

Ostracods of the Ordovician–Silurian boundary beds: Jūrmala core (Latvia) and its implications for Baltic stratigraphy

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Abstract. Ostracods of the Ordovician and Silurian transition interval in the Jūrmala section, Latvia, were studied. The diverse pre-Hirnantian ostracod assemblage is replaced by the *Harpabollia harparum* association that has been recorded across the Baltoscandian region and northwestern Poland and is confined to the Hirnantian. The first complete ostracod succession throughout the Kuldīga and Saldus formations reveals a remarkable diversity decline and rise of dominance of ostracods in this interval. The appearance level of the *H. harparum* association in other sections is drawn distinctly above the range of *Spinachitina taugourdeaui*, nearly coinciding with the appearance of *Conochitina scabra* and *Noixodontus girardeauensis*. The transition from the Saldus Formation into the Stačiūnai Formation marks a complete ostracod turnover. The newly appearing assemblage, dominated by *Longiscula smithii*, is of low diversity. Slow diversity rise may in part be ascribed to the overall low recovery rate of post-glaciation faunal assemblages. The shape of the stable carbon isotopic curve in the Jūrmala core suggests that this section is one of the most complete successions across the Ordovician–Silurian boundary in the Baltoscandian area. The correlation of this curve with that of the Monitor Range, Nevada, and comparison with other curves of Latvia and Estonia suggest that the well-known appearance level of the ‘Silurian faunas’ is confined to the upper *M. persculptus* graptolite Zone. Judging from the chemostratigraphic correlation, the latter zone ranges for more than 10 m into the Stačiūnai Formation in the Jūrmala core.

Key words: ostracods, Ordovician, Silurian, Hirnantian, Baltoscandia, disconformity.

INTRODUCTION

The eastern Baltic region is characterized by one of the best preserved and studied lower–middle Palaeozoic successions in the world. The area is well known for its high-resolution stratigraphic framework that was well elaborated by the middle of the 20th century and further improved over the last decades (Rõõmusoks et al. 1997; Männik 2014; Meidla et al. 2014). The faunal record of the Ordovician and Silurian carbonates in this area is one of the richest worldwide (see the summaries in Raukas & Teedumäe 1997).

The faunal changes related to the Hirnantian glaciation in this area were documented already in the 18th century. An overview of the faunal changes published by Nestor et al. (1991) demonstrates that the major gap in the Ordovician–Silurian boundary interval marks a great faunal turnover among stromatoporoids, tabulates, brachiopods,

trilobites, ostracods, conodonts, chitinozoans and graptolites. It is expressed as the extinction of 92% of species, 54% of genera and 34% of families recorded from the Porkuni Regional Stage in Estonia, Latvia and Lithuania (Nestor et al. 1991). These data are still largely correct in spite of the fact that the taxonomy of several groups has been or needs to be updated.

The relationships between the faunal changes, the glaciation and the stable isotopic changes coinciding with the appearance of elements of the Hirnantian fauna in the offshore sections were addressed much later (Brenchley et al. 1994 and numerous subsequent papers). The results of the stable isotopic studies initiated in the 1990s provided additional stratigraphic markers for identifying the Porkuni Regional Stage that has mostly been considered as an equivalent to the global Hirnantian Stage. Isotopic evidence is nowadays widely used to identify the Porkuni/Hirnantian strata in non-graptolitic sections

(e.g. Kaljo et al. 2008; Ainsaar et al. 2010 and references therein).

Ostracods of the Ordovician–Silurian transition interval have been studied since the mid-20th century in the Baltic region. A specific ostracod assemblage confined to the Hirnantian, the so-called *Harpabollia harparum* association, was first described from the outcrops of Scania (southern Sweden) by Troedsson (1918). Its wide distribution in the eastern Baltic region was documented much later (Gailīte 1968, 1970; Szejn 1989, Meidla 1996a, 1996b, 2007; Truuver et al. 2012 and in press; Truuver & Meidla 2015). The association has only weak taxonomic relationship to the indigenous ostracod assemblages and its disappearance marks the beginning of the postglacial recovery of shallow marine assemblages after the mass extinction.

The present paper aims to analyse the distribution of ostracod faunas on the background of stable isotopic data in the Ordovician–Silurian boundary interval of the Jūrmala core, Latvia (Fig. 1). The study addresses faunal dynamics, timing of bioevents and the position of the lower boundary of the Silurian System in the eastern Baltic area.

GEOLOGICAL SETTINGS AND STRATIGRAPHY

In the eastern Baltic region, the outcrop area of the Upper Ordovician to Llandoveryan strata forms a latitudinal belt in northern and central Estonia (Fig. 1). The strata are slightly dipping to the south, which brings them to a

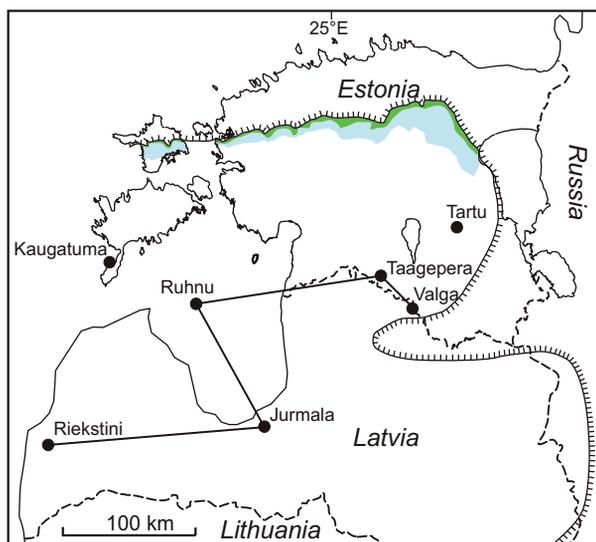


Fig. 1. The study area, sections addressed in the text and outcrop belts of the Porkuni (green) and Juuru (blue) regional stages. Based on Gailīte et al. (1967), Birkis et al. (1976), Kaljo & Jürgenson (1977), Ulst et al. (1982), Hints & Meidla (1997) and Nestor (1997).

considerable depth in South Estonia and in Latvia where the Upper Ordovician and Llandovery are overlain by younger Silurian and Devonian sediments up to 800 m thick. The total distribution area of the Ordovician and Silurian strata comprises most of the territory of the Baltic states and reaches further to the south and east. A large number of core sections are available for geological investigation in the region.

The deposition during the latest Ordovician and earliest Silurian took place in a (sub)tropical shelf basin (Nestor & Einasto 1997) with moderately high sedimentation rates. The deposition pattern was largely controlled by the availability of accommodation space and this resulted in numerous gaps and discontinuities, sometimes hidden ones, especially in nearshore areas in northern Estonia and eastern Latvia. It is generally understood (e.g. Bergström et al. 2006; Kiipli & Kiipli 2020) that there are gaps near the systemic boundary and this has always complicated the correlation of the strata in this interval.

In the 1960s–1970s, the concepts of structural-facies zones (by Männil 1966) and confacies belts (by Jaanusson 1976) were introduced for the Ordovician of Baltoscandia. The facies zonation of the Silurian strata has been addressed in numerous papers (see Kaljo 1970; Nestor & Einasto 1997 and references therein). The palaeontological studies in this interval, based largely on the core sections, facilitated revelation of a distinctive biogeographic differentiation pattern in the form of sublatitudinal belts in Estonia (e.g. Kaljo & Rubel 1982; Meidla 1996a) that grades into the submeridional zonation in Latvia (e.g. Ulst et al. 1982). In the topmost Ordovician, the biofacies zonation is less distinct, due to gaps and unfossiliferous units, as well as a high grade of faunal differentiation.

