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Conodont biostratigraphy in the Middle–Upper Ordovician boundary beds of Estonia

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Abstract. Conodonts of the uppermost Uhaku, the Kukruse, and the lower Haljala stages (uppermost Darriwilian and lower Sandbian) of Estonia are discussed. The distribution of conodonts within the *Pygodus serra*, *P. anserinus*, and *Amorphognathus tvaerensis* zones is considered on the basis of 2 outcrop and 15 drill core sections. Judging by the Global Stratotype Section, Fågelsång, Sweden, the base of the Upper Ordovician Series should be lower than the first appearance of *A. tvaerensis.* The Estonian material shows that elements of *A. tvaerensis* from the lowermost range of the species are of a morphotype similar to *A. inaequalis.* It is proposed that the *A. inaequalis* Subzone be upgraded to the *A. inaequalis* Zone. The best level for the Middle–Upper Ordovician boundary in Estonia is at the lower boundary of the Kukruse Stage below the appearance of *A. tvaerensis* and/or *A. inaequalis*.

Key words: conodonts, correlation, biostratigraphy, Ordovician, Estonia.

INTRODUCTION

The Fågelsång locality in southern Sweden has been approved and ratified as the Global Stratotype Section and Point (GSSP) for the lower boundary of the upper series of the Ordovician System. The base of the Upper Ordovician Series is defined by the appearance of the graptolite *Nemagraptus gracilis* 1.4 m below the Fågelsång Phosphorite in the *Dicellograptus* shale (Bergström et al. 2000; Bergström 2007a). In the Swedish stratotype section there have been identified conodonts of the *Pygodus serra*, *P. anserinus*, and *Amorphognathus tvaerensis* zones, defining the exact level of the lower boundary of the Upper Ordovician in the *P. anserinus* Zone. Graptolite findings are very rare in Estonia and the *N. gracilis* Zone is usually considered to coincide with the Kukruse Stage (Männil 1966, 1976, 1986; Männil & Meidla 1994). Rare occurrences of *Nemagraptus* in various stratigraphical levels and of *N. gracilis* in the upper part of the Kukruse Stage are summarized in Nõlvak & Goldman (2004). Recent studies of chitinozoans, conodonts, and scolecodonts in the Middle–Upper Ordovician boundary beds show that the boundary could be traced at different levels within the Kukruse Stage and in the upper part of the preceding Uhaku Stage (Hints et al. 2005, 2007; Nõlvak et al. 2006; Männik 2007).

In the present paper the distribution of conodonts within the *P. serra*, *P. anserinus*, and *A. tvaerensis* zones is considered on the basis of the Estonian material and the position of the Middle–Upper Ordovician boundary level in Estonia is proposed. The index species of the upper subzone of the *P. anserinus* Zone, *Amorphognathus inaequalis*, lacking in the Swedish stratotype but found in a few sections in Estonia, is investigated and morphologically compared with its successor *A. tvaerensis*.

MATERIAL

Data on the distribution of conodonts in the Middle–Upper Ordovician boundary beds are available from many core sections all over Estonia and from two outcrop sections (Kohtla outcrop and Viru mine) in the type area of the Kukruse Stage, NE Estonia. The conodonts discussed in this paper have been studied at different times and for different purposes. First of all, conodont data from the Seliste-173, Are-171, Häädemeeste-172, Viljandi-91, Abja-92, and Karula-320 boreholes, drilled during the geological mapping of Estonia in 1960–1970, are used. Depending on the lithology and necessity of defining the stage boundaries, the sampling interval in these cores was 1–2 to 12–14 m. The first published conodont succession in Estonia through the entire Ordovician was based on the Ohesaare core, where the sampling interval was 1–3 m (Viira 1967). All conodont collections of the drill cores extracted during mapping, as well as the Ohesaare core and unpublished collections of the Kaagvere and Äiamaa drill cores, were re-examined for this paper. Also conodont data from the Taga-Roostoja-25A, Mehikoorma-421, Tartu-453, Valga-10, Ruhnu-500, and Kerguta-565 cores, published in the series *Estonian Geological Sections* issued by the Geological Survey of Estonia, are used. Only the interval covering the Uhaku, Kukruse, and Haljala stages (lower part) is considered in all these cores. The location of the drill cores mentioned above is shown in Fig. 1.

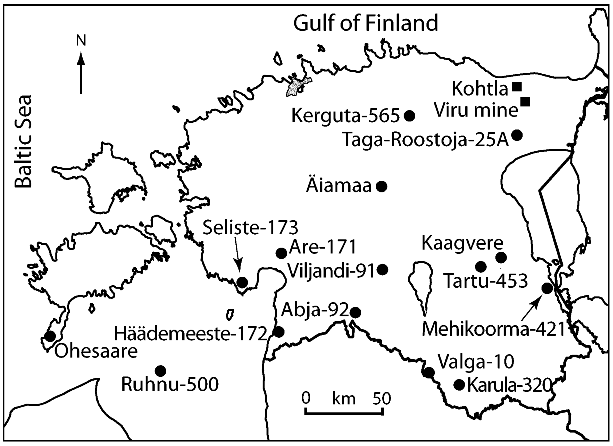

Fig. 1. Location of the studied outcrops and drill cores in Estonia. Filled circles – drill cores; squares – outcrops.

The stratigraphical scheme with the conodont zonation of the studied interval is given in Fig. 2. Collections of conodonts are deposited in the Institute of Geology at Tallinn University of Technology. The illustrated specimens form the collection GIT 549.

	Bergström 2007a		This paper	
HALJALA STAGE	*Amorphognathus tvaerensis* Zone	*Baltoniodus alobatus* Subzone	*Amorphognathus tvaerensis* Zone	*Baltoniodus alobatus* Subzone
		Baltoniodus gerdae Subzone		*Baltoniodus gerdae* Subzone
KUKRUSE STAGE		*Baltoniodus variabilis* Subzone		*Baltoniodus variabilis* Subzone
	Pygodus anserinus Zone	*Amorphognathus inaequalis* Subzone	*Amorphognathus inaequalis* Zone	
UHAKU STAGE		*Sagittodontina? kielcensis* Subzone	*Pygodus anserinus* Zone	

Fig. 2. Stratigraphical scheme with the conodont zonation of the studied interval.

THE CONODONT DISTRIBUTION IN THE SECTIONS

The studied outcrop and core sections represent different facies belts. In North Estonia the considered interval is generally characterized by argillaceous limestone, in the northeastern outcrop area with intercalations of kukersite (oil shale) and marl. In central and southern Estonia the cores are westwards represented by bioclastic limestone, southwards by micritic limestone and argillaceous limestone with pyritized skeletal detritus. Below the distribution of conodonts in these sections, arranged from north to south, is discussed.

Kohtla section

In this section, located in the centre of the oil shale field in NE Estonia, the most kukersite-rich and fossiliferous portion of the Viivikonna Formation is exposed. *Amorphognathus tvaerensis* Bergström appears at the base of the Kukruse Stage, about 25–30 cm from the lowermost part of the first limestone interbed A/B (Viira et al. 2006a). Therefore it was suggested that the lower part of the Kukruse Stage should be assigned to the *A. tvaerensis* conodont Zone and that the base of the Upper Ordovician lies at or beneath the base of the Kukruse Stage. This conclusion revises earlier published data, which indicated that the lower boundary of the *A. tvaerensis* Zone was somewhere within the Kukruse Stage (Bergström 1971, 2007b; Männil 1986; Nõlvak 1997; Männik 2007).

