Geological Quarterly, 2006, **50** (3): 323–332

A new high-resolution chitinozoan composite standard for the East Baltic Lower Silurian succession based on numerical analysis

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Rubel M., Nestor V., Harris M. T., Sheehan P. M., Ainsaar L., Männik P. and Nõlvak J. (2006) — A new high-resolution chitinozoan composite standard for the East Baltic Lower Silurian succession based on numerical analysis. Geol. Quart., **50** (3): 323–332. Warszawa.

The chitinozoan successions (zonation) in the Llandovery and Wenlock deposits, accumulated along the northern shelf edge of the Livonian Basin, an embayment of the Palaeobaltic sea, is studied and used for time-rock correlation of the area. Analysis of the ranges of 180 taxa from 44 sections (41 of them well-sections) by graphic correlation revealed largely compatible successions of taxa as well as local stratigraphic gaps in both shelf and basin sections. Alternatives to graphic methods also produced composite standards based on stratigraphic relationships (below, co-occurring, or above) of taxonomic ranges and considered as palaeontological time scales (composites) similar to zonal schemes. We constructed such a scale using the DISTR algorithm to analyse the distribution of 84 taxa and recognized 41 datum planes. This scale includes the traditional regional and global chitinozoan zones and the associated chronological standards (including regional stages). The BioGraph and DISTR algorithms were used to study diversity changes, and to illustrate patterns of originations and extinctions of the chitinozoans. Correlation plots between composite standard and particular sections reveal variations in sedimentary rock accumulation patterns, supporting the results of sequence stratigraphic analysis of the study interval.

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Key words: Palaeobaltic basin, chitinozoan timescales, Llandovery, Wenlock.

INTRODUCTION

The temporal framework of stratigraphy is usually based on fossils, or, more specifically, on biozones. The Baltic Silurian is not an exception to this pattern. The section includes a relatively complete Llandovery and Wenlock interval characterized by facies belts that range from shelly and lagoonal carbonates to graptolitic shales and that persist with only minor geographical shifts (Bassett *et al*., 1989; Kaljo *et al*., 1991; Nestor and Einasto, 1997; Fig. 1). These strata are dated by regional biozones and palaeontological events into regional and global chronostratigraphic scales (Kaljo, 1990; Nestor, 1997; Paškevičius, 1997). Most biozones, particularly those based on graptolites, conodonts, ostracodes, thelodonts, corals and other faunas, are generally restricted to one or two facies belts.

Studies in the last decade show that many chitinozoan biozones can be traced from shelf to basin deposits and, in that way, provide a reliable basis for establishing regional biozones throughout the East Baltic region independently of facies assessments (Nestor, 1994). Chitinozoans are missing in lagoonal and reef rocks, as well as in red-colored strata (probably due to diagenetic alteration of these rocks). The distribution of some chitinozoans seems to be also ecologically controlled (Nestor, 1998). Co-occurrences of graptolites and chitinozoans in the Ohesaare and Aizpute-41 core sections allowed correlation of most of the Llandovery chitinozoan zones directly with the graptolite succession (Loydell *et al*., 1998; Loydell *et al*., 2003).

The present study examines chitinozoan zonations in the lower Silurian of the East Baltic using a numerical analysis of their temporal successions to establish a high-resolution tool, a relative time scale, making possible a detailed interpretation of changes in the sedimentological patterns and in the taxonomic

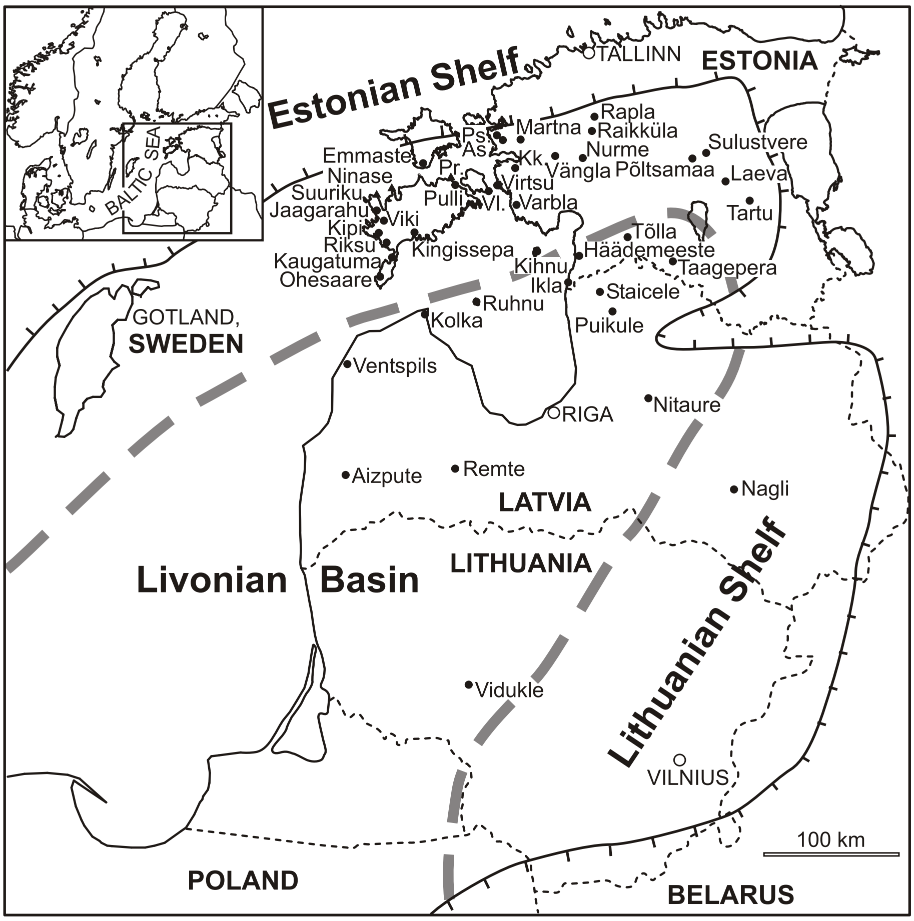

Fig. 1. Location of core-sections studied and early Wenlock facies belts (modified from Bassett *et al.*, 1989)

Ps. — Pusku, As. — Asuküla, Kk. — Kirikuküla, Pr. — Paramaja, Vl. — Viirelaid; present-day erosional limit of Silurian deposits is shown by hatched line and facies belts boundary by grey dashed line

content of the chitinozoans. It also allows the positioning of biozones within a persistent scale that improves correlations to regional and global chronostratigraphic standards (such as the regional standards of Kaljo, 1990 and Paškevičius, 1997).