The latest pre-Hirnantian strata in southern and southwestern Estonia and western Latvia are attributed to the Jonstorp or Jelgava formations, comprising reddish-brown or greenish-grey marls and argillaceous limestones (Fig. 2). It may also contain one or several micritic limestone units (sometimes distinguished as the Parovēja Member, formerly the Parovēja Formation), overlain by variegated argillaceous nodular limestones and marls sometimes distinguished as the Kuili Member (formerly the Kuili Formation). The Jelgava Formation is missing in southwestern mainland Estonia (Taagepera, Ikla, Ruhnu). It is often assumed that its absence is due to a gap in the succession but this has not been convincingly demonstrated.

The Jonstorp and Jelgava formations are overlain by the Kuldīga Formation that is subdivided into the Bernāti (argillaceous wackestones) and Ēdole (variegated bioclastic marls) members. The overlying Saldus Formation represents the most shallow-water unit in the succession, consisting of bioclastic or oolitic limestones, replaced

System	Stage	Graptolite zone	Conodont zone	Chitinozoan zone	Regional stage	Formations				C isot. curve & zones 0 2 4	
						North & Central Estonia	S Estonia N Latvia	S & W Latvia			
Silurian	Aeron.	<i>D. triangulatus</i>	<i>Aspelundia expansa</i>	<i>Conochitina alargada</i>	RAIK-KÜLA	Hilliste	Raik-küla	Nurme-kund	Saarde	Dobele	
	Rhudd.	<i>Coronograpt. cyphus</i> <i>Orthogr. vesiculosus</i> <i>Parakid. acuminatus</i> <i>Akidogr. ascensus</i>	<i>Distomodus kentuckyensis</i>	<i>Spinachitina maennili</i> <i>Euconochitina electa</i>							
Ordovician	Hirnantian	<i>Metabolograptus persculptus</i>	?	interzone	JUURU	Varbola	Saldus	Saldus	Staçiunai		
		<i>Metabolograptus extraordinarius</i>	Noixodontus interval	<i>Conochitina scabra</i> <i>Spinachitina taugourdeaui</i>							Kuldiga
	Kat.	<i>Dicellograptus anceps</i>	Amorphogn. ordovicicus	<i>Belonechitina gamachiana</i> <i>Tanuchitina anticostiensis</i> <i>Conochitina rugata</i>	PIRGU	Arina	Jelgava	Jelgava	Jelgava		
						Adila	Halliku	Jons-torp	Jelgava		

Fig. 2. Correlation of the Ordovician–Silurian boundary strata in Estonia and Latvia (after Lukševics et al. 2012 and Meidla et al. 2014) and the graptolite, conodont and chitinozoan zones (compiled after Nõlvak et al. 2006, Loydell et al. 2010, Nestor 2012 and Männik 2014). The lower boundary of the *Spinachitina taugourdeaui* chitinozoan Zone is drawn by considering the appearance of this species in the Pirgu Regional Stage, below the HICE excursion, in the Tartu core (Bauert et al. 2014) and the Rapla core (Kaljo et al. 2004). The shaded text in the column of graptolite zonation refers to the lack of graptolite evidence in the respective zonal units within the study area. The dashed lines for the zonal boundaries refer to their uncertain position. The isotopic zones BC14, BC15 and BC16 (Ainsaar et al. 2010) are marked by one, two or three asterisks (respectively) in the right column.

upwards by thinly laminated sandy limestones and marls with siltstone laminae. Ripple marks and mud cracks are common in that unit. These two formations have been considered to represent the Hirnantian in this area (e.g. Männil & Meidla 1994; Brenchley et al. 2003; Meidla et al. 2014).

The Saldus Formation is overlain by the greenish-grey marls and variegated limestones of the Õhne Formation in southern Estonia and northern Latvia. In western Latvia, this unit is replaced by the Staçiunai Formation comprising mainly nodular limestones and marls (Gailite et al. 1987). The Õhne and Staçiunai formations were earlier attributed entirely to the Silurian. The lower boundary of the Silurian System has traditionally been aligned with the lower boundary of the Juuru Stage (see Fig. 2) but recent results (Meidla et al. 2011; Bauert et al. 2014; Hints et al. 2014; Ainsaar et al. 2015) shift it higher, into the Juuru Regional Stage. The stratigraphic hiatuses and rarity of graptolites and conodonts in this interval are complicating the identification of the systemic boundary in the area.

MATERIAL AND METHODS

This study is based on the results of a high-resolution micropalaeontological investigation and stable isotopic study of the Jürjala core section. Complementary

information comes from the published data on ostracod distribution in the Estonian and Latvian sections (Meidla 1996a, 2001, 2003; Pöldvere et al. 1998; Brenchley et al. 2003; Meidla & Tinn 2008). The isotopic curves referred to in this study were published in several recent papers (Ainsaar et al. 2010; Meidla et al. 2011 and references therein).

The studied interval of the Jürjala core (Fig. 3) represents a complete and almost continuously fossiliferous succession across the Ordovician–Silurian boundary interval.

The micropalaeontological samples, 300–500 g in weight, were coarsely crushed (pieces about 1–2 cm in diameter) and subsequently repeatedly heated in a concentrated solution of sodium hyposulphite, leaving a considerable cooling time (usually 24 h) between the heating cycles (for details see Meidla 1996a; Tinn & Meidla 1999). The resultant ostracod-containing fine residue was wet-sieved, dried and subsequently picked under a stereo-microscope. Photos of ostracods were taken using a Zeiss EVO MA 15 scanning electron microscope in the Department of Geology, University of Tartu (Estonia). In addition to the specimen count data and species diversity curve, the dominance curve from the software package PAST (version 4.03 – Hammer et al. 2001) was added to Fig. 3. The collection is stored in the Natural History Museum of the University of Tartu.

