

The lower boundary of the Haljala Regional Stage (Sandbian, Upper Ordovician) in Estonia

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Received 30 August 2019, accepted 6 January 2020, available online 13 April 2020

Abstract. Multi-proxy correlation is used to address the boundary of the Kukruse and Haljala regional stages across the Estonian part of the Baltoscandian Ordovician Palaeobasin. New biostratigraphic information on conodonts, chitinozoans and ostracods from the Peetri outcrop, northwestern Estonia, integrated with micropalaeontological data from five core sections all over Estonia, allows justification of the position of the stage boundary and correlation between conodont and chitinozoan biozones. In the Peetri outcrop a marked stratigraphic hiatus was recognized at the Kukruse–Haljala boundary – the *Baltoniodus gerdae* conodont Subzone and the *Armoricochitina granulifera*, *Angochitina curvata*, *Lagenochitina dalbyensis* and *Belonechitina hirsuta* chitinozoan zones are missing in the section. The lowermost part of the Tatruse Formation in central Estonia and the Adze Formation in southern Estonia are older than previously thought, and the results show a principal advantage of the multi-proxy method over single-group studies. The lower boundary of the Haljala Regional Stage is tied to the interval with gaps that are common all over the stratotype region.

Key words: conodonts, chitinozoans, ostracods, biostratigraphy, Haljala Regional Stage, Upper Ordovician, Estonia.

INTRODUCTION

The Middle and Upper Ordovician outcrop area in northern Estonia is characterized by shallow-water carbonate sediments. The succession is incomplete and yields numerous discontinuities and gaps (Männil 1966; Jaanusson 1976; Nestor & Einasto 1997). Ostracods, chitinozoans, conodonts and acritarchs are main fossils used in stratigraphic work on Estonian sections. Although different groups have often been used to characterize a section, the consistency of correlation between zonations based on them has not always been discussed.

Regional stages are the principal category in the chronostratigraphy of the Ordovician System in Estonia. The basic concepts used by Schmidt (1858, 1881) have further been developed by many authors (Meidla et al. 2014 and references therein). Estonian time-stratigraphic nomenclature is still serving as a proxy for the Middle and Upper Ordovician of the Baltoscandian region (e.g. Bergström et al. 2009), although this is becoming a matter of debate (see Appendix A in Kumpulainen 2017).

The Haljala Regional Stage (RS), introduced by V. Jaanusson in 1995, is the newest stage in the Ordovician

chronostratigraphic scheme of Estonia. It replaced the former Idavere and Jõhvi regional stages that are now treated as substages of the Haljala RS (Jaanusson 1995). This change was caused by difficulties in distinguishing the former two stages in sections located outside the North Estonian outcrop area. The lower boundary of the Haljala RS is defined as that of the former Idavere RS (Jaanusson 1995) and is marked by a distinct discontinuity surface in its type area (Jaanusson 1945). Later, the lower boundary of the Haljala RS was proposed to correspond to the base of the *Armoricochitina granulifera* chitinozoan Zone (Hints et al. 1994). In the conodont succession, the lower boundary of the Haljala RS corresponds to a level slightly above the base of the *Baltoniodus gerdae* conodont Subzone (Männil 1986). The upper boundary of the Haljala RS coincides with the base of the Kinnekulle K-bentonite (= upper boundary of the former Jõhvi RS) and is defined as the base of the overlying Keila RS (Hints & Nõlvak 1999). No proposals have been made for defining a stratotype for the base of the Haljala RS.

A gap at the lower boundary of the Haljala RS in northern Estonia is well known (Rõõmusoks 1970; Nõlvak 1972; Männil et al. 1986; Põlma et al. 1988; Hints

& Nõlvak 1990; Nõlvak & Hints 1991, 1996; Hints et al. 1994; Hints 1997a). In numerous outcrops, including also the Peetri section, it is marked by a considerable change in macrofossil successions (Rõõmusoks 1970; Põlma et al. 1988). The reduced thickness of the Idavere Regional Substage (RSs) in the Peetri section is generally recognized (see references above) but some papers also emphasize the difficulties with locating the boundary between the Idavere and Jõhvi substages in this section (Hints & Nõlvak 1990).

The present paper addresses the distribution of microfossils in the Peetri section and the problems related to both boundaries: the lower boundary of the Haljala RS and the boundary between the substages in the section as well as in the Estonian part of the Ordovician Baltoscandian Palaeobasin in general. It is noteworthy that in many older papers the faunal logs are restricted just to limited intervals of the Peetri section (the Haljala RS or the Kukruse RS – for example, Öpik 1930; Rõõmusoks 1970; Jaanusson 1976; Põlma et al. 1988; Hints & Nõlvak 1990; Nõlvak & Hints 1991, 1996) and the expression of the stage boundary in the distribution of different fossil groups is rarely addressed. A continuous succession across this boundary in the Peetri section has not been published before. We carried out a multi-proxy analysis of biostratigraphy (conodonts, chitinozoans, ostracods, algae) in the Peetri section and compared the results with the published data on other representative sections all over Estonia, in order to clarify the chronostratigraphy in this interval.

GEOLOGICAL SETTING

The Baltoscandian Ordovician Palaeobasin represents a typical epicontinental basin with a relatively low but variable rate of subsidence. The nearshore area of the Baltoscandian Ordovician Palaeobasin (designated as ‘Estonian shelf’ by Harris et al. 2004) was characterized by discontinuous accumulation of relatively pure shallow-water carbonates, whilst more argillaceous deposits occur in its deeper parts (Scandinavian and Livonian basins by Harris et al. 2004) (Fig. 1). The Kukruse RS and the Haljala RS comprise the lowermost part of the Upper Ordovician succession in Estonia. The Kukruse RS is also known as an interval containing the commercially exploited oil shale (kukersite). The thickness of the stage varies between 3 m in West Estonia and 20 m in East Estonia (Hints 1997b). The Haljala RS is overlying the Kukruse RS and capped by the thick Kinnekulle K-bentonite layer marking the boundary between the Haljala RS and the Keila RS. The thickness of the Haljala RS in Estonia varies between 10 and 20 m (Hints 1997a).