Viru mine section

A 7-m interval of the uppermost part of the Uhaku Stage (Kõrgekallas Formation) and the lowermost part of the Kukruse Stage (Viivikonna Formation) yields mainly *Baltoniodus variabilis* (Bergström) (Fig. 3A–M, P, Q)

Fig. 3. Conodonts from the Uhaku Stage of Viru mine, except F. **A–M**, **P**, **Q**, *Baltoniodus variabilis* (Bergström); A–F, Pa element: A, sample 47, GIT 549-57, ×100; B, C, sample 44, GIT 549-58, GIT 549-59, ×80; D, sample 45, GIT 549-60, ×100; E, sample 48, GIT 549-61, ×80; F, Abja core, depth 443.0 m, GIT 549-62, ×100; G–I, Pb element: G, H, sample 48, GIT 549-63, ×100, GIT 549-64, ×80; I, sample 47, GIT 549-65, ×80; J, K, Sc element: J, sample 48, GIT 549-66, ×45; K, sample 49, GIT 549-67, ×80; L, Sa element, sample 44, GIT 549-68, ×100; M, Sd element, sample 49, GIT 549-69, ×80; P, Q, M element: P, sample 49, GIT 549-70, ×80; Q, sample 44, GIT 549-71, ×100. **N**, **O**, *Baltoniodus*? sp., Sd element, sample 32, GIT 549-72, ×70, GIT 549-73, ×80. **R**, *Drepanoistodus* aff. *D. venustus* (Stauffer), sample 46, GIT 549-74, ×100. **S**, **T**, *Panderodus sulcatus* (Fåhraeus), sample 43, GIT 549-75, ×100, GIT 549-76, ×80. **U**, **V**, *Oslodus semisymmetricus* (Hamar), sample 43, GIT 549-77, ×70, GIT 549-78, ×80. **W**, **X**, *Drepanoistodus suberectus* (Branson & Mehl); W, sample 45, GIT 549-79, ×70; X, sample 48, GIT 549-80, ×80. **Y–AE**, *Semiacontiodus carinatus* Dzik; Y, sample 49, GIT 549-81, ×100; Z, sample 46, GIT 549-82, ×80; AA, AC, AE, sample 31, GIT 549-83, ×100, GIT 549-84, ×100, GIT 549-85, ×70; AB, sample 50, GIT 549-86, ×80; AD, sample 48, GIT 549-87, ×70.


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and some long-ranging species, but not a single specimen of the zonal indices *Pygodus anserinus* Lamont & Lindström or *A. tvaerensis* (see Hints et al. 2005, 2007). However, some S elements referred to as *Baltoniodus*? sp. (Fig. 3N, O), with big denticles on the posterior process, in a sample from the upper part of the section show a similarity to the S elements of *Amorphognathus* sp.

Taga-Roostoja-25A drill core

The biostratigraphical distribution of conodonts is given in Viira & Männik (1999). In the present paper the ranges of selected species are given in Fig. 4. No elements of *Pygodus anserinus* have been found in this section at a level below what is shown in Fig. 4 but *P. serra* (Hadding) was present in the sample from 104.6 m in the lower part of the Uhaku Stage and *Eoplacognathus* aff. *lindstroemi* (Hamar) in the sample from 98.6 m. From this level up to 93.6 m *Complexodus pugionifer* (Drygant) has been identified in five samples. *Amorphognathus tvaerensis* appears in the lower part of the Kukruse Stage at 77.8 m and is numerous throughout its range. *Baltoniodus* cf. *gerdae* and *B.* cf. *alobatus* are also abundantly represented, the former in two and the latter in four samples.

Kerguta-565 drill core

The biostratigraphical distribution of conodonts is given in Viira et al. (2006b). *Pygodus serra* has been identified at 172.8 m in the lower part of the Uhaku Stage, at the beginning of the range (170.6–172.8 m) of *E. lindstroemi*. From the Uhaku Stage upwards the samples are poor in conodonts, which may partly be due to small sample sizes. The transition from *Baltoniodus prevariabilis* (Fåhraeus) to *B. variabilis* is rather difficult to follow and was tentatively considered to take place at 163.8 m. The lower boundary of the Kukruse Stage is at 163.5 m. *Amorphognathus* sp. is found only in one sample from 144.8 m in the Tatruse Formation of the Haljala Stage.

Äiamaa drill core

Pygodus anserinus is lacking but *Pygodus* sp. is found in the sample from 220.1 m (Fig. 4). In two samples, from 222.1 and 224.0 m, *E. lindstroemi* has been identified. *Amorphognathus tvaerensis* makes its first appearance at 210.8 m with well-preserved specimens and is quite numerous until its disappearance at 195.0 m. *Baltoniodus alobatus* (Bergström), *B. gerdae* (Bergström), and *Eoplacognathus elongatus* (Bergström) have been found in separate samples at depths of 195.0, 200.1, and 210.8 m. Some Pa elements of *A. tvaerensis* from samples at 196.0 and 210.8 m were illustrated in Viira (1974, pl. VII, figs 18, 19, 23, 24).

Ohesaare drill core

The biostratigraphical distribution and illustrations of conodonts throughout the Ordovician in the Ohesaare drill core are given in Viira (1967), and selected species ranges of the studied interval are given in Fig. 4 of the present publication. Some specimens of *A. tvaerensis* are illustrated in Viira (1967, figs 3–20; 1974, fig. 108 and pl. VII, figs 15–17; in this paper Fig. 5A–L). In the Uhaku Stage, besides *Pygodus* cf. *anserinus* (one specimen of the Pb element) at a depth of 485.3 m, *P. serra* has been found lower down at 494.5–495.9 (490.6?) m, *Eoplacognathus lindstroemi* in the interval 489.9–493.5 m (Fig. 6P), and *Periodon aculeatus* Hadding in the sample from 489.9 m (Fig. 6S). *Baltoniodus variabilis* occurs probably at a depth of 488.9 m and upwards. *Amorphognathus tvaerensis* (Pb element) appears at 482.5 m, 2.8 m higher than the previously mentioned find of *P.* cf. *anserinus*, and is present in all samples up to 471.8 m (Fig. 5A–L). Within the lower part of the *A. tvaerensis* range, *E. elongatus* has been encountered in two samples, from 478.8 and 480.1 m (Fig. 6Q). *Baltoniodus gerdae* has been found within the upper range of *A. tvaerensis* at 472.8 and 473.8 m. Rare *Baltoniodus* cf. *alobatus* have been identified at 468.0 and 469.2 m, above the range of *A. tvaerensis*. The last occurrence of *B. variabilis* is at 474.8 m, just before the appearance of *B. gerdae*.

Conodont specimens have been counted in all samples (on average 500–600 g) of this drill core (Fig. 4). In the Uhaku–Kukruse–Haljala stages interval the elements are most numerous in the *P. serra* Zone, for example 662 specimens in the sample from 495.9 m. Samples from the interval 489.9–493.5 m each yielded about 180–200 specimens. The number of specimens per sample was smallest in the interval 485.3–488.9 m, where 9–27 specimens were encountered. Such a conodont-poor interval in the uppermost part of the Uhaku Stage has been noticed also in some other sections. From 483.7 m upwards, samples contained 40–176 specimens. *Amorphognathus tvaerensis* is quite numerous in the interval 474.8–478.8 m, where the total yield was 100 specimens or more per sample.