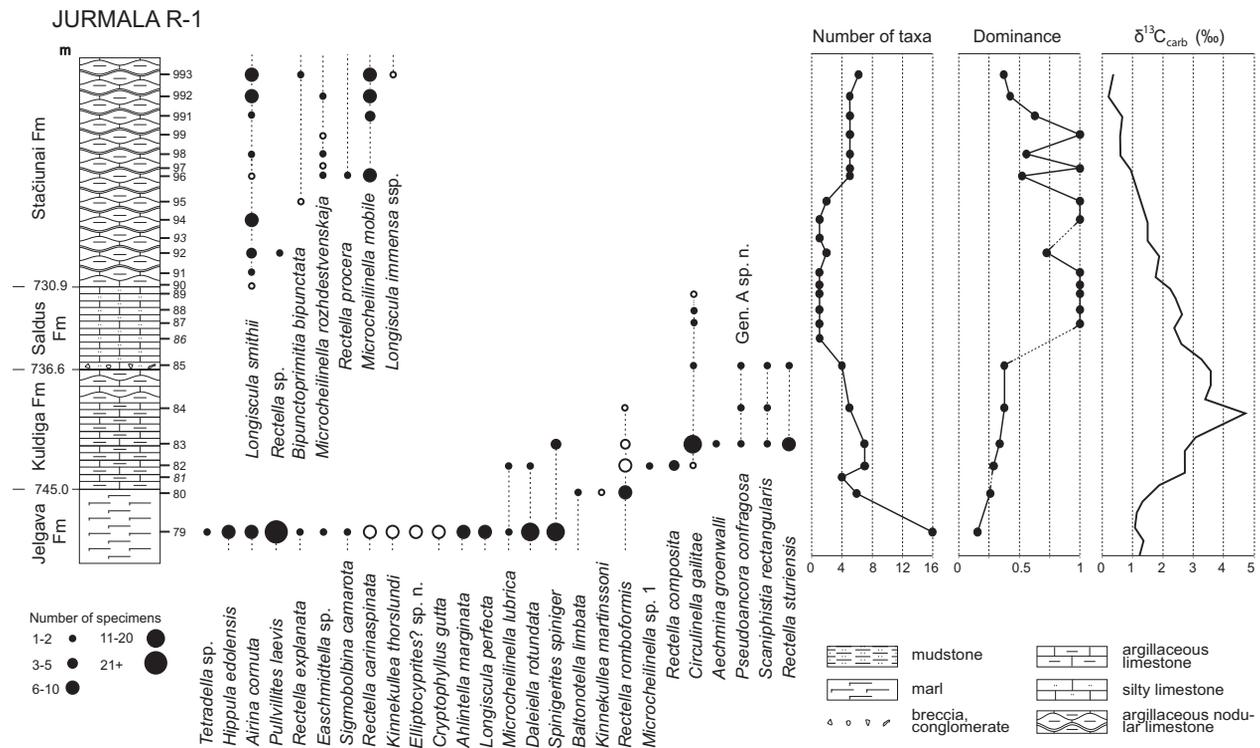


Fig. 3. Ostracod distribution in the Jürjala core, species diversity and dominance, and the stable carbon isotopic curve after Ainsaar et al. (2010). Numbers of unfossiliferous samples (81, 86, 93) are indicated in italics, tentative occurrences are shown as empty circles. Extensions of species ranges into the Katian and upwards into the Silurian are based on the information on the stratigraphic ranges from previous publications (Gailite et al. 1967; Pranskevičius 1971, 1972; Sarv & Meidla 1984; Meidla 1996a).

THE JÜRJALA CORE

The upper part of the Pirgu Stage is represented by the Jeļgava Formation in the Jürjala core (Fig. 3). This 32.7 m thick variegated unit consists predominantly of marls and argillaceous limestones. As this unit is palaeontologically rather monotonous in other sections, only its uppermost part was included in the present study.

The Jeļgava Formation is overlain by the Kuldīga Formation, 8.4 m (736.6–745 m) of greenish-grey massive argillaceous limestone, grading into seminodular limestone in its upper part, and the Saldus Formation, 5.7 m (730.9–736.6 m) of greenish-grey thin-bedded silty-sandy oolitic limestone. On the basis of faunal evidence from different groups (trilobites, brachiopods, ostracods, chitinozoans and conodonts), this part of the succession was considered to be equivalent to the Hirnantian (e.g. Kaljo et al. 2008 and references therein). The overlying Stačūnai Formation consists of greenish-grey argillaceous nodular limestones and marls in more than 15 m thickness (above 730.9 m).

The stable carbon isotopic curve from the bulk-rock samples (from Ainsaar et al. 2010) is shown in Fig. 3. The

curve displays a low in the interval of 745–750 m, grading upwards into the Hirnantian Isotope Carbon Excursion (HICE), reaches a peak in the upper half of the Kuldīga Formation and shows a very gradual decline leading to background isotopic values only in the middle of the Stačūnai Formation. The comparison with the Baltic carbon isotopic standard zones (Ainsaar et al. 2010) suggests that the main (lower) part of the Kuldīga Formation comprises the isotopic zone BC16, whilst the upper part of the Kuldīga Formation and the Saldus Formation comprise the main part of the isotopic zone BC17.

DISTRIBUTION OF OSTRACODS

Altogether 256 specimens were collected from 24 samples ranging from the topmost pre-Hirnantian up to the Ordovician–Silurian boundary interval (supplementary data online at <https://doi.org/10.23679/503>). This ostracod material is of moderate to low abundance compared to, for example, the Råsnäsudden section, southern Sweden (Aeronian), where altogether 4733 ostracod specimens

were picked from 15 samples (Truuver et al. 2012, or to the Putilovo quarry (northwestern Russia, Darriwilian) (Tolmacheva et al. 2001, 2003) with about 5000 ostracod specimens per 100 g in clay samples. Direct comparison of ostracod abundance data is always difficult as the abundance may depend on the rock type, stratigraphic horizon but also on the particular details of laboratory treatment, as noted by Perrier et al. (2012). Still, it is noteworthy that the basal parts of the Varbola and Õhne formations are characterized by particularly low ostracod abundance and diversity in the Jūrmala section as well as in other sections (e.g. Gailīte et al. 1967; Pranskevičius 1972; Meidla 1996a).

Twenty-one out of 24 samples contained ostracods. The barren samples were taken from the lowermost Kuldīga Formation, the lowermost Saldus Formation and the basal Stačiūnai Formation. The fossil material is of moderate quality and contains predominantly preadult carapaces and valves that are often fragmented.

Ostracods are the most abundant in the micritic argillaceous limestones and marls of the topmost Jelgava Formation. More than 100 specimens were picked from the lower sample of the Jelgava Formation. The taxonomic composition of ostracods in this formation is well characterized in earlier publications (e.g. Gailīte in Ulst et al. 1982; Meidla 1996a). The ostracod association is dominated by typical members of the Baltoscandian late Katian assemblage like *Pullvillites laevis* Abushik & Sarv, *Daleiella rotundata* Meidla, *Spinigerites spiniger* Schallreuter, *Hippula edolensis* (Gailīte), *Airina cornuta* (Neckaja), etc. (see Fig. 4: 6–17). Several sections in central and southern Estonia (e.g. Laeva-18, Viljandi-91, Ruskavere-451, Abja-92 cores in Meidla 1996a) contain a very similar species association in the topmost part of the Pirgu Regional Stage. In the Jūrmala core, the ostracod fauna in the topmost Jelgava Formation is of highest diversity and lowest dominance although some diversity decrease is recorded in the upper sample.

At the lower boundary of the Kuldīga Formation, this association is replaced by a very distinct and only moderately diverse assemblage known as the *Harpabollia harparum* association (Meidla 2007), which is thoroughly described in several papers (Gailīte 1970; Meidla 1996a, 1996b, 2007; Truuver & Meidla 2015; Truuver et al. in press). One of the most common species in this association, apart from the nominate species, is *Circulinella gailitae* Meidla (Fig. 4: 4). The species recorded in this interval are described also in Central and South Estonian localities (Meidla 1996a) and in several sections in Latvia (Gailīte 1970; Brenchley et al. 2003). Recent studies have pointed out that the assemblage may be of higher diversity and some species seem to be confined to the deeper shelf sections only, like Gen. A sp. n (see Fig. 4: 5) (= *Tvaerenella?* sp.: Truuver & Meidla 2015), recorded in the Jūrmala and

Ketrzyn sections only, and *Cryptophyllus pius* Truuver & Meidla (only at Ketrzyn). Rare specimens of *Rectella romboformis* Neckaja, *Spinigerites spiniger*, *Daleiella rotundata* and *Microcheilinella lubrica* (Stumbur) range from the Jelgava Formation into the basal part of the Kuldīga Formation but not into the main part of it. The Kuldīga Formation is marked by a slow decrease in the number of species and slowly increasing dominance values (Fig. 3).