The principal kukersite-containing interval in the North Estonian succession, starting from the base of the

lowermost commercial oil shale bed, is treated as the Viivikonna Formation (Fm). The original concept of the formation (Männil & Rõõmusoks 1984) was wider and included also part of the underlying Kõrgekallas Fm and of the overlying Tatruse Fm, but was revised later by Männil (1986). The Viivikonna Fm is distributed in the northern, northeastern and central parts of Estonia, northeast of the line between Osmussaar Island in NW Estonia and Mehikoorma Village located on the southwestern coast of Lake Peipsi (Hints 1997b). The Viivikonna Fm grades westwards into a bioclastic limestone unit termed as the Pihla Fm and southwards into a kukersite-free limestone with dark pyritized skeletal debris – the Dreimani Fm (Hints 1997b). The lower boundary of the Viivikonna Fm in northern Estonia coincides by definition with the base of the Kukruse RS, with the lower boundary of the kukersite bed A that represents a well recognizable marker horizon in northern-northeastern Estonia (Hints 1997b). The distinction between the Viivikonna Fm and the overlying Tatruse Fm is rather problematic. Originally, in the subsurface of northeastern Estonia the boundary was treated as corresponding to a distinct marker horizon, to the upper surface of the kukersite seam X (Männil 1986). Within and near the outcrop belt, however, the upper part of the Viivikonna Fm is missing due to a gap in the succession (Männil 1986). In the areas of the incomplete sedimentary interval, this sedimentary gap coincides with the boundary between the Kukruse RS and Haljala RS. This boundary is usually drawn at a double pyritized discontinuity surface (characterized by distinctive cavities, 5 cm or more in diameter and sometimes extending more than 40 cm downwards) or to the lowermost discontinuity surface of a series of surfaces (Põlma et al. 1988), or to a level between them in some cases (Nõlvak 1972). The biostratigraphic evidence for this boundary is rather limited.

In the latest correlation charts (Männil & Nestor 1987; Männil & Meidla 1994; Meidla et al. 2014), the Haljala RS comprises the Tatruse Fm and the lower parts of the Kahula (in North Estonia) and Adze (in South Estonia) formations. The Tatruse Fm is known as regularly bedded hard bioclastic limestone. It was originally (Männil & Rõõmusoks 1984) established as a member within the Viivikonna Fm but later on (Männil 1986) raised to the rank of formation that represents the lower part of the Haljala RS. The Tatruse Fm can be recognized all over northern Estonia, the area between Keila and Raasiku being a likely exception (Rõõmusoks 1983). Argillaceous limestones of the lower Kahula Fm represent the upper part of the Haljala RS. The lower part of the Kahula Fm comprises the Vasavere Member (Mb), usually attributed to the Idavere RSs of the Haljala RS, which consists of argillaceous limestones with marl and bentonite

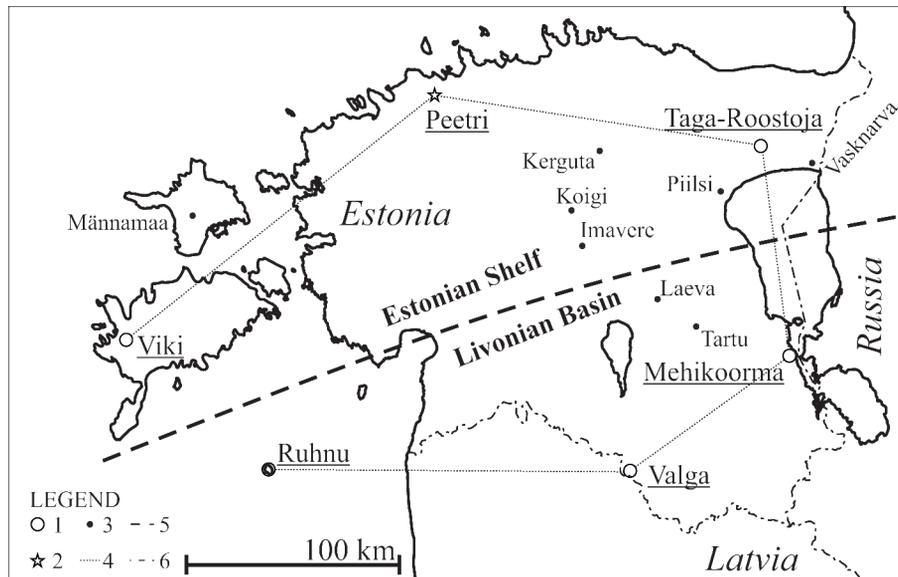


Fig. 1. Location of the sections discussed or referred to in the text. Legend: 1, core section shown in Fig. 6; 2, outcrop; 3, supplementary core sections referred to in the text; 4, profile in Fig. 6; 5, facies boundary; 6, state border.

interlayers. The Adze Fm replaces the Tatruse and Kahula formations in southern Estonia. It is represented by strongly argillaceous limestones with thin bentonite layers and in places with phosphatic ooids (Hints 1997a).

K-bentonites (beds of volcanic ash) are regionally useful lithostratigraphic marker horizons (Bergström et al. 1995). The Haljala RS contains the absolute majority of bentonites of the Ordovician succession in Estonia. The number of K-bentonite beds in this interval reaches up to 18 in Hiiumaa Island, western Estonia (Hints 1997a). The number of K-bentonites increases further towards Sweden where they are attributed to the Grefsen and Sinsen bentonite groups (Bergström et al. 1995). The Vasavere Mb in eastern and northeastern Estonia contains two K-bentonite beds of the Grefsen bentonite group. The upper bed, historically designated as the bentonite ‘b’ (by Jürgenson 1958 as metabentonite b), marks the boundary between the Idavere RSs and Jõhvi RSs of the Haljala RS (Männil 1963). Southwards, the number of K-bentonites decreases and the boundary K-bentonite is difficult to recognize (Hints 1997a). Additionally, K-bentonites of the Grefsen group are difficult to distinguish from other stratigraphically closely located K-bentonites not only lithologically but also geochemically (Bergström et al. 1995; Kiipli et al. 2014). This suggests that K-bentonites should be used with precaution as markers of stratigraphic boundaries within the Haljala RS (see also Nölvak & Hints 1996). However, as no significant faunal changes occur at the boundary between the substages in the Haljala RS, it is difficult to recognize without applying the ‘bentonite criteria’ (Öpik 1930; Männil 1963; Rõõmusoks

1970; Jaanusson 1976, 1995; Põlma et al. 1988; Hints & Nölvak 1990; Hints et al. 1999).

Among different fossil groups, graptolites have rather limited value for the correlation of the lower boundary of the Haljala RS, mainly because of their overall scarcity in the Ordovician carbonate rocks in Estonia (Meidla et al. 2014). According to Männil (1976), the quantity of graptolites in the Estonian succession decreases markedly in this interval. In several correlation charts (Tikhij 1965; Männil & Nestor 1987; Männil & Meidla 1994), the strata equivalent to the Haljala RS are tentatively referred to the *Diplograptus foliaceus* (*D. multidens*) graptolite Zone but this correlation is based on indirect evidence only. The occurrence of *Pseudoclimacograptus* cf. *scharenbergi* (= *Pseudoclimacograptus scharenbergi* f. *typica*; Männil 1976, fig. 4) in the Haljala RS mentioned by Kaljo (1997) has very limited stratigraphic value: *P. scharenbergi* (Lapworth, 1876) ranges from the mid-Darriwilian up into the lower Katian in the U.K. (Zalasiewicz et al. 2009). *Amplexograptus baltoscandicus* (Jaanusson 1995) (= *A. maxwelli*, Goldman et al. 2015) was formerly considered as a good marker for the base of the Jõhvi RSs (Männil 1976, 1990), but was later recorded also in the Vasavere Mb in the Peetri section (Hints & Nölvak 1990).

