

## A bio-chemostratigraphical test of the synchronicity of biozones in the upper Silurian of Estonia and Latvia with some implications for practical stratigraphy

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**Abstract.** The paper discusses the reliability of different biozones in terms of their synchronicity when crossing facies boundaries within a sedimentary basin. Graptolite biozones are the most trusted ones, but also biozones based on conodonts, chitinozoans and less ‘authoritative’ groups like ostracodes and vertebrates are used. The integration of bio- and chemostratigraphy aids the understanding of the pattern and timing of fossil distribution. Despite different environments most of the analysed biozones are in general synchronous units and in the majority of cases their time signals do not contradict each other. The much discussed *Ozarkodina crispera* (and its two morphs) has a stratigraphical range in the East Baltic that is longer than commonly recognized elsewhere. Its first occurrences in Estonia have been reported from shallow-water facies below the Mid-Ludfordian Carbon Isotope Excursion. The geographical distribution of *Oz. crispera* is much wider in the upper Ludfordian open shelf rocks and a few occurrences are also known in the lowest Přídolí in the East Baltic. Analogous ecostratigraphical trends are characteristic of some other fossil species. The analysis demonstrates that, when properly studied, all of the fossil groups considered can provide useful biostratigraphical information. The subdivision of the Přídolí Series into two stages is discussed. Bio-chemostratigraphical data confirm the late Ludfordian age of the Kuressaare Formation and its correlatives. The bio- and chemostratigraphical testing of biozonal indices suggests some tentative correlations with other areas, in particular the type Ludlow area, and enables identification of the Silurian–Devonian boundary in the East Baltic.

**Key words:** Baltica, biostratigraphy, chemostratigraphy, facies, Silurian, synchronicity of units.

### INTRODUCTION

Ecostratigraphy was officially inaugurated as an IGCP project in 1973 and became popular within the next two decades. A leading idea was that most fossils occur in specific facies (wider or more limited) suitable to them. Facies changes over a larger basin are as a rule diachronous and biozones are tied to them, especially in a shallow sea. The inhabitants of deeper waters could therefore more likely be used as precise chronostratigraphic tools.

Our project in the 1980s aimed at testing these ideas; however, it was left unfinished. Much time has passed and not all participants are among us now, but we would like to note important contributions by colleagues from Riga (Latvia) – Lilita Gailite and Rita Ulst, and from the Institute of Geology, Estonian Academy of Sciences in Tallinn – Einar Klaamann, Reet Männil, Heldur Nestor, Madis Rubel and Lembit Sarv (all except Heldur are deceased). Here we discuss just a fraction of the data collected and concentrate on one aspect – how reliable

different biozones are in terms of their synchronicity when crossing facies boundaries within a sedimentary basin or over a wider area. Graptolite biozones are usually the most trusted ones, but we will also analyse the behaviour of biozones based on conodonts and chitinozoans, and also on less ‘authoritative’ groups of fossils such as ostracodes and ‘microvertebrates’ (mostly thelodont and acanthodian microremains).

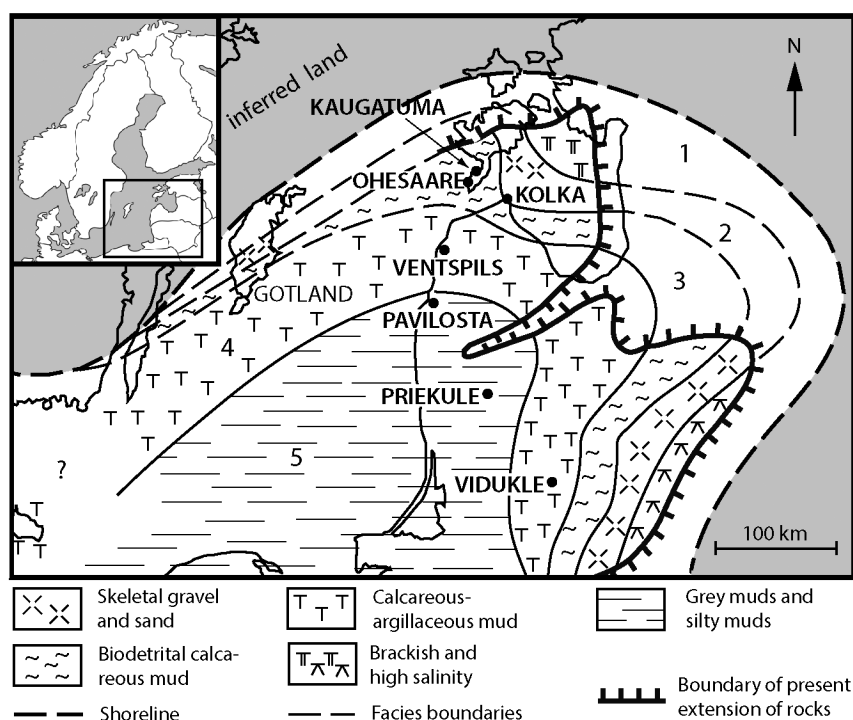
Sporadic occurrences of macrofossils (e.g. stromatoporoids, tabulate corals, brachiopods, trilobites, graptolites) show a community pattern that is in harmony with the changing facies pattern (Kaljo et al. 1983). Microfossils like ostracodes (Sarv 1982; Gailite et al. 1987) and especially chitinozoans (Nestor 2009, 2011, 2012), conodonts (Viira 1982, 1999, 2000) and vertebrate microremains (Märss 1986, 1997; Märss & Männik 2013) that have recently been revised enable more perfect biozonations. Still, in addition to knowledge-based distrust, there remain discrepancies between biostratigraphical datings using fossil groups, especially when shelly faunas are considered.

Nowadays we have carbon isotope chemostratigraphy with the possibility of using  $\delta^{13}\text{C}$  excursions as time markers for the independent checking of the diachroneity or synchronicity of biozonal units. As a basis for this discussion three drill core sections (Ohesaare, Ventspils-D3 and Pavilosta-51) studied for  $\delta^{13}\text{C}$  and also some data from three others located in the same area on the east coast of the Baltic Sea were considered. The Kaugatuma and Ohesaare boreholes on the Sõrve Peninsula in Estonia and the Kolka-54 borehole in the north of the Kurzeme Region of Latvia are located rather close to the Silurian shore and three more Latvian ones (Ventspils, Pavilosta and Priekule-20) are in the offshore area (Fig. 1). In addition to the main goal of the paper, expressed above, we use results of the complex bio-chemostratigraphical synchronicity test for elaborating our views about several current topics of upper Silurian stratigraphy, including details of chrono- or time correlation, boundary criteria and Pridoli subdivisions. Being familiar with a recent paper by Cramer et al. (2015), we should note that in our paper terms like ‘time marker’, ‘dating’, etc. are used from the positions of relative time concept in geology.

Samples for geological and isotope studies (whole-rock  $\delta^{13}\text{C}$  analyses) from the Ohesaare, Ventspils and Pavilosta cores are kept at the Institute of Geology at Tallinn University of Technology (see [www.sarv.gi.ee](http://www.sarv.gi.ee)). A more complete set of carbon isotope data (including new analyses from the Pavilosta core) is available online at <http://dx.doi.org/10.15152/GEO.14>. All palaeontological collections studied for biozonal indices are referred to in the papers quoted above.

### GEOLOGICAL SETTING

The study interval embraces the entire upper Silurian. Based on the commonly accepted stratigraphical framework (Gailite et al. 1987; Nestor 1997; Männik 2014), the sections (Fig. 2) are subdivided into four regional stages (RSs): the Paadla and Kuressaare RSs of the Ludlow and the Kaugatuma and Ohesaare RSs of the Pridoli. This chronostratigraphy is complicated in the shallower sea area (Estonia) by some gaps in the Paadla RS (Märss 1992; Jeppsson et al. 1994; Nestor 1997; Viira & Aldridge 1998), which have partly been filled in



**Fig. 1.** Location of the discussed core sections on the background of the general facies zonation of the Baltic Gulf in early Ludlow time. Modified from Bassett et al. (1989) and Kaljo & Martma (2006). Facies belts (signature shows the presence of sediments, white area – postsedimentary erosion or no data): 1, tidal-flat-lagoonal; 2, high-energy shoal-bar; 3, open shelf, mid-ramp (facies 1–3 form shallow carbonate shelf in Fig. 2); 4, offshore shelf, outer ramp; 5, ramp/shelf depression.

by recent studies (Viira & Einasto 2003) or confirmed by chemostratigraphy (Kaljo & Martma 2006; Kaljo et al. 2012). Thus, the Paadla RS fits rather uncomfortably into the type Ludlow framework even if a plausible correlation of some horizons is possible (Viira & Aldridge 1998; Märss & Miller 2004; Loydell & Frýda 2011).