The Saldus Formation is often unfossiliferous. This may be due to the dilution effect or simple destruction and/or washout of valves, considering indication of very high hydrodynamic activity. The sandy oolitic limestones in the Jūrmala core do, however, contain rare *Circulinella gailitae*, *Pseudoancora confragosa* Gailīte and *Scaniphistia rectangularis* (Troedsson). Only *Pseudoancora confragosa* ranges into the upper part of the formation and the dominance values are, accordingly, high to very high in this interval (Fig. 3). The disappearance of the *H. harparum* association is tied to a disconformity (730.9 m) in the Jūrmala core.

The transition from the Saldus Formation into the Stačiūnai Formation marks a complete faunal turnover. The dominant species in the newly appearing assemblage is *Longiscula smithii* (Jones) (see Fig. 4: 1, 2) that is accompanied by *Microcheilinella mobile* Gailīte and *Microcheilinella rozhdestvenskaja* Neckaja (Fig. 4: 3), whilst *Bipunctoprimitia bipunctata* (Gailīte), *Rectella procera* Abushik & Sarv and *Longiscula immensa* Pranskevičius are less common. The same species (mostly *L. smithii*) are recorded in the basal Varbola and Õhne formations in several sections in Estonia (Viljandi, Laeva-18, Aidu; Meidla 1996a), Latvia (Gailīte et al. 1967) and Lithuania (Pranskevičius 1972). *Longiscula smithii* and *Microcheilinella mobile* are the most abundant taxa also in the Motala Formation (Östergötland, Sweden) that is somewhat younger (of late Rhuddanian–Aeronian age according to Truuver et al. 2012). The number of species per sample is rising slowly but the dominance index drops below 0.5 only 12 m above the lower boundary of the formation (Fig. 3).

NOTES ON THE *HARPABOLLIA HARPARUM* ASSOCIATION

In the Baltoscandian region, the faunal association established in the Kuldīga and Saldus formations of the Jūrmala section has been widely recorded in the sections of South Estonia, most of Latvia, northern Lithuania and northeastern Poland. Based on the distribution of other groups and chemostratigraphic correlation, the assemblage was usually attributed to the Porkuni Regional Stage and the strata with this fauna were considered an equivalent of the Hirnantian.