In the conodont succession, the lower boundary of the Haljala RS lies within the *Amorphognathus tvaerensis* conodont Zone (Bergström 1971) and is tentatively drawn slightly above the base of the *Baltoniodus gerdae* conodont Subzone (Männil 1986, fig. 2.1.1; Meidla et al. 2014 and references therein). In the chitinozoan succession, the lower boundary of the Haljala RS was confined to the base

of the *Lagenochitina dalbyensis* chitinozoan Zone in older papers (Tikhij 1965; Männil & Nestor 1987). The discovery of strata with *Armoricochitina granulifera* (= *Cyathochitina* cf. *reticulifera* in Männil 1986) and *Angochitina curvata* below the first appearance level of *L. dalbyensis* in some core sections in central Estonia changed the concept of the Idavere RSs (Männil 1986; Nõlvak & Grahn 1993; Männil & Meidla 1994; Nõlvak 1997; Nõlvak et al. 2006). Today, the lower boundary of the Haljala RS is drawn below the *A. granulifera* chitinozoan Zone and is thought to coincide with the top of the *Laufeldochitina stentor* chitinozoan Zone (Nõlvak & Grahn 1993). The illustrations and discussion of characteristic chitinozoans can be found in Nõlvak et al. (1999), Grahn & Nõlvak (2010) and Bauert et al. (2014).

There is no characteristic species of macrofossils useful for the definition of the lower boundary of the Haljala RS (Hints 1997a). Alternatively, carbon isotope chemostratigraphy has become an important tool for regional correlations (Ainsaar et al. 2010) with the Lower Sandbian Excursion (Bauert et al. 2014), which is also known as ‘upper Kukruse low’ (Kaljo et al. 2007) and found to correlate with the upper part of the Kukruse RS. Constancy of the latter excursion needs further research inside Baltoscandian successions and is beyond the scope of this paper.

THE PEETRI OUTCROP

The Peetri outcrop is located in the Saue Parish, Harju County, west of Tallinn, near the Tallinn–Keila Highway. It consists of two outcrops: an inclined shaft exposes the lower part of the succession, and a trench along the eastern edge of the excavation (59.364869°N, 24.499064°E) in front of the historical military fortification (59.365461°N, 24.499975°E), termed in former papers as ‘deep trench’ (Hints & Nõlvak 1990), exposes the upper part of the succession. The overlap between them is shown in Figs 2 and 3. The upper Peetri outcrop (trench) exposes argillaceous limestones of the Kahula Fm, with the Vasavere Mb being represented in a rather limited thickness (0.5–0.6 m) at its base (Rõõmusoks 1983). The basal part of the succession contains two K-bentonites of the Grefsen complex (Bergström et al. 1995; Kiipli 2008). The lower Peetri outcrop (shaft) exposes the lower part of the Kahula Fm with the same two K-bentonites exposed in the uppermost part of the succession. Below the distinct discontinuity surface, which is regarded as the upper boundary of the Viivikonna Fm, the section is represented by argillaceous to bioclastic limestone with kukersite-rich interbeds.

The first reference to the Peetri outcrop by Pogrebov (1920) reports the thickness of the kukersite-rich part of

the section reaching 9 m, and this was confirmed by Bekker (1921). Rõõmusoks (1970, pp. 132–134) gave one of the first full descriptions of the Peetri composite section. His lithological description and macrofaunal data are still extensively used (Hints & Nõlvak 1990; Nõlvak & Hints 1991, 1996; Kiipli 2008) and serve as reference material for the current study (Figs 2, 3).

METHODS

Altogether 15 conodont samples were collected from both outcrops at Peetri in 2014–2016 (see Table 1). The sampling was aimed at covering the transition from the Kukruse RS to the Haljala RS, based on the published information (Rõõmusoks 1970; Nõlvak & Hints 1996). The average sample weight was about 3.6 kg. Each sample was broken down to pieces with diameter up to 10 cm for further processing. The weighed samples were soaked in acetic acid, to dissolve the limestone, following the procedure described by Jeppsson et al. (1999). The 7–8% solution of acetic acid was replaced in every 2 weeks, when most of the acid had reacted with limestone. Simple washing with water through a 64 µm sieve was used to dispose the clay component after the complete dissolution of a sample. The washed residue was further treated with formic acid, to get rid of dolomite, and with hydrogen peroxide, to get rid of organics when needed. The particles of different density were then separated in heavy liquid (bromoform) and the light fraction was discarded. The heavy fraction was inspected and the conodont elements were picked under the stereo microscope at a magnification of ×16–25. The sample preparation was carried out in the Department of Geology, University of Tartu, and the specimens studied are deposited at the Natural History Museum, University of Tartu (TUG), under the collection number TUG 1793.

In addition to the previous collection of chitinozoans (Hints & Nõlvak 1990), six samples (Table 1) were collected to cover the transition interval between the Kukruse and Haljala regional stages. The collected samples (weight 0.5–0.9 kg) were dissolved using hydrochloric and acetic acids. Chitinozoan samples and preparations are deposited at the Department of Geology, Tallinn University of Technology (institutional repository code GIT).

To complement the ostracod data from Peetri, six ostracod samples with a weight of 500–1000 g were collected in 2016 (Table 1). Coarsely crushed rock material (fragment size 2–3 cm) was treated using a standard physical disintegration method of sodium hyposulphite, repeated heating and cooling cycles (Meidla 1996; Perrier et al. 2012) (about 10–40 cycles, depending on rock properties, were required). The disintegrated