GEOLOGICAL SETTING AND DATASET

The Llandovery and Wenlock deposits in Estonia and Latvia accumulated along the carbonate Estonian Shelf and shelf edge of the Livonian Basin, an embayment of the Palaeobaltic epicontinental sea (Bassett *et al.*, 1989; Kaljo *et al.*, 1991; Nestor and Einasto, 1997). The interval is represented by an essentially complete sequence which is truncated at its updip/onshore limit (to the north and east) due to post-Silurian erosion (see Paškevičius, 1997). Updip sections are thinner and contain more sedimentary gaps than the basinward sections to the south. Lithostratigraphic units (formations, members, beds) reflect their positions within facies belts and are grouped into regional stages that are based upon biozones (Fig. 2). Past studies of depositional facies models,

GLOBAL SERIES	ESTONIAN STAGES	CENTRAL AND WEST ESTONIA	WEST-ESTONIAN ISLANDS	SOUTH ESTONIA SÕRVE PENINSULA	LATVIA
WENLOCK	ROOTSIKÜLA, K_1	Sakla Fm.	Rootsiküla Formation	Rootsiküla Formation	Siesartis Fm.
	JAAGARAHU, J_2	hiatus	hiatus	Sõrve Formation	Rīga Formation
		Muhu Fm.	Jaagarahu Fm. / Riksu Fm.	Jamaja Formation	
	JAANI, J_1	Jaani Formation	Jaani Formation / Riksu Fm.		
LLANDOVERY	ADAVERE, H	Velise Formation	Velise Formation	Velise Formation	Jūrmala Fm.
		Rumba Formation	Rumba Formation	hiatus	Dobele Fm.
	RAIKKÜLA, G_3	hiatus / Raikküla Fm. / Hilliste Fm.	hiatus / Nurmekund Fm.	Saarde Formation	Dobele Fm. / Remte Fm.
	JUURU, G_{1-2}	Tamsalu Formation	Tamsalu Formation	Õhne Formation	Stačiunai Fm.
		Varbola Formation	Varbola Formation		

Fig. 2. Silurian stratigraphy of the area studied (modified from Nestor, 1997 and Gailīte *et al.*, 1987)

lithological cycles and stratigraphic sequences provide the depositional framework for this study (Nestor and Einasto, 1997; Harris *et al*., 2005).

The present dataset includes 44 sections (three outcrops and 41 core-sections) that yielded Llandovery and/or Wenlock chitinozoans in the study area (Fig. 1). Four of these sections, Ohesaare, Ruhnu-500, Ikla and (studied partly) Kolka-54, include the entire stratigraphic interval from the Juuru to the Rootsiküla stages. The first (FO) and last occurrences (LO) of 180 chitinozoan taxa (species as well as those in open nomenclature) have been tabulated for all 44 sections in the form of range charts that summarize the 1114 samples in the database (Nestor, 1994, 2003, 2005). Doubtful identifications at range terminations are tracked separately in the database, and are not included in the analysis presented here. Ranges within each section are based only on FO and LO data, and do not take into account frequency of the taxa (i.e., acme-zones of Nestor, 1994) or the vertical continuity of taxa distribution. The database of the Silurian chitinozoans from Estonia is created by Viiu Nestor.

FAUNAL ZONATIONS AND GAPS

The consistency of the sequence of FO-s and LO-s of taxa indicates their value in establishing faunal zonations. Numerous chitinozoan taxa have been used to establish faunal zones (Nestor, 1994; Fig. 3). The number of taxa that occur in more or less the same succession in different sections is greater than usually recognized because all taxa, even those that are not used to define zones, can be ordered by their occurrences “above”, “below”, or “co-occurring” with the zonal taxa. The entire dataset can be used to place most taxa into a consistent sequence despite the short ranges and limited environmental distribution of some taxa.

Graphic correlation (Shaw, 1964) is one example of a method that uses all taxa to develop a faunal zonation for correlation. Comparisons of pairs of sections show that the taxa used in this paper are statistically well ordered (Fig. 4). Common chitinozoans occur widely in compatible sequences in shelf (Viki) and the most offshore (Aizpute-41) sections, although they are absent in intervals with extensive dolomitization, reefs or red-coloured rocks. The consistency of the chitinozoan successions in different sections makes them valuable for construction of a faunally-based zonation.

Interpretation of the line of correlation (LOC) on some of the graphic correlation plots of the pair-wise section comparisons reveals some horizontal segments (see Ohesaare/Ikla graph, Fig. 4). The horizontal segments are due to the occurrence of FO and LO events near one horizon and the fact that other common chitinozoans are missing in one section (in this example, around the 370 m horizon in the Ohesaare section). This pattern is due to the presence of a stratigraphic gap or an interval with an extremely low sedimentation rate (as in the Ohesaare section). These gaps can be detected by comparisons with other, more complete sections (such as Ikla). If the same gap occurs in two sections, it cannot be detected in comparing the two sections. This is why the gap in the Ohesaare section is less obvious in the Ohesaare–Ruhnu-500 LOC and undetectable in the Ohesaare–Viki LOC (Fig. 4). Some chitinozoans might be missing due to their limited environmental distribution, but the stratigraphic position of the gaps along discrete horizons suggests that the common gap may be due to a true stratigraphic gap (in this case, probably due to erosion or slumping along the shelf-slope transition).

A reference section must be selected in applying graphic correlation to a group of sections. The main criteria to select a reference section is that it should be the most complete section, with the most uniform sedimentation rates, so that it can be used for detecting stratigraphic gaps and changes in relative rates of accumulation in other sections. The ranges of all taxa from other sections are projected onto the reference section. As a result, it becomes a composite section that incorporates the range data from all studied sections. Stratigraphic gaps and