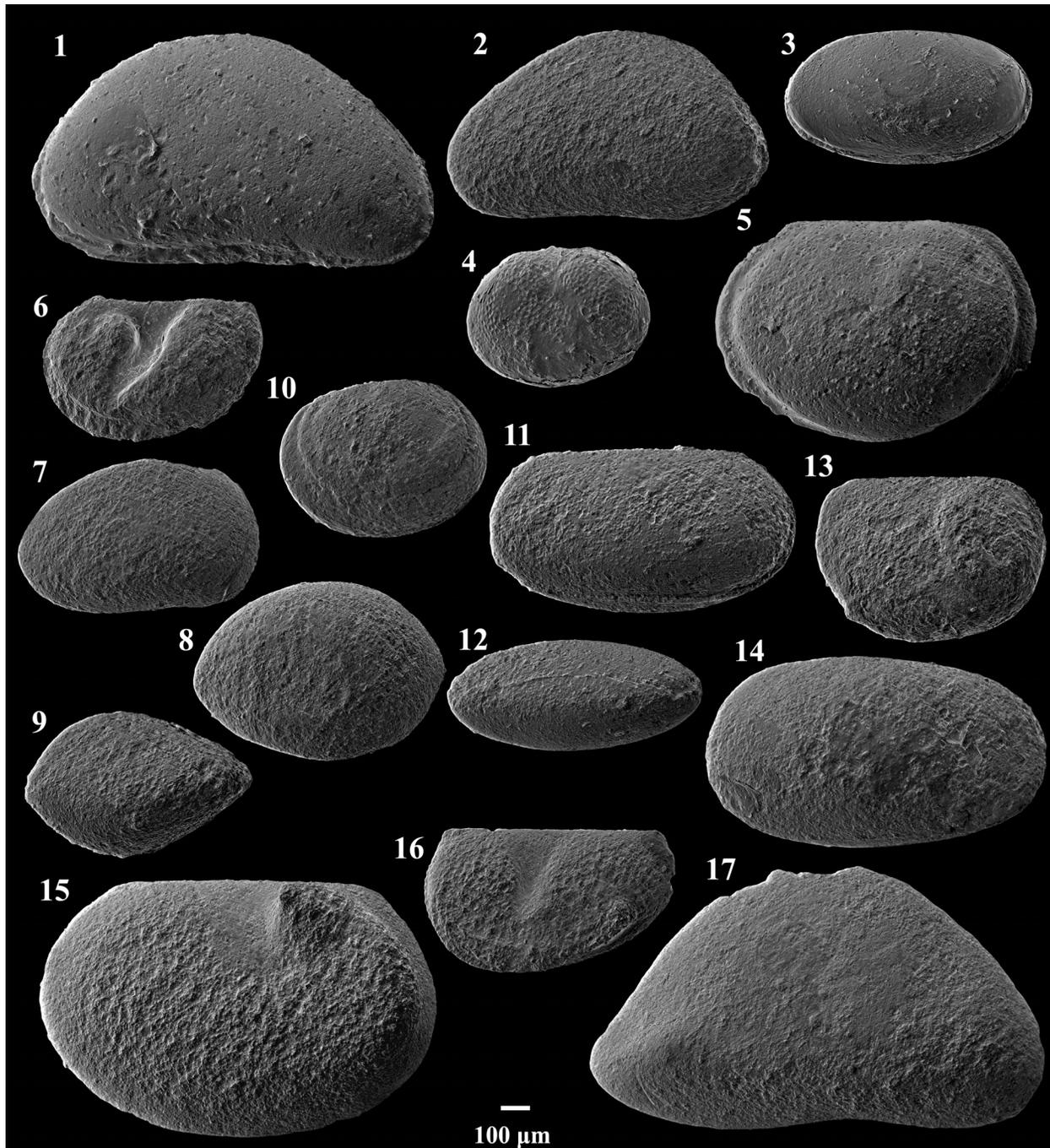


Fig. 4. Selected ostracods from the Stačiunai (1–3), Kuldiga (4), Saldus (4) and Jelgava (6–17) formations of the Jūrmala core. **1, 2,** *Longiscula smithii* (Jones); 1, right lateral view, TUG 1820-1, sample 992, depth 717.6 m; 2, juvenile carapace, TUG 1820-2, left lateral view, sample 996, depth 716.2 m. **3,** *Microcheilinella rozhdestivenskaja* Neckaja, juvenile carapace, right lateral view, TUG 1820-3, sample 992, depth 717.6 m. **4,** *Circulinella gailitae* Meidla, juvenile right(?) valve, TUG 1820-4, sample 83, depth 742 m. **5,** Gen. A sp. n., TUG 1820-5, sample 85, depth 736.5 m. **6,** *Sigmbolbina camarota*, juvenile left valve, TUG 1820-6, sample 79, depth 748 m. **7,** *Daleiella rotundata* Meidla, juvenile right valve, TUG 1820-7, sample 79, depth 748 m. **8,** *Daleiella rotundata* Meidla, juvenile left valve, TUG 1820-8, sample 79, depth 748 m. **9,** *Daleiella rotundata* Meidla, juvenile carapace, ventral view, TUG 1820-9, sample 79, depth 748 m. **10,** *Easchmidtella* sp., right valve, TUG 1820-10, sample 79, depth 748 m. **11, 12,** *Elliptocyprites* sp.; 11, right(?) lateral view, TUG 1820-11, sample 79, depth 748 m; 12, juvenile carapace, ventral view, TUG 1820-12, sample 79, depth 748 m. **13,** *Airina cornuta* Neckaja, right valve, TUG 1820-13, sample 79, depth 748 m. **14,** *Rectella romboformis* Neckaja, left lateral view, TUG 1820-14, sample 79, depth 748 m. **15,** *Kinnekullea thorslundi* Henningsmoen, right valve, TUG 1820-15, sample 79, depth 748 m. **16,** *Hippula edolensis* (Gailite), right valve, TUG 1820-16, sample 79, depth 748 m. **17,** *Pullvillites laevis* Abushik & Sarv, right valve, TUG 1820-17, sample 79, depth 748 m.

The composition of the *Harpabollia harparum* association is very specific and different from both the Upper Katian and Llandoveryan ostracod assemblages in the Baltoscandian region (Truuver et al. in press). It has been interpreted as a cold-water immigrant assemblage from higher latitudes (Meidla 1996b, 2007). A number of characteristic short-lived genera in this assemblage make their first appearance in the region in the Hirnantian. The faunal relationship with the ostracod record from the Carnic Alps and Bohemia (see Schallreuter 1990) suggests a rapid immigration of the most characteristic members of the association into the Baltoscandian Palaeobasin, likely from higher palaeolatitudes (Meidla 1996b). This view gains further support from the discovery of *H. harparum* in the Hirnantian of Brazil (L. Gonçalves et al. pers. comm. 2019).

The ostracod record from the Riekstini (Brenchley et al. 2003, fig. 8) and Ruhnu cores (Meidla 2003) shows that most species of the *H. harparum* association range evenly through the Kuldīga Formation (Fig. 5). In the South Estonian sections (Valga, Taagepera), the ranges of these taxa are usually shorter and more variable, likely due to a higher environmental stress in the peripheral part of the distribution area of this association. The faunal pattern in the Jūrmala core, surprisingly with relatively short ranges of most key species (see Fig. 3), is more similar to the sections of the marginal distribution area. At the same time, only very few samples are barren and nearly a full record of ostracods from the Saldus Formation is considered particularly valuable, showing that the *H. harparum* association does range up to the boundary discontinuity and the appearance level of the new, post-glaciation fauna. There is no direct indication of possible redeposition that has been suggested in case of other fossil groups (Hints et al. 2010; Sorci et al. 2020) – there are no anomalies in terms of preservation or taxonomic composition.

The *H. harparum* association in the Jūrmala core is accompanied only by a few pre-Hirnantian species in the lower part of its distribution interval, as is characteristic of most of the Hirnantian ostracod successions. A rich and representative mixed assemblage where the key species of the *H. harparum* association co-occur with the species otherwise documented in the Adila or Ärina formations of North Estonia has so far been found only in the Ruhnu core (Meidla 2003) that has an intermediate position on the facies profile (Fig. 5).

In terms of graptolite zonation, the age of the *H. harparum* association was usually characterized as being confined to the *extraordinarius*–*persculptus* interval and being diagnostic of the Hirnantian in Baltoscandia. The comparison of the ostracod distribution data with the distribution ranges of other taxa of biostratigraphical importance in the sections where such data are available, allows us to address this relationship in more detail.

The cross section along the Valga–Taagepera–Ruhnu–Jūrmala–Riekstini line (Fig. 5) shows that the species of the *H. harparum* association make their first appearance usually above the lower boundary of the Kuldīga Formation. The appearance level is distinctly above the range of *Spinachitina taugourdeau* in these sections, coinciding nearly with the appearance levels of the zonal chitinozoan species *Conochitina scabra* and the conodont *Noixodontus girardeauensis*. It is noteworthy that the brachiopod taxa which, according to Hints & Harper (2015), are confined to the Hirnantian only, appear nearly at the same level in the Ruhnu core and are found a few metres higher than the appearance level of the *H. harparum* association in the Riekstini core. No co-occurrences of *S. taugourdeau* and the *H. harparum* association have been recorded so far. In addition to the sections shown in Fig. 5, *S. taugourdeau* is known from several North and Central Estonian sections (Rapla, Tamme, Vodja; Kaljo et al. 2001, 2004) but no ostracod data are available from these. Both groups have been studied in the Tartu core (Pöldvere et al. 1998). The appearance of *S. taugourdeau* has been recorded in the Halliku Formation 16.5 m below the lower boundary of the Saldus Formation and the beginning of the partially preserved HICE (Bauert et al. 2014). In the Tartu section the ostracod assemblage in this stratigraphic interval contains typical pre-Hirnantian taxa and no elements of the *H. harparum* association. The Kaugatuma section (Brenchley et al. 2003) contains *S. taugourdeau* in the oolitic limestone which is almost barren of ostracods.

There are several estimates of the duration of the post-Hirnantian recovery. Sepkoski (1998) suggested that the post-Hirnantian rebound lasted until the end of the Wenlock (about 16 My on the modern timescale). Analysing the recovery rates after the Hirnantian extinction, Krug & Patzkowsky (2004) concluded that the diversity in Laurentia rebounded within the first 5 My but they also emphasized that this figure could be different for different taxonomic groups and areas. These results were based on large data sets of alpha diversity. There are no reliable data currently available on the lowermost Silurian ostracods in Baltoscandia to compare the alpha diversity patterns. It is still noteworthy that the diversity of the new ostracod assemblage in the Stačiūnai Formation does not reach the diversity values characteristic of the Jelgava or lower Kuldīga formations in the Jūrmala section and the dominance index drops below 0.5 only 12 m above the lower boundary of the formation. Although data from a single section cannot be conclusive, this delayed diversification could, at least partly, be ascribed to the slow rates of post-extinction recovery. Analysing the response of ostracods to a massive volcanic ash fall, Perrier et al. (2012) suggest that the recovery on a regional scale may have lasted only 10^3 – 10^5 years