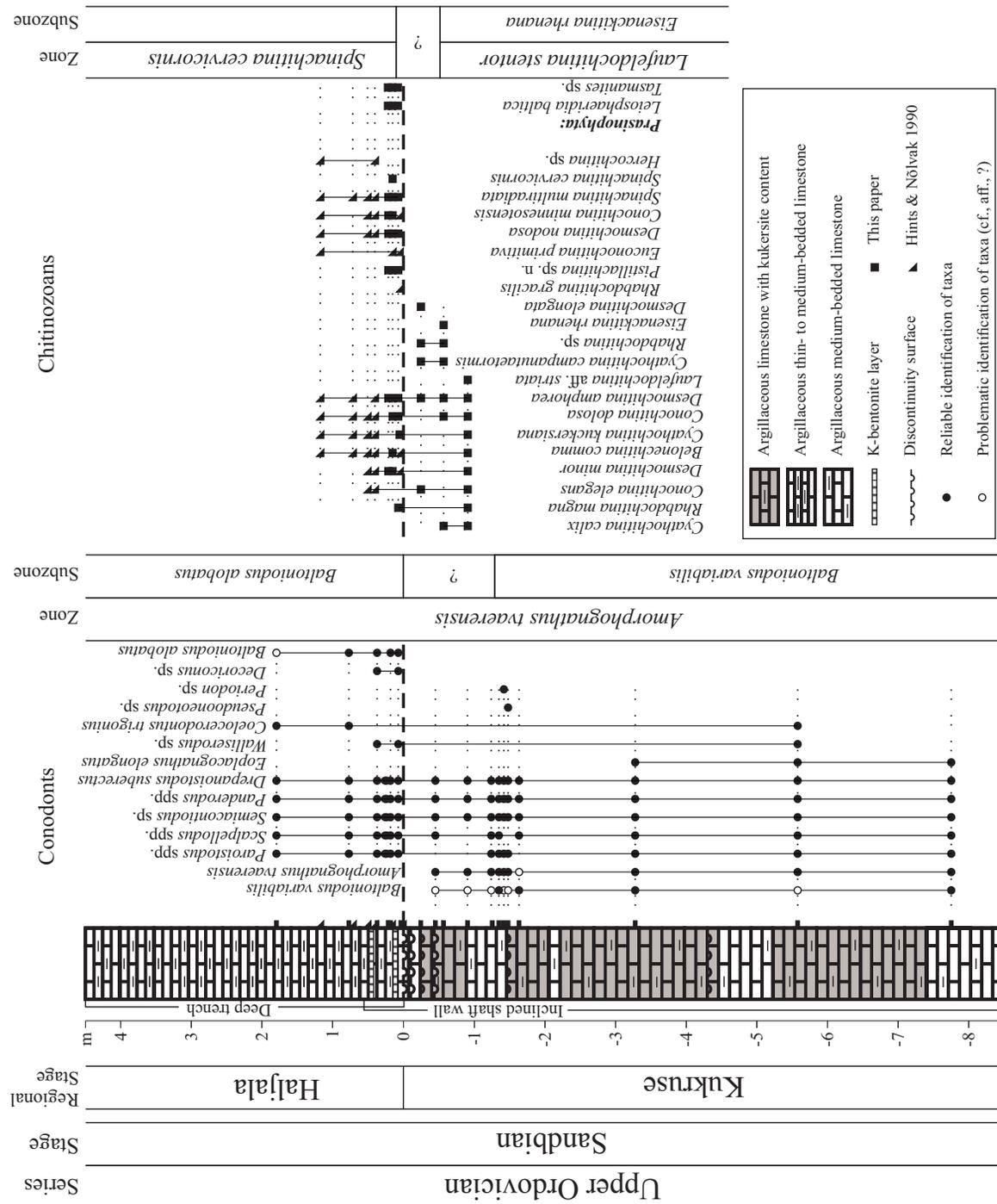


Fig. 2. Distribution of conodonts, chitinozoans and prasinophyceans in the Peetri section.

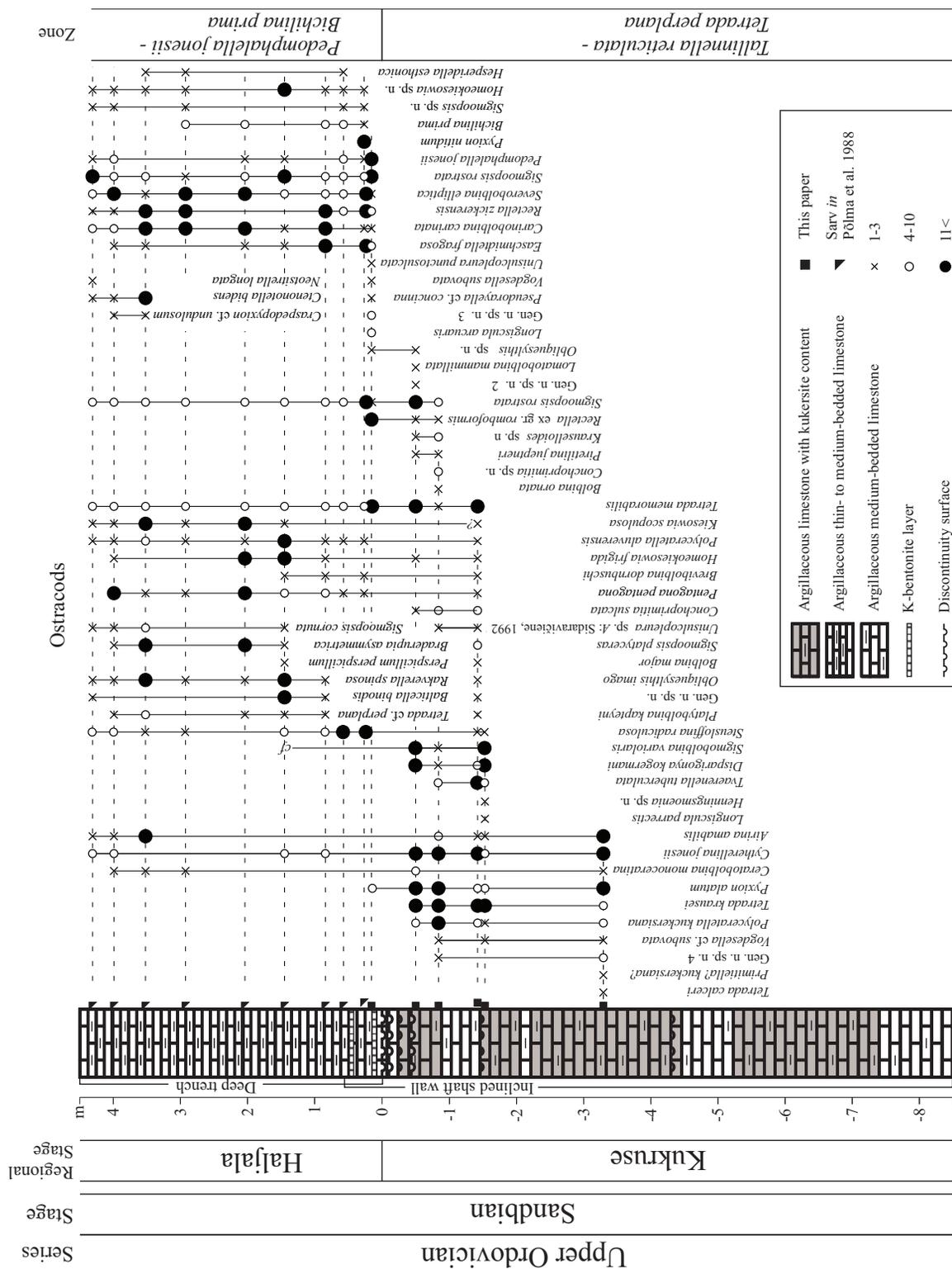


Fig. 3. Distribution of ostracods in the Peetri section.