In terms of lithostratigraphy, the Torgu, Kuressaare, Kaugatuma, Ohesaare, Dubysa, Pagegiai (Mituva and Engure), Ventspils, Minija and Jura (Targale) formations (below Fm. or fms) have been established (Fig. 2) and mostly subdivided into beds or members (not shown here). Such a terminology reflects changes in three main lithofacies belts, from the shoreface towards the deeper shelf and basin, as well as sea level fluctuations and a general regressive trend through the late Silurian. The list of facies belts below is based on a model of facies zonation of the Palaeobaltic Basin compiled by Nestor & Einasto (1977) and later modified terminologically by different authors (Bassett et al. 1989; Kaljo et al. 1991; Nestor & Einasto 1997). It is presented here in a slightly generalized manner and without involving aspects of shelf/ramp relationships. We assume in general that these changed during the late Silurian regression when a wide epicontinental shelf sea narrowed to a pericontinental sea of the ramp type.

In Fig. 2 the three generalized facies belts (compare the caption of Fig. 1) are marked by colours for easier consideration of the differences in environmental conditions where the biozonal index species under study were living:

- (1) *shallow carbonate shelf* (green) – different lime- and dolostones with marl intercalations dominate the entire study interval of the Ohesaare and Kolka-54 (not shown; location in Fig. 1) sections, the upper and middle parts of the Ventspils core and the upper part of the Pavilosta core;
- (2) *gentle slope of the carbonate shelf (= outer shelf)* (blue) – marls with limestone nodules and rare interbeds occupy most of the lower part of the Ventspils core and the middle part of the Pavilosta core;
- (3) *intracratonic and basinal depression* (grey) – relatively deep-water graptolitic marls and argillites occur in most of the lower part of the Pavilosta core and at the bottom of the Ventspils core.

## MATERIAL AND METHODS

To understand the synchronicity problems, we used carbon isotope data for chemostratigraphical checking of biostratigraphical data. The  $\delta^{13}\text{C}$  curves are based on ca 300 whole-rock analyses from the Ohesaare, Ventspils (Kaljo et al. 1997, 1998, 2012) and Pavilosta

(new data; Table 1) cores. The Ventspils curve is the most complete showing the major Mid-Ludfordian Carbon Isotope Excursion (MLCIE) peaking with a  $\delta^{13}\text{C}$  value of 5‰ at a depth of 465 m in the uppermost Mituva Fm., and the Late Ludfordian twin excursion (LLCIE) with two minor peaks within the Ventspils Fm., respectively LLCIE1 (1‰) at 446 m and LLCIE2 (1.4‰) at 427 m. The same set of excursions, but less complete, is identified in the Pavilosta core at the boundary of the Dubysa and Pagegiai fms (MLCIE 4.2‰ at 739 m) and in the lowermost part of the latter (LLCIE1 2‰ at 723.7 m). The Late Ludfordian twin excursion is rather weakly represented in the Ohesaare section (LLCIE1 0.5‰ at 95 m and LLCIE2 1‰ at 72 m), but the MLCIE is missing there due to a stratigraphical gap. There are several discontinuity surfaces that can serve as a probable MLCIE level in the uppermost part of the Torgu Fm. Based on fossil occurrences (Figs 2 and 3), we have used here the one at 97.4 m. However, this is only tentative, as there are several surfaces that, alone or together, could mark a bigger gap.

Presuming that the approximate peak levels of the  $\delta^{13}\text{C}$  excursions are more-or-less synchronous, especially in such closely located sections as the studied ones, we apply these levels as chronostratigraphical benchmarks for analysing the stability and synchronicity issues of the first appearance datums (= FADs). We use the FADs of index species, not the full ranges of biozones, believing that this method makes Fig. 3 more readable without significant loss of information. Anyway, when discussing the figure, we consider also whole range data (e.g. of *Eisenackitina lagenomorpha*). Plotting the FADs of the most valuable biozonal index species against the noted benchmarks according to the actual depths of occurrences along the sections (Fig. 3), we try to understand how stable the consecutive order of the FADs is and whether these appearances are synchronous in sections of different facies origin. For this purpose the FADs of five graptolite biozonal species and nine ostracode indices in the Latvian sections are shown according to data from Gailite et al. (1987) and Ohesaare ostracode data from Sarv (1971). Those of seven chitinozoan biozones are presented according to Nestor (2009, 2011, 2012), seven conodont ones from Viira & Aldridge (1998) and Viira (1999, 2000) and seven vertebrate indices according to Märss (1986, 1997) and Märss & Männik (2013).

## GENERAL COMMENTS ON BIOSTRATIGRAPHY

Deeper-water rocks of the Dubysa Fm. in the Pavilosta and Ventspils cores contain numerous graptolite remains (Gailite et al. 1987) and the respective biozones

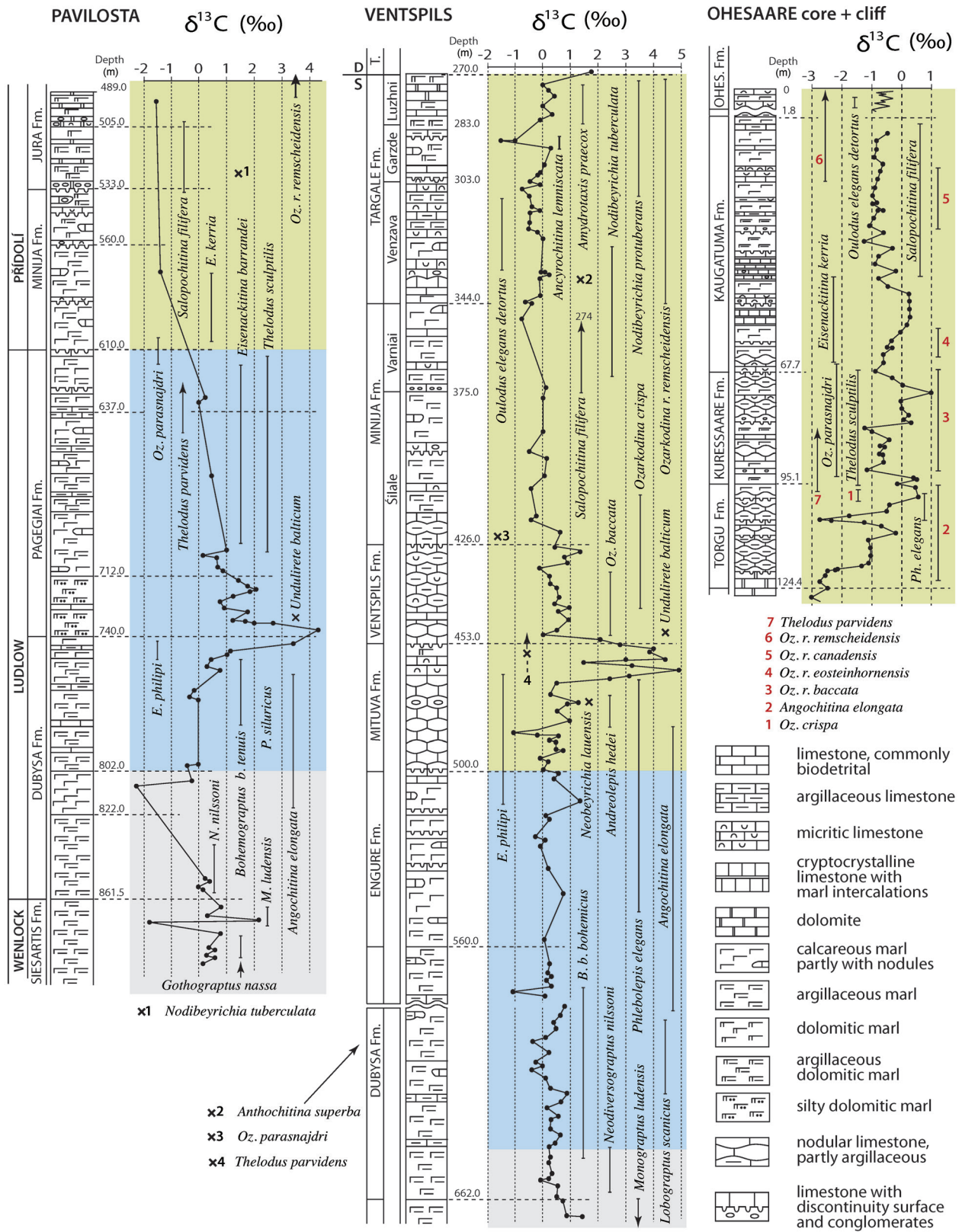
**Table 1.** Whole-rock carbon isotope data from the Pavilosta (Kurzeme, Latvia) drill core