Seliste-173 drill core

The studied interval is represented only by a few conodont samples. Nevertheless, *P. anserinus* has been identified in two samples, at 426.8 and 429.6 m, in the Uhaku Stage. *Amorphognathus tvaerensis* has also been found in two

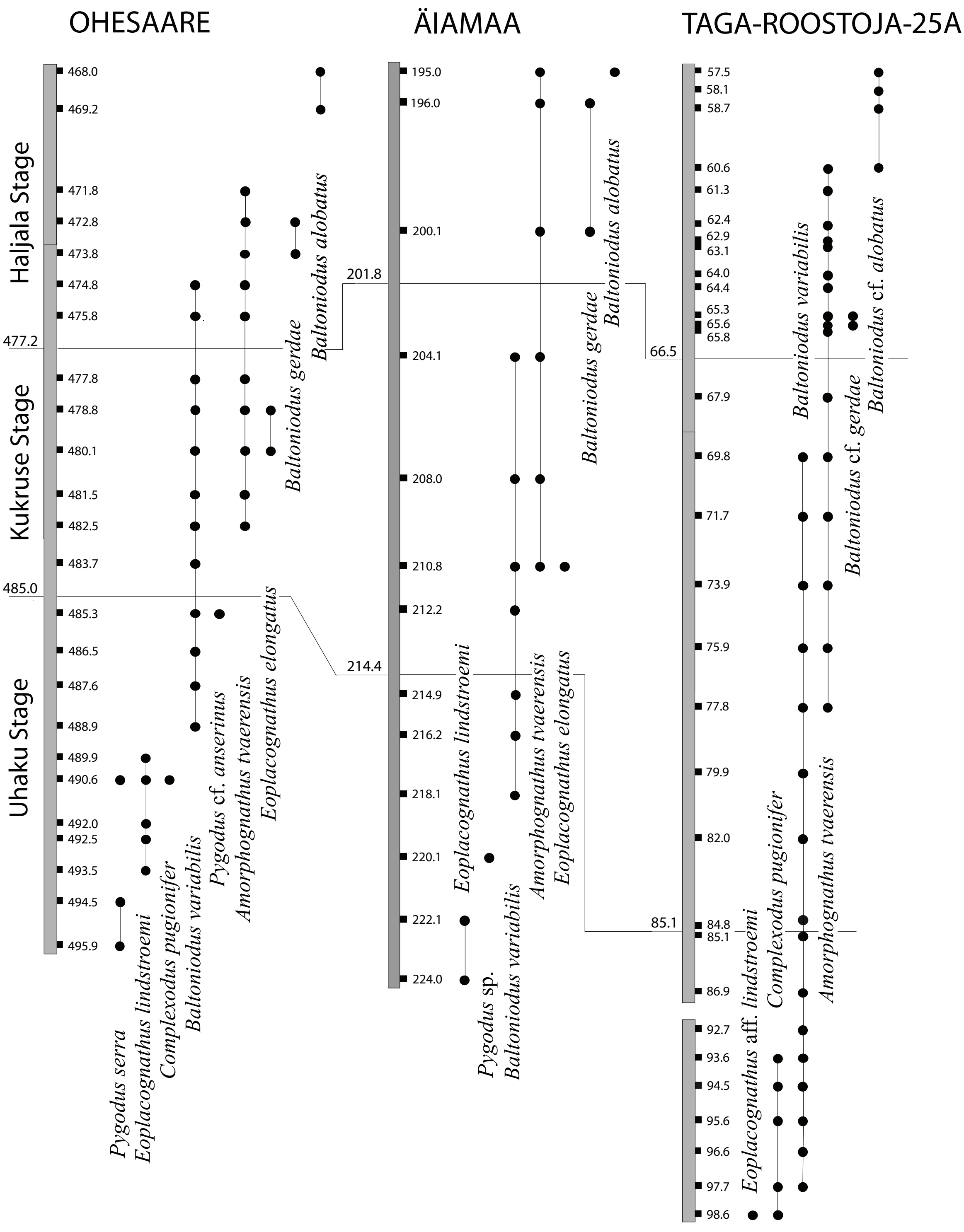
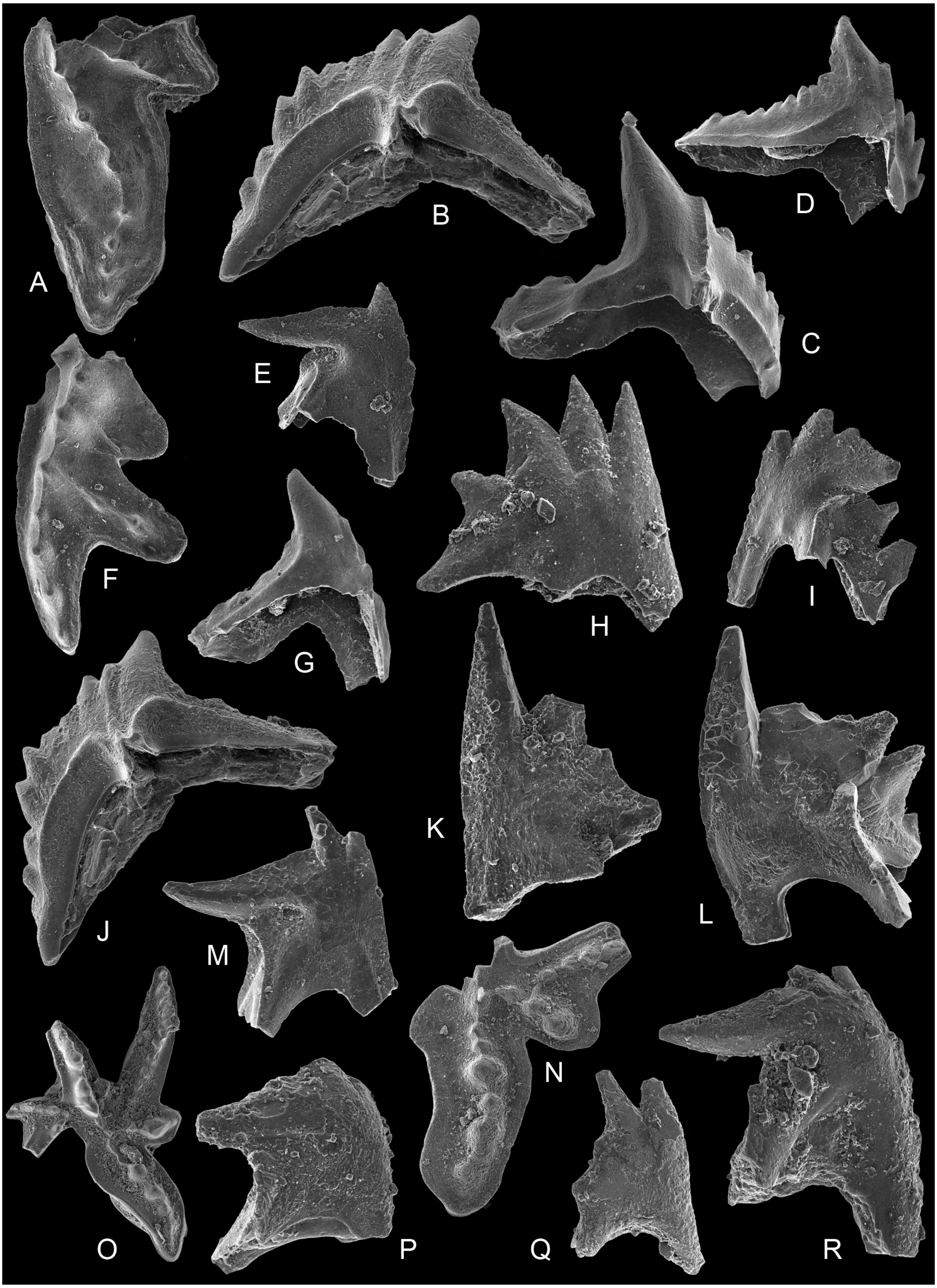


Fig. 4. Ranges of selected conodonts in the Ohesaare, Äiamaa, and Taga-Roostoja-25A cores. Depth in metres.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samples, at 404.5 m (numerous specimens) and 412.8 m (Fig. 5O–Q). *Baltoniodus alobatus* has been encountered in the sample from 401.9 m in the Haljala Stage. Some Pb specimens of *A. tvaerensis* are illustrated in Viira (1974, pl. XI, figs 34–37).

Are-171 drill core

Eight conodont samples are available from the studied interval 291.7–318.2 m. *Pygodus anserinus* has not been found but *P. serra* occurs in the sample from 318.0 m. A few specimens of *E.* cf. *lindstroemi* have been identified in the lower part of the Uhaku Stage in two samples, at 318.0 and 318.2 m. *Complexodus pugionifer* was also found at 318.0 m. *Amorphognathus tvaerensis* occurs in five samples from 291.7 to 305.5 m, in the Kukruse and Haljala stages. Like in Seliste, *A. tvaerensis* is most numerous in the uppermost sample (Fig. 5M, N, R). *Eoplacognathus* cf. *elongatus* has been recognized at a depth of 305.5 m. *Baltoniodus gerdae* is found in samples from 297.7 and 298.5 m (Fig. 6R). Some Pa specimens of *A. tvaerensis* are illustrated in Viira (1974, pl. VII, figs 20–22).

