

Recent developments in the Upper Ordovician and lower Silurian conodont biostratigraphy in Estonia

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Abstract. The current state of and the latest developments in the conodont-based biostratigraphical studies of Upper Ordovician and lower Silurian strata in Estonia are discussed. An updated conodont zonation is proposed, based on successive first and/or last occurrences of taxa as interpreted from the stratigraphical record of Estonia as well as of other parts of the world. The zonation includes mainly units proposed by different authors at different times, with some revision by the author. Currently, 32 zones (with 14 subzones) and 3 informal units can be recognized in the Upper Ordovician to upper Wenlock (Homerian) of Estonia.

Key words: conodonts, biostratigraphy, Upper Ordovician, Llandovery, Wenlock, Estonia.

INTRODUCTION

Systematic studies of conodonts in Estonia started in the middle of the 1960s. Since then, a wealth of data about conodont taxonomy, palaeoecology, and biostratigraphy in Estonia has been collected. In accordance with the development of conodont studies in other areas, a conodont biozonation has been worked out and updated for the East Baltic (e.g. Viira & Männik 1997). Most of the biozones described elsewhere (e.g. Walliser 1964; Bergström 1971; Jeppsson 1997) are recognized in the East Baltic region. In addition, detailed studies of the Estonian conodont successions have provided valuable information for improving the resolution of the so-called international conodont standard (Viira 1999; Männik in press). Recognition of various ecological associations of conodonts has resulted in different local conodont zonations for shallow and deeper shelf environments of some stratigraphical intervals (Viira 1982). In recent years, studies of the conodont succession have obtained sufficient detail to locate and date several gaps in the Silurian sequence in Estonia (Jeppsson et al. 1994). The main aim of the present paper is to summarize the current state of, and the latest developments in conodont-based biostratigraphical studies of Upper Ordovician and lower Silurian strata in Estonia.

CONODONT ZONATION

The zonation discussed below is based on a succession of units proposed by different authors at different times,

with some revisions by the author. The Upper Ordovician zonation corresponds mainly to that of Bergström (1971, 1983); the Wenlock zonation was developed by Jeppsson (Jeppsson 1997; Jeppsson & Calner 2003); an updated version of the Telychian zonation is available in Männik (in press). At present, 32 zones (with 14 subzones) and 3 informal units can be recognized in the Upper Ordovician to upper Wenlock (Homerian) strata of Estonia (Fig. 1).

*The *Pygodus anserinus* and *Amorphognathus tvaerensis* zones*

The latest data indicate that the boundary between the Middle and Upper Ordovician in Estonia most probably correlates with the boundary between the Uhaku and Kukruse stages (Nõlvak et al. 2006). In the conodont succession this level lies in the middle part of the *Pygodus anserinus* Zone, in the uppermost *Sagittodontina kielcensis* Subzone (Männik 2003; Männik & Viira, 2005; Fig. 2). Probable correlations between the Ordovician conodont, chitinozoan, and graptolite zonations in Estonia can be found in Nõlvak et al. (2006).

*The *Pygodus anserinus* Zone*

The lower boundary of the *Pyg. anserinus* Zone coincides with the level where *Pyg. serra* is replaced by *Pyg. anserinus*, and its upper boundary is marked by the appearance of *Amorphognathus tvaerensis*. Two subzones, Lower and Upper, have been distinguished in this zone (Bergström 1971). Their boundary corresponds

| Series | Stage | Super-zone | Zone | Subzone | Selected conodont ranges | |
|--------------------------------------|-----------------------------|--|---------------------------------------|------------------------------------|--------------------------|------------------------------|
| WENLOCK | Homerian | | <i>C. murchisoni</i> | | ↑ | |
| | | | <i>K. o. absidata</i> | | | |
| | | | <i>Ozarkodina bohemica longa</i> | 4 | | |
| | | | | 3 | | |
| | | | | 2 | | |
| | Sheinwoodian | <i>Kockelella ortus ortus</i> | <i>O. s. sagitta</i> | | ↑ | |
| | | | <i>K. o. ortus</i> | | | |
| | | | post- <i>K. walliseri</i> interregnum | | | |
| | | Upper <i>Kockelella walliseri</i> | uppermost <i>K. walliseri</i> range | | | |
| | | | <i>K. patula</i> | | | |
| | | | Middle <i>K. walliseri</i> | | | |
| | | <i>O. sagitta rhenana</i> | Lower <i>K. walliseri</i> | | | |
| | | | <i>O. s. rhenana</i> | | | |
| | | <i>Kockelella ranuliformis</i> | Upper <i>K. ranuliformis</i> | | | |
| Lower <i>K. ranuliformis</i> | | | | | | |
| <i>P. pennatus procerus</i> | Upper <i>P. p. procerus</i> | | | | | |
| | Lower <i>P. p. procerus</i> | | | | | |
| <i>Ps. bicornis</i> | Upper <i>Ps. bicornis</i> | | | | | |
| | Lower <i>Ps. bicornis</i> | | | | | |
| LLANDOVERY | Telychian | | <i>Pterospathodus a. amorphogn.</i> | Upper <i>P. a. amorphogn.</i> | ↑ | |
| | | | <i>P. a. lithuanicus</i> | Lower <i>P. a. amorphogn.</i> | | |
| | | | <i>P. celloni</i> | <i>P. a. lennarti</i> | | |
| | | | | <i>Pterospathodus a. angulatus</i> | | Upper <i>P. a. angulatus</i> |
| | | | Lower <i>P. a. angulatus</i> | | | |
| | <i>P. eopennatus</i> | <i>Pterospathodus eopennatus</i> ssp. n. 2 | Upper <i>P. eop. ssp. n. 2</i> | | | |
| | | <i>P. eopennatus</i> ssp. n. 1 | Lower <i>P. eop. ssp. n. 2</i> | | | |
| | Rhuddanian-Aeronian | <i>Aspelundia</i> | <i>D. staurognathoides</i> | | | |
| | | | <i>As. fluegeli</i> | | | |
| | | | <i>As. expansa</i> | | | |
| | | | <i>D. kentuckyensis</i> | | | |
| | UPPER ORDOVICIAN | Stage 6 | | "Noixodontus" | | ↑ |
| | | | | <i>A. ordovicicus</i> | | |
| | | <i>A. superbis</i> | | | | |
| <i>A. ventilatus</i> | | | | | | |
| "uppermost <i>Baltoniodus</i> range" | | | | | | |
| "uppermost <i>B. alobatus</i> range" | | | | | | |
| Stage 5 | | <i>Amorphognathus tvaerensis</i> | | <i>B. alobatus</i> | | |
| | | | | <i>B. gerdæ</i> | | |
| | | | | <i>B. variabilis</i> | | |
| M.O. | | Darr. | | <i>Pygodus anserinus</i> | <i>A. inaequalis</i> | |
| | | | <i>S. kielcensis</i> | | | |