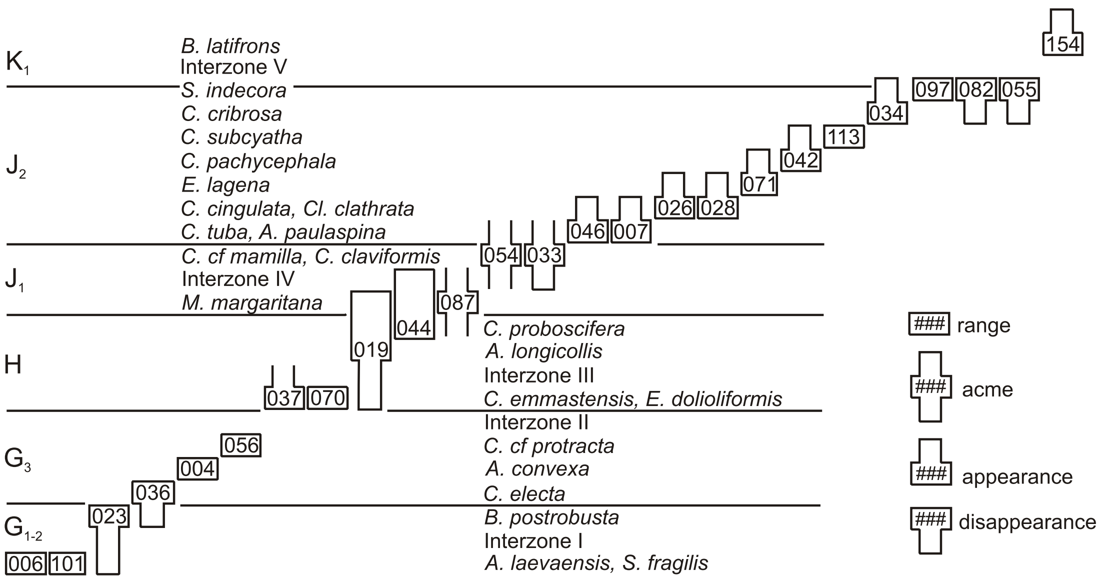

Fig. 3. Relationships between the ranges of the zonal species by Nestor (1994)

For full generic names see Figure 6

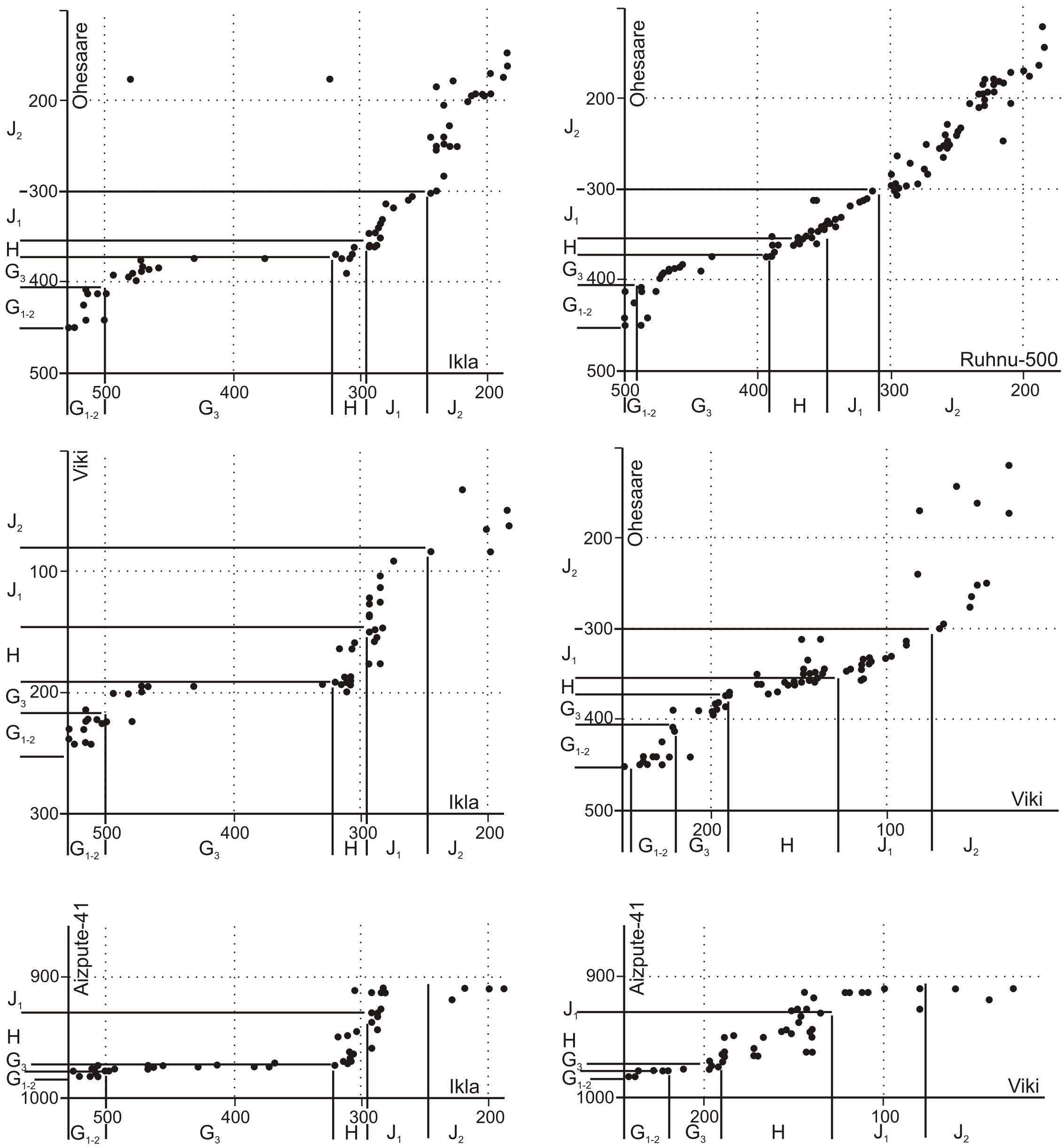

Fig. 4. Graphic correlations of the Ikla, Ruhnu-500, Ohesaare, Viki and Aizpute-41 sections based on the FO-s and LO-s of common chitinozoans

changes in relative sedimentation rates can be then detected by plotting individual sections against the composite section. Of three sections, Ikla, Ohesaare and Ruhnu, that encompass Llandovery and Wenlock strata overall, no single one approximates the requirements of an initial reference section because of highly variable sedimentation rates and the occurrence of gaps. To overcome the problems connected with the composite metrics this paper adopts the approach to construct the composite described below.

THE STANDARD SUCCESSION AND TIME

Alternative methods to graphic correlation have been developed that use the succession of taxa (and ultimately a faunal zonation) to derive a relative time scale (Guex, 1989; Agterberg, 1990). In this paper, we apply the DISTR algorithm (Pak, 1984, 1989; Rubel and Pak, 1984) and the corresponding computer program (written by D. Pak of Tadjikistan State University in 1986 and adapted for PC in 1998 by M. Kull, University of Tartu, Estonia) to construct the taxa successions and the relative time scale. In addition, the BioGraph algorithm (Guex, 1989) and its program from the Palaeontological Statistics package (PAST; Hammer *et al.*, 2001) have been used to incorporate all chitinozoan taxa into an integrated succession. This succession allows us to describe changes in distribution of chitinozoans within the study interval.