Ruhnu-500 drill core

The conodont distribution is given in Männik (2003). The *P. serra* Zone includes the interval 671.7–678.6 m. The *P. anserinus* Zone is represented in four samples from the interval 666.7–670.8 m. *Eoplacognathus lindstroemi* has been found in the boundary beds of these zones. *Periodon aculeatus* and *Sagittodontina kielcensis* (Dzik) occur in the *P. serra* Zone. The appearance of *B. variabilis* at 666.7 m marks the Uhaku–Kukruse stage boundary at 666.8 m. *Amorphognathus inaequalis* Rhodes has been identified in two samples at 663.8 and 664.8 m, just below the appearance of *A. tvaerensis* at 662.8 m. *Eoplacognathus elongatus* is found at 663.8 m in the Kukruse Stage, *B. gerdae* at 667.8 m and *B. alobatus* at 662.8 m in the Haljala Stage. *Amorphognathus tvaerensis* disappears at 653.8 m, just before the last specimens of *B. alobatus* at 652.8 m.

Häädemeeste-172 drill core

Only six samples have been taken from the studied interval. In the Uhaku Stage, *E.* cf. *lindstroemi* is found in samples from 506.2 and 507.6 m. *Pygodus anserinus* has been identified at 505.6 m in the Uhaku Stage and *A. tvaerensis* 2 m higher, at 503.6 m in the Kukruse Stage. This 2-m interval, devoid of both these index species, is the smallest "barren interval" among all other studied sections, except for the Ruhnu section where *A. inaequalis* first appears only 1.9 m higher than the last specimens of *P. anserinus*. The next sample in the Häädemeeste core, from 489.7 m, also contains *A. tvaerensis*, but the highest studied sample, from 483.9 m, only *B.* cf. *alobatus*.

Viljandi-91 drill core

All index species, except *P. serra*, have been found in the few samples taken from this section. *Pygodus anserinus* has been identified at 378.0 m and *A. tvaerensis* in three samples from 356.5–372.6 m. *Baltoniodus gerdae* occurs at depths of 356.5 and 360.8 m, and *B. alobatus* in the interval 353.7–354.4 m.

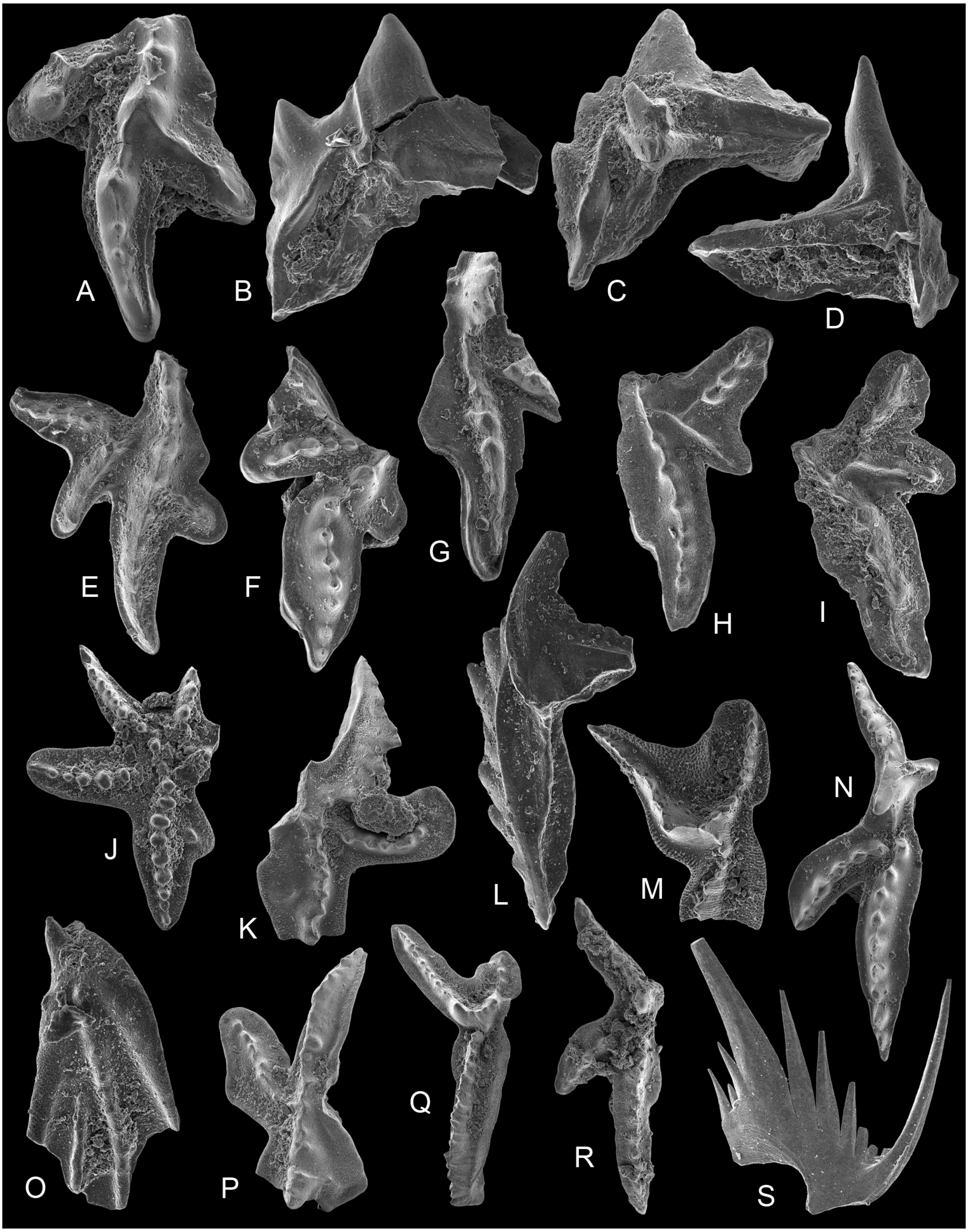
Abja-92 drill core

Pygodus anserinus has not been found, but *P. serra* and *E. lindstroemi* have been identified at 449.1 m. *Baltoniodus variabilis* makes its first appearance approximately at 443.0 m. *Amorphognathus tvaerensis* is represented in five samples from the interval 425.6–434.2 m (Fig. 6A–I), in the two uppermost samples together with *B. gerdae*.