to the level at which *Baltoniodus prevariabilis* is evolutionally replaced by *B. variabilis* (Fig. 1). Later, based on the suggestion by Dzik (1978) that *S. kielcensis* is replaced by *Amorphognathus inaequalis* at the same level, Bergström (1983) proposed renaming the Lower and Upper subzones, respectively, as the *S. kielcensis* and *A. inaequalis* subzones. However, as these taxa occur sporadically, the boundary between the subzones can be identified mainly on the basis of changes in the *Baltoniodus* lineage. Unfortunately, as Dzik (1978) pointed out, early specimens of *B. variabilis* had an amorphognathiform (Pa) element barely distinguishable from that of its ancestor *B. prevariabilis*. For that reason precise location of the boundary in a section is often problematic. Data from Estonia agree with Dzik's conclusions: morphological changes in the *B. prevariabilis*–*B. variabilis* transitions are gradational, thus the exact position of the boundary between the subzones is often hard to define.

In Estonia, the *Pyg. anserinus* Zone correlates with the upper Uhaku and lower Kukruse stages; the boundary between the *S. kielcensis* and *A. inaequalis* subzones has been recognized in the lowermost Kukruse Stage (Männik 2003; Männik & Viira 2005; Fig. 2). The boundary interval of the *Pyg. serra* and *Pyg. anserinus* zones is characterized by the occurrence of *S. kielcensis*, and the uppermost part of the *A. inaequalis* Subzone of the *Pyg. anserinus* Zone by the occurrence of *Eoplacognathus elongatus* Bergström. *Eoplacognathus elongatus* ranges into the lower part of the overlying *A. tvaerensis* Zone. In all studied sections *Scabbardella* ex gr. *altipes* appears together with *B. variabilis*. In the Ruhnu-500 and Mehikoorma-421 core sections probable specimens of *A. inaequalis* have been identified in the upper *A. inaequalis* Subzone (Männik 2003; Männik & Viira 2005).

The *Amorphognathus tvaerensis* Zone

The *A. tvaerensis* Zone was defined by Bergström (1971) as the interval from the first appearance of *A. tvaerensis* up to that of *A. superbis*. The *A. tvaerensis* Zone was subdivided into three subzones (in ascending order): *Baltoniodus variabilis*, *B. gerdae*, and *B. alobatus* (Bergström 1971). Recently it was demonstrated, at least in Estonia, that the disappearance of *A. tvaerensis* is followed by an interval where *Amorphognathus* is

missing or is too rare to be found in samples available from a core (corresponds approximately to the upper Haljala and Keila stages). Also, *A. superbis* appears in the uppermost Oandu Stage and is preceded by an interval with *A. ventilatus* (= main part of the Oandu Stage) (Männik 2003, 2004; Männik & Viira 2005). Currently, the *A. tvaerensis* Zone in Estonia is considered to correspond to the upper Kukruse and lower Haljala (= the Idavere Substage) stages (Fig. 2), up to Datum 1 *sensu* Männik (2004) of the Mid-Caradoc Event. All three subzones of the *A. tvaerensis* Zone are well represented by their nominal taxa and easy to recognize in Estonia.

The Mid-Caradoc Event interval

In the conodont succession, the Mid-Caradoc Event is considered to correspond to the interval from the level of disappearance (considerable decrease in abundance?) of *A. tvaerensis* (= Datum 1 of the event) up to the level of disappearance of the *Semiacontiodus* lineage (= Datum 5) (Männik 2004). Five datums (levels of major changes in conodont faunas) have been recognized in the event interval. These datums have proved useful in regional stratigraphy for recognition and correlation of several informal units (Männik 2003, 2004; Männik & Viira 2005).

“The uppermost *Baltoniodus alobatus* range”

This informal unit corresponds to the interval between Datum 1 (level of disappearance of *A. tvaerensis*) and Datum 2 (level of disappearance of *B. alobatus*) of the Mid-Caradoc Event, and has been recognized in several sections in Estonia (Männik 2003, 2004; Männik & Viira 2005; Fig. 1). “The uppermost *B. alobatus* range” correlates with the upper part of the Haljala Stage (Fig. 2).

“The uppermost *Baltoniodus* range”

The unit corresponds to the interval between datums 2 and 4 of the Mid-Caradoc Event. At Datum 2 the abundance of conodonts decreases considerably and faunas become dominated by coniform-bearing taxa, such as, for example, *Decoriconus*, *Drepanoistodus*, and *Panderodus* (Männik 2004). Ramiforms are extremely

Fig. 1. Upper Ordovician–lower Silurian conodont zonation. Dashed parts of the ranges indicate scattered presence of a taxon. Short horizontal lines mark the fixed levels of appearances and/or disappearances of taxa. M.O., Middle Ordovician; Darr., Darriwilian; *A.*, *Amorphognathus*; *As.*, *Aspelundia*; *B.*, *Baltoniodus*; *C.*, *Ctenognathodus*; *D.*, *Distomodus*; *K.*, *Kockelella*; *K. o.*, *Kockelella ortus*; *O.*, *Ozarkodina*; *O. s.*, *Ozarkodina sagitta*; *P.*, *Pterospathodus*; *P. a.*, *Pterospathodus amorphognathoides*; *P. eop.*, *Pterospathodus eopennatus*; *P. p.*, *Pterospathodus pennatus*; *Ps.*, *Pseudooneotodus*; *S.*, *Sagittodontina*.