The DISTR algorithm sequences taxa into a composite standard so that the range of a taxon is "above" or "below" that of a second taxon range (if the first taxon occurs above or below the second taxon in all sections), or the taxa are "co-occurring" if the ranges overlap in at least one section. Taxa are arranged in a way that will avoid or minimize contradictions. Taxa which are involved in most contradictions, and are least common, are sequentially excluded to eliminate the contradictions. In real successions the number of excluded taxa can be remarkably high, reaching 62% in an analysis of Ordovician ostracodes from Lithuania (Ainsaar *et al*., 1999), 61–78% of Silurian ostracodes from Estonia (Rubel and Sarv, 1996), and 52% of Silurian brachiopods from Lithuania (Musteikis, 1989). Chitinozoans differ from these groups in their relatively low percentages of excluded taxa: 9–25% in the case of Estonian, Latvian and Lithuanian Ordovician chitinozoans (Nõlvak, 1989), and 36% (46 of 129 taxa) in this study of Silurian chitinozoans.

Before processing our dataset, we excluded taxa which occur only in one section (commonly in one sample), eliminating 30 taxa (Fig. 5). *Ancyrochitina ancyrea* was not included in the DISTR analysis due to its extremely long and variable ranges in sections, which led to many contradictions in ordering the taxa. Nearly 70% of the remaining 129 taxa occur in 2 to 8 sections (Fig. 5) mainly because the large majority of the core-sections did not penetrate the Llandovery and Wenlock interval completely. Thus, the number of sections representing different stages is not equal: 26 of them sampled the Juuru Stage, 18 the Raikküla Stage, 23 the Adavere Stage, 20 the Jaani Stage, 11 the Jaagarahu Stage, and only 3 sections for the Rootsiküla Stage. The DISTR analysis excluded 46 of the 129 taxa, leaving 83 that can be arranged into a reasonable standard succession that unambiguously summarises their relative positions in time. This succession defines 41 datum planes based on FO-s and LO-s, and is denoted herein as the standard 129/83/41 (Fig. 6).

Ideally, all existing zonal species would be included in this standard. In fact, only one (*Eisenackitina lagena*) was excluded in the construction of the standard 129/83/41 (see below). The DISTR analysis was rerun with the required inclusion of *E. lagena*, and the revised standard included 81 taxa and 39 datum planes. This standard is denoted as the standard 129/81/39. The differences between these two standards are small and only involve taxa in the middle of the Jaagarahu Stage. Using common taxa between these standards, the position of *E. lagena* as a zonal species can be determined on the standard 129/83/41 to be below *Belanechitina* sp. 1 (24) and above *Conochitina* aff. *pachycephala* (49), consistent with its position in the traditional zonal scheme (see Fig. 3). The standard 129/83/41 was used to correlate with the Baltic zones and stages (Figs. 7 and 8), and to describe sedimentation patterns (Fig. 10). The examination of the dynamics of chitinozoan diversity (Fig. 9) uses also the standard 129/83/41 because it includes more taxa than the standard 129/81/39 as well as the succession of taxa resulting from the BioGraph analysis.

A relative time scale is represented in the standard 129/83/41 (Fig. 6) by a series of rows. Each row represents a unique association of taxa (termed as unitary associations by Guex, 1989) that differs from adjacent rows at least in two taxon: at least one disappearing and one appearing taxa in each time step. The immediately successive LO-s and FO-s in different rows of the standard define the datum planes (actually intervals) of the standard. The LO and FO datums in the standard allow correlation to individual sections, and the determination of a LOC (Fig. 7). The LOC can be determined by statistical means through an averaging function through the data points. But this averaging line tends to smooth the abrupt distributional effects of stratigraphic gaps and for that reason it is not shown on most figures.

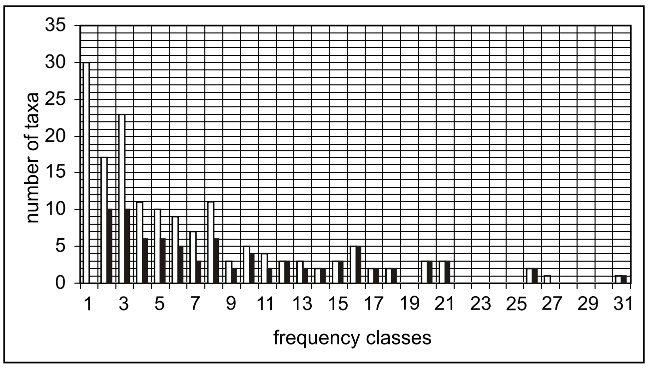

Fig. 5. Distribution of taxa by frequency in the dataset studied

White bars include all taxa in the dataset and black bars include only the taxa in the standard 129/83/41

THE STANDARD VERSUS STAGES AND ZONES

In stratigraphic terms, the range zone of each taxon consists of a row or successive rows within the standard (and its corresponding associations of taxa). Ranges can be considered as a concurrent zone if the row or rows representing one taxon overlap part of the range of another taxon. An assemblage or interval zone can be recognized if multiple taxa correspond to a row or series of rows. The ranges of established zonal species on the standard (indicated in bold in Fig. 6) show some overlap as in the case of the ranges of *Spinachitina fragilis* (taxon 101), *Ancyrochitina laevaensis* (6) and *Belonechitina postrobusta* (23). There are also intervals without preserved taxa or containing only scarse chitinozoans without specific forms (denoted as “interzones” by Nestor, 1994; Fig. 3) such as that between the ranges of *Conochitina* cf. *protracta* (56) and *Eisenackitina dolioliformis* (70).

However, all zonal species appear in the succession in a well-established order that can be used to make regional correlations such as those proposed by Kaljo (1990) and Nestor (1997). Those studies used the following chitinozoan events to identify the bases of the regional stages: the FO of *A. laevaensis* (6) for the Juuru Stage; the abundant FO-s of *Euconochitina electa* (36) and the FO of *Spinachitina maennili* (102) for the Raikküla Stage; the FO of *Eisenackitina dolioliformis* (70) or *Conochitina emmastensis* (37) for the Adavere Stage; the common FO-s of *Margachitina margaritana* (87) here associated with the FO of *Ramochitina nestorae* (78) for the Jaani Stage; the FO of *Cingulochitina cingulata* (26) for the Jaagarahu Stage; and the LO of *Sphaerochitina indecora* (97) for the Rootsiküla Stage. So defined stage boundaries coincide with datum planes identified in this study. The datum planes that correspond to the bases of the following stages are: datum plane 4 for the Raikküla Stage, datum plane 12 for the Adavere Stage, datum plane 24 for the Jaani Stage, and datum plane 29 for the Jaagarahu Stage (Figs. 6 and 8). The base of the