Tartu-453 drill core

The biostratigraphical distribution of conodonts is given in Põldvere et al. (1998), wherein the conodonts were identified by S. Stouge. *Pygodus serra* has been found at 348.3–350.1 m, followed by *E. lindstroemi* at 344.2–344.7 m and *P. anserinus* in the upper part of the Uhaku

Fig. 5. *Amorphognathus tvaerensis* Bergström from the Kukruse Stage of the Ohesaare, Are, and Seliste cores. **A**, **B**, Ohesaare core, depth 480.1 m; A, Pa element, GIT 549-20, ×100; B, Pb element, GIT 549-21, ×100. **C**, **F**, Ohesaare core, depth 478.8 m; C, Pb element, GIT 549-22, ×100. F, Pa element, GIT 549-23, ×100. **D**, Ohesaare core, depth 477.8 m; Pb element, GIT 549-24, ×100. **E**, **G**, **I**, Ohesaare core, depth 474.8 m; E, M element, GIT 549-25, ×100. G, Pb element, GIT 549-26, ×80; I, M element, GIT 549-27. **H**, Ohesaare core, depth 475.8 m; M element, GIT 549-28, ×130. **J–L**, Ohesaare core, depth 471.8 m; J, Pb element, GIT 549-29, ×100; K, M element, GIT 549-30, ×130; L, M element, GIT 549-31, ×130. **M**, **N**, Are core, depth 291.7 m; M, M element, GIT 549-32, ×130. N, Pa element, GIT 549-33, ×100. **O**, **Q**, Seliste core, depth 404.5 m; O, Pa element, GIT 549-34, ×55; P, M element, GIT 549-35, ×130; Q, M element, GIT 549-36, ×100. **R**, Are core, depth 298.5 m; M element, GIT 549-37, ×130.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Stage, at 339.7–342.9 m. The interval with *Periodon aculeatus* is 345.2–347.8 m. The level of 339.4 m marks the boundary between the Uhaku and Kukruse stages. In the lower part of the Kukruse Stage *E. elongatus* appears before *A. tvaerensis* and ranges between 334.0 and 335.7 m. *Amorphognathus tvaerensis* appears first at 334.5 m and is subsequently found in seven samples up to 329.0 m. This species is succeeded by *A.* cf. *tvaerensis* at 324.8–327.8 m, *Amorphognathus* n. sp. at 323.2 m, and by *Amorphognathus* sp. A at 319.0–320.5 m. *Baltoniodus gerdae* has been identified at 324.8–327.8 m and *B. alobatus* at 318.0–323.2 m.

Kaagvere drill core

Selected conodont species with their ranges are shown in Fig. 7. Due to rather close sampling, the intervals of all zonal species have been defined. *Pygodus serra* and *P. anserinus* occur at depths of 315.7–316.6 and 312.0–313.4 m (Fig. 6O). *Eoplacognathus lindstroemi* and *Complexodus pugionifer* are also represented in the Uhaku Stage. The interval 312.0–316.6 m, with numerous conodonts including the index species, is followed by the interval 305.0–310.5 m, yielding mostly long-ranging conodonts. *Amorphognathus tvaerensis* makes its first appearance at 304.2 m and is then present in all samples up to 293.9 m (Fig. 8A–S). This species is particularly numerous in the sample from 298.2 m. *Eoplacognathus elongatus* has been found in five samples in the interval 298.2–305.0 m (Fig. 6J–L). The index species *B. gerdae* (Fig. 6M, N) and *B. alobatus* are also represented, the former in the boundary beds of the Kukruse and Haljala stages and the latter in the Haljala Stage.

Mehikoorma-421 drill core

The biostratigraphical distribution of conodonts is given in Männik & Viira (2005). In this core section, as well as in the Ruhnu core, ?*A. inaequalis* has been identified 3 m higher than the last specimens of *P. anserinus* and disappears just before the first appearance of *A. tvaerensis* (Fig. 7). All the index species for the interval are present in the Mehikoorma core. In the *P. serra* and *P. anserinus* zones also *Periodon aculeatus*, *E. lindstroemi*, and *Sagittodontina kielcensis* occur. The index species *B. gerdae* and *B. alobatus* are represented by numerous specimens.

Valga-10 drill core

The distribution of conodonts is available in Männik (2001). *Pygodus serra* has been identified in the interval 419.6–424.3 m and *E. lindstroemi* a few metres higher at 415.8 m. *Pygodus anserinus* has not been found. *Amorphognathus tvaerensis* occurs in the interval 396.7–403.3 m and *Amorphognathus* sp. has been found at 405.1 m. Other important occurrences are: *E. elongatus* in the interval 403.9–406.8 m, *B. gerdae* at 400.0 m, and *B. alobatus* at 395.8–397.7 m.

Karula-320 drill core

The ranges of selected species are given in Fig. 7. *Pygodus serra* is not found but *E. lindstroemi* occurs at a depth of 427.0 m. *Pygodus anserinus* and *Complexodus pugionifer* have been identified in the sample from 426.5 m and *B. variabilis* appears at about the same level. The range of *A. tvaerensis* is in the interval 407.8–420.0 m. *Eoplacognathus elongatus* is represented in the sample from 417.1 m. The index species *B. alobatus* and *B. gerdae* have been found respectively at 407.8–409.0 and 411.5 m.

CONODONT BIOSTRATIGRAPHY

Subsequently a short characterization of the *P. serra*, *P. anserinus*, *A. inaequalis*, and *A. tvaerensis* zones in Estonia is given.

The ***Pygodus serra* Zone** occurs in the Lasnamägi and Uhaku stages and has been identified in 10 of the 15 core sections studied. The index species is more

Fig. 6. Conodonts from the Kukruse Stage of the Abja, Kaagvere, Ohesaare, and Are cores. **A–I**, *Amorphognathus tvaerensis* Bergström; A, B, Abja core, depth 434.2 m: A, Pa element, GIT 549-38, ×100; B, Pb element, GIT 549-39, ×100; C–E, G–I, Abja core, depth 431.5 m: C, Pb element, GIT 549-40, ×80; D, Pb element, GIT 549-41, ×100; E, Pa element, GIT 549-42, ×70; G, Pa element, GIT 549-43, ×70; H, Pa element, GIT 549-44, ×80; I, Pa element, GIT 549-45, ×70; F, Abja core, depth 429.3 m; Pa element, GIT 549-46, ×80. **J–L**, **Q**, *Eoplacognathus elongatus* (Bergström); J–L, Kaagvere core: J, depth 304.2 m, Pa element, GIT 549-47, ×80; K, depth 302.6 m, Pa element, GIT 549-48, ×80; L, depth 294.5 m, Pb element, GIT 549-49, ×100; Q, Ohesaare core, depth 480.1 m, Pb element, GIT 549-50, ×45. **M**, **N**, **R**, *Baltoniodus gerdae* (Bergström); M, N, Kaagvere core, depth 298.2 m: M, Pb element, GIT 549-51, ×80; N, Pa element, GIT 549-52, ×55; R, Are core, depth 298.5 m, Pa element, GIT 549-53, ×55. **O**, *Pygodus anserinus* (Lamont & Lindström), Kaagvere core, depth 312.0 m, Pa element, GIT 549-54, ×100. **P**, *Eoplacognathus lindstroemi* (Hamar), Ohesaare core, depth 489.8 m, Pa element, GIT 549-55, ×55. **S**, *Periodon aculeatus* Hadding, Ohesaare core, depth 489.9 m, Sb element, GIT 549-56, ×80.