Stratigraphy Formation, Beds	Depth (m)	$\delta^{13}\text{C}$ (‰)	Remarks	Stratigraphy Formation, Beds	Depth (m)	$\delta^{13}\text{C}$ (‰)	Remarks
Pagegiai	630.3	0.2		Dubysa, Nova	750.0	0.6	
Pagegiai	636.0	0.02		Dubysa, Šešupe	752.0	0.65	
Pagegiai	663.6	0.42		Dubysa, Šešupe	754.8	0.53	
Pagegiai	696.4	0.96		Dubysa, Šešupe	760.0	0.78	
Pagegiai	698.9	0.33		Dubysa, Šešupe	777.1	-0.1	
Pagegiai	700.5	0.81		Dubysa, Šešupe	781.6	-0.25	
Pagegiai	711.4	0.84		Dubysa, Šešupe	782.9	-0.01	
Pagegiai	713.1	0.98		Dubysa, Šešupe	799.2	-0.01	
Pagegiai	717.0	1.3		Dubysa, Šešupe	800.0	-0.32	
Pagegiai	721.0	1.68		Dubysa, Šešupe	811.5	-0.27	
Pagegiai	723.7	2.01	LLCIE1 peak level	Dubysa, Šešupe	813.35	-2.19	
Pagegiai	724.7	1.83		Dubysa, Šešupe	850.00	0.13	
Pagegiai	726.4	1.13		Dubysa, Šešupe	852.0	0.29	
Pagegiai	728.8	0.76		Dubysa, Šešupe	857.00	-0.06	
Pagegiai	730.4	0.95		Dubysa, Šešupe	858.00	0.09	
Pagegiai	733.3	1.78		Dubysa, Šešupe	862.0	0.71	
Pagegiai	734.3	1.7		Siesartis	869.00	0.41	
Pagegiai	735.2–3	1.24		Siesartis	872.0	2.14	Late Homeric CIE
Pagegiai	736.3	1.7		Siesartis	872.6	-1.87	
Pagegiai	737.7	1.99		Siesartis	883.0	0.77	
Pagegiai	738.4	2.66		Siesartis	892.0	0.32	
Pagegiai	739.0	4.23	MLCIE peak level	Siesartis	894.0	0.45	
Dubysa, Nova	744.0	3.49		Siesartis	896.0	0.21	
Dubysa, Nova	746.7	1.1		Siesartis	898.2	0.48	
Dubysa, Nova	749.0	1.01		Riga, Jugla	900.5	0.07	

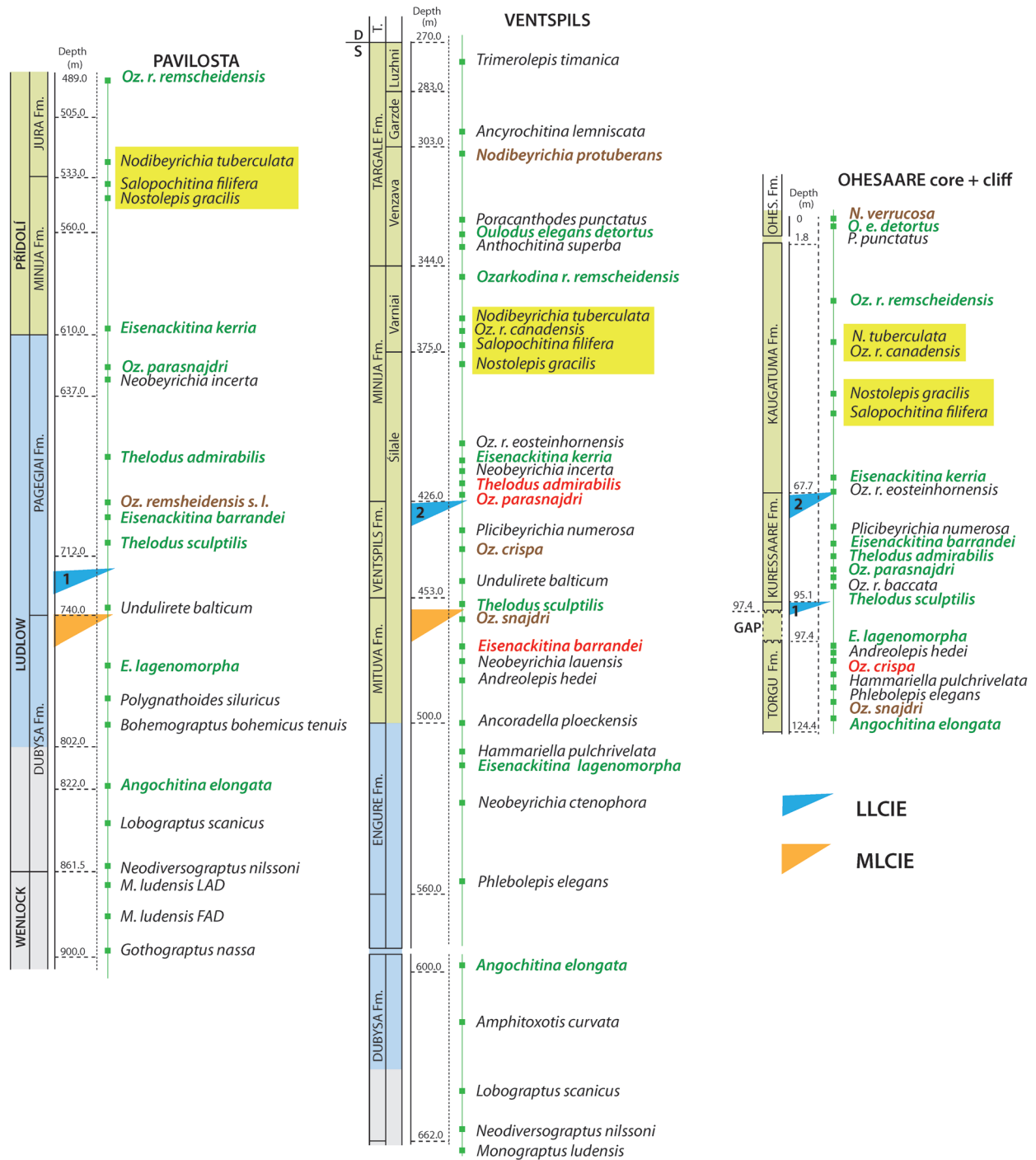
(*Neodiversograptus nilssoni*, *Lobograptus scanicus*) date the lowermost Ludlow without any notable problems (Figs 2, 3). Graptolites became rarer higher in the section, but still the upper Gorstian *Pristiograptus tumescens minor* Biozone (Bz. below) and a continuation into the lower Ludfordian with *Bohemograptus bohemicus tenuis* and *Pseudomonoclimacis tauragensis* are recognizable. Paškevičius (1997) considers the latter (according to Urbanek 1997 synonymous with *Monograptus haupti* Kühne) as an index species of a rather wide biozone between the *L. scanicus* Bz. and the *Monograptus balticus* Bz. (see Loydell 2012). The last occurrences of *B. b. tenuis* are known from the topmost Dubysa Fm. of the Pavilosta core below the *Eisenackitina lagenomorpha* Bz. and the MLCIE. Simultaneously with facies changes (shallowing of sea and appearance of the corresponding carbonate rocks) shelly fauna became dominant in fossil associations.

Conodonts traditionally play a leading role in Silurian microfossil biostratigraphy but chitinozoans have also

proved their high value. The most important papers for understanding the conodont faunas of Baltica are Jeppsson (1983, 2005) and Viira (1999, 2000). For chitinozoans those by Eisenack (1968), Laufeld (1974) and Nestor (2009, 2011, 2012) are the most valuable (a general background is available in Verniers et al. 1995). The vertebrate microremains of the region have been thoroughly studied by many authors (Gross 1967; Karatajūtė-Talimaa, 1978; Märss 1986, 1997; Fredholm 1988; Talimaa 2000). The biostratigraphical renown of these fossils is high, but the low level of knowledge in many areas elsewhere hampers their wider usage. Numerous studies (e.g. Martinsson 1967, 1977 in Gotland; Gailite in Gailite et al. 1967; Sarv 1968, 1971 and Rubel & Sarv 1996 in the East Baltic; Siveter 1989, 2009 in Britain) have made ostracodes popular in Silurian stratigraphy. The present authors believe that ostracode information is worthy of wider stratigraphical use in this part of the world. To support this view, a few examples are given below.