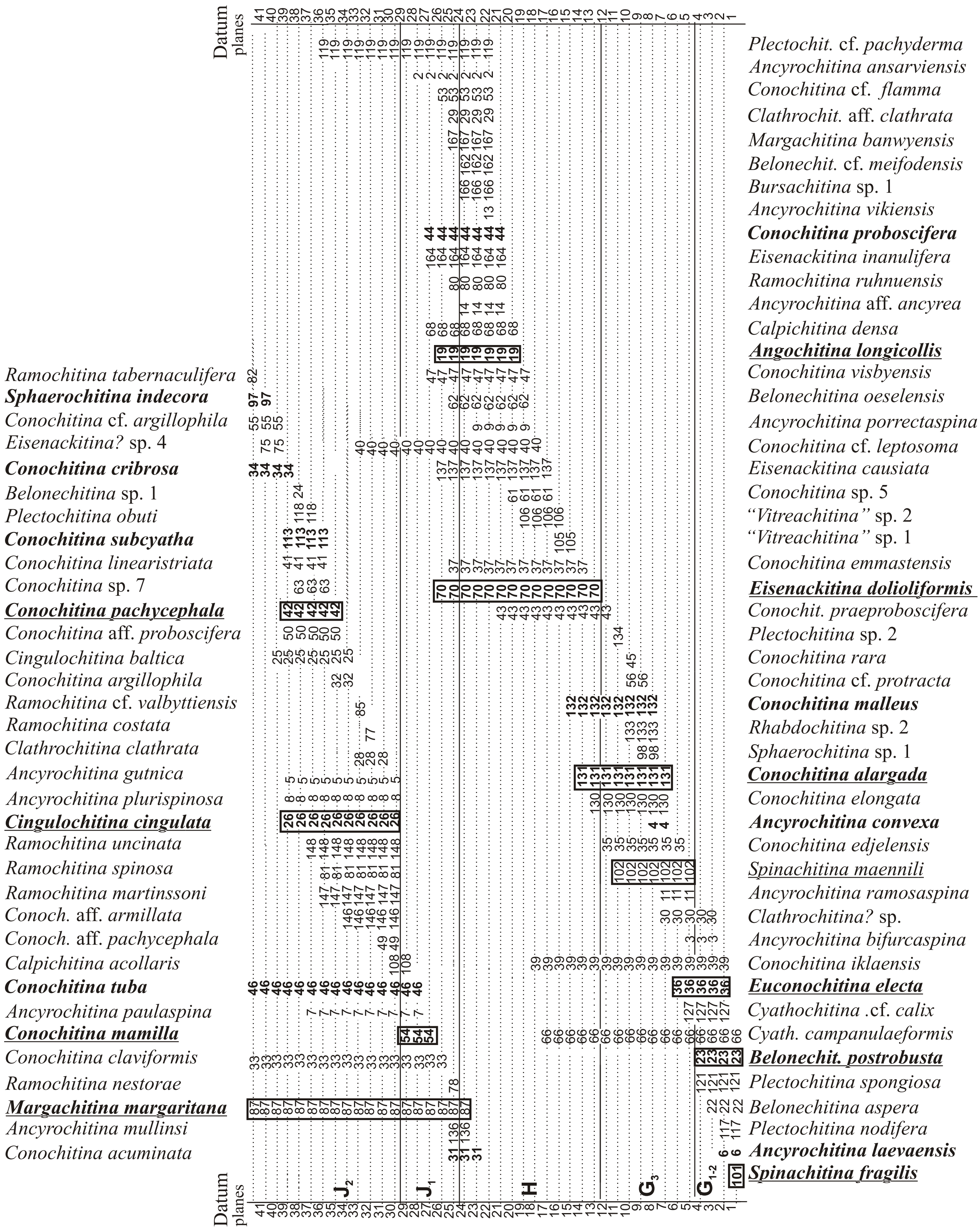

Fig. 6. Standard 129/83/41 with taxa arranged in order of their appearances

Taxa numbering (in the range chart) reflect their order in the entire dataset and the taxon names are given above and below the range chart; taxa in bold are zonal species (Nestor, 1994), and taxa with boxed ranges are index species of the global zones (Verniers *et al*., 1995); datum planes (1 to 41) are given along the sides of the range chart

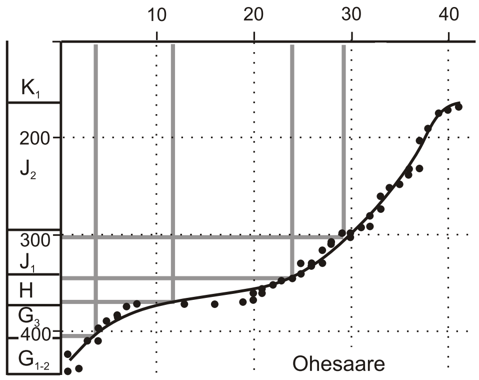

Fig. 7. Cross-plot of the Ohesaare section against the standard 129/83/41 using the datum planes based on FO-s and LO-s (circles) and a running average of their positions using a spline function

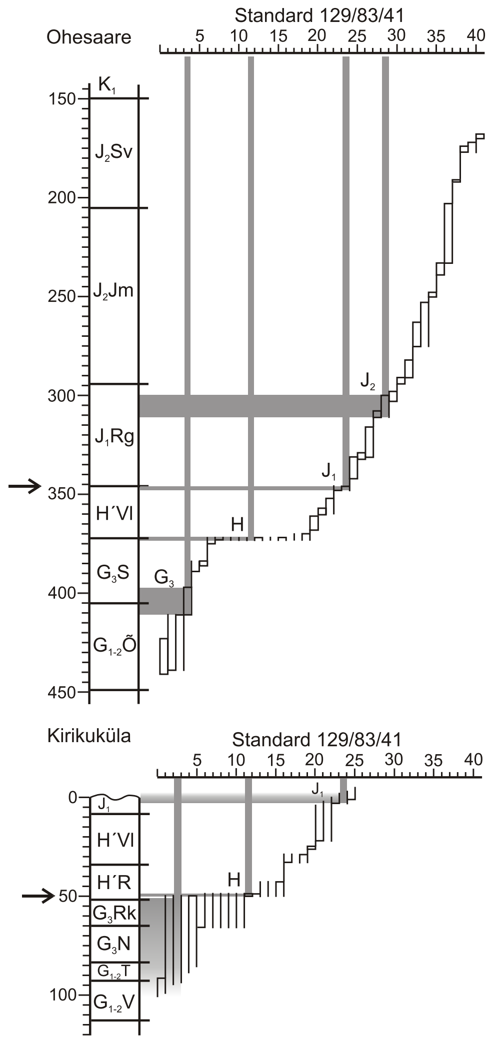

Fig. 8. Positions of the stage boundaries in the Ohesaare and Kirikküla sections based on cross-plots of the section position (vertical scale in metres) against the standard 129/83/41 (horizontal scale in numbered units)