| Series | Stage | Regional stage | Superzone | Zone | Subzone | Conodont zonation in Viira & Männik (1997) | | | |
|---------------------|--------------|----------------|-----------------------------|---|---------------------------------------|--|------------------------------------|---|---|
| WENLOCK | Homerian | Rootsiküla | | <i>C. purchisoni</i> | | | <i>O. b. bohémica</i> | <i>C. purchisoni</i> | |
| | | | | <i>K. o. absidata</i> | | | | | |
| | | | | <i>Ozarkodina bohémica longa</i> | | | | | 4 |
| | | | | | | | | | 3 |
| | | | | | | | | | 2 |
| | | | | | | | | | 1 |
| | Sheinwoodian | Jaagarahu | | <i>Kockelella ortus ortus</i> | <i>O. s. sagitta</i> | | | <i>Kockelella absidata</i> | |
| | | | | | <i>K. o. ortus</i> | | | | |
| | | | | | post- <i>K. walliseri</i> interregnum | | | | |
| | | | | | uppermost <i>K. walliseri</i> range | | | | |
| | | | | | <i>K. patula</i> | | | | |
| | | | | | Middle <i>K. walliseri</i> | | | | |
| Telychian | Adavere | | <i>P. pennatus procerus</i> | Lower <i>K. walliseri</i> | | | <i>Kockelella amsdeni</i> | | |
| | | | | <i>O. s. rhenana</i> | | | | | |
| | | | | Upper <i>K. ranuliformis</i> | | | | | |
| | | | | Lower <i>K. ranuliformis</i> | | | | | |
| | | | | Upper <i>P. p. procerus</i> | | | | | |
| | | | | Lower <i>P. p. procerus</i> | | | | | |
| Rhuddanian-Aeronian | Raikküla | | <i>Ps. bicornis</i> | Upper <i>Ps. bicornis</i> | | | <i>Kockelella walliseri</i> | <i>O. sagitta rhenana</i> | |
| | | | | Lower <i>Ps. bicornis</i> | | | | | |
| | | | | Upper <i>Pterospathodus a. amorphogn.</i> | | | | | |
| | | | | Lower <i>P. a. amorphogn.</i> | | | | | |
| | | | | Upper <i>P. a. lithuanicus</i> | | | | | |
| | | | | <i>P. a. lennarti</i> | | | | | |
| Hirnantian | Porkuni | | <i>P. celloni</i> | Upper <i>P. a. angulatus</i> | | | <i>Kockelella ranuliformis</i> | <i>Pterospathodus amorphognathoides</i> | |
| | | | | Lower <i>P. a. angulatus</i> | | | | | |
| | | | | Upper <i>P. eopennatus</i> ssp. n. 2 | | | | | |
| | | | | Lower <i>P. eop. ssp. n. 2</i> | | | | | |
| | | | | <i>P. eopennatus</i> ssp. n. 1 | | | | | |
| | | | | <i>D. staurognathoides</i> | | | | | |
| Stage 6 | Oandu | | <i>Aspelundia</i> | <i>As. fluegeli</i> | | | <i>Pterospathodus celloni</i> | <i>Pterospathodus eopennatus</i> | |
| | | | | <i>As. expansa</i> | | | | | |
| | | | | <i>D. kentuckyensis</i> | | | | | |
| | | | | <i>A. ordovicicus</i> | | | | | |
| | | | | <i>A. superbis</i> | | | | | |
| | | | | <i>A. ventilatus</i> | | | | | |
| Stage 5 | Haljala | | <i>Pygodus anserinus</i> | “uppermost <i>Baltoniodus</i> range” | | | <i>Distomodus staurognathoides</i> | <i>Pranognathus tenuis</i> | |
| | | | | “uppermost <i>B. alobatus</i> range” | | | | | |
| | | | | <i>Amorphognathus tvaerensis</i> | | | | | |
| | | | | <i>B. alobatus</i> | | | | | |
| | | | | <i>B. gerdae</i> | | | | | |
| | | | | <i>B. variabilis</i> | | | | | |
| Stage 4 | Kukuruse | | | <i>A. inaequalis</i> | | | <i>Distomodus kentuckyensis</i> | | |
| | | | | <i>S. kielcensis</i> | | | | | |
| | | | | <i>A. ordovicicus</i> | | | | | |
| | | | | <i>A. superbis</i> | | | | | |
| | | | | <i>A. ventilatus</i> | | | | | |
| | | | | “uppermost <i>Baltoniodus</i> range” | | | | | |
| Stage 3 | Keila | | | <i>A. superbis</i> | | | <i>Pygodus anserinus</i> | | |
| | | | | <i>A. ventilatus</i> | | | | | |
| | | | | <i>A. inaequalis</i> | | | | | |
| | | | | <i>S. kielcensis</i> | | | | | |
| | | | | <i>A. ordovicicus</i> | | | | | |
| | | | | <i>A. superbis</i> | | | | | |
| Stage 2 | Keila | | | <i>A. inaequalis</i> | | | <i>Pygodus anserinus</i> | | |
| | | | | <i>S. kielcensis</i> | | | | | |
| | | | | <i>A. ordovicicus</i> | | | | | |
| | | | | <i>A. superbis</i> | | | | | |
| | | | | <i>A. ventilatus</i> | | | | | |
| | | | | <i>A. inaequalis</i> | | | | | |
| Stage 1 | Keila | | | <i>A. inaequalis</i> | | | <i>Pygodus anserinus</i> | | |
| | | | | <i>S. kielcensis</i> | | | | | |
| | | | | <i>A. ordovicicus</i> | | | | | |
| | | | | <i>A. superbis</i> | | | | | |
| | | | | <i>A. ventilatus</i> | | | | | |
| | | | | <i>A. inaequalis</i> | | | | | |
| Stage 0 | Keila | | | <i>A. inaequalis</i> | | | <i>Pygodus anserinus</i> | | |
| | | | | <i>S. kielcensis</i> | | | | | |
| | | | | <i>A. ordovicicus</i> | | | | | |
| | | | | <i>A. superbis</i> | | | | | |
| | | | | <i>A. ventilatus</i> | | | | | |
| | | | | <i>A. inaequalis</i> | | | | | |

rare in this interval, but small unidentifiable fragments of *Baltoniodus* occur sporadically. The upper boundary of “the uppermost *Baltoniodus* range” corresponds to the level of appearance of *A. ventilatus* (Fig. 1). The “uppermost *Baltoniodus* range” corresponds to the uppermost Haljala, Keila, and the lowermost Oandu stages (Fig. 2).