**Fig. 2.** Lithological logs, stratigraphy, facies interpretation,  $\delta^{13}\text{C}$  trend and a selection of ranges of fossils dating certain stratigraphical levels in the Pavilosta, Ventspils and Ohesaare core and cliff sections. Background colours denote general facies situation as follows: green – carbonate shelf; blue – outer shelf; grey – intracratonic depression.



**Fig. 3.** First appearance datums of the upper Silurian biozonal index species in the three core sections plotted according to actual occurrence depths and their synchronicity evaluated based on the chemostratigraphical time levels. Font colours are as follows: black – normal synchronous occurrences; green – in general the same but some comments are needed; red – for some reason the occurrence is abnormal; brown – the occurrence may be doubtful due to problems with taxonomy, identification, etc. The FADs of a group of typical mid-Přidolí index species are highlighted with yellow background. Abbreviations: LLCIE – Late Ludfordian Carbon Isotope Excursion twin peaks (1 and 2). MLCIE – Mid-Ludfordian CIE.

## THE DISTRIBUTION OF THE FIRST APPEARANCE DATUMS

The Ventspils section (Fig. 3) is the most complete and we have listed there 31 FADs of biozonal index species (four species occur only in this section) from the bottom of the Ludlow to the end of the Přídolí. The Ohesaare core, consisting of shallower-water rocks, is incomplete due to slight erosion at the top and gaps in the lower and middle Ludlow. The Pavilosta section, representing the deepest part of the basin, is complete in the main part but more deeply truncated at the top (the uppermost Přídolí is missing). For easier reading the names of index species are coloured according to the evaluation given in the text and explained in the caption of Fig. 3.

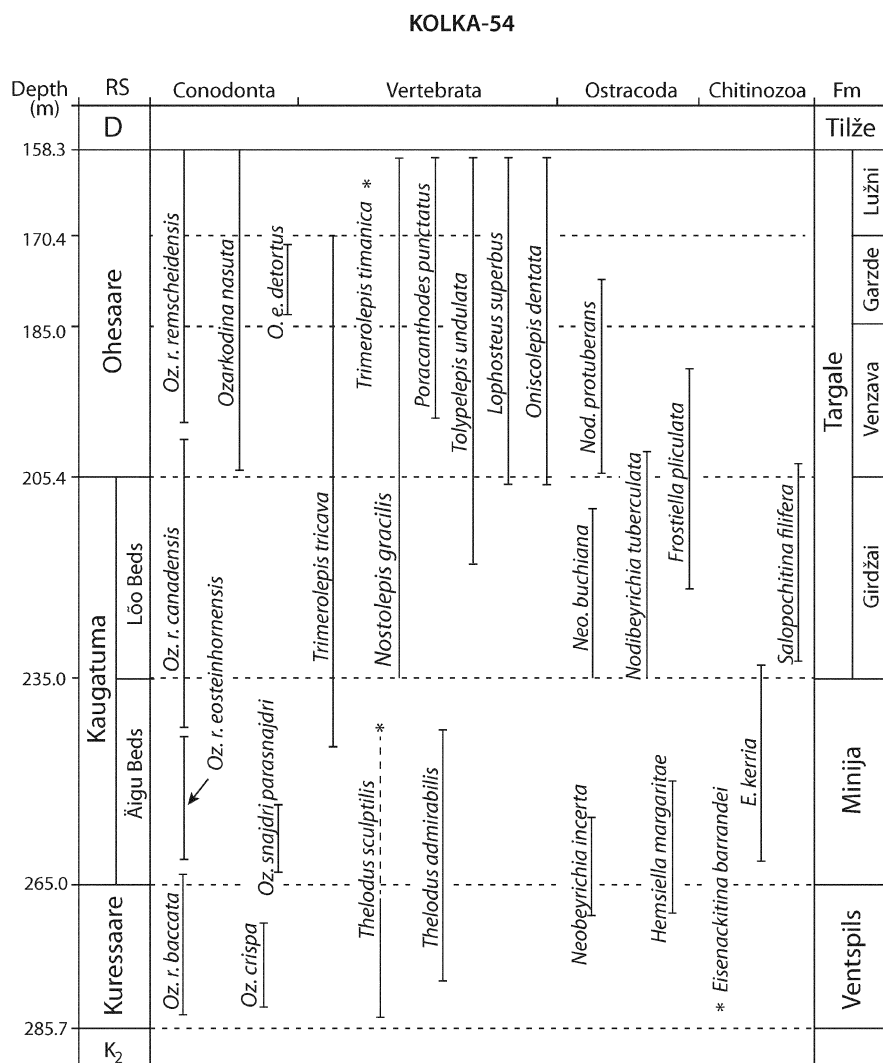
Graptolite biozonal indices are featured in black in Fig. 3, i.e. all appearances are considered synchronous as far as these are not only single occurrences but supported by ranges. The FAD of the deep-water conodont *Polygnathoides siluricus* in Pavilosta (Viira 1982) is also shown in black because its several occurrences in this section are recorded at an expected level below the MLCIE (e.g. as in the Vidukle core, Martma et al. 2005 and on Gotland, Jeppsson 2005). This species is not found in shallower facies but its value as a chronostratigraphic marker is high. Other fossils indicated in black will be commented on below.

The consecutive order of the FADs of the analysed indices is mostly logical or the FADs occur at least in the ‘right’ interval with slight variation in order. This convinces us that these FADs (green and black font in Fig. 3) are more or less synchronous (e.g. *Angochitina elongata*, *Eisenackitina lagenomorpha*), especially when their correlation lines do not cross the levels with carbon isotope excursions (MLCIE, LLCIE). The FAD of the latter species occurs in Ohesaare just below a gap, believed to mark the MLCIE in that section, and above another possible gap (a discontinuity surface at 100.0 m), which may suggest that this first occurrence is a slightly belated ‘FAD’. Other indices, e.g. the vertebrates *Thelodus sculptilis* and *T. admirabilis*, ostracodes *Undulirete balticum* and *Neobeyrichia incerta*, conodont *Ozarkodina remscheidensis eosteinhornensis*, chitinozoan *Eisenackitina barrandei*, can cross facies boundaries (i.e. also formational boundaries), but remain generally in the same time interval as in the Ventspils section. *Thelodus admirabilis* and *Oz. snajdri parasnajdri* (Fig. 3) show a slight diachroneity when they appear above the LLCIE2 level. All the named examples of FADs occur close to the MLCIE and LLCIE so that the isotope excursions control well these appearance levels.

However, as usual, not all is so straightforward. For example, *Oz. snajdri* appears in the lower Torgu Fm. in the Ohesaare core, which is well below a gap where

the MLCIE is anticipated, just below the MLCIE in the Ventspils core and a doubtful broken specimen was found far above the LLCIE1 in the Pavilosta core. According to Viive Viira, there might be some taxonomic problem involved, as was the case with *Oz. crispa*, which is not represented by its typical form in the Baltic but by morphs  $\alpha_2$  and  $\alpha_3$  (Viira & Aldridge 1998). The distribution of the morphs seems more or less random, with slight preference for  $\alpha_2$  occurring more commonly at some localities but without a clear pattern. This allows us to use in our discussion the name *Oz. crispa*, provided that we remember we are not talking about a typical morph  $\alpha_1$ , but about two others still belonging to the same species concept (Viira & Aldridge 1998). This policy is in accord with the comment by C. Corradini after checking these early morphs in 2014 confirming that ‘these are clearly conspecific with those in Sardinia and mostly elsewhere’ (Peep Männik, pers. comm.). Taking *Oz. crispa*, as represented in our data set, we see (Figs 2–4; the Kaugatuma core and several localities in the outcrop area; Viira & Aldridge 1998) that FADs in shallow-water facies appear in the Sauvere and Himmiste beds of the Paadla Fm. These beds are usually correlated with the Upper Bringewood–Lower Leintwardine fms of Britain (Märss & Miller 2004) or Upper Hemse Beds of Gotland (Jeppsson et al. 1994), clearly underlying the MLCIE level in these areas. Slightly southwards (and seawards) from the shoreface, in the Kaugatuma and Ohesaare cores, *Oz. crispa* occurs also in the topmost Paadla (Uduvere Beds) and Torgu fms, whereas a LAD is reported from the lowermost Kuressaare Fm. in Kaugatuma. A bit farther southwards in the Kolka core (see Fig. 1 for location) the range of *Oz. crispa* is entirely within the Kuressaare Fm., and in the Ventspils core to the time represented by the Ventspils Fm. with a LAD at the bottom of the Minija Fm. In summary, we see here a striking ecostratigraphical trend, where a species was widening its distribution area towards the deeper sea during the second half of the Ludlow when a general regression was dominating and a relatively big sedimentary hiatus formed in peripheral areas of the basin in the mid-Ludfordian. In general, the range of this index species characterizes well the upper Ludfordian with its FAD in the middle of the stage and LAD very low in the Přídolí.