Table 1. List of samples from the Peetri composite section. Sample depths with respect to the top of a complex of discontinuity surfaces 0.1 m below the lower K-bentonite layer

Conodont sample	Sampled interval (m)	Chitinozoan sample	Sampled interval (m)	Ostracod sample	Sampled interval (m)
Co1	1.73 to 1.88	Ch1	0.20 to 0.21	O1	0.14 to 0.24
Co2	0.73 to 0.83	Ch2	0.14 to 0.17	O2	–0.40 to –0.43
Co3	0.33 to 0.43	Ch3	0.06 to 0.10	O3	–0.70 to –0.74
Co4	0.14 to 0.24	Ch4	–0.24 to –0.27	O4	–1.38 to –1.45
Co5	0.06 to 0.10	Ch5	–0.54 to –0.57	O5	–1.45 to –1.50
Co6	–0.43 to –0.46	Ch6	–0.88 to –0.92	O6	–3.25 to –3.30
Co7	–0.88 to –0.92				
Co8	–1.22 to –1.28				
Co9	–1.31 to –1.38				
Co10	–1.38 to –1.45				
Co11	–1.45 to –1.50				
Co12	–1.58 to –1.68				
Co13	–3.25 to –3.30				
Co14	–5.50 to –5.65				
Co15	–7.55 to –7.95				

samples were wet sieved and dried. Ostracods were subsequently picked from the dry residue (fractions >2 mm, 0.5–2 mm, 0.25–0.5 mm). We also used published ostracod data (Sarv in Põlma et al. 1988, fig. 18) from the upper part of the section. The new collection is stored in the Natural History Museum, University of Tartu (TUG), under the collection number TUG 1794.

RESULTS AND DISCUSSION

Updated biostratigraphy of the Peetri section

The *Baltoniodus variabilis* and *B. alobatus* subzones of the *Amorphognathus tvaerensis* conodont Zone were identified (Fig. 2). The index species of the *A. tvaerensis* (Figs 4A–F, 5A–D) conodont Zone occurs below the top of a complex of discontinuity surfaces in the majority of samples studied. *Baltoniodus variabilis* (Fig. 5E–H) was found in samples Co9, Co12, Co13, Co15 and *B. alobatus* (Fig. 5I–L) in samples Co2–Co5. Several samples in the section contain only poorly preserved, unidentifiable elements of *Baltoniodus* (Fig. 5M, N) (samples Co1, Co6–Co8, Co10, Co11, Co14). Lack of *B. gerdae* (Fig. 4G–J) in the boundary interval of the Kukruse RS and Haljala RS seems to be specific to the Peetri region and suggests that the basal part of the Haljala RS is missing due to a sedimentary hiatus. The specimen of *B. gerdae* illustrated from the Peetri section by Viira (1974, p. 61, fig. 57; identified as *Amorphognathus* cf. *gerdae*) is, most probably, an element of *B. alobatus*.

The *Eisenackitina rhenana* chitinozoan Subzone and *Spinachitina cervicornis* chitinozoan Zone were identified in the Peetri succession (Fig. 2). The lack of the *Armoricochitina granulifera*, *Angochitina curvata*, *Lagenochitina dalbyensis* and *Belonechitina hirsuta* chitinozoan zones suggests a gap and lack of most of the Idavere RSs of the Haljala RS (see also Hints 1997a, fig. 45). The *E. rhenana* chitinozoan Subzone was identified 0.54 m below the top of a complex of discontinuity surfaces in the section. This is in agreement with the position of the lower boundary of the Haljala RS as suggested by the conodont and ostracod record.

The ostracod assemblage in the Peetri section consists of 64 species. The major change in the ostracod succession was recorded at 0.14 m above the top of a complex of discontinuity surfaces (Fig. 3). The new assemblage above this level contains *Bichilina prima* and *Pedomphalella jonesii*, the index species of the *Pedomphalella egregia* (= *P. jonesii*)–*Bichilina prima* ostracod Zone (Meidla & Sarv 1990), together with other key taxa of the ostracod assemblage in the Haljala–Keila transition (*Sigmoopsis rostrata*, *Rectella zickerensis*, *Carinobolbina carinata*, etc.), replacing *S. platyceras*, *Disparigonyia kogermani* and *Conchoprimitia sulcata* known from the underlying strata only (Sarv in Põlma et al. 1988). The rearrangement within the ostracod assemblage usually coincides with the change in macrofauna in North Estonia (Sarv in Põlma et al. 1988).

Many studies (Männil 1966; Nõlvak 1972, 2001, 2010; Nõlvak et al. 1999; Stouge et al. 2016) refer to abundant appearance of the near-macroscopic prasino-phycean *Leiospheridia baltica* across Baltoscandia as an