The uppermost Ordovician

The Amorphognathus ventilatus Zone

Dzik (1999) recognized an interval with *A. ventilatus* between the ranges (zones) of *A. tvaerensis* and *A. superbus*. Later, the *A. ventilatus* Zone was identified in several core sections in Estonia (Männik 2003; Männik & Viira 2005), with its lower boundary (the level of appearance of *A. ventilatus*) coinciding with Datum 4 of the Mid-Caradoc Event. The upper boundary of the zone is marked by the appearance of *A. superbus* (Fig. 1). Previously in Estonia, an interval almost identical to the *A. ventilatus* Zone was correlated with the *Ozarkodina* aff. *rhodesi*–*Icriodella* cf. *superba* Zone (Viira 1974; = *I. superba*–*Plectodina* sp. Subzone of the *A. superbus* Zone in Viira & Männik 1997; Fig. 2). The zone corresponds to the main part of the Oandu Stage.

The Amorphognathus superbus Zone

Bergström (1971) defined the *A. superbus* Zone as a unit corresponding to the interval from the first appearance of *A. superbus* up to the first appearance of *A. ordovicicus*. In Bergström’s scheme the *A. superbus* Zone follows directly the *A. tvaerensis* Zone. As we know now, a considerable interval separates the ranges of *A. tvaerensis* and *A. superbus* (see above; Fig. 1). In the lower part of this interval *Amorphognathus* is very rare or absent; in its upper part *A. ventilatus* occurs. Besides, according to Dzik (1999), *A. superbus* is not directly followed by *A. ordovicicus*, but these taxa are evolutionally linked by a form called by Dzik *Amorphognathus* sp. n., and the interval between the *A. superbus* and *A. ordovicicus* zones can be considered as a separate unit. In the zonal scheme proposed by Viira (1974) the interval identified here as the *A. superbus* Zone corresponds to the main part of the “*Ambalodus triangularis frognoeyensis*” Zone, and in Viira & Männik (1997) to the upper part of the

A. superbus Zone (including the *Hamarodus europaeus* Subzone; Fig. 2).

The *A. superbus* Zone corresponds to the uppermost Oandu(?), Rakvere, and Nabala stages, possibly the uppermost part of the Nabala Stage excluded (see below the discussion of the *A. ordovicicus* Zone). *Amorphognathus complicatus* Bergström occurs in this zone, particularly in its lower part (e.g. Männik 2003; Fig. 1).

The Amorphognathus ordovicicus Zone

Originally, this zone was defined as corresponding to the total range of *A. ordovicicus* (Bergström 1971). *Amorphognathus ordovicicus* was considered to be the last member in the evolutionary lineage of *Amorphognathus*, which became extinct at the Ordovician–Silurian boundary. However, as Dzik (1999) demonstrated, *A. ordovicicus* is not the last species in the lineage but is followed by *A. duftonus* Rhodes. So far, *A. duftonus* has not been identified in Estonia, but the uppermost Ordovician conodont faunas of the Valga-10 and Ruhnu-500 core sections (Porkuni Stage, its lower part – the Bernati Member – excluded) differ considerably from that of the underlying strata with *A. ordovicicus* (Männik 2001, 2003). In both sections the Ordovician strata above the Bernati Member yield very poor faunas, mainly dominated by *Noixodontus girardeauensis*. *Amorphognathus* is missing in these strata (in the Valga-10 core) or is extremely rare and represented by unidentifiable fragments (in the Ruhnu-500 core).

In the Mehikoorma-421 core section, the lowermost specimens of *A. ordovicicus* are found at 270.00–270.10 m, in the upper part of the Saunja Formation (Männik & Viira 2005). The species is almost continuously present in all samples above this level. In the light of the present data it is likely that in Estonia *A. ordovicicus* appears already in the upper Nabala Stage and not in the lowermost Vormsi Stage as reported earlier (Männik 1992). However, a single M element of *Amorphognathus*, identical to that of *Amorphognathus* sp. n. Dzik (1999), was found in the uppermost sample from the Saunja Formation (at 269.10–269.20 m). This may indicate that the lowermost part of the *A. ordovicicus* Zone (corresponding to the upper Nabala Stage), as identified in the Mehikoorma-421 core section, is an equivalent to the *Amorphognathus* sp. n. interval *sensu* Dzik (1999).

Fig. 2. Correlation of the Upper Ordovician–lower Silurian conodont zonation with regional stages and with the conodont zonation proposed earlier (in Viira & Männik 1997). Conodont zonation: in the Upper Ordovician part, zones are indicated in the left-hand column and subzones in the right-hand column; in the Silurian part, zonation for distal (deep-water) environments is indicated in the left-hand column and zonation for proximal (shallow-water) environments is shown in the right-hand column. Dashed lines indicate probable levels of zonal boundaries. *H.*, *Hamarodus*; *I.*, *Icriodella*; *P.*, *Plectodina*. For other abbreviations refer to Fig. 1.

In Estonia, the *A. ordovicicus* Zone corresponds to the Vormsi (or the uppermost Nabala?, see above), Pirgu, and lower Porkuni stages (Fig. 2).