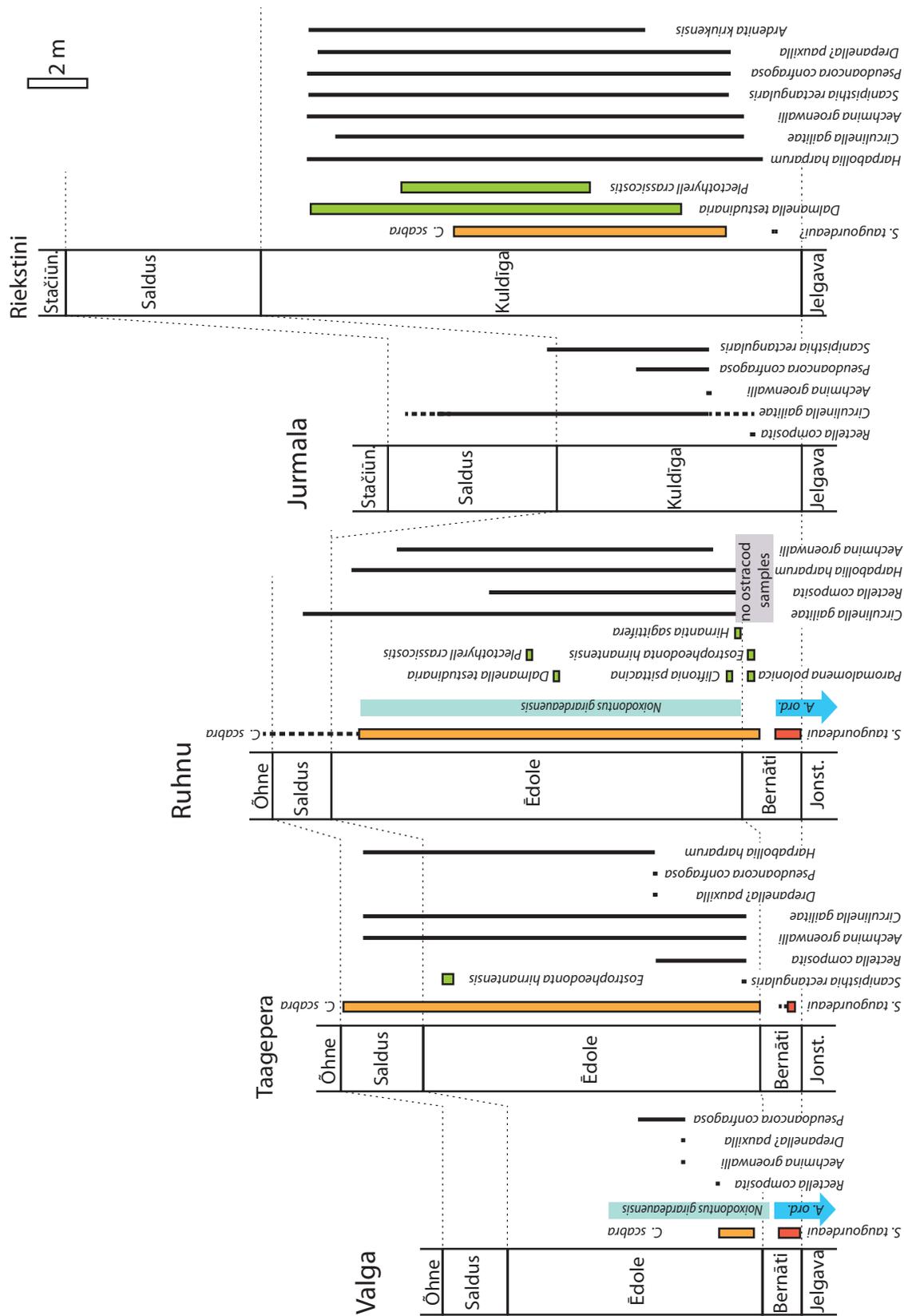


Fig. 5. Distribution of ostracods, selected brachiopods and zonal conodont and chitinozoan ranges along the Valga–Riekstini profile (see Fig. 1). Valga core after Männik (2001), Meidla (2001), Pöldvere (2001) and Kaljo et al. (2008); Taagepera core after Meidla (1996a), Brechley et al. (2003) and Harper & Hints (2016); Ruhnu core after Brechley et al. (2003), Meidla (2003) and Harper & Hints (2016); Riekstini core after Brechley et al. (2003). Abbreviations: *A. ord.*, *Amorphognathus ordovicicus*; Jonst., Jonstorp; Stačiün., Stačiünai.

depending on the magnitude of disturbance. If we accept the estimated 5 My recovery period for the post-Hirnantian recovery as suggested by Krug & Patzkowsky (2004), we should expect the influence traced throughout the Juuru and Raikküla regional stages. This means that the studied interval of the Jürjala section may be too short for analysing the recovery pattern.

REMARKS ON THE STABLE CARBON ISOTOPE STRATIGRAPHY

The Jürjala core was the first section studied where the HICE clearly reaches the strata formerly attributed to the Silurian (Meidla et al. 2011). The section and the isotopic curve have been addressed in several papers (e.g. Ainsaar et al. 2010, 2015; Meidla et al. 2011) but the stratigraphic implications of the data are often viewed cautiously.

The HICE peak in the Jürjala section is confined to the middle part of the Kuldīga Formation. Unlike the majority of isotopic curves from Estonia, the Jürjala curve has a very smooth falling limb that extends for more than 10 m into the Staciūnai Formation. The shape of different HICE curves in the sections of the Baltic states was thoroughly analysed by Brenchley et al. (2003) who interpreted the differences in the shape of falling limbs of the isotopic curves as evidence of gaps in successions. On this basis, the Jürjala core can be interpreted as one of the most complete sections of the Ordovician–Silurian boundary interval in the region.

The comparison of the stable carbon isotopic curve from the Jürjala core with the classical composite curve of the Monitor Range (LaPorte et al. 2009) is presented in Fig. 6.

The curve of the Monitor Range is complemented with the actual distribution ranges of some key zonal taxa and the biozonation from Finney et al. (1999) and LaPorte et al. (2009). It is noteworthy that the erosional surface marking the maximum sea-level lowstand in the section is apparently confined to the *M. persculptus* Zone and the only specimens of *M. persculptus* in this section are recorded 11 m higher this level. Fit of shapes of the two isotopic curves (Fig. 6) is remarkably good, with synchronous rising limbs and plateaus, as well as the falling limbs of similar shape. This fit suggests that a substantial part of the non-graptoliferous Staciūnai Formation should be attributed to the *persculptus* Zone.

ON THE LOWER BOUNDARY OF THE SILURIAN SYSTEM IN ESTONIA AND LATVIA

The lower boundary of the Silurian System was ratified in 1984 (Holland 1985). After the standardization of the

boundary, the tentative correlation of rock units in the eastern Baltic region with the standard graptolite zonation was re-evaluated (e.g. Kaljo et al. 1988; Nestor 1997; Nõlvak 1997). Due to insufficient biostratigraphic evidence, it was reasonable to leave the correlation of local rock units against the global stage boundaries unchanged, as the strata above the major gap are often unfossiliferous or lack biostratigraphically important taxa.

Regionally, the systemic boundary was drawn at the most remarkable gap in the succession and the overlying strata were traditionally attributed to the Silurian. Kaljo et al. (2001) correlated the entire Ärina Formation and the main part of the Kuldīga Formation with the *N. extraordinarius* Biozone and the interval of decline of the $\delta^{13}\text{C}$ values with the *N. persculptus* Biozone. The actual graptolite evidence at this level is, however, very limited (poorly constrained graptolite zones are shown in grey in Fig. 2). *Climacograptus?* sp. (*extrordinarius?*) and *Glyptograptus* ex. gr. *persculptus* were identified above the occurrence level of *Dalmanella testudinaria* in a core section drilled in the Baltic Sea area near the Kaliningrad Region (Ulst 1992; see also Kaljo et al. 2008). There is no record of microfossils nor stable carbon isotopic data available from this section. Additionally, *N. persculptus* is recorded in the material derived from the Borenshult locality in Östergötland, Sweden, in the same limestone block with ostracods of the *H. harparum* association (Meidla 2007; Truuver & Meidla 2015). The overlying Juuru Regional Stage comprises a regional interzone in graptolite zonation, with only sporadic graptolite occurrences tied to its uppermost part (Kaljo 1997; Nestor 1997).