Trying to clarify some taxonomic problems, Viira & Aldridge (1998) described a new subspecies *Oz. snajdri parasnajdri* from a short interval in the uppermost part of the Ludlow and lowermost Přídolí. Its FAD is between LLCIE1 and LLCIE2 in the Kuressaare Fm. in the Ohesaare core (and in the Kaugatuma core as well) and continues into the lower Kaugatuma Fm. in both cores. In the Kolka core the whole range of



**Fig. 4.** Ranges of the most important conodont, vertebrate, ostracode and chitinozoan species in the Kolka-54 core section, based on partly modified data from Viira (1999), Märss (1986) and Sarv (1977) and new data by V. Nestor.

*Oz. s. parasnajdri* is within the lower Kaugatuma RS, which is in harmony with the ecostratigraphical trend mentioned in the case of *Oz. crispa*. A single occurrence of *Oz. s. parasnajdri* in Ventspils is documented above the LLCIE2 very low in the Minija Fm. but still below the FAD of *Eisenackitina kerria*. In the Pavilosta core the range of *Oz. s. parasnajdri* begins lower – at the top of the Pagegiai Fm. (Fig. 3) and its LAD reaches the level of *E. kerria*. The index species *E. kerria*, partly together with *Oz. r. eosteinhornensis*, seems to be a good marker for the bottom of the Pridolí Series in certain sections, but regional differences are complicating the interpretation (Nestor 2011, p. 200). The lower boundary of the Minija Fm. might also be diachronous as it commonly is.

*Eisenackitina barrandei* shows an identical FAD of the biozone in the Ohessaare and Pavilosta sections between the MLCIE and LLCIE2 within the upper Ludfordian Kuressaare Fm. Only two Ludlow specimens (both cf.) have been identified from the Ventspils core and a few more (without cf.) from the bottom of the Pridolí (in all sections, see Nestor 2011). These data seem too scarce for fixing the FAD of *E. barrandei* below the MLCIE. The taxonomy needs to be revised. Based on the occurrences of *E. barrandei* in Ohessaare and Pavilosta, it seems reasonable to consider the upper Ludfordian a typical level for this species but some occurrences in the bottom of the Pridolí are normal as well as are known from the type Prague area (Paris in Kříž et al. 1986).



The Přídolí begins in the Ohesaare and Ventspils core sections just above the LLCIE2 and is defined by the FADs of *Oz. r. eosteinhornensis* and *E. kerria*. The latter marks the same level also in the Pavilosta core, but the records of *Oz. remscheidensis s.l.* need a revision. In the middle of the Přídolí there appear *Salopochitina filifera*, *Nostolepis gracilis* and *Oz. r. canadensis*, and slightly higher *Oz. r. remscheidensis* and *Nodibeyrichia tuberculata* (Fig. 3). Rubel & Sarv (1996, p. 185) noted that the *N. tuberculata* Bz. is ‘the best known and widely used time marker in upper Silurian stratigraphy’, and despite its seeming diachroneity in Fig. 3 (caused by differences in unit thicknesses), the FADs listed above are more likely synchronous. Based on the above considerations, we accept that the upper boundary of the Minija Fm. is diachronous as is common in lithostratigraphy.

The highest FADs established in the Baltic Silurian are harder to characterize due to the incompleteness of core sections. The top of the Pavilosta section is rather deeply eroded so that only the lower part of the Jura Fm. is represented. The uppermost layers of the Ohesaare section are also missing but still *Oulodus elegans detortus*, *Poracanthodes punctatus* and *Nodibeyrichia protuberans/verrucosa* (previously called *N. jurassica*, Sarv 1982; see Hansch & Siveter 1994) occur in the cliff section (Fig. 3). The first species occurs in the highest levels of the Přídolí at Klonk and elsewhere (Jeppsson 1988; Viira 1999, 2000). On the other hand, *Anthochitina superba* is not recorded from the Ohesaare cliff, even if several other members of this association are common in that section (see above and Fig. 3). We do not think that there is a real sedimentary gap but additional sampling might help to clarify this issue. The last biozonal FAD (*Trimerolepis timanica*) shown in Fig. 3 co-occurs with several other vertebrates (e.g. *Goniporus alatus*, *Loganellia cuneata*, *Oniscolepis dentata*) in the very top of the traditional Silurian in the Ventspils core. *Turinia pagei* (index of the eponymous biozone) and *Paralogania kummerovi* appeared at the bottom of the lower Lochkovian Tilže Fm. and practically the entire vertebrate association of the earlier biozone, except for *Trimerolepis timanica* range into that level. Such a situation at a systemic boundary points to a rather continuous transition. In a few core sections (Stoniškiai, Nida; Karatajūtė-Talimaa 1978; Karatajūtė-Talimaa & Brazauskas 1995) in southwestern Lithuania nearly the same vertebrate assemblage as in the Ventspils core occurs at the Silurian/Devonian (S/D) boundary. The exception is that the position of *Trimerolepis timanica* is occupied by *Trimerolepis lithuanica*, while *Paralogania kummerovi* appears before the latter.

The *N. ‘jurassica’* problem is illustrated in Fig. 4. This figure demonstrates that the key species of conodonts

(Viira 1999), chitinozoans (V. Nestor, unpublished data), vertebrates (Märss 1986 revised) and ostracodes (Sarv 1977) found in the Kolka-54 core are the same as in the Ohesaare cliff and Ohesaare 1 and 2 core sections and they occur at comparable stratigraphical levels and order. We have used here the ostracode nomenclature as suggested by Hansch & Siveter (1994) – in Estonia ‘*verrucosa*’, in Latvia ‘*protuberans*’. However, we think that a distinction algorithm should be based on morphological differences, which are not very convincing as yet, and not so much on geography. On the other hand, there is nothing out of ordinary in two rather closely related species occurring in neighbouring sections at the same stratigraphical level, whereas one of those species is long-ranging through all of the Přídolí (ca 4 My; Melchin et al. 2012). *Nodibeyrichia verrucosa* has been described from the Platyschisma Shale Member of the Downton Castle Sandstone (Shaw 1969). If the correlation by Loydell & Frýda (2011) is correct (discussed below), its FAD will move to the middle Ludfordian.

#### DATING THE MID-LUDFORDIAN CIE AND THE SCOPE OF THE LATE LUDFORDIAN

The main idea of our paper was the refinement of relative age determinations by using jointly bio- and chemostratigraphical methods. Some results are reported above. Chronostratigraphical terms like Ludlow and Ludfordian mark formal units that should meet certain rules and were officially introduced by the IUGS for global use in order to secure uniformity in the correlation and timing of geoevents. Terms like e.g. late/upper Ludfordian refer to informal, experience-based units and may vary in certain limits. For example, Urbanek & Teller (1997) included six graptolite zones (from *Saetograptus leintwardinensis* to *Neocucullograptus kozlowskii*) in the lower Ludfordian and four zones (*Pseudomonoclimacis latilobus* to *Monograptus spineus*) in the upper Ludfordian. Cramer et al. (2011) defined three stage slices in the Ludfordian as follows: Lu1 – includes all of the *S. leintwardinensis* Bz. + a part of the *Bohemograptus* Bz. up to the top of the *Polygnathoides siluricus* conodont Bz.; Lu2 – the *Oz. snajdri* Bz. corresponding to the upper part of the *Bohemograptus* Bz. and the *N. kozlowskii* + lowermost *Monograptus formosus* graptolite biozones; Lu3 – the *Oz. crispa* Bz. embracing the remaining part of the *M. formosus* Bz. up to the base of the *M. parultimus* Bz. This tripartite approach seems to be a mainstream one, even if the terms ‘lowermost’ and ‘remaining part of the *formosus* Bz.’ are too vague (see below) for usage. However, the conodont criteria are exact and make us wonder why a part of the

Ludfordian of Gotland that ‘encompasses the topmost Hemse Group and the overlying Eke ... and basal Hamra–Sundre fms’, corresponding to the upper *P. siluricus–Oz. snajdri* conodont biozones (Jeppsson 2005), has been called ‘Late Ludfordian’ (Eriksson & Calner 2008, p. 255). A reason for this dating remains enigmatic (cf. also Loydell & Frýda 2011).