“*The Noixodontus interval*”

This informal unit corresponds to the uppermost Ordovician strata, to the Edole Member of the Kuldiga Formation (Porkuni Stage; Fig. 2), and has thus far been recognized only in the Valga-10 and Ruhnu-500 core sections in southern Estonia (Männik 2001, 2003). Conodonts are extremely rare in this unit. The most common species is *N. girardeauensis*. Single specimens of *Decoriconus*, *Panderodus*, *Walliserodus*, and unidentifiable fragments of *Amorphognathodus* may occur sporadically.

Llandovery (Rhuddanian to lowermost Telychian)

As elsewhere, in the Baltic region the Rhuddanian is characterized by long-ranging coniform-bearing conodont taxa. Diverse and abundant faunas with several new lineages appear in the uppermost Rhuddanian, occurring mainly in the Aeronian (Männik 2001). Several alternative zonations have been proposed for the Rhuddanian–Aeronian interval in other regions (e.g. Nicoll & Rexroad 1968; Aldridge 1972; Cooper 1975; McCracken & Barnes 1981; Uyeno & Barnes 1983; Bischoff 1986; Armstrong 1990; Zhang & Barnes 2002). The possibility of a more universal (global) zonation for the Rhuddanian–Aeronian strata has been discussed (e.g. SSS 1995; Männik 2001). Two lineages, *Aspelundia* and *Distomodus*, seem to possess the greatest potential for a global zonation. In Estonia, four zones and one superzone are recognized in the Rhuddanian–lowermost Telychian interval (Fig. 1). The *Oulodus? nathani* Zone (McCracken & Barnes 1981) and the *Ozarkodina hassi* Zone (Zhang & Barnes 2002), considered to be the oldest in the Silurian, are not known in Estonia.

The Distomodus kentuckyensis Zone

This zone was introduced by Nicoll & Rexroad (1968) as the “*Icriodina irregularis*” Zone and renamed later by Cooper (1975) as the *D. kentuckyensis* Zone (“*I. irregularis*” is the Pa element of *D. kentuckyensis*). In Estonia, it corresponds to the Juuru and lowermost Raikküla stages (Fig. 2) and is mainly represented by poor conodont faunas dominated by several long-ranging coniform-bearing taxa (Nestor et al. 2003). As the zonal taxon is very rare in the studied sections (only a few specimens have been found, provisionally

identified as *D. cf. kentuckyensis*), the zone can be defined only tentatively. In the Estonian sections, the Silurian strata below the level of appearance of *Aspelundia* have been assigned to the *D. kentuckyensis* Zone.

The Aspelundia Superzone

This Superzone corresponds to the interval from the level of appearance of *Aspelundia* up to the level of appearance of *Pterospathodus eopennatus* Männik. It correlates with the main part of the Raikküla Stage and the lowermost Adavere Stage in Estonia (Figs 1, 2). Three zones, *As. expansa*, *As. fluegeli*, and *Distomodus staurogathoides*, discussed in Nestor et al. (2003), are recognized in the *Aspelundia* Superzone. The lower boundaries of all three zones correspond to the levels of appearance of the nominal taxa.

The Rhuddanian–Aeronian zonation based on *Aspelundia* was first proposed by Armstrong (1990) for Greenland and can be applied in several other regions (e.g. Timan–northern Ural region and Siberia). Judging from the co-occurrences of conodonts and graptolites, it seems that *Aspelundia* appears in the uppermost Rhuddanian, in the *cyphus* graptolite Zone (Loydell et al. 2003). This fits well with the data from Greenland (Armstrong 1990). The data in Loydell et al. (2003) also suggest that the lower boundary of the *As. fluegeli* Zone evidently lies in the uppermost *leptotheca* graptolite Zone and that of the *D. staurogathoides* Zone probably in the *convolutus* graptolite Zone.

Llandovery (Telychian)

The Pterospathodus eopennatus and P. celloni superzones, and P. amorphognathoides amorphognathoides Zone

A revised detailed conodont zonation, based mainly on the evolutionary lineage of *Pterospathodus*, has been proposed for the Telychian (Männik in press; Fig. 1). Six biozones (*P. eopennatus* ssp. n. 1, *P. eopennatus* ssp. n. 2, *P. amorphognathoides angulatus*, *P. a. lennarti*, *P. a. lithuanicus*, and *P. a. amorphognathoides*) were recognized, five of which are grouped into two superzones (*P. eopennatus* and *P. celloni*). Two subzones were distinguished in the *P. eopennatus* ssp. n. 2, *P. a. angulatus*, and *P. a. amorphognathoides* zones. In Estonia, all these zones correspond to the Adavere Stage, except the uppermost *P. a. amorphognathoides* Zone, which correlates with the lowermost Jaani Stage (Fig. 2). Most of these zones can be recognized worldwide (Männik 1998, in press, and references in these papers). Correlations of the Estonian Telychian conodont

zones with the graptolite succession are based on data by Loydell et al. (1998, 2003).

The Lower Pseudooneotodus bicornis Zone

A detailed conodont zonation for the uppermost Telychian and Sheinwoodian and its applicability in different regions is presented in Jeppsson (1997). The zonal boundaries in the lower part of this interval correspond to the datums of the Ireviken Event.

The Lower *Ps. bicornis* Zone forms the lower part of the *Ps. bicornis* Superzone. Its lower and upper boundaries coincide, respectively, with Datum 1 and Datum 2 of the Ireviken Event. Datum 2 correlates with the Llandovery–Wenlock boundary in its type section at Leasows (Welsh Borderland) (Aldridge et al. 1993). Recent studies of the graptolite sequence (Männik et al. 2002; Loydell et al. 2003) show that Datum 2 of the event, and accordingly also the Llandovery–Wenlock boundary, does not coincide with the base of the *centrifugus* Zone but lies higher in the section, in the (upper) *murchisoni* Zone. In Estonia, the Lower *Ps. bicornis* Zone corresponds to the lower Jaani Stage (Fig. 2).