In the conodont record, the range of *Amorphognathus ordovicicus* reaches the lower half of the Kuldīga Formation and the range of *Noixodontus girardeauensis* spans the rest of the formation (Männik in Hints et al. 2010). The Saldus Formation is poorly characterized and may locally contain redeposited conodont material (*ibid.*). In numerous Estonian and Latvian sections (Tartu, Valga, Ruhnu, Viki, Kolka, Stirnas), the lowermost part of the Juuru Regional Stage contains a scanty conodont fauna mostly determined only in open nomenclature (Männik 2001, 2003, 2010; Hints et al. 2010; Loydell et al. 2010). The resolution of conodont biostratigraphy is low in the Rhuddanian (Männik 2007). The appearance of *Walliserodus curvatus* is occasionally recorded in the basal part of the Juuru Regional Stage but this species is also found in the *Amorphognathus ordovicicus* conodont Zone (Zhang & Barnes 2007).

The chitinozoan biozonation is more detailed but the available evidence is somewhat controversial. Most of the Kuldīga Formation and the overlying Saldus Formation comprise the *Conochitina scabra* Biozone (Nõlvak & Grahn 1993; Hints et al. 2010). The lower part

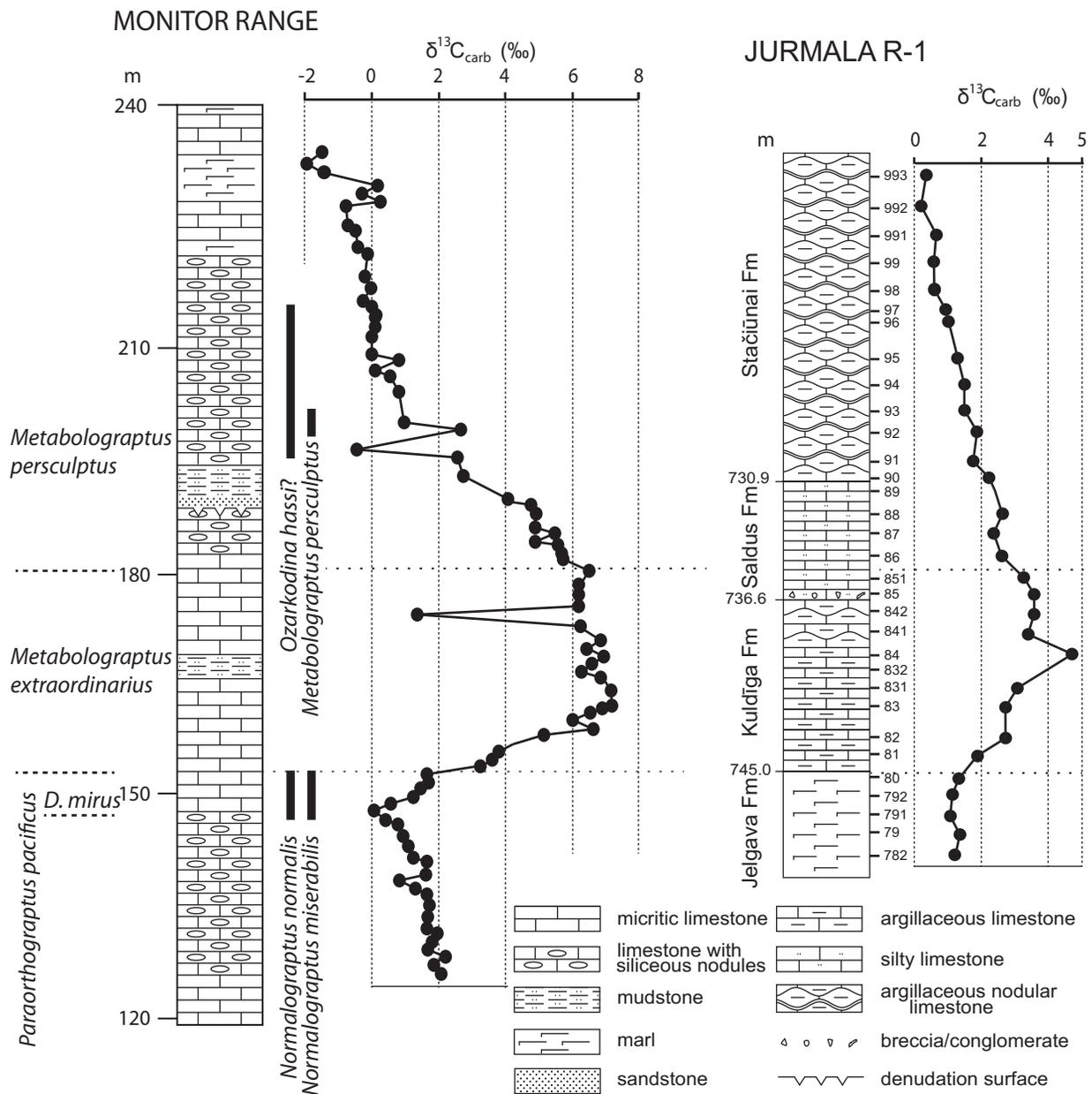


Fig. 6. Comparison of the HICE excursions in the Monitor Range section and Jürjala core. The Monitor Range composite section is drawn after LaPorte et al. (2009), graptolite zonation and distribution of selected graptolite and conodont species are complemented after Finney et al. (1999). The isotopic curve of the Jürjala section according to Ainsaar et al. (2010).

of the Õhne Formation is attributed to the *Ancyrochitina laevaensis* Biozone (Nestor 1994, p. 118; = *Spinachitina fragilis* Zone, renamed in Loydell et al. 2010). According to V. Nestor, ‘*A. laevaensis* Zone corresponds evidently to the lower part of the *acuminatus* graptolite Zone’ (Nestor 1994, p. 118) and ‘Interzone I is tentatively assigned to the upper part of the *acuminatus* Zone’ (*ibid.* p. 119). At the same time, the appearance of *A. laevaensis* and/or *S. fragilis* is confined to the falling limb of the

HICE in several sections (Ruhnu – Nestor 2003; Tartu – Põldvere et al. 1998). In addition, the index species of the successive range zones of *Conochitina scabra* and *Spinachitina fragilis* are co-occurring in the Tartu core, about 2.6 m above the lower boundary of the Õhne Formation.

It is obvious that finding a good biostratigraphic marker for an approximation of the lower boundary of the Silurian in the eastern Baltic region is rather complicated

and requires further study of the Juuru Regional Stage. Among the existing zonal markers, the closest suitable biostratigraphic horizon would likely be the base of the *Belonechitina postrobusta* conodont Zone, usually confined to the middle parts of the Varbola and Õhne formations (Nestor 1994) and tentatively drawn within the *Parakidograptus acuminatus* graptolite Zone (Verniers et al. 2008) or at the base of the *Cystograptus vesiculosus* graptolite Zone (Nestor 2012).

