y. foliaceus*'e alamtsooni määranguid Eestis. Selgus, et stratigraafiliselt piiratud levikuga *Y. protoramosus* on seniarvatust tavalisem ja sobib alamtsoonina hästi regionaalse biotsonaalse skeemi täiendamiseks. Konodontide ja kitiinikute integreeritud bio-tsonaalne skaala sisaldab antud intervallis üle 20 lokaalse ning regionaalse korrelatsioonitaseme ja selle ajaline lahutus-võime ulatub Hilis-Darriwili kihtides tõenäoliselt 0,1 miljoni aastani.