Arrows — lower boundary stratotype position (SSP) of the Adavere Stage (H; Kirikküla section) and the Jaani Stage (J_1; Ohesaare section); for other stage symbols see Figure 2; formations: Õ — Õhne; S — Saarde; Vl — Velise; Rg — Rīga; Jm — Jamaja; Sv — Sõrve; V — Varbola; T — Tamsalu; N — Nurmekund; Rk — Raikküla; R — Rumba; each datum column may be closed at the top and base by horizontal lines or open; closed boundaries are limited by a FO and/or LO whereas open boundaries are limited by the limits on adjacent datums

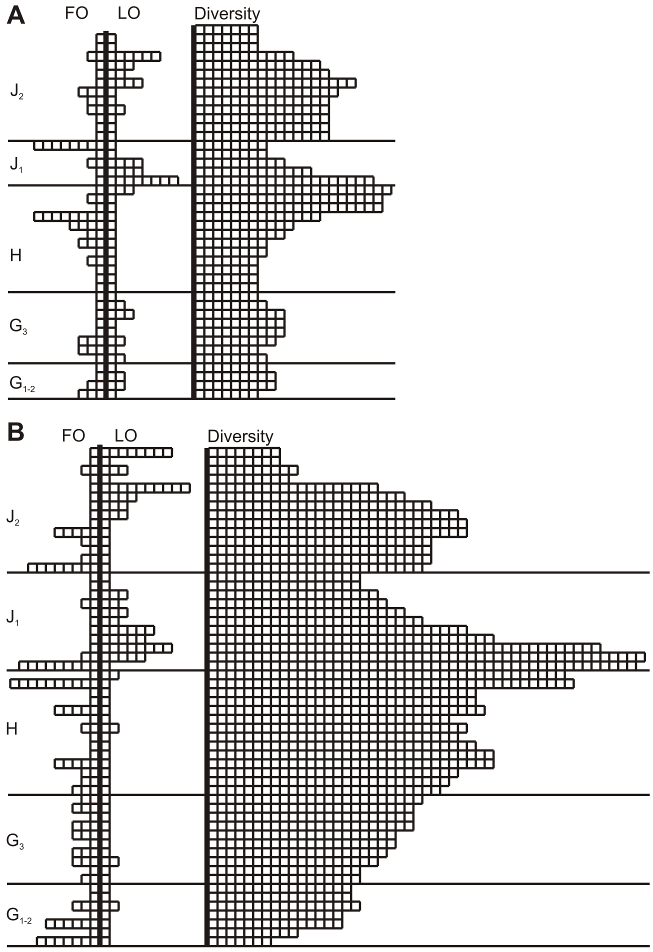

Fig. 9. Distribution of originations (FO-s) and extinctions (LO-s), and diversity of chitinozoan taxa according to the DISTR standard 129/83/41 (A) and the BioGraph analysis 180/180/56 (B)

Rootsiküla Stage is problematic due to the scarcity or absence of chitinozoans (Nestor, 1994).

The boundary stratotypes (SSP) of two of the Baltic stages are in the sections studied: the base of the Adavere Stage is at 50.3 m in the Kirikküla core-section, and the base of the Jaani Stage is at 345.8 m in the Ohesaare core-section (Nestor, 1997). Both horizons are effectively dated by the chitinozoan standard 129/83/41 using the species appearances noted above. In addition, boundary stratotypes of the lower boundaries of two other regional stages occur in the sections studied as the hypostratotypes for the Jaagarahu Stage at 21.4 m in the Jaagarahu core-section and the Rootsiküla Stage at 53.6 m in the Kipi core-section (Nestor, 1997). However in both of these sections, chitinozoans are too poorly represented to delineate the boundaries.

The Silurian chitinozoan global zones are defined by a succession of appearances of index species (indicated in Fig. 6 by the ranges enclosed in boxes; Verniers *et al.*, 1995). These index taxa are all positioned in the standard 129/83/41 in the sequence predicted by their zones except for the youngest such, *Sphaerochitina lycoperdoides* which is absent in the given dataset. A significant result is that the appearance of *Margachitina margaritana* (87), which marks the base of the Wenlock Series in the global zonation, occurs below the base of the Jaani Stage suggesting that the bases of these units are not equivalent (see also Loydell *et al.*, 1998; Nestor, 2005).