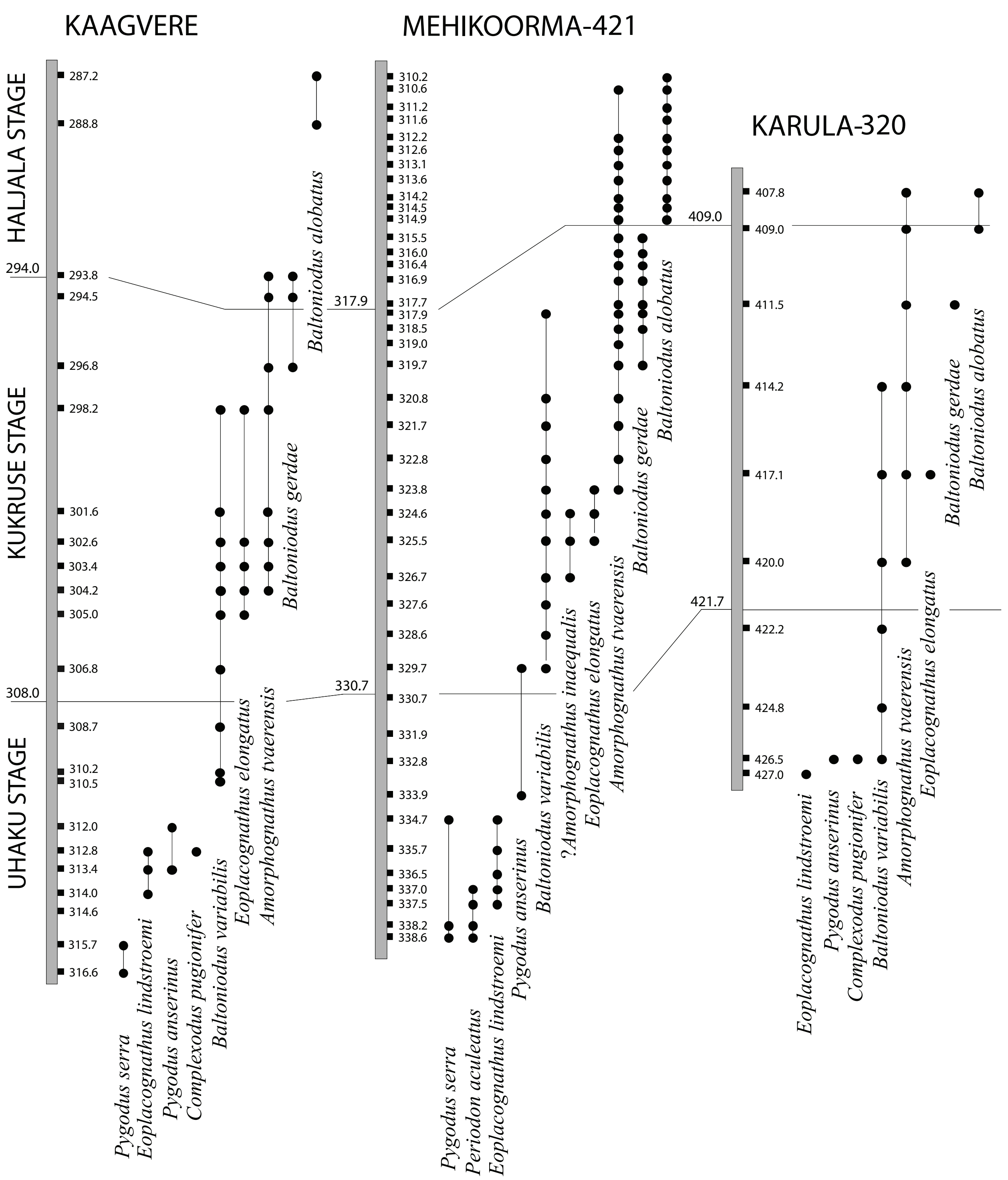


Fig. 7. Ranges of selected conodonts in the Kaagvere, Mehikoorma-421, and Karula-320 cores. Depth in metres.

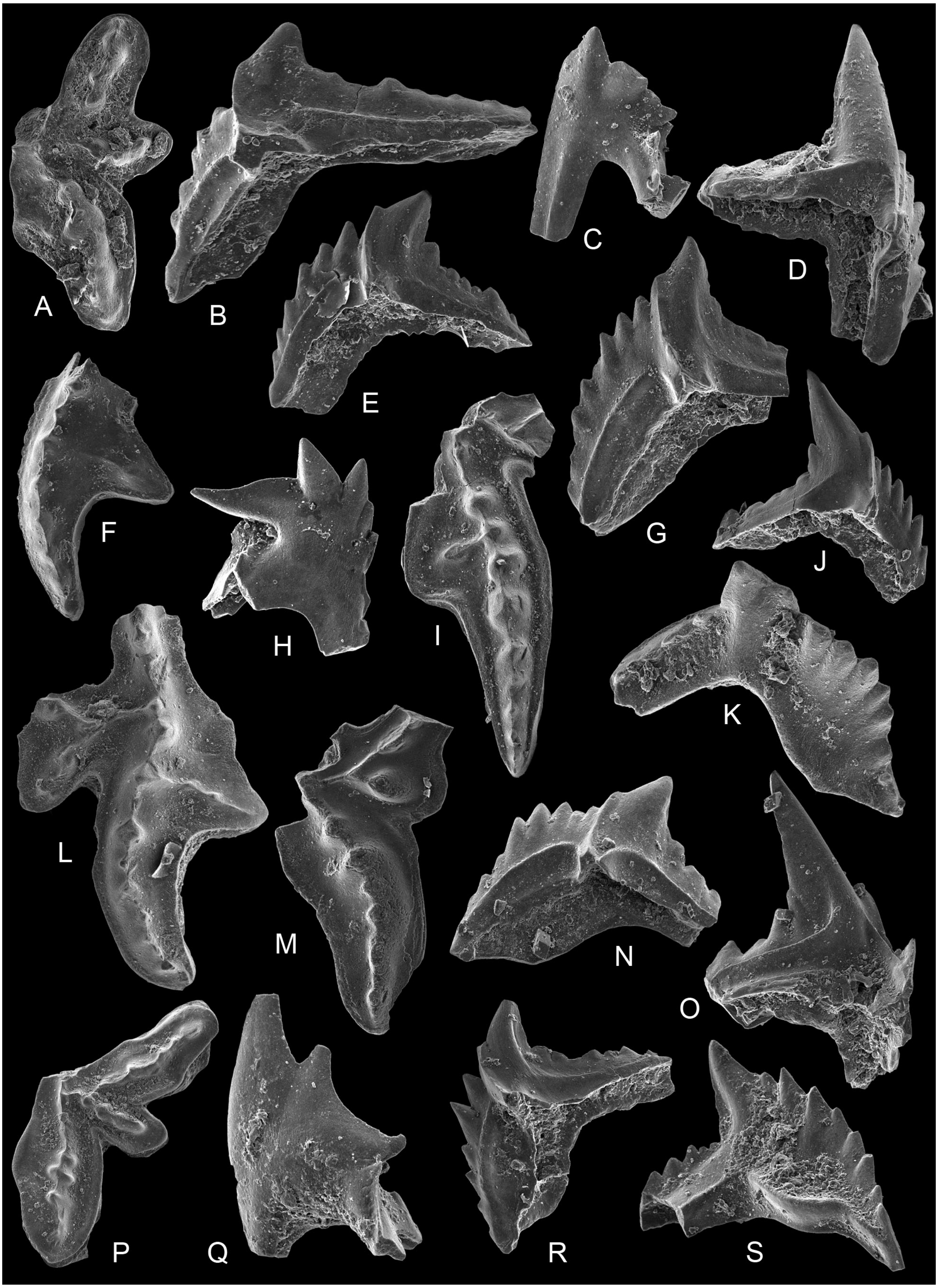
frequent in the Ohesaare and Ruhnu cores of southwestern Estonia, in three and six samples, respectively. In eight cores the *P. serra* Zone is represented by only one or two samples and in five core sections it has not been found at all. Three of the latter sections (Taga-Roostoja, Kerguta, and Äiamaa) are situated in northern Estonia. *Eoplacognathus lindstroemi* has been found in many cores in the upper part of this zone. Its range often extends to the lower part of the *P. anserinus* Zone. *Eoplacognathus lindstroemi* in the *P. anserinus* Zone in Estonia is probably of a morphotype like that described by S. Bergström as "a type present in the lower part of the *P. anserinus* Zone elsewhere" (Pålsson et al. 2002, p. 46). *Sagittodontina kielcensis* is found in the boundary interval of the *P. serra* and *P. anserinus* zones in the Mehikoorma, Ruhnu, and Valga core sections.