The precise dating of the MLCIE in terms of biostratigraphy is to some extent uncertain, particularly the upper limit of the excursion above the LAD of *N. kozłowskii* (the top of this biozone in the Czech Republic is noted as an erosional surface by Lehnert et al. 2003). Recent data from the Mielnik IG-1 core of Poland (Kozłowski & Sobien 2012) and Kosov Quarry in the Barrandian (Frýda & Manda 2013) demonstrate convincingly that a gradual and small increase in  $\delta^{13}\text{C}$  values begins in the middle of the *N. kozłowskii* Bz. and a rapid shift to high values (6.7‰ in Mielnik; ca 9‰ in Kosov) occurs just above it. The peak of the excursion occurs in an interzone between the LAD of *N. kozłowskii* and the FAD of *Pseudomonoclimacis latilobus*, marking the beginning of the late Ludfordian according to Urbanek & Teller (1997). Kozłowski & Sobien (2012) show clearly that the interzone belongs to the mid-Ludfordian. Frýda & Manda (2013, fig. 5), however, are less exact, placing the *Pristiograptus dubius postfrequens* Partial-range Interval Zone in their section below the *Ps. latilobus–Slovinograptus balticus* Bz., but correlating it with the lower part of the latter elsewhere, i.e. into the upper Ludfordian. It seems to be a technical error and in the text they classify the CIE as Mid-Ludfordian.

Indeed, it is rather difficult to show this level correctly, because some authors have not noticed the data of Urbanek (1997) that a group of specific graptolites appeared in the Mielnik section in the lower part of the upper Ludfordian: first *Ps. latilobus* (at 823.0 m), then *Monograptus (Wolynograptus) hamulosus* and *S. balticus* (at 819.85 m) and half a metre higher *Monograptus (Formosograptus) formosus*. The practically nearly synchronous appearance of the group complicates the usage of *M. formosus* for defining stage slices Lu2 and Lu3 as suggested by Cramer et al. (2011). For full clarity let us quote all details from the Mielnik core based on data by Urbanek (1970, 1997): *Neocucullograptus kozłowskii* ranges from 873.4 to 854.6 m (= LAD or the *kozłowskii* Event). The following 31.6 m of core above that level, with a low-diversity assemblage of *Pr. dubius postfrequens* (this subspecies occurs throughout the Ludfordian; Urbanek et al. 2012), is classified as an interzone or Partial-range Interval Zone between the LAD of *N. kozłowskii* and FADs of the index species of the next graptolite biozone (listed above). Thus, the interzone discussed belongs by definition to the

*N. kozłowskii* Bz., making up its uppermost part, and is thus mid-Ludfordian in age. This fact is important for the exact dating of the MLCIE and the lower boundary of the upper Ludfordian follows at the FAD of *Ps. latilobus* or some other species of the group mentioned above (Urbanek & Teller 1997; Kozłowski & Sobien 2012).

Kaljo et al. (1997) reported the last index species (*Ps. latilobus*) from the Priekule core (Latvia) ca 50 m above the peak of the MLCIE. *Pseudomonoclimacis latilobus* is not a long-ranging species and its occurrence in the Mietuva Fm. in Priekule is an incidental find that cannot be classified as a FAD or LAD. It occurs in a logical position, indicating that the bottom of the upper Ludfordian in this section is below the 975.8 m level. At the same time this causes some doubts about the correctness of the lithostratigraphy applied in Priekule. Paškevičius et al. (1995) reported several late Ludfordian graptolites from the lower part of the 178 m thick Pagegiai Fm. (or RS according to their terminology) in Stoniškiiai (SW Lithuania), beginning with *Ps. latilobus* and *Ps. tauragensis* (the latter comes from the Dubysa Fm.) at the very bottom. The ranges of *S. balticus* and *M. cf. valleculosus* begin ca 20 m higher. Other pristiograptid species including *P. dubius* subspecies are also rather common. The upper part of the Pagegiai Fm. is graptolite-bearing also in the Torava core, located rather close in the Kaliningrad region of Russia and there three occurrences of *Monograptus formosus* have been registered within the upper 20 m. The very high sedimentation rate in the study area during the late Ludlow (and Přidolí) that might mean also an unsuitable environment for graptolites may have resulted in the rather sporadic and limited graptolite ranges observed. Another reason may be insufficient study, but it is very intriguing that the appearance of specific late Ludfordian graptolites (*latilobus–balticus–formosus*), which in the Mielnik section is practically simultaneous (within 3 m), is extended over a much wider section thickness in the central part of the same basin, but probably not over a much longer time interval.

## THE AGE OF THE KURESSAARE FORMATION

Männik (2014) revised the age determinations of the uppermost Paadla and Kuressaare stages, using for this purpose the records of the conodont *Ozarkodina crispa* by Viira (1999). The above results of a more complex analysis show that the occurrences of this conodont species might be trusted despite the taxonomic problems mentioned earlier. Its range in the Baltic is essentially wider than shown by Jeppsson et al. (2006) or Cramer

et al. (2011), namely the FAD of *Oz. crispera* in the Ohesaare section occurs below the MLCIE (correlated into a gap within the uppermost Paadla RS) and surely below the LLCIE1. In the Ventspils core it occurs above the MLCIE and LLCIE1, i.e. within the upper Ludfordian (Fig. 3) as commonly accepted and continues above the LLCIE2 in the lower beds of the Minija Fm. (Viira 1999). However, the fact that *Oz. crispera* has a longer range in our sections and its LAD occurs in the bottom of the Pridolí does not change earlier chrono-correlations of the Kuressaare and Ventspils fms (Kaljo & Martma 2006; Kaljo et al. 2012) supported both bio- and chemostratigraphically. In addition to carbon isotope data (above and Fig. 2), close correlation between these two formations is indicated by different fossil occurrences, especially of the chitinozoan *E. barrandei*, the conodont *Oz. r. baccata*, the ostracode *Plicibeyrichia numerosa* and the thelodont *T. sculptilis*. The bottom of both formations is clearly marked by the MLCIE and LLCIE1, but the positions of their tops depends on how well the lower boundary of the Pridolí Series can be correlated into the Baltic sections. The official definition is based on a GSSP in the Požary section of the Prague Basin within bed No. 96 where a primary guide is the FAD of *Monograptus parultimus* (Kříž et al. 1986). This species is not found in the East Baltic but has been reported from Poland (Urbanek 1997). The data available on chitinozoans (*E. barrandei*) and conodonts as discussed in this paper above are most promising and support without doubt our current age determinations.

Advocating for an upper Silurian standard conodont biozonation, Corradini (2009) stressed some important views related to the issues considered above. We agree with his opinion about the taxonomic revision of some ozarkodinids and prefer to use the subspecies concept of *Oz. remscheidensis s.l.*, allowing a rather clear conodont biozonation for the Pridolí Series in the East Baltic. Every area has some specific characters in conodont and other faunas, e.g. most authors show the *Oz. crispera* Bz. at the top of the upper Ludfordian (Corradini 2009), but in our sections the FAD of this species is within the middle Ludfordian and the LAD is in the lowermost Pridolí (see above). On the other hand, Corradini (2009) and Corrigan et al. (2009) show that the *Oulodus e. detortus* Bz. is much wider in Sardinia (including half of the Pridolí and continuing into the Devonian) than in the Barrandian (Jeppsson 1988) and Baltic areas (Viira 2000). There may be a taxonomic problem involved but all such peculiarities like the long-ranging *Oz. eosteinhornensis s.l.* Bz. in the type Pridolí or highly detailed icriodontid biozones on Gotland should be considered when a global biozonation is attempted. Anyway, we agree with Corradini (2009) that there is still a long way to go.