Wenlock

The conodont zonation for the interval from the uppermost Telychian (Lower *Ps. bicornis* Zone) to upper Homerian (*Ctenognathodus murchisoni* Zone), revised by Jeppsson, includes 17 zones (Jeppsson 1997; Calner & Jeppsson 2003). Most of these zones have been recognized in Estonia. The identification of Jeppsson's zones in Estonia is, as a rule, complicated due to the limited size of samples available from core sections. Besides, some zones evidently correspond to gaps in many of the studied sections, particularly in the outcrop area (e.g. Jeppsson et al. 1994). Often, only the superzones proposed by Jeppsson (1997) can be defined.

The Pseudooneotodus bicornis, Pterospathodus pennatus procerus, and Kockelella ranuliformis superzones

In Estonia, this interval corresponds to the main part of the Jaani Stage (Fig. 2). Six zones, Lower *Ps. bicornis* (discussed above), Upper *Ps. bicornis*, Lower *P. pennatus procerus*, Upper *P. p. procerus*, Lower *K. ranuliformis*, and Upper *K. ranuliformis*, corresponding, respectively, to the *Ps. bicornis*, *P. p. procerus*, and *K. ranuliformis* superzones, are all easy to identify in the shallow shelf area of the East Baltic (e.g. Jeppsson & Männik 1993; Männik, unpublished data), but somewhat problematic to distinguish in deeper shelf environments (Loydell et al. 2003; Männik 2003). Co-occurrences of conodonts

and graptolites in the Aizpute-41 core section (Latvia) allowed precise correlation of these zones, and of the Ireviken Event, with the graptolite succession (Männik et al. 2002; Loydell et al. 2003).

The Ozarkodina sagitta rhenana Superzone

This superzone includes the *O. s. rhenana* and Lower *Kockelella walliseri* zones (Jeppsson 1997). The lower superzone boundary is defined by the appearance of *O. s. rhenana* (Fig. 1). In Estonia, the lower boundary of the *O. s. rhenana* Superzone, and of the *O. s. rhenana* Zone, lies close to the boundary between the Jaani and Jaagarahu stages (Fig. 2). The lower boundary of the Lower *K. walliseri* Zone is marked in Estonia by the appearance of *K. walliseri* in the lowermost part of the Jaagarahu Stage. The zone is characterized by the co-occurrence of *O. s. rhenana* and *K. walliseri*, and its upper boundary corresponds to the level of disappearance of *O. s. rhenana*.

The Kockelella walliseri Zonal Group

This unit was defined by Jeppsson (1997) as corresponding to the interval of total range of *K. walliseri* and comprising the Lower *K. walliseri* Zone (characterized by co-occurrence of *K. walliseri* and *O. s. rhenana*; forms the upper part of the *O. s. rhenana* Superzone; see above) and the Upper *K. walliseri* Superzone with three zones (in ascending order, the Middle *K. walliseri* Zone, *K. patula* Zone, and the uppermost *K. walliseri* range). The strata of the Lower *K. walliseri* Zone are probably the youngest beds preserved below the major gap between the Jaagarahu and Rootsiküla stages in the outcrop area in Estonia (Jeppsson et al. 1994). The zones of the Upper *K. walliseri* Superzone cannot be identified in Estonia on the basis of the data available but, evidently, the unit correlates roughly with the middle of the Jaagarahu Stage (Fig. 2). The main problem seems to be too rare occurrence of *K. patula*, the nominal species of the *K. patula* Zone (= middle zone in the *K. walliseri* Superzone; Fig. 1), in the sections. According to L. Jeppsson (pers. comm. 2006), at least 30 kg of rock is needed to find one identifiable specimen of *K. patula* on Gotland.

The Kockelella ortus ortus Superzone

This superzone corresponds to the interval from the level of disappearance of *K. walliseri* up to the level of disappearance of *Ozarkodina sagitta sagitta* (Jeppsson 1997) (to Datum 1 of the Mulde Event, Jeppsson & Calner 2003). Three units (in ascending order), the

post-*K. walliseri* interregnum, *K. o. ortus* Zone, and *O. s. sagitta* Zone, form the *K. o. ortus* Superzone. In Estonia, the strata corresponding to the *K. o. ortus* Superzone are preserved only in the southwesternmost sections. The lower boundary of the superzone lies in the upper Jaagarahu Stage (Männik 2003; Fig. 2) and probably coincides with the boundary between the Middle and Upper Riksu beds of the Riksu Formation *sensu* Nestor et al. (2001).

The post-Kockelella walliseri interregnum

This unit corresponds to the interval from the level of disappearance of *K. walliseri* up to the level of appearance of *K. o. ortus* (Jeppsson 1997). On the basis of the data from the Riksu core (SW Saaremaa; Nestor et al. 2001), it lies in the upper Jaagarahu Stage. In the paper by Nestor et al. (2001), the post-*K. walliseri* interregnum was evidently included into the *K. walliseri* Zone as its upper part.

The Kockelella o. ortus Zone

The boundaries of this zone are marked by the appearance of *K. o. ortus* (lower one) and *O. s. sagitta* (upper one) (Jeppsson 1997). In Estonia, the lower boundary of the zone is defined in the Riksu core in the upper part of the Jaagarahu Stage (in the Upper Riksu Beds; Nestor et al. 2001). The upper boundary of the *K. o. ortus* Zone, based on the data from the Ruhnu-500 core section (Männik 2003), lies also in that stage (Fig. 2).

The Ozarkodina sagitta sagitta Zone

The zone corresponds to the interval of total range of *O. s. sagitta* (Jeppsson 1997; Jeppsson & Calner 2003). In Estonia, the *O. s. sagitta* Zone correlates with the uppermost part of the Jaagarahu Stage (Männik 2003; Fig. 2). So far it has been recognized only in the Ruhnu-500 core section but it is possible that at least the lowermost part of the *O. s. sagitta* Zone is preserved also in the Ohesaare core. The occurrence of *Pseudooneotodus linguicornis* at 163.55 m in the Ohesaare core (Männik, unpublished data) indicates that the uppermost strata of the Sõrve Formation in that section may correspond to the *O. s. sagitta* Zone. *Pseudooneotodus linguicornis*, described in Calner & Jeppsson (2003), has a very short range. According to Jeppsson (Jeppsson in Calner & Jeppsson 2003), this taxon appears just below the lower boundary of the *O. s. sagitta* Zone and becomes extinct during the Mulde Event.