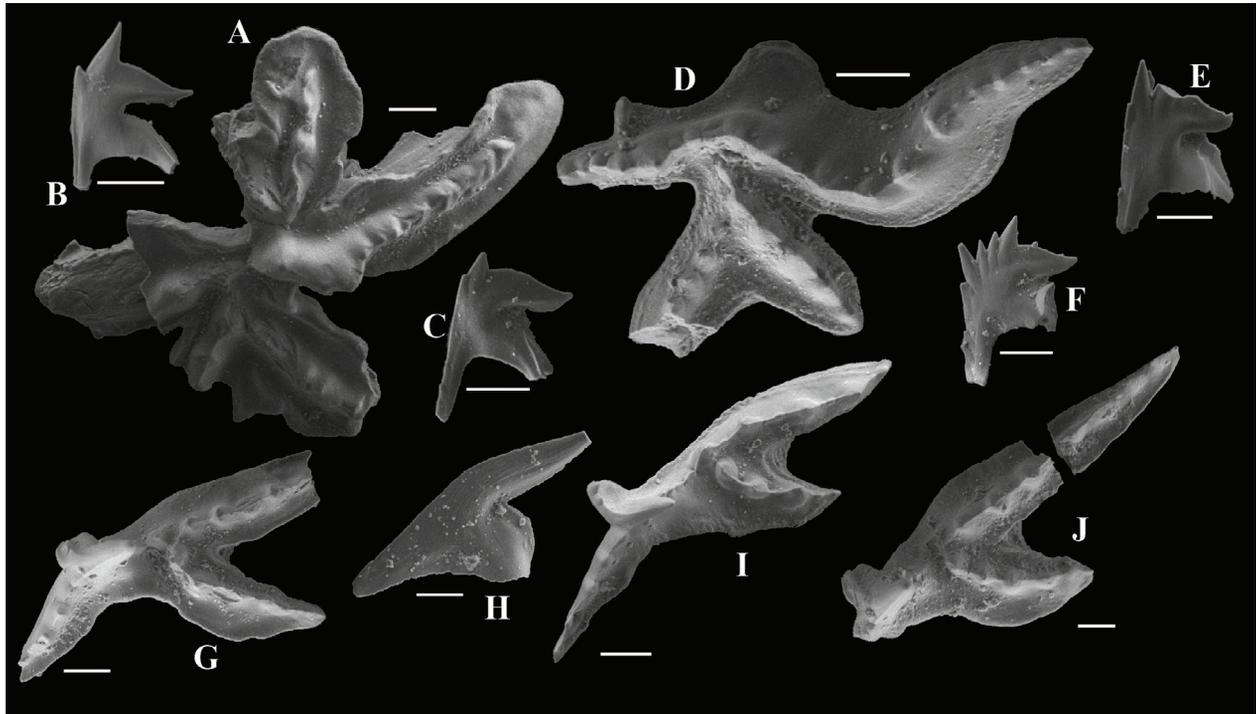


Fig. 4. Selected conodonts from the Mehikoorma (421) drill core. Scale bar represents 100 μm . **A–F**, *Amorphognathus tvaerensis* Bergström: A, D, P_1 elements, 314.9–315.0 m (*Baltoniodus alobatus* conodont Subzone) and 315.5–315.7 m (*Baltoniodus gerdae* conodont Subzone); B, C, M elements, 314.9–315.0 m (*Baltoniodus alobatus* conodont Subzone); E, F, M elements, 319.75–319.85 m (*Baltoniodus gerdae* conodont Subzone) and 320.8–320.9 m (*Baltoniodus variabilis* conodont Subzone). **G–J**, *Baltoniodus gerdae* Bergström: G, H, P_1 and M elements, 315.5–315.7 m; I, J, P_1 elements, 319.75–319.85 m.

additional possible marker for the lower boundary of the Haljala RS. Also in the Peetri section the first appearance level of *L. baltica* coincides with the lower boundary of the Haljala RS, as suggested by conodonts, chitinozoans and ostracods. However, only mass appearance of these easily recognizable palynomorphs could be used as a secondary biostratigraphical marker of this boundary: in the Mehikoorma core section the first *L. cf. baltica* is found (together with the conodont *B. variabilis*) within the upper *L. stentor* chitinozoan Zone, in the *E. rhenana* chitinozoan Subzone (Nölvak 2005). Similarly, *L. baltica* appears in the strata older than the *A. granulifera* chitinozoan Zone in the Ruhnu core section (Nölvak 2003). Evidently, in both sections the first *Leiospheridia* appears below the lower boundary of the Haljala RS as suggested by other biostratigraphic markers.

Correlation of strata in the Kukruse–Haljala boundary interval

Micropalaeontological data from the Peetri outcrop and five core sections (Nölvak 1999, 2001, 2003, 2005, 2010; Viira & Männik 1999; Männik 2001, 2003, 2010; Männik & Viira 2005; Hints et al. 2014) from the boundary

interval of the Kukruse RS and Haljala RS were integrated in order to analyse the available criteria for recognition of the lower boundary of the Haljala RS across the Estonian part of the Baltoscandian Palaeobasin (Fig. 6). In the Ruhnu and Viki core sections the base of the *A. granulifera* chitinozoan Zone coincides with the level of the first appearance of the conodont *B. gerdae*. In the Mehikoorma core section, however, *B. gerdae* appears already in the topmost part of the *L. stentor* chitinozoan Zone (in the uppermost *E. rhenana* chitinozoan Subzone). Earlier appearance of *B. gerdae*, compared to the *L. stentor* chitinozoan Zone and the *E. rhenana* chitinozoan Subzone, is also observed in the Tartu core section (Stouge 1998). However, the *A. granulifera* and *A. curvata* chitinozoan zones were not recognized in the Mehikoorma and Tartu core sections, and the appearance of *B. gerdae* compared to that of *A. granulifera* needs further research. On the other hand, the integrated succession from the Koigi-72 and Laeva core sections (Männik 1986; see Fig. 1) shows that to the south of the outcrop belt *B. gerdae* appears at a level below the lowermost *A. granulifera* but above the uppermost *E. rhenana* (= *Conochitina oelandica* in Fig. 2.1.1 of Männik 1986) and co-occurs together with *L. stentor*.



Fig. 5. Selected conodonts from the Peetri outcrop. Scale bar represents 100 μm . **A–D**, *Amorphognathus tvaerensis* Bergström: A, P_1 element, sample Co6; B–D, M elements, samples Co6, Co14 and Co15. **E–H**, *Baltoniodus variabilis* Bergström: E, P_1 element, sample Co9; F, G, P_1 and M elements, sample Co12; H, P_1 element, sample Co15. **I–L**, *Baltoniodus alobatus* Bergström: I, J, P_1 and M elements, sample Co5; K, L, P_1 elements, samples Co4 and Co2. **M, N**, *Baltoniodus* sp. Lindström: P_1 elements, samples Co7 and Co8.

The basal part of the Haljala RS was thought to be incomplete within and near the outcrop belt in Estonia (Hints et al. 1994, fig. 4; Hints 1997a, fig. 45) but this conflicts with the new data on the occurrence of *A. granulifera* in the Männamaa-367 (Nölvak 2008), Piilsil-729 and Vasknarva-639 sections (Bauert et al. 2014, fig. 1). Hence, the previous generalized stratigraphic model of the Kukruse–Haljala boundary interval needs some revision.

The generally accepted idea that the sections within the Livonian Basin (Valga, Ruhnu – see Fig. 1) are biostratigraphically more complete than those in its peripheral part needs to be revised as well. The synchronous first appearance of *B. gerdae* and *A. curvata* (see Fig. 6) and lack of the interval of concurrent ranges of *B. gerdae*, *L. stentor* and *E. rhenana* (like in the Mehikoorma and Taga-Roostoja sections) suggests gaps in the Valga and Ruhnu sections.

The comparison of faunal successions in the Kukruse–Haljala transition interval in the studied sections (Fig. 6) shows that the Peetri succession is the most incomplete

(as already suggested by several earlier authors; e.g. Männil 1966; Jaanusson 1976; Nestor & Einasto 1997). The strata corresponding to the Tatruse Fm, and probably also to the lower part of the Vasavere Mb, are missing in the Peetri section. The succession missing from the Peetri section stratigraphic interval is 5.5+ m thick in the Viki and Ruhnu core sections.

The section in the Peetri shaft (strata 1–13 according to Rõõmusoks 1970) is designated as the stratotype for the Peetri Mb of the Viivikonna Fm (Männil & Rõõmusoks 1984). However, the K-bentonite layer between sedimentary cycles VI and VII in the upper part of the Viivikonna Fm *sensu* Männil (1986; Männil & Bauert 1986) is not recorded in the Peetri section and the uppermost part of the Viivikonna Fm here, most probably, exposes only equivalents of the kukersite beds V or VI, suggesting that the sedimentary cycles VII–X are missing. In the Imavere core section (Männil & Bauert 1986, fig. 3.2.1.), the corresponding stratigraphic interval is up to about 6 m thick.