## CORRELATIONS WITH THE TYPE LUDLOW AREA

Searching for the MLCIE in the type Ludlow area (Shropshire), Loydell & Frýda (2011) evaluated critically different data sets from Europe and elsewhere, and the East Baltic in particular. Most of their analyses and results are very much in harmony with our views, expressed in this paper or earlier. Now we wish to comment on and clarify some aspects. Let us begin with the MLCIE ‘coinciding’ with the *N. kozłowskii* Bioevent. According to Lehnert et al. (2007), cited by the former authors, the MLCIE commences just above the LAD of *N. kozłowskii*, thus the CIE follows the extinction event that ended within the eponymous biochron. Such details seem important when looking for environmental implications or reasons for events. However, the main idea of Loydell & Frýda (2011) was based on the pattern that the MLCIE elsewhere in the world is associated with a clear facies change (shallowing event) marked by lithology (more carbonate rocks in Vidukle; Martma et al. 2005), gaps (several in Ohesaare; Fig. 2), etc. The authors took samples across two most striking formational boundaries (Upper Leintwardine/Lower Whitcliffe fms and Upper Whitcliffe/Downton Castle Sandstone fms) and subsequently analysed them for carbon isotopes. As a result an organic carbon isotope excursion (of ca 3‰), commencing in the uppermost Upper Whitcliffe Fm. and continuing into at least the first 1.28 m of the Downton Castle Sandstone Fm., was identified. Analysis of the published biostratigraphical data from the Upper Whitcliffe and Downton Castle Sandstone fms followed, with the conclusion that these were consistent with a mid-Ludfordian (rather than Pridolí) age for the lower part of the Downton Castle Sandstone Formation. Such a conclusion brought about rather serious changes in the Silurian stratigraphy of Britain and elsewhere and therefore the conodont, chitinozoan and thelodont data used as evidence deserve appropriate attention.

The conodont data, summarized from the Ludfordian of the Welsh Borderland by Märss & Miller (2004), include an association of species very similar to the one known in the Baltic and elsewhere but the local distribution pattern remains obscure. Only *Oz. cf. crispera* or morph  $\alpha_3$  of this species (Miller 1995; Viira & Aldridge 1998), recognized from the top of the Upper Whitcliffe Fm. and used by Loydell & Frýda (2011) in their discussion, needs a comment.

In the text above we evaluated the occurrences of FADs of all upper Silurian biozonal indices established in three Baltic core sections. As much space was devoted to *Oz. crispera*, here we stress only the main idea – it can serve as a trusted biozonal index for the upper Ludfordian in many areas, but it should be remembered

that in shallow-water settings in Estonia its FAD is recorded from the Paadla and Torgu fms underlying the MLCIE. In open shelf areas in Latvia it mainly ranges throughout the upper Ludfordian with a few occurrences at the very bottom of the Kaugatuma and Minija fms of the Põidoli. A similar pattern is obvious also in the case of the *Oz. parasnajdri* Bz., which in Ohesaare occurs in the upper Ludfordian but is found in the lower Põidoli in the Kolka and Ventspils cores (Figs 3, 4). Having in mind the ecostratigraphical trend described above for *Oz. crispera* in the East Baltic, we can agree that the uppermost Upper Whitcliffe Fm. containing morph  $\alpha_3$  ‘could be considerably older than latest Ludfordian’ (Loydell & Frýda 2011, p. 201). Still, it seems much less probable than the previous conclusion that this cf. *crispera* is present in Britain in the most usual interval of the species above the MLCIE. We consider it highly improbable to push all of the ‘*remscheidensis* plexus’ conodonts (*Oz. r. baccata* a.o.; Märss & Miller 2004) together with morph  $\alpha_3$  to a slightly but significantly lower stratigraphical level.

Chitinozoan ranges seem to be less ambiguous. Only the exact identification of *E. barrandei* sometimes causes problems, but in general its biozone is a good analogue of the *Oz. crispera* Bz. for the topmost Ludlow. A dissonance seems to be *E. clunensis* reported from the Upper Whitcliffe Fm. (Loydell & Frýda 2011), which occurs in the Baltic together with *E. philipi* below the MLCIE. The latter species is known from the upper beds of the Upper Leintwardine Fm. and higher, up to the lower part of the Upper Whitcliffe Fm., above which the chitinozoan record is very poor indeed.

In Estonia and Latvia (Pavilosta) the *E. barrandei* Bz. is documented in the upper Ludfordian beds 15–40 m above the MLCIE. This explains the absence of this species on Gotland because the upper Hamra–Sundre Beds reach the equivalent of only the lowermost Kuressaare Fm. (Kaljo & Martma 2006). The occurrence of *Oz. crispera* in the Sundre Fm. (in Holmhällar 1; Jeppsson et al. 2005) causes some uncertainty in the last statement, but is well within the range known in Latvia. The ranges of *Angochitina elongata*, *E. philipi* (except those with cf. in Ohesaare) and *E. clunensis* are all below the peak level of the MLCIE, whereas some LADs are very close. *Eisenackitina lagenomorpha* is long-ranging (LAD in the Põidoli), but appears at some distance below the MLCIE (Figs 2–4) in beds correlated with the uppermost Gorstian in Baltic (Nestor 2009) and the Lower Bringewood Fm. in Britain (Sutherland 1994). All the above information on chitinozoans indicates that most likely the Lower Whitcliffe Fm., underlain by the *Saetograptus leintwardinensis* Bz., belongs partly to the middle Ludfordian and the MLCIE should be looked for in its upper part or in the bottom of the Upper

Whitcliffe Fm. Perhaps there is not any highly striking facies change available, but Baltic (*sensu lato*) experience shows that also more discrete changes will do.

Such a correlation is also supported by thelodont data, e.g. the first occurrences of long-ranging *Thelodus parvidens* in the Lower Whitcliffe Fm. (Märss & Miller 2004) and these in the uppermost Paadla RS (Märss 1986: rare finds, mass occurrences in the Kuressaare Fm.) but below the MLCIE in the East Baltic (details in Fig. 2) and in the Eke Beds, exactly at the MLCIE level, on Gotland (Miller & Märss 1999) seem to be nearly synchronous. The distribution pattern of *Paralogania ludlowiensis* (Miller & Märss 1999) is interpreted by us as nothing but an additional example of environmentally controlled distribution of a long-ranging species.

We have always stressed that bio- and chemostratigraphy should be considered together, because rather often poor biostratigraphy hampers getting reliable results. However, the situation is vice versa in the case of the type Ludlow area – the chemostratigraphical studies embrace only two small parts of the whole section exposed in the area. Kaljo et al. (2012) established two smaller  $\delta^{13}\text{C}$  excursions within the upper Ludfordian of the East Baltic. It means that there are other excursions that could be correlated with that at the Ludlow Bone Bed, e.g. LLCIE2, and then *Frostiella groenvalliana* might be in the right position (cf. Siveter 2009). As we said above, we consider the idea by Loydell & Frýda (2011) very interesting, but an additional series of carbon isotope analyses from (at least) the entire Upper Whitcliffe Fm. would contribute considerably to further discussions.

## IDENTIFICATION OF THE SILURIAN/DEVONIAN BOUNDARY IN THE EAST BALTIC

In addition to the above remarks on vertebrate distribution within the S/D boundary interval, we will comment on some other data. In general this boundary is relatively easy to fix in the East Baltic due to fundamental differences in the lithologies comprising the neighbouring systems – carbonate rocks (including mudstones and shales) dominating below and sand- and siltstones above the S/D boundary, and due to the occurrence of a more or less conspicuous hiatus at the boundary in most areas. Only a few sections in the northern part of the Kurzeme Peninsula (Latvia) and in southwestern Lithuania are more complete. The lithological change is accompanied by the replacement of Silurian marine faunas by a specific early Devonian vertebrate-dominated community. *Turinia pagei*, *Traquairaspis*, *Corvaspis*, etc. occur in the bottom of the Devonian (Tilže Fm.,

Lochkovian) together with some ‘Silurian’ elements (Karatajūtė-Talimaa 1978; Karatajūtė-Talimaa & Brazauskas 1995). These vertebrate fossils have commonly been considered as ‘heralds’ of the Devonian Period but we cannot decide without other details which part of the Lochkovian is represented if ‘Silurian’ elements are missing.

The most complete sections include the Ventspils and Kolka-54 sections discussed above (see Fig. 4) and several others where Ul’st (1974) described a transitional unit (the Lužni Member of the Targale Fm.) at the S/D boundary. However, the boundary markers mentioned above cannot be used for exact correlation with the S/D boundary stratotype in Klonk (GSSP, in bed No. 20), where the primary criteria are graptolites not found in the East Baltic.

Potentially, carbon isotope chemostratigraphy could be of more help, as demonstrated by several papers (Saltzman 2002; Buggisch & Joachimski 2006; Malkowski et al. 2009) describing a major  $\delta^{13}\text{C}$  excursion at the S/D (= SIDE of Kaljo et al. 2012). Only the last analysis from the very top of the Ventspils core showed an elevated value, which seems to fit the pattern seen elsewhere. Conodonts are promising as well. Jeppsson (1988) showed that *Oulodus e. detortus* occurs at Klonk in a short interval (less than 2 m thick) called the ‘post-*Monograptus transgrediens* Interzone’ (the range of *detortus* occupies about half of it). He cited also some data from the neighbourhood – the situation is in general the same in the Cellon section, but the level of the S/D boundary is not exact. The interzone is much longer (127 m) in the Chelm core (East Poland). However, it should be remembered that this core comes from an area of great thickness of the Přídolí, where *O. e. detortus* occurs in the uppermost 24 m.