Kaljo et al. (2011) state that the highest species diversity of major fossil groups in the Ordovician–Silurian boundary interval is confined to the uppermost Katian and the losses in the Pirgu Regional Stages comprise 72% of the species. Among ostracods, there is a less dramatic change: 51% of the species known in the underlying strata range into the Porkuni Regional Stage (revised data based on Meidla 1996a and unpublished data) and the transitional taxa are forming 77% of all ostracod species recorded in the Porkuni Regional Stage. In the Jürjala core, this stage boundary (depth 745 m) marks a sharp diversity drop and rise of dominance among ostracods.

The boundary between the Saldus and Stačiūnai formations that is marking a turnover among ostracods in the Jürjala core corresponds to the major regional disconformity and a gap in the absolute majority of sections in the eastern Baltic region. For decades, this gap has been referred to as the lower boundary of the Juuru Regional Stage and a marker of the lower boundary of the Silurian System in the Baltic area. Analysing large datasets of species distribution across the Ordovician–Silurian boundary, Nestor et al. (1991) and Kaljo et al. (2011) emphasize the meaning of this boundary. The species loss in the Porkuni Regional Stage comprises 92% of the major fossil groups, clearly exceeding the normal background extinction rate, whilst the overlying Juuru Regional Stage is characterized by an extremely high appearance rate (93% – Kaljo et al. 2011). Among ostracods, this level marks a complete turnover, both in the major data set of alpha diversity and in the Jürjala core at a depth of 730.9 m. Rare references to the ostracod species possibly crossing this boundary need to be reviewed. This regional disconformity is equivalent to the deepest regression (regression after the transgressive–regressive (T–R) cycle IV) by Kiipli & Kiipli (2020, fig. 7). The other T–R cycles distinguished in this paper are not observable in the Jürjala core. The two gaps recognized in the Jürjala section may be correlated with the widespread Hirnantian unconformities HA and HB by Bergström et al. (2006). Their correlation with the regressive events distinguished by Kiipli & Kiipli (2020) could not be well substantiated based on the ostracod record only and is further complicated by the fact that the stratigraphic order of the members of the Ärina Formation may vary even in nearby sections (Ainsaar et al. 2015).

CONCLUDING REMARKS

1. The studied interval of the Jürjala core (Fig. 3) represents an almost complete succession throughout the Ordovician–Silurian boundary interval, containing ostracods in the majority of micropalaeontological samples. The transition from the latest Katian into the Hirnantian is characterized by a remarkable drop in ostracod diversity and the appearance of the *Harpabolliia harparum* association above the disappearance of *Spinachitina taugourdeau*, within the *Conochitina scabra* chitinozoan Zone. The lowermost part of the *H. harparum* association still contains a mix of taxa from the underlying strata and exotic binodicope species that are interpreted as immigrants from higher latitudes, whereas higher in the section the long-ranging taxa disappear.
2. The *H. harparum* association disappears at the regional disconformity at the base of the Stačiūnai Formation. It is replaced by a low-diversity fauna dominated by *Longiscula smithii* (previously termed ‘the Silurian ostracod fauna’ in many research papers), likely within the *M. persculptus* Zone. Very high ostracod dominance values are observed in the upper Kuldīga Formation, in the Saldus Formation and also in the lower part of the Stačiūnai Formation. A slow rise in species diversity can be ascribed to the slow recovery rates after the Hirnantian biotic crisis.
3. The isotopic curve of the Jürjala section shows a good fit with the isotopic curve from the Monitor Range, Nevada, with parallel rising limbs and plateaus, as well as the long falling limbs of similar shape. Although the isotopic correlation has currently gained no support from the biostratigraphy of the Baltoscandian region, the graptolite data from the Monitor Range section, particularly the record of *M. persculptus*, support the correlation of a substantial part of the non-graptoliferous Stačiūnai Formation with the *persculptus* Zone. This shows that the regional disconformity, which traditionally has been equated with the lower boundary of the Silurian, marks a major turnover among ostracods in the Jürjala section and the appearance of ‘Silurian faunas’ among the principal fossil groups all over the region is actually confined to the upper Hirnantian.
4. The fact that the falling limb of the HICE curve reaches the strata formerly attributed to the Silurian has been documented before, but its stratigraphic implications have to be considered. In spite of the fact that the systemic boundary interval is characterized by low diversity in most fossil groups, it might be reasonable to look for a new suitable biostratigraphic marker to be used as an approximation of the lower boundary of the Silurian System in the region. Of the well-known zonal markers, the closest suitable horizon would currently be the base of the *Belonechitina postrobusta* chitinozoan

Zone in the middle parts of the Varbola and Õhne formations that has so far been tentatively correlated within the *Parakidograptus acuminatus* graptolite Zone.

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Supplementary online data

Supplementary online material to this article can be found at <https://doi.org/10.23679/503>. It contains numerical occurrence data of ostracods and sample information.

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Ordoviitsiumi ja Siluri piirikihtide ostrakoodid Jūrmala puursüdamikus ning tulemuste mõju Balti regiooni stratigraafia

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Ordoviitsiumi ja Siluri piirikihtide ostrakoodide levik Jūrmala puursüdamikus võimaldas detailselt analüüsida Ordoviitsiumi lõpu väljasuremisega seotud muutusi selle fossiiligrupi levikus. Väga mitmekesine pre-Hirnantia ostrakodikooslus vahetus Hirnantia ea algul *Harpabollia harparum*'i assotsiatsiooniga, mis on levinud kogu Baltoskandia regioonis ja Kirde-Poolas ning on iseloomulik Hirnantia lademele. Ostrakoodide liigiline mitmekesisus väheneb Kuldīga ja Salduse kihistus märgatavalt ning selle taastumine lasuvas Stačiūnai kihistus on aeglane. See võib seotud olla mereliste faunade mitmekesisuse üldiselt aeglase jäätumisjärgse taastumisega Ordoviitsiumi lõpul ja Siluri algul. *H. harparum*'i assotsiatsioon ilmub läbilõigetel *Spinachitina taugourdeaui* leidudest kõrgemal ja selle ilmumise tase langeb ligikaudu kokku *Conochitina scabra* ning *Noxodontus girardeauensis*'e ilmumisega. Vähesel mitmekesisusega *Longiscula smithii* assotsiatsiooni ilmumine Salduse ja Stačiūnai kihistuse piiril tähistab ühtlasi fauna täielikku uuenemist. Stabiilsete süsinikusotopide suhte muutuste kõver Jūrmala läbilõikes lubab oletada, et tegemist on ühe kõige täielikuma Ordoviitsiumi–Siluri piirikihtide läbilõikega Baltoskandia regioonis. Selle kõvera võrdlus teiste lähipiirkonna kõverate ja Monitor Range'i (Nevada) isotopkõveraga näitab, et traditsiooniliselt Siluri alumise piirina käsitletud regionaalse põiksuse tasemel toimuv ostrakoodide ning muu fauna uuenemine on seotud Ordoviitsiumi ladestu kõige nooremaks osaks oleva *M. persculptus*'e graptoliiditsooniga, mis võib ulatuda enam kui 10 m Stačiūnai kihistusse. Siluri alumise piiri asendi täpne kindlaksmääramine ja selle leidmiseks sobiva regionaalse biostratigraafilise markeri leidmine nõuab täiendavaid uuringuid.