According to the distribution of the *B. alobatus* conodont Subzone and the *L. stentor* chitinozoan Zone (*E.*

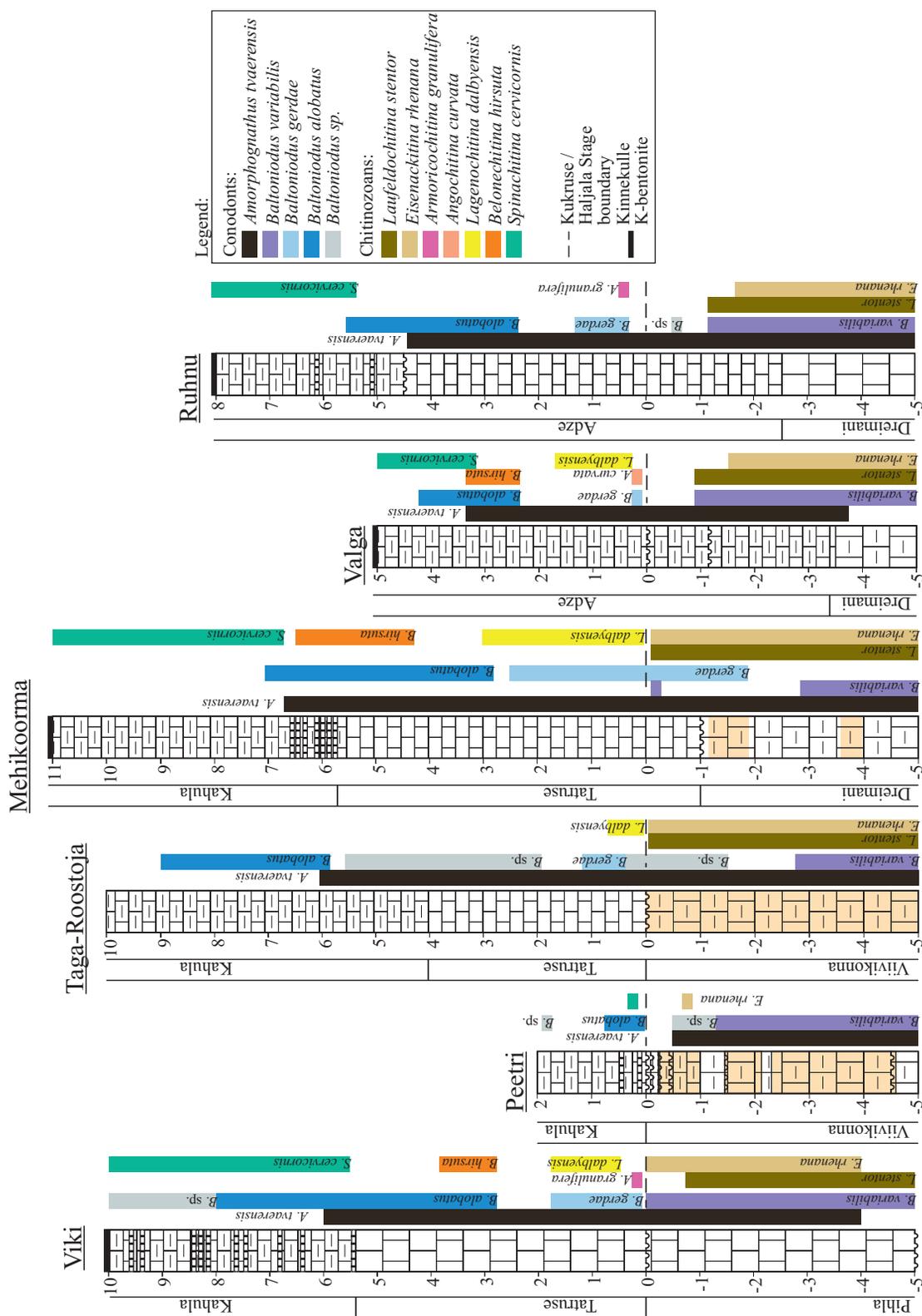


Fig. 6. Correlation of the Kukruse–Haljala boundary interval. The zero levels in the sections are aligned with the lower boundary of the Haljala RS in original publications: Viki – Hints et al. 2014; Taga–Roostoja – Nõlvak 1999, Viira & Männik 1999; Mehikoorma – Männik & Viira 2005, Nõlvak 2005; Valga – Männik 2001, Nõlvak 2001; Ruhnu – Männik 2003, Nõlvak 2003. Depth scales in metres.

rhenana chitinozoan Subzone), corresponding to the Kukruse RS, south of the outcrop area, the lower part of the Tatruse Fm in central Estonia (Mehikoorma core section) and the lower part of the Adze Fm in South Estonia (Valga and Ruhnu core sections) are clearly of late Kukruse Age (Fig. 6). This means that the traditional lithostratigraphic marker, a distinct discontinuity surface, may work for the lower boundary of the Haljala RS in the Estonian Shelf area but is of different age (has different duration) in central and South Estonia (Fig. 7).

The correlation between conodont and chitinozoan biozones near the lower boundary of the Haljala RS in Estonia is shown in Fig. 7. As the uppermost specimens of *L. dalbyensis* are found together with the lowermost *B. alobatus* in the Mehikoorma core section (Männik & Viira 2005; Nölvak 2005), the position of the lower boundary of the *B. alobatus* conodont Zone should be drawn lower than indicated in the previous correlation schemes (Nölvak & Grahn 1993; Nölvak 1997).

The graptolite *Amplexograptus maxwelli* (Goldman et al. 2015) (= *A. baltoscandicus*, Jaanusson 1995) that has been used as a boundary marker for the base of the Jõhvi RSs (Männil 1976) above the K-bentonite ‘b’ (Männil 1986), is recorded in older strata at Peetri, within the *B. alobatus* conodont Zone and *S. cervicornis* chitinozoan Zone, distinctly below the traditional K-bentonite marker within the Kahula Fm (Hints & Nölvak 1990). This makes

the substages rather obsolete. Even though they could be traced within and near the outcrop belt using the K-bentonite marker, their practical correlation value is limited in a wider area.

The original definition of the lower boundary of the Haljala RS was based on sections in the North Estonian outcrop area characterized by considerable sedimentary hiatuses (Jaanusson 1995). According to the traditional view, the boundary corresponds to a discontinuity surface in North Estonia and the gap at this boundary was filled gradually towards the centre of the basin (towards the south; Hints et al. 1994). However, integrated biostratigraphic analysis shows that the gap marked by a discontinuity surface is older in central and southern Estonia and this complicates location of the stage boundary. The order of the first appearance datums of conodonts and chitinozoans in the Kukruse–Haljala boundary interval is as follows: *B. gerdae*, *A. granulifera*, *A. curvata*, *L. dalbyensis*, *B. alobatus*, *Belonechitina hirsuta* and *Spinachitina cervicornis* but a complete record of conodont and chitinozoan zones based on these taxa is not available in the same section in Estonia. Based on the wide distribution and different duration of gaps in the Kukruse–Haljala boundary interval, the Haljala RS should be considered a poorly defined (gap-bounded) unit, without particular hope of re-defining it on the basis of a suitable boundary stratotype ‘... in a section representing