The ***Pygodus anserinus* Zone**, as well as the *Amorphognathus tvaerensis* Zone and its subzones, were first recognized by Bergström (1971, 2007a) at Fjäcka, south-central Sweden. In Estonia the *P. anserinus* Zone occurs in the upper part of the Uhaku Stage. The longest ranges of the zonal species have been detected in four samples of the Ruhnu core and in six samples of the Tartu core. Besides, *P. anserinus* has been found in five cores of southern Estonia – Seliste, Häädemeeste, Abja, Viljandi, and Karula, in 1–2 samples in each section. This species has not been found in northern Estonia and in an interval of 7 m of the Viru mine section. Although *P. anserinus* has not been identified in some sections in southern Estonia partly due to too sparse sampling, its complete absence in northern Estonia may rather be due to the occurrence of a specific facies of kerogenous, kukersite-bearing argillaceous limestones in that region. The *P. anserinus* Zone has been subdivided into two subzones since the first establishment of the Middle–Upper Ordovician conodont zonation in Europe (Bergström 1971). The lower subzone was distinguished by the presence of *B. prevariabilis* and the upper by *B. variabilis.* Later these species were replaced by *A. kielcensis* as the index species for the lower part and by *A. inaequalis* for the upper part (Bergström 1983). In Estonia, *A. inaequalis* has been identified in the Kukruse Stage of the Ruhnu and Mehikoorma cores (Männik 2003; Männik & Viira 2005). The zonal species *P. anserinus* itself has never been found in the Kukruse Stage, except for the Mehikoorma core. As discussed below, *A. inaequalis* is morphologically close to *A. tvaerensis*, belongs to the same evolutionary lineage, and is consequently very suitable as a zonal index. Therefore I prefer to return to the zonal scheme of Dzik (1978) where the ***A. inaequalis* Zone** was positioned between the *P. anserinus* and *B. variabilis* (appearance of *A. tvaerensis*) zones.

The index species of the ***Amorphognathus tvaerensis* Zone** in the Kohtla outcrop section and all core sections (except Kerguta) has a stratigraphical range extending from the lower part of the Kukruse Stage to some level in the Haljala Stage. Between the last occurrence of *P. anserinus* and the first find of *A. tvaerensis* there is an interval without any of these index species. The thickness of this interval in Estonian sections increases from deeper-water sediments in southern Estonia to shallow-water sediments in northern Estonia. In the southern Ohesaare, Ruhnu, and Häädemeeste drill cores the first *A. tvaerensis* appears 2–3 m above the occurrence of *P. anserinus*. In all other northward cores where *P. anserinus* has been identified the interval between the two species is 4.5–7.8 m. Obviously the change in the thickness of the interval is caused by the decrease in *P. anserinus* finds towards the area of kukersite (oil shale) deposits in northeastern Estonia. No such "barren" interval has been recorded in the Fågelsång stratotype section of Sweden (Bergström et al. 2000; Bergström 2007b).

The first specimens of *A. tvaerensis* in core sections are found in the lower or middle part of the Kukruse Stage, probably depending on sampling density. However, one circumstance should be kept in mind, which became evident in the study of the Kohtla outcrop section, where much larger samples than from the cores were taken from all layers. At Kohtla the first rare specimens appeared in the lower part of the Kukruse Stage (in bed A/B); more numerous specimens were only found higher up, above bed G (Viira et al. 2006a). The first occurrences in core sections often remain undiscovered due to too low sampling density or too small sample sizes.

All three subzones of the *A. tvaerensis* Zone are represented in Estonia. The index species of the lower subzone *Baltoniodus variabilis* has been found in the upper part of the Uhaku Stage and in the Kukruse Stage. The *B. variabilis* Subzone is represented by the upper range of the index species. *Baltoniodus variabilis* has been identified in all studied sections and is the most numerous of all conodont taxa, especially in the Uhaku and Kukruse stages. In many sections *B. variabilis* first appears at different levels in the Uhaku Stage, usually 6–10 m or even more below the first appearance of *A. tvaerensis*. In the Valga, Mehikoorma, and Ruhnu drill cores its first appearance coincides approximately with the boundary between the Uhaku and Kukruse stages (Männik 2001, 2003; Männik & Viira 2005). As a rule, the replacement of *B. prevariabilis* by *B. variabilis* is transitional and, therefore, this level is difficult to establish (Dzik 1978; Männik 2003; Viira et al. 2006a). Moreover, the specimens of the taxonomically important Pa element of these two species are often broken and hardly possible to distinguish from each other. In the Ordovician conodont zonation the *B. variabilis* Subzone is placed in the lower part of the *A. tvaerensis* Zone, where all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elements of the index species of the subzone, *B. variabilis*, are usually advanced enough to be clearly distinguishable from those of its ancestor *B. prevariabilis*. *Baltoniodus variabilis* probably disappears in connection with the first appearance of *B. gerdae* in all studied sections, except for Mehikoorma, where the ranges of *B. variabilis* and *B. gerdae* overlap (Männik & Viira 2005). The *B. gerdae* and *B. alobatus* subzones have been established in almost all studied cores, with the best representation in the Mehikoorma core. *Eoplacognathus elongatus* appears before or at the level of the first appearance of *A. tvaerensis*, which helps to characterize this zone. The last specimens of *A. tvaerensis* are found in the Haljala Stage, often in the *B. alobatus* Subzone, or disappear even lower, in the middle of the *B. gerdae* Subzone.

In addition to the index species, the long-ranging species *Semiacontiodus carinatus* Dzik, which was described and illustrated by Viira et al. (2006a), is quite numerous in the studied interval. This species has been identified under different names from the published drill cores: as *S. cornuformis* in the Tartu, Valga, and Taga-Roostoja cores, as *S.* ex gr. *cornuformis* in the Ruhnu core, and as *Semiacontiodus* spp. in the Mehikoorma core (Põldvere et al. 1998; Männik 2001, 2003; Männik & Viira 2005; Viira & Männik 1999). At some levels in the Uhaku Stage *Panderodus sulcatus* (Fåhraeus) is quite numerous. Besides this species, *P.* ex gr. *panderi* (Stauffer) has been identified in the Ruhnu, Mehikoorma, and Valga cores, *P.* ex gr. *equicostatus* (Rhodes) in the Valga and Ruhnu cores, and *Panderodus* sp. A in the Tartu core. Single specimens of *Complexodus pugionifer* have been found on different levels of the Uhaku Stage at least in six cores.

AMORPHOGNATHUS INAEQUALIS AND *A. TVAERENSIS* IN ESTONIA

Amorphognathus inaequalis was first described in the format of a Pa element from the Golden Groove Quarry, South Wales, Great Britain (Rhodes 1953). From the same locality also *B. prevariabilis* has been identified (Bergström & Orchard 1985). *Amorphognathus inaequalis* is also known from other localities in South Wales: the Ffairfach railway cutting in the type section of the Ffairfach Group, the Bryn-banc Quarry in the Narberth area, and at Nantgaredig east of Carmarten (Bergström 1964, 1971; Bergström & Orchard 1985; Bergström et al. 1987). Together with *A. inaequalis*, *E. lindstroemi* and *B. prevariabilis* have been found in the Ffairfach railway cutting, *A. tvaerensis*, *E. elongatus*, and *B. variabilis* in the Bryn-banc Quarry, and *B. variabilis* has been recognized at Nantgaredig. It is worth mentioning that Bergström et al. (1987, p. 305) identified *A. inaequalis* and *A. tvaerensis* together in the Bryn-banc Quarry of Wales. Lindström et al. (1974) described and illustrated the first multielement apparatus of *A. inaequalis* with amorphognathiform, ambalodiform, and holodontiform (Pa, Pb, M) elements from the Postolonnec Formation of the Armoricain Massif, Brittany, France. These authors noted that *A. inaequalis* is undoubtedly transitional to *A. tvaerensis* and the differences are mainly in the amorphognathiform (Pa) elements; the inner lateral lobes are more strongly developed in *A. tvaerensis*. The holodontiform (M) elements of *A. inaequalis* have a more regular denticulation and a smaller cusp than those of *A. tvaerensis*. As Bergström et al. (1987) noted, the distinction between *A. tvaerensis* and *A. inaequalis* is mainly in the appearance of the M element. Besides Wales and Brittany, France, *A. inaequalis* has been recognized in Poland, where Dzik (1976) found three elements from the Mojcza Limestone samples A-6 and A-7. The biostratigraphical position of the *A. inaequalis* Zone, erected by Dzik (1978), was between the *P. anserinus* and *B. variabilis* zones. Bergström (1983) changed the rank of the *A. inaequalis* Zone to be the upper subzone of the *P. anserinus* Zone. Later Dzik (1994) changed his opinion about his Polish specimens of *A. inaequalis* and preferred to attribute them to *A. tvaerensis*, as an early form. In Estonia P. Männik has identified *A. inaequalis* in the Ruhnu and Mehikoorma cores directly before the appearance of *A. tvaerensis* (Männik 2003; Männik & Viira 2005). In other Estonian sections where *A. inaequalis* has not been recognized, specimens similar to the M element of *A. inaequalis* have been found, for example, in the Kaagvere core, where they were identified as early specimens within the range of *A. tvaerensis*.