The Ozarkodina bohémica longa Zone

The zone corresponds to the main part of the upper Wenlock (middle Homeric) Mulde Event (Calner & Jeppsson 2003). It includes five subzones, identified as subzones 0 to 4. Datum 1 of the event, at which the relatively diverse fauna of the *O. s. sagitta* Zone disappears, is considered as the lower boundary of the *O. bohémica longa* Zone. According to Jeppsson (in Jeppsson & Calner 2003, p. 139): “The succeeding fauna lacks zonal taxa but otherwise is closely related to the first fauna with *O. bohémica longa*. Both are markedly less diverse and strongly dominated by ramiforms, in most collections by *O. excavata*. They are therefore separated as Subzone 0 (zero) and Subzone 1 of the *O. b. longa* Zone.” The most characteristic event in the conodont succession at Datum 2 of the Mulde Event, at the boundary between subzones 1 and 2 of the *O. b. longa* Zone, is the change of the dominant taxon. The faunas between datums 1 and 2 were dominated by *O. excavata*, which at Datum 2 was replaced by *Panderodus equicostatus* (Jeppsson & Calner 2003). In Subzone 3, ramiforms, particularly *O. excavata*, regained dominance. Subzone 4 has a more balanced conodont fauna.

In Estonia, the Mulde Event interval has been determined in the Ohesaare (see Jeppsson & Calner 2003 and references therein) and Ruhnu-500 core sections. In the latter core, Datums 1 and 2 of the Mulde Event, and accordingly the lower boundary of subzones 0 and 2 of the *O. b. longa* Zone, were recognized (Männik 2003). Due to the lack of adequate information (evidently because of too small samples) Datum 1.5 cannot be identified, and subzones 0 and 1 of the *O. b. longa* Zone are not distinguished in the Ruhnu-500 core. The upper part of the *O. b. longa* Zone (subzones 3, 4) has not been recognized in Estonia yet. Because the strata above the sample with the Subzone 2 fauna were not studied in the Ruhnu-500 core, the upper part of the zone may still be represented there. In Estonia, the *O. b. longa* Zone corresponds to the uppermost Jaagarahu Stage and the lower part of the Rootsi-küla Stage (Fig. 2).

The Kockelella ortus absidata Zone

This zone, introduced by Jeppsson (in Calner & Jeppsson 2003), has not yet been recognized in Estonia. It corresponds to the uppermost part of the Mulde Event and correlates with the topmost Halla Formation on Gotland. In the majority of sections studied in Estonia, this interval most probably corresponds to a gap.

The Ctenognathodus purchisoni Zone

The lower boundary of this zone corresponds to the level of appearance of *C. purchisoni* (Fig. 1). The *C. purchisoni* Zone was originally distinguished in Estonia as a regional unit for shallow-water environments and considered to correspond to the upper part of the *O. bohémica* Zone recognized in the offshore environments (Viira 1982). Later, Jeppsson (in Calner & Jeppsson 2003) recognized the *C. purchisoni* Zone on Gotland and showed that on the basis of other taxa characteristic of the zone (*O. b. longa* and morphologically very distinct *O. confluens densidentatus*), the unit can be defined in offshore environments where *C. purchisoni* is rare or missing. In Estonia, the *C. purchisoni* Zone is easy to identify and corresponds, in general, to the Rootsiküla Stage (Fig. 2).

CONCLUDING NOTES

Zonation and evolution of faunas

The boundaries of the zones discussed above have been defined by the appearances or disappearances of taxa. The duration of the zones (thickness in the section) is highly variable, due to different rates of the evolution of taxa and of faunas in general (e.g. Jeppsson 1998). Changes in conodont faunas appear in a specific order and are mostly cyclic (Ziegler & Lane 1987). The last authors recognized low- and high-diversity intervals in their cycles. This agrees with Jeppsson's model of Silurian oceanic episodes and events (Jeppsson 1990). According to Jeppsson, low-diversity intervals correspond to secundo episodes and high-diversity intervals to primo episodes. Secundo episodes are as a rule characterized by long-ranging taxa that do not allow detailed biostratigraphy (e.g. the Spirodden Secundo Episode in the Rhuddanian to lower Aeronian corresponds mainly to the *D. kentuckyensis* Zone). Primo episodes are usually represented by taxonomically variable, rapidly evolving faunas, easy to use in high-resolution biostratigraphy (e.g. the Telychian Snipklint Primo Episode faunas; Männik 2001, in press). Rapid and distinct changes in the successions of conodonts during an oceanic event allow the greatest resolution in biostratigraphy and reliable high-precision correlations between different regions (Jeppsson 1997, 1998; Jeppsson & Männik 1993). Detailed characterization of the general composition of faunas (co-occurrences, changes in the dominating taxon or taxa, etc.) provides additional valuable information and, in some cases, contributes to further subdivision of the zonal units (e.g. subzones in the *O. b. longa* Zone, Jeppsson & Calner 2003; possible

subzones in the *O. s. rhenana* Zone, Jeppsson 1997, pers. comm. 1999). Moreover, detailed information about the succession of populations allows subdivision of the intervals poor in conodonts and, in some cases, provides criteria for tracing biostratigraphical boundaries from one facies into another.