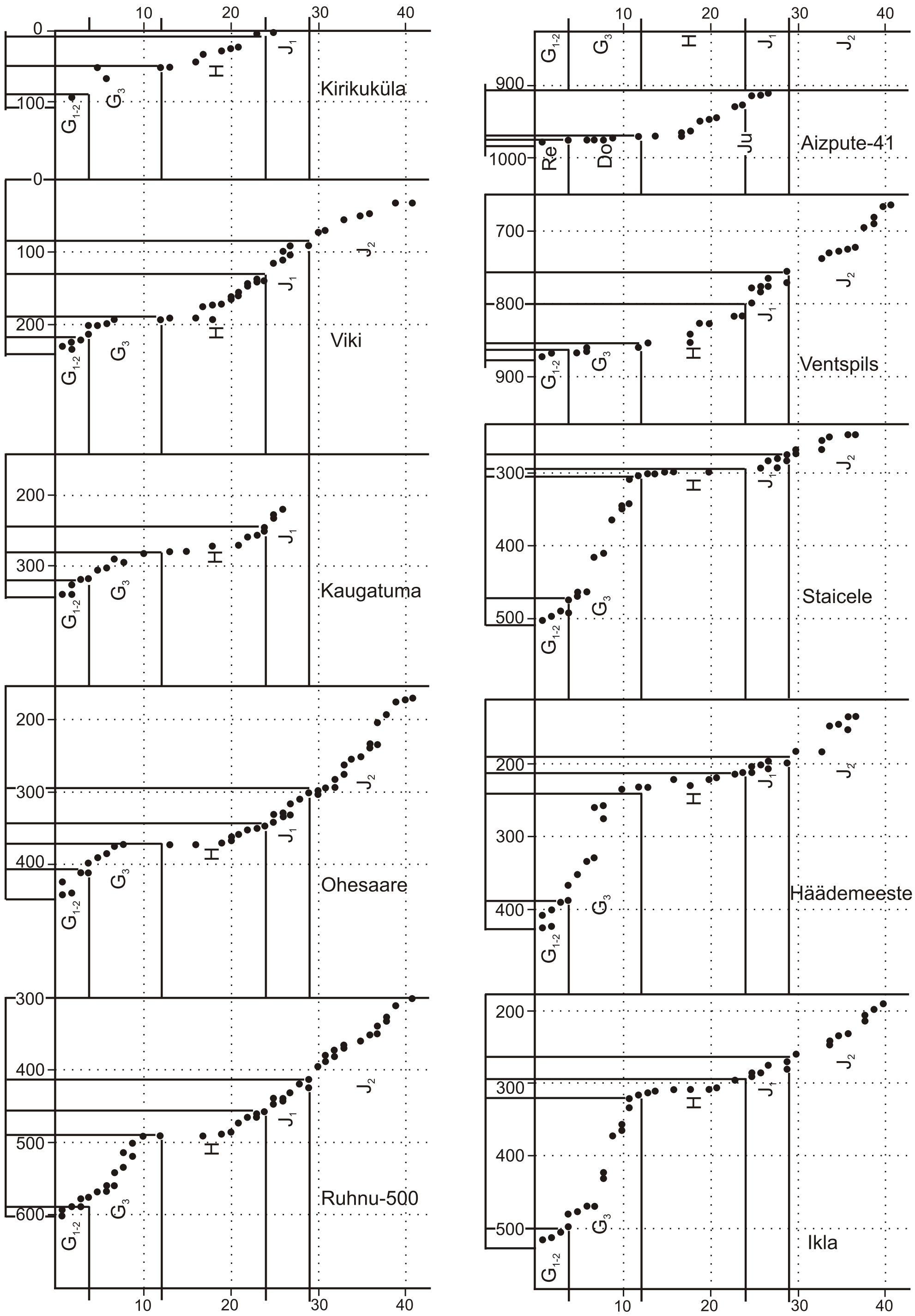

Fig. 10. LOC-s of eight sections according to their dating points

Formations in the Aizpute-41 section: Re — Remte; Do — Dobele; Ju — Jūrmala; see text for discussion of stratigraphic gaps and sediment accumulation patterns

CHITINOZOAN DYNAMICS AND SEDIMENTATION PATTERNS

The chitinozoan standard zonation (unitary associations by Guex) can be used to analyse the dynamics of chitinozoan diversity, sedimentation patterns, and the occurrences of stratigraphic gaps on a fine scale. The numerous datums of the standards developed here (Fig. 6) provide a finer temporal resolution than the traditional zones.

The chitinozoan standard introduced here provides a zonation based on the sequence of originations and extinctions recorded in the sections studied. The number of originations and extinctions, and the diversity by each row of the standard varied through the time interval studied. The general pattern is the same in both tabulations, i.e. according to the DISTR using the zonal species of the standard 129/83/41and BioGraph embracing all species in the dataset (Fig. 9). The lowest diversity characterised the beginning of the Silurian, probably resulting from the mass extinctions at the end of the Ordovician (see Brenchley *et al*., 2003). The number of chitinozoan zones in the Juuru Stage is fewer than in other stages due to the relatively low diversity and turnover at that time. The diversity steadily increased into the earliest Jaani Stage (near the base of the Wenlock Stage) and the resulting turnovers allow finer resolution in this interval. This helps to resolve the details of the stratigraphic gaps in the Raikküla and Adavere stages (see below). Chitinozoan diversity decreases through the Jaani Stage, limiting the resolution of the succession. The base of the Jaagarahu Stage is marked by an abrupt increase in chitinozoan diversity, and another diversity decline occurs in the upper part of the stage. The Rootsiküla Stage contains few chitinozoans because the three sections studied are predominantly lagoonal deposits in which chitinozoans are poorly preserved.

SEDIMENTATION RATES AND STRATIGRAPHIC GAPS

The chitinozoan standard allows comparison of sedimentation patterns in sections of the Estonian Shelf and the Livonian Basin. The accumulation patterns can be illustrated by cross-plotting the chitinozoan intervals against section thickness (well depths in most sections) in the same way that graphic correlation cross-plots local FO and LO horizons against a composite section (Fig. 10). Here the chitinozoan standard forms the horizontal axis, and the slopes of LOC-s are proportional to sediment accumulation rates (steeper slopes correspond to higher accumulation rates). Horizontal LOC segments represent stratigraphic gaps or intervals with very low sedimentation rates. A vertical LOC offset would indicate that some time was missing in the chitinozoan standard, and the absence of such offsets suggests that the standard represents a complete record of the strata deposited in the study area.

The stratigraphic gaps or intervals of low accumulation tend to occur at discrete times (based on the chitinozoan zonation) and to be best developed in geographically coherent areas. One example occurs at the beginning of the Juuru Stage ($G_{1\text{-}2}$ in Fig. 10). The earliest zonal species, *Spinachitina fragilis* (101), *Ancyrochitina laevaensis* (6), and *Plectochitina nodifera* (117), are missing in onshore sections in northern Estonia (Kirikuküla, Emmaste, Martna, Asuküla, Pusku, Rapla, Raikküla), but occur in more basinward sections (Ikla, Häädemeeste, Ruhnu-500). Another example is the gap at the end of the Raikküla Stage that is well developed in onshore but absent in basinal sections. The plots also illustrate the differences in overall accumulation rates across the study area, as demonstrated by the stratigraphic thickness variations in equivalent intervals.

The LOC-s against the standard in ten well-studied sections demonstrate regional changes in accumulation rates (Fig. 10). Transects across the Estonian Shelf (Kirikuküla to Ruhnu sections) show that deposition during the Juuru ($G_{1\text{-}2}$) and Raikküla (G_3) times was interrupted by a stratigraphic gap in the late Raikküla. The gap had the longest duration in the updip areas (Kirikuküla section). This gap is either not present or too brief to be recognized in the basinward sections (Staicele, Ikla, Häädemeeste), and the sections at Aizpute and Ventspils are too thin for a clear interpretation. The Adavere Stage may contain one or more gaps but the record is difficult to interpret because of low accumulation rates in all sections, a rapid transgression and variable accumulation in the lower part of the stage, and local erosion at the top of the stage (Harris *et al*., 2005). A gap at the boundary between the Jaani (J_1) and Jaagarahu (J_2) stages occurs in all studied sections penetrating this interval, except in the Ohesaare and Ruhnu-500 sections that provided the detailed data used to establish the chitinozoan standard. The stratigraphic gaps identified in this analysis correspond to sequence boundaries defined by depositional facies shifts, erosional surfaces and faunal zones (Harris *et al*., 2005).

CONCLUSIONS

1. Llandovery and Wenlock chitinozoans in the Estonian Shelf and Livonian Basin share the same temporal succession. Common species succeed each other in nearly the same order in all sections across the facies gradient.

2. The succession of chitinozoan species determined by the relative age relations (“above”, “below”, and “co-occurring”) defines a standard succession of taxa that provides a high-resolution time scale for dating the sections studied.

3. Regional and global chitinozoan zones can be tied to the chitinozoan standard by the ranges of index fossils in the standard. The index fossils and traditional zones are properly positioned on the chitinozoan standard.

4. Chitinozoan diversity steadily increases during the Llandovery epoch (Juuru to Adavere times). In the Wenlock, a diversity decline in Jaani time was followed by an abrupt increase in early Jaagarahu time and a second decline in late Jaagarahu time.