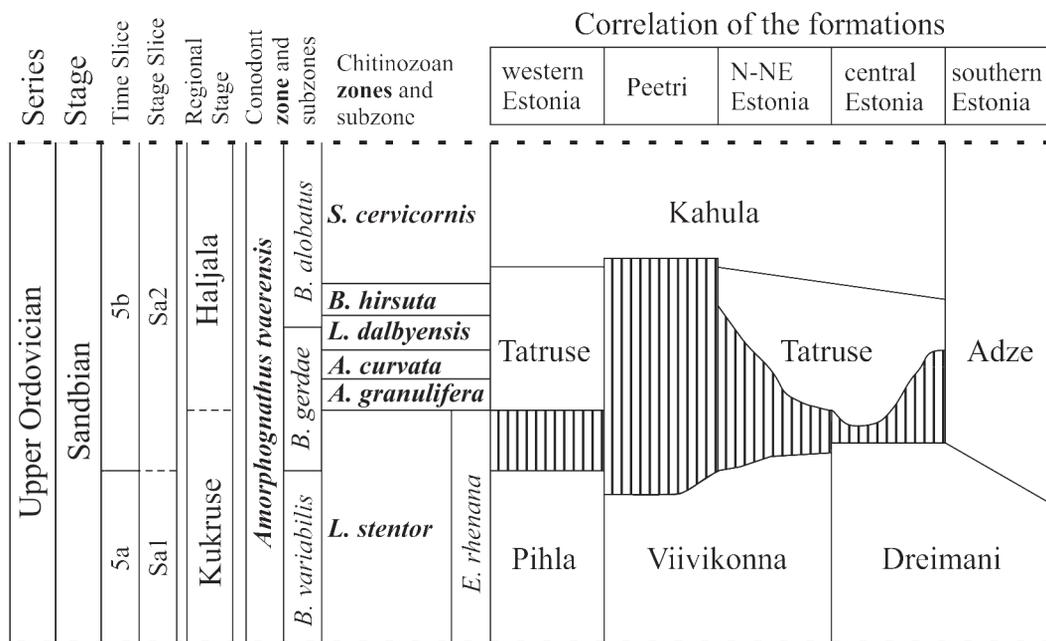


Fig. 7. Ordovician stratigraphy of Estonia in the Kukruse–Haljala boundary interval. Correlation of the formations is based on the Viki core section for western Estonia; Kerguta (Nölvak & Bauert 2006), Taga–Roostoja, Vasknarva and Piilsu core sections for N–NE Estonia; Koigi, Tartu and Mehikoorma core sections for central Estonia; Valga and Ruhnu core sections for southern Estonia. Time Slices are according to Webby et al. (2004) and Stage Slices according to Bergström et al. (2009).

essentially continuous deposition' (Murphy & Salvador 1999, p. 269).

The guide for geological nomenclature in Sweden (Kumpulainen 2017) expresses concerns about the topostratigraphic nature of the gap-bound chronostratigraphic units applied in Swedish and Estonian chronostratigraphic classification (but actually across the entire Baltic Region). It states that such units should be validated in future as lithostratigraphic units in all cases where possible and urges for abandoning their topostratigraphic usage (*ibid.*, Appendix A). The Kukruse RS and the Haljala RS are in active use in Latvia and Lithuania (e.g. Paškevičius 1997) but were never properly established in the Swedish chronostratigraphic classification because of the problems described above. In this light, the possibility of exploiting more widely the substantially detailed Global Stages Slices (Bergström et al. 2009) as an independent means of correlation deserves to be investigated in future. Additionally, the proposed Time Slice 5b (Webby et al. 2004) correlates to the base of the *B. gerdae* conodont Zone (Leslie & Bergström 1995) and can be used as an additional stratigraphic level near the Kukruse RS and Haljala RS boundary interval.

CONCLUSIONS

The integrated conodont, chitinozoan and ostracod biostratigraphy allows us to locate a distinct gap in the Peetri succession at the top of a complex of discontinuity surfaces 0.1 m below the lower K-bentonite layer. This is in agreement with previous studies and confirms the lack of a part in the stratigraphic succession corresponding to the upper Kukruse and lower Haljala strata (at least the *Baltoniodus gerdae* conodont Subzone is missing).

The lowermost parts of the Tatruse and Adze formations in central and southern Estonia contain conodont and chitinozoan taxa that allow correlation of these strata with the upper part of the Kukruse RS.

The lower boundary of the Haljala RS is poorly defined and its location in many sections (regions) remains problematic. The occurrence of gaps all over Estonia in the probable interval of this boundary shows that there is no particular hope of finding a suitable section (a boundary stratotype) for defining it. The order of the first appearance datums of conodont and chitinozoan species (from oldest to youngest: *Baltoniodus gerdae*, *Armoricochitina granulifera*, *Angochitina curvata*, *Lagenochitina dalbyensis*, *Baltoniodus alobatus*, *Belonechitina hirsuta*, *Spinachitina cervicornis*) is established but a complete record of conodont and chitinozoan zones based on these taxa has not been found in the same section in Estonia.

The multi-proxy correlation of the Kukruse–Haljala boundary strata across Estonia shows the complexity of

this interval and points at the principal advantage of this method over single-group studies.

Acknowledgements. S. M. Bergström and T. Tolmacheva are acknowledged for their constructive reviews and improvements of the manuscript. The publication was financially supported by project IUT20-34 'The Phanerozoic journey of Baltica: sedimentary, geochemical and biotic signatures of changing environment – PalaeoBaltica' and PRG836 'Tracing the origins of early Paleozoic stable carbon isotope excursions – global, regional and local drivers' from the Estonian Science Agency and Ministry of Education and Research. This is a contribution to the International Geoscience Programme (IGCP) Project 653 'The onset of the Great Ordovician Biodiversification Event'. The publication costs of this article were partially covered by the Estonian Academy of Sciences.

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Haljala lademe (Sandby, Ülem-Ordoviitsium) alumine piir Eestis

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On käsitletud Haljala lademe alumise piiri kontseptsiooni ja markereid erinevate fossiilirühmade ning muude geoloogiliste markerite leviku alusel. Loode-Eesti andmeid Peetri paljandist võrreldi konodontide, ostrakoodide ja kitiinikute avaldatud levikuandmetega teistest läbilõigetest. Peetri läbilõiget iseloomustab ulatuslik settekatekestus Haljala lademe alumisel piiril, mida näitab *Baltoniodus gerdae* konodontitsooni ja *Armoricochitina granulifera*, *Angochitina curvata*, *Lagenochitina dalbyensis*'e ning *Belonechitina hirsuta* kitiinikutsooni puudumine. Konodontide ja kitiinikute levik Lõuna-Eesti läbilõigetes tõendab, et Tatruse ning Adze kihistu basaalkihid on seni arvatust vanemad. Haljala lade on püstitatud seni täpselt määratlemata alumise piiri kriteeriumide ühikuna ja puudub piiristatootüüp. Käesoleva töö tulemused kajastavad ilmekalt erinevate faunagruppide stratigraafilise leviku andmete integreerimisest tekkinud lisaväärtust.