Baltic data about the range of *O. e. detortus* (Viira 2000) fit well into this biozonation pattern. In the Ventspils core it occurs between depths of 306.2 and 333.0 m in the lower half of the Targale Fm., i.e. its LAD is 36 m below the S/D boundary, marked on the Silurian side by occurrences of *Trimerolepis timanica* just below the boundary at 270 m. The Kolka-54 core adds a piece of information about the uppermost Silurian in the discussed area. As commonly accepted, a small gap occurs at the S/D boundary, but perhaps in the bottom of the Lochkovian above the FADs of *O. e. detortus* and *Tr. timanica* that are represented there together with several other ‘Silurian’ fossils (Fig. 4). Proceeding from this information, we accept the S/D as it is, and as *O. e. detortus* occurs at a depth of 173–182 m (within 9 m), its LAD is 15 m below the S/D boundary. Summarizing the above data about the occurrences of *O. e. detortus* in several environmentally different areas, it seems justified to stress two aspects. First, as a

specific biozonal unit the *O. e. detortus* Bz. occurs within the limits of the *Oz. r. remscheidensis* range close to the S/D boundary but usually not at the boundary. Second, as shown by Jeppsson (1988), the *O. e. detortus* Bz. is stable, lying in a non-graptolitic interzone between the *Monograptus uniformis* and *M. transgrediens* biozones. This observation allows us to date in terms of graptolite biostratigraphy also the topmost Silurian rocks in the shelly facies realm. Still, data from Sardinia, quoted above, indicate that the situation may not be so regular or simple.

## BIOZONES AND POSSIBLE STAGES OF THE PŘÍDOLÍ SERIES

The first author of this paper touched upon the topic at the Lund meeting of the Subcommittee on Silurian Stratigraphy in 2013 and it seems that some discussion has begun. Perhaps the information available to us is inadequate, but the undivided series is still disturbing the Silurian picture. When working on this paper every author was asked to note which level would be most appropriate for subdividing the Přídolí based on ‘their group of fossils’ if such a subdivision is at all justified. The answers were not very enthusiastic. For example, Viiru Nestor noted: if any at all, we could take the level of a more serious change in the chitinozoan assemblage at the very top within the *Ancyrochitina lemniscata* Bz. This is a logical change just before the Devonian, but no use for the topic. Viive Viira expressed a rather similar opinion, but stressed that the subspecies of *Ozarkodina remscheidensis*, dominating throughout the upper Silurian above the MLCIE, enable establishment of four rather well recognizable biozonal units. Especially the one based on *Oz. remscheidensis remscheidensis* occurring in most of the Targale and Ohesaare fms seems promising for the subdivision of the series. Several elements of a new conodont assemblage appear in the higher part of the last biozone (e.g. *Amydrotaxis? praecox* and *Oz. nasuta*), showing some links to Devonian species (Viira 2000), and also the range of *Oulodus e. detortus* is a specific element. Tiiu Märss pointed out that the lower part of the Přídolí (Kaugatuma and Minija fms, see also Karatajūtė-Talimaa 1978) is richly dominated by acanthodians, but different heterostracans become important in the upper half. This change in the bottom of the Ohesaare Fm. is well demonstrated in the Kolka and other core sections studied (Figs 2–4). Ostracode evidences suggest two possibilities for defining stage boundaries of the Přídolí – the FAD of *Nodibeyrichia verrucosa/protuberans* in the bottom of the Ohesaare Fm., or that of *N. tuberculata* in the Lõo Beds of the Kaugatuma Fm. Both of them, especially the latter, are

typical representatives of the so-called Beyrichien-Kalk association (Martinsson 1977; Hansch 1985), very characteristic of the uppermost Silurian in the carbonate rock and shelly fauna realm. Surely ostracodes, in association with conodont and microvertebrate data, are promising for defining a stage level boundary within the Přídolí. As we are aiming at the subdivision of a series with the duration of ca 4 My or less and there are no serious environmental reasons for striking lithological or faunal changes, we could try to correlate rather small events. It seems most important to detect the boundary level by considering several fossil groups, including the pelagic graptolites. A possibility of involvement of graptolites was mentioned when discussing *O. e. detortus* and its links to the *M. transgrediens* Bz. Data from the Łeba and other drill cores in North Poland indicate some relationships between graptolite and ostracode associations (Witwicka 1967; Zbikowska 1974). Conodonts and chitinozoans in the type sections of the Přídolí in the Prague area (Kříž et al. 1986) offer some additional tie points. Based on the above information it seems possible to achieve a reasonable correlation between graptolite and non-graptolite assemblages. Such an ecostratigraphical approach is rather troublesome and not so popular nowadays; however, carbon isotopes are not very promising in the Přídolí, at least as yet. Still, we do have an alternative – we can declare that the Přídolí is not a series but the youngest stage in the Ludlow. This would not be a bad alternative, but we prefer to keep the stratigraphy as stable as possible.

## CONCLUSIONS

The results of our study confirmed that not only archistratigraphical groups (here graptolites, conodonts and chitinozoans) but also such groups as ostracodes and microvertebrates, when properly studied, can provide useful biostratigraphical information.

Despite the changing environment, most of the analysed FADs and the corresponding biozones are, in general, synchronous units and in the majority of cases their ‘time signals’ do not contradict each other. However, some conodont species (e.g. *Oz. crista* within a stage and slightly also *Oz. snajdri parasnajdri*) show a certain ecostratigraphical trend where earlier representatives occurred in shallower facies and younger ones farther from the shoreface.

Our study is based mostly on data from three core sections located within a rather small sedimentary basin. Thus we cannot be sure that longer distances and larger facies differences may have greater influence on the synchronicity of the FADs.

Integration of bio- and chemostratigraphy helps the understanding of the pattern and timing of fossil distribution. Based on these and lithological markers, we can find reasons for discrepancies in biodata and secure a trustworthy correlation of sections that formed in different facies conditions.

An ecostratigraphical or a complex bio-chemostratigraphical correlation of the Přídolí rocks in different facies realms of the East Baltic and Poland can provide trustworthy and sufficiently widely distributed criteria for the subdivision of this series into stages. The following steps in this issue depend on the International Subcommission on Silurian Stratigraphy of the IUGS.

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## Supplementary online data

Supplementary online data associated with this article can be found in a table at <http://dx.doi.org/10.15152/GEO.14>. The table presents a set of whole-rock carbon isotope data from the Pavilosta (Kurzeme, Latvia) drill core.

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## Eesti ja Läti Siluri ülaosa biotsoonide sünkroonsuse bio- ning kemostratigraafiline testimine ja mõned väljundid praktilisse stratigraafiasse

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On selgitatud biotsoonide piiride sünkroonsuse säilimist korrelatsioonidel üle settebasseini faatsiiste piiride. Graptoliiditsoonid on usaldusväärsemad, järgnevad konodontidel ja kitiinikutel ning seejärel vähem tunnustatud fossiilidel, nagu ostrakoodid ja selgroogsete mikrojäänukid, põhinevad biotsoonid, mida on samuti edukalt kasutatud. Bio- ja kemostratigraafia integratsioon võimaldab senisest paremini selgitada fossiilide levikut ajas ning ruumis ja väita, et analüüsitud biotsoonid on üldiselt sünkroonsed üksused, mille ajaline sõnum ei ole enamasti vastuoluline. Ühtlasi on rõhutatud, et tõsine väärtus on vaid korralikult uuritud fossiilidel. Kuid on kaalutud ka teisi andmeid, kus rannalähedastes faatsiistes on täheldatav indeksliikide varasem levik, kui see on tuvastatud avamerelisemates läbilõigetes. Viimastes on nende liikide levik kõige kestvam. Niisugust ökostratigraafilist seaduspära tuleb arvestada ka kihtide suhtelise vanuse hindamisel ja bio-kemostratigraafia ühisandmetel peame Kuressaare kihistut endiselt Ludlow' ülemisse ossa kuuluvaks. Samadel andmetel on näidatud võimalusi Pridoli ladestiku jaotamiseks kaheks lademeks, korrelatsiooniks Briti Siluri tüüpalaga ja Siluri ning Devoni ladestu Baltikumi piiri paremaks identifitseerimiseks.