5. Cross-plots of section thickness against the chitinozoan standard reveal variations in sediment accumulation patterns. Thickness patterns and stratigraphic gaps reflect palaeogeographic positions of sections within the basin, and the major stratigraphic gaps correspond to identifiable sequence boundaries.

Acknowledgements. Financial support for this research was provided by Estonian Science Foundation grant 5290 (Rubel), 5406 (Männik), 5920 (Nestor), 5922 (Nõlvak) and 6460 (Ainsaar) as well as National Science Foundation grants EAR-9909286 (Harris) and EAR-9910198 (Sheehan). Authors are grateful to M. A. Kleffner and the anonymous reviewer for most valuable comments and suggestions.

REFERENCES

AINSAAR L., MARTMA T., Meidla T., RUBEL M. and Sidaravičienė N. (1999) — Quantitative stratigraphy of sedimentary sequences: a case study of the Middle Ordovician event. In: Computerized Modeling of Sedimentary Systems (eds. J. Harff, W. Lemke and K. Stattegger): 275–287. Springer Verlag. Berlin.

AGTERBERG F. P. (1990) — Automated Stratigraphic Correlation. Developments in Palaeontology and Stratigraphy, **13**. Elsevier. Amsterdam.

BASSETT M. B., KALJO D. and TELLER L. (1989) — The Baltic Region. In: A global Standard for the Silurian System (eds. C. H. Holland and M. G. Bassett). Nat. Mus. Wales. Geol. Ser., **9**: 158–170.

BRENCHLEY P. J., CARDEN G. A., HINTS L., KALJO D., MARSHALL J. D., MARTMA T., MEIDLA T. and NÕLVAK J. (2003) — High resolution stable isotope stratigraphy of Upper Ordovician sequences: constraints on the timing of bioevents and environmental changes associated with mass extinction and glaciation. GSA Bull., **115**: 89–104.

GAILĪTE L. K., ULST R. Z. H. and YAKOVLEVA V. I. (1987) — Stratotipicheskie i tipovye razrezy silura Latvii. Zinatne. Riga.

GUEX J. (1989) — Biochronological Correlations. Springer Verlag. Berlin.

HAMMER O., HARPER D. A. T. and RYAN P. D. (2001) — PAST. Palaeontological Statistics Software Package for Educational and Data Analysis. Palaeontologica Electronica, **4**.

HARRIS M. T., SHEEHAN P. M., AINSAAR L., HINTS, L., MÄNNIK, P., NÕLVAK, J. and RUBEL M. (2005) — The lower Silurian of Estonia: facies, sequences and basin filling. Sixth Baltic Stratigraphical Conference, St. Petersburg, Russia, Abstract: 30–33.

KALJO D. (1990) — The Silurian of Estonia. In: Field Meeting. Estonia 1990. An Excursion Guidebook. (eds. D. Kaljo and H. Nestor): 21–26. Inst. Geol., Estonian Acad. Sc., IUGS. Tallinn.

KALJO D., NESTOR H. and EINASTO R. (1991) — Aspects of Silurian carbonate platform sedimentation. In: The Murchison Symposium (eds. M.G. Bassett *et al*.). Spec. Pap. Palaeont., **44**: 205–224.

LOYDELL D. K., KALJO D. and MÄNNIK P. (1998) — Integrated biostratigraphy of the lower Silurian of the Ohesaare core, Saaremaa, Estonia. Geol. Mag., **135**: 769–783.

LOYDELL D. K., MÄNNIK P. and NESTOR V. (2003) — Integrated biostratigraphy of the lower Silurian of the Aizpute-41 core, Latvia. Geol. Mag., **140**: 205–229.

MUSTEIKIS P. (1989) — Results of quantitative stratigraphic correlation in the Silurian of Lithuania: Brachiopods. In: Retrospective Evaluation and Future Development (eds. A. Oleynikov and M. Rubel): 155–167. Acad. Sc. Estonian SSR, Inst. Geol. Tallinn.

NESTOR H. (1997) — Silurian. In: Geology and Mineral Resources of Estonia (eds. A. Raukas and A. Teedumäe): 89–106. Estonian Acad. Publ. Tallinn.

NESTOR H. and EINASTO, R. (1997) — Ordovician and Silurian carbonate sedimentary basin. In: Geology and Mineral Resources of Estonia (eds. A. Raukas and A. Teedumäe): 192-204. Estonian Acad. Publ. Tallinn.

NESTOR V. (1994) — Early Silurian chitinozoans of Estonia and Latvia. Academia, **4**. Estonian Acad. Publ. Tallinn.

NESTOR V. (1998) — Chitinozoan biofacies of late early Llandovery (*Coronograptus cyphus*) age in the East Baltic. Proc. Estonian Acad. Sc. Geol., **47**: 219–228.

NESTOR V. (2003) – Distribution of Silurian chitinozoans in Ruhnu (500) drill core. Estonian Geol. Sections, **5**: 13–14.

NESTOR V. (2005) — Chitinozoans of the *Margachitina margaritana* Biozone and the Llandovery-Wenlock boundary in the West Estonian drill cores. Proc. Estonian Acad. Sc. Geol., **54**: 87–111.

NÕLVAK J. (1989) — Results of quantitative stratigraphic correlation of the Upper Ordovician in the Baltic: Chitinozoans. In: Retrospective Evaluation and Future Development (eds. A. Oleynikov and M. Rubel): 139 –154. Acad. Sc. Estonian SSR, Inst. Geol. Tallinn.

PAK D. N. (1984) — Mathematical model for the construction of composite standards from occurrences of fossil taxa. Computers and Geosc., **10**: 107–110.

PAK D. N. (1989) — Construction of palaeontological time scale by means of linear criterion. In: Retrospective Evaluation and Future Development (eds. A. Oleynikov and M. Rubel): 61–72. Acad. Sc. Estonian SSR, Inst. Geol. Tallinn.

PAŠKEVIČIUS J. (1997) — The Geology of the Baltic Republics. Vilnius Univ. and Geol. Surv. Lithuania. Vilnius.

RUBEL M. and PAK D. N. (1984) — Theory of stratigraphic correlation by means of ordinal scales. Computers and Geosc., **10**: 97–105.

RUBEL M. and SARV L. (1996) — Reconstruction and use of the succession of East Baltic Silurian ostracodes. Proc. Estonian Acad. Sc. Geol., **45**: 177–188.

SHAW A. B. (1964) — Time in Stratigraphy. McGraw-Hill Book Co. New York.

VERNIERS J., NESTOR V., PARIS F., DUFKA P., SUTHERLAND S. and VAN GROOTEL G. (1995) — A global chitinozoa biozonation for the Silurian. Geol. Mag., **132**: 651–666.