As the studies by L. Jeppsson have shown, only collections of adequate size enable proper zonation. It means that often very large samples have to be processed (more than 100 kg of rock). However, the time and effort expended on such studies will not be wasted. A good example is the conodont zonation for the Wenlock. For a long time, the Wenlock was one of the most problematic intervals in Silurian conodont biostratigraphy. In most of the sections studied, faunas appeared to be composed mainly of long-ranging taxa. Other potentially biostratigraphically useful taxa (e.g. *Kockelella*) occurred sporadically and were too poorly represented to allow reliable biostratigraphical subdivisions. But, after detailed studies of outcrops in Gotland and processing of hundreds of samples (with an average weight from several tens of kilograms to more than 100 kg) from these sections, adequate information about conodont succession in the Wenlock became available and a high-resolution zonation was possible (Jeppsson 1997; Jeppsson & Calner 2003). As demonstrated by Jeppsson, this zonation can be applied in many sections of Wenlock age all over the world, provided that adequate information is available. Although the samples processed from the Estonian core sections are limited in size (usually less than 1 kg) and, as a result, often very poor in conodonts, the thorough characterization of faunas from each zonal unit provided by Jeppsson makes it possible to recognize these units in Estonia. The difficulties with identification of some of the zonal units defined by Jeppsson in Estonia are evidently caused by the lack of adequate data (mainly, too small size of samples available from the core) (e.g. zones in the *K. walliseri* Zonal Group) or by gaps (e.g. the Mulde Event interval in most of the Estonian sections).

The boundary between the Adavere and Jaani stages, and the Llandovery–Wenlock boundary

The boundary between the Adavere and Jaani stages in Estonia has traditionally been considered to correlate with the Llandovery–Wenlock boundary (e.g. Nestor 1997). The stage boundary, marked by a bentonite, has been drawn at 345.8 m in the Ohesaare core section (Aaloe 1970, p. 244) and considered to coincide with the lower boundary of the *centrifugus* graptolite Zone. Until recently, it was believed that the base of this

graptolite zone corresponds to the Llandovery–Wenlock boundary as it was defined in its type section (Holland 1980). Aldridge et al. (1993) show that the series boundary in its type section lies very close to, or coincides with, Datum 2 of the Ireviken Event. According to recent biostratigraphical and geochemical studies, the boundary between the Adavere and Jaani stages (as defined in the Ohesaare core, see above) correlates with a bentonite at 121.03 m (about 8 m below Datum 2, and 7.2 m below Datum 1, of the Ireviken Event) in the Viki core (Männik et al. 2002 and references therein). It is evident from the data above that (1) the Llandovery–Wenlock boundary is younger than the *centrifugus* graptolite Zone (lies in the *murchisoni* graptolite Zone; Männik et al. 2002) and (2) the lowermost Jaani Stage is of Telychian age (Fig. 2).

Some problems for consideration in future

The revision of the latest developments in conodont biostratigraphy in Estonia revealed several problems in need of special attention in future studies.

1. Owing to ecological changes in faunas, it is difficult to trace several datums of the Ireviken Event and zonal boundaries in distal offshore environments (e.g. Loydell et al. 2003). Additional studies of those changes are needed.
2. The zonation in the Rhuddanian–Aeronian strata needs to be elaborated. Because of the rare, sporadic occurrence of conodonts in most of the sections studied, the exact levels of appearances of zonal taxa (i.e. *A. expansa*, *A. fluegeli*, and *D. staurognathoides*) in the succession are not known.
3. Some lineages contain transitional forms between the taxa used to define the zonal boundaries. As said above, late forms of *B. prevariabilis* are difficult to distinguish from the early forms of *B. variabilis*. Gradual morphological transition seems to occur between *Aspelundia expansa* and *As. fluegeli*. Special morphological studies are needed to find distinct criteria for separating taxa in these lineages.
4. Several zonal boundaries are still problematic in Estonia. The boundary between the *A. superbus* and *A. ordovicicus* zones has long been considered to lie in the lowermost Vormsi Stage (Männik 1992). The recent data from the Mehikoorma-421 core section, however, show that *A. ordovicicus* may appear as low as the upper Nabala Stage (Männik & Viira 2005). Still, it might be that the boundary between these zones was identified correctly in the

lowermost Vormsi Stage, and the upper Nabala Stage corresponds to the *Amorphognathus* sp. n. interval *sensu* Dzik (1999).

5. The succession of changes during the end-Ordovician Event, one of the most thoroughly investigated intervals, is still poorly known, mainly due to a lack of good sections. Additional information could be obtained from detailed studies of core sections of the offshore part of the Baltic basin (e.g. Valga-10 and Ruhnu-500).
6. A serious problem, which is rarely addressed explicitly, is whether the observed pattern in the distribution of faunas in a section is a result of biological changes (evolutionary and extinction events) or an artefact of the structure of the stratigraphical record. It has been established that species ranges in shelf strata reflect beside biological processes also preservation bias imposed by predictable patterns of deposition and erosion in response to eustatic sea-level fluctuations. Therefore, the ranges, used to erect biostratigraphic zones and on which evolutionary lineages and bioevents are based, must be interpreted in the light of this bias to exclude occurrences that are explicable by sequence architecture (Barrick & Männik 2005).

It is evident that some additional studies would increase the resolution of the conodont zonation. The most promising targets are the event intervals. At present, several datums, not yet used to define zonal units, can be employed effectively in the regional high-resolution stratigraphy. The current resolution of conodont biostratigraphy provides an opportunity to analyse the sedimentary history of the (eastern) Baltic palaeobasin in detail, particularly with respect to sequence stratigraphy. Preliminary results of such studies have already been published (Harris et al. 2004, 2005). On the other hand, consideration of sequence stratigraphy in biostratigraphical studies is essential to avoiding misinterpretations of palaeontological data and allows selection of appropriate sections for defining the boundaries of regional and global stratigraphical units.

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Ülem-Ordoviitsiumi ja Alam-Siluri konodontide biostratigraafia viimased arengud Eestis

Peep Männik

Artiklis lühidalt iseloomustatud Ülem-Ordoviitsiumi ja Alam-Siluri konodontide tsonaalne skeem põhineb erinevate autorite poolt varem välja töötatud skeemidel, mida on mitmes intervallis oluliselt täpsustatud ja täiendatud. Praeguse seisuga on intervallis Kukruse lademest (Ülem-Ordoviitsiumi basaalne osa) kuni Rootsiküla lademeni (Wenlocki ülemine osa) eristatavad 32 tsooni, 14 alamtsooni ja 3 mitteformaalset ühikut.