Fig. 8. *Amorphognathus tvaerensis* Bergström from the Kukruse Stage of the Kaagvere core. **A**, **B**, depth 304.2 m; A, Pa element, GIT 549-1, ×55; B, Pb element, GIT 549-2, ×100. **C**, **D**, **E**, depth 303.4 m; C, M element, GIT 549-3, ×100; D, Pb element, GIT 549-4, ×100; E, Pb element, GIT 549-5, ×100. **F**, depth 302.6 m, Pa element, GIT 549-6, ×100. **G**, depth 301.6 m, Pb element, GIT 549-7, ×100. **H–K**, depth 298.2 m; H, M element, GIT 549-8, ×130; I, Pa element, GIT 549-9, ×100; J, Pb element, GIT 549-10, ×100; K, Pb element, GIT 549-11, ×100. **L–O**, depth 296.8 m; L, Pa element, GIT 549-12, ×100; M, Pa element, GIT 549-13, ×100; N, Pb element, GIT 549-14, ×100; O, Pb element, GIT 549-15, ×100. **P–S**, depth 294.5 m; P, Pa element, GIT 549-16, ×55; Q, M element, GIT 549-17, ×130; R, Pb element, GIT 549-18, ×100; S, Pb element, GIT 549-19, ×100.

In the studied sections the specimens of *A. tvaerensis* (particularly its Pa and M elements) are highly variable in all samples. The elements of *A. tvaerensis* also demonstrate the variability in the morphology of this species from its appearance until the end of its range. Due to the variable morphology of *A. tvaerensis* during its stratigraphic range, at least three successive morphotypes of this species can be distinguished. The first morphotype, low in the range of *A. tvaerensis*, is similar to *A. inaequalis*. For example, the M element of *A. tvaerensis* found at a depth of 303.4 m in the Kaagvere core (Fig. 8C) has a large straight denticle in the anterior part of the oral denticle row, similar to the M element of *A. inaequalis* in Bergström et al. (1987, pl. 18.1, fig. 10) and that of *A. tvaerensis* early form in Dzik (1994, pl. 22, fig. 8). The second morphotype with a very characteristic posteriorly directed denticle in the M element occurs in the middle part of the *A. tvaerensis* range. Such specimens come from the sample at 298.0 m of the Kaagvere core (Fig. 8H) and samples at 474.8 and 475.8 m of the Ohesaare core (Fig. 5E). The third morphotype of late specimens of *A. tvaerensis* is characterized by an orally directed large denticle in the anterior part and occurs on the level of the *B. gerdae* range. This type of the M element has been found at 294.5 m in the Kaagvere core (Fig. 8Q) and at 471.8 m in the Ohesaare core (Fig. 5K). Special morphological studies are needed to find more criteria for distinguishing between these morphotypes.

CORRELATION WITH THE FÅGELSÅNG AND MIDDLE–UPPER ORDOVICIAN BOUNDARY

In the Fågelsång locality conodonts occur sparsely on shale surfaces and more numerously on two specific levels (Bergström et al. 2000; Bergström 2007a). The first level is the so-called Hadding's conodont bed with a relatively diverse conodont fauna typical of the *Pygodus serra* Zone. The second is a thin limestone bed just beneath the Fågelsång Phosphorite. It has yielded conodonts of the upper part of the *P. anserinus* Zone: *Baltoniodus variabilis*, *Complexodus pugionifer*, *Periodon aculeatus*, and *Cahabagnathus sweeti*. *Amorphognathus tvaerensis* occurs on shale bedding-planes a few centimetres above the Fågelsång Phosphorite. The graptolite *Nemagraptus gracilis* appears about 1.4 m below the Fågelsång Phosphorite in the *P. anserinus* range interval. *Amorphognathus inaequalis* has not been identified in the stratotype section and morphological details of the *A. tvaerensis* elements there are not known.

Judging by the Fågelsång section, the Middle–Upper Ordovician boundary should be lower than the first appearance of *A. tvaerensis* and *B. variabilis* (Bergström et al. 2000; Bergström 2007b). In the Kohtla section *A. tvaerensis* appears at the beginning of the Kukruse Stage. Therefore the contact between the Middle and Upper Ordovician has been placed at the lower boundary of the Kukruse Stage or even in the upper part of the Uhaku Stage (Viira et al. 2006a). In all studied Estonian core sections *A. tvaerensis* first appears in the lower part of the Kukruse Stage. Consequently, this boundary in all these sections could as well be placed at the lower boundary of the Kukruse Stage. In the Ruhnu and Mehikoorma cores where *A. inaequalis* has been identified, the Middle–Upper Ordovician boundary is at the level of the first appearance of that species, which again is approximately the lower boundary of the Kukruse Stage. Such a position of the series boundary in Estonia seems to fit also with the data by Bergström (2007b, fig. 5). In the biostratigraphic scheme of the present investigation the rank of the *A. inaequalis S*ubzone is changed to the *A. inaequalis Z*one (Fig. 2), which means returning to the original denomination of this interval between the *P. anserinus* and *A. variabilis* zones (Dzik 1978). It is taken into consideration that *A. inaequalis* and an early morphotype of *A. tvaerensis* may be conspecific.

To sum up, the best position for the Middle–Upper Ordovician boundary in Estonia is at the lower boundary of the Kukruse Stage, because it lies below the *A. tvaerensis* Zone or even below the *A. inaequalis* Zone. This is in accordance with the type locality at Fågelsång in Sweden.

CONCLUSIONS

The base of the Upper Ordovician Series is defined by graptolites. In successions without graptolites, this level can be correlated by conodonts.

In this paper the distribution of conodonts within the *Pygodus serra*, *P. anserinus*, *Amorphognathus inaequalis*, and *A. tvaerensis* zones was considered on the basis of 2 outcrop and 15 drill core sections of Estonia. The replacement of *Baltoniodus prevariabilis* by *B. variabilis* is successive and difficult to establish, and is therefore considered unsuitable for the definition of the Middle–Upper Ordovician boundary. The morphology of *A. tvaerensis* changes successively through its range. The morphotype in the lowermost part of the *A. tvaerensis* range is similar to *A. inaequalis*. It is proposed to change the denomination of the *A. inaequalis* Subzone to the *A. inaequalis* Zone.

The appearance of early *A. tvaerensis* or of *A. inaequalis* in the lowermost Kukruse Stage is undoubtedly very close to the base of the Upper Ordovician. Therefore, the best level for the Middle–Upper Ordovician boundary in Estonia is at the base of the Kukruse Stage.

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Konodontide biostratigraafia Eesti Kesk- ja Ülem-Ordoviitsiumi piirikihtides

Viive Viira

Kahes paljandis ja 15 puuraugus on jälgitud konodontide levikut Uhaku lademe ülemises osas, Kukruse lademes ja Haljala lademe alumises osas. On kindlaks tehtud *Amorphognathus tvaerensis*'e morfoloogiline mitmekesisus ja kõige varajasema morfotüübi sarnasus *A. inaequalis*'ega. On tehtud ettepanek muuta konodondi tsonaalses skeemis *A. inaequalis*'e alamtsoon *A. inaequalis*'e tsooniks. Parimaks Kesk- ja Ülem-Ordoviitsiumi stratigraafilise taseme piiriks on Kukruse lademe alumine piir.