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Conodont biostratigraphy of the Oandu Stage (Katian, Upper Ordovician) in NE Estonia

Peep Männik

Institute of Geology at Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia; peep.mannik@ttu.ee

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Abstract. Conodonts from the type region of the Oandu Stage (Katian, Upper Ordovician) in NE Estonia were studied. Here, the lower boundary of the stage corresponds to a discontinuity surface at the base of the Hirmuse Formation and, in conodont succession, is marked by the disappearance of *Semiacontiodus* sp. and *Besselodus*? sp. The most characteristic taxa of the Oandu Stage are *Phragmodus undatus*, *Icriodella* cf. *superba* and *Plectodina* sp., which are rare or missing below and above this stratigraphic interval in Estonia. The comparison of conodont faunas from North and South Estonia suggests that the strata in North Estonia correspond to the upper part of the Oandu Stage only as identified in sections in South Estonia. However, the position of the lower boundary of the stage in South Estonia is highly problematic. The boundary between the *Amorphognathus tvaerensis* and *A. superbus* conodont zones in Estonia lies within the (upper) Oandu Stage.

Key words: conodonts, biostratigraphy, Oandu Stage, Katian, Upper Ordovician, Estonia.

INTRODUCTION

The strata corresponding to the nowadays Oandu Stage were first described as *Hemicosmites*-limestone (‘Hemicosmitenkalk von Wassalem’) from the Vasalemma region by Eichwald (1854) and later referred to as the Vasalemma Bed (‘Wasalemm’sche Schicht’) by Schmidt (1881). Because of the geographically limited distribution area of these rocks, they were treated in general as part (a specific facies) of the Keila Stage until the 1930s. Öpik (1934) described an interval of claystone and marlstone from eastern North Estonia and called it the Oandu Beds. He found that these strata were a time-equivalent of the Vasalemma and Saku facies occurring in western North Estonia and proved that a distinct unit, represented by a specific set of rocks (facies), existed between the Keila and Rakvere stages. Later, this unit was mainly treated as the Vasalemma Stage or as the upper part of the combined Keila–Vasalemma Stage. Based on a much wider geographical distribution of the Oandu marlstone than of the Vasalemma limestone, Männil (1958) suggested to rename the stage as Oandu Stage, with its stratotype on the Oandu River in eastern North Estonia.

Two different lithofacies characterize the Oandu Stage in North Estonia. In the western part of the region, in the Saku area (Fig. 1), the stage is represented by the Saku Member of the upper Vasalemma Formation (Fig. 2; Ainsaar & Meidla 2001; Kröger 2014a). The unit is composed of bioclastic and reefal limestone. To the east of that region, the main part of the Oandu Stage consists of various marlstone and argillaceous limestone comprising the Hirmuse Formation (Fig. 2). The uppermost part of the stage is represented by fine-grained bioclastic wackestone of the Tõrremägi Member of the lower Rägavere Formation (Põlma et al. 1988). In Central Estonia the Oandu Stage is considered to correspond to the middle part of silty marlstone and siltstone of the Variku Formation, in southern Estonia to calcareous marlstone of the middle Mossen Formation (Meidla et al. 2014). However, biostratigraphically the stage is poorly constrained in these regions (Ainsaar et al. 1999; Põldvere 2003, 2005).

The lower boundary of the Oandu Stage in its type region coincides with the base of the Hirmuse Formation and is marked by a prominent pyritized discontinuity surface. Earlier studies have revealed distinct changes in lithology and in the composition of several groups of fossils at this level (Rõõmusoks 1970; Põlma et al. 1988; Meidla 1996; Ainsaar et al. 1999). According to Hints et al. (1989), in the faunal succession it is the most remarkable boundary in the Post-Tremadocian Ordovician sections of the East Baltic. The upper boundary of the stage in the region is also marked by a discontinuity

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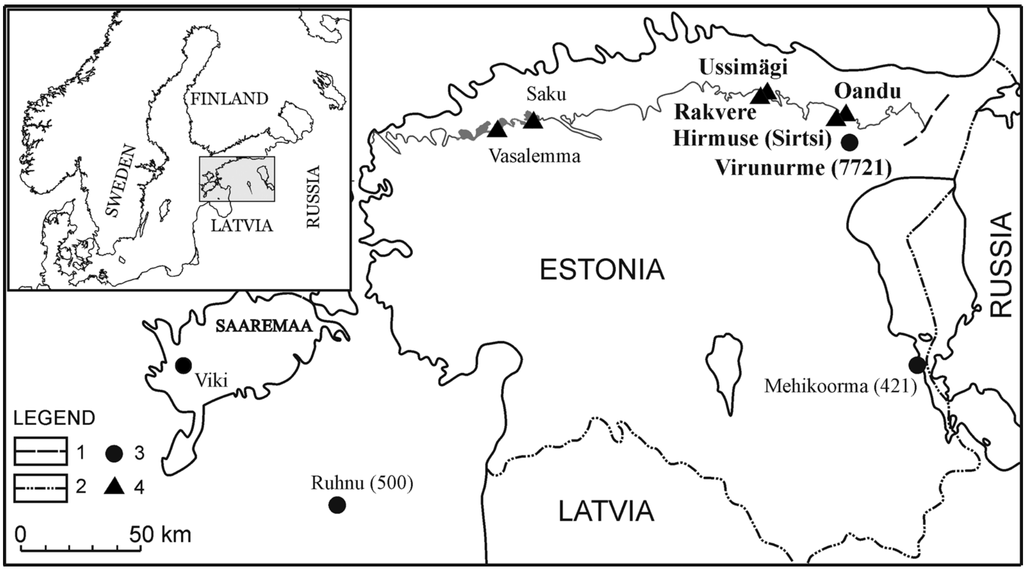


Fig. 1. Location of the sections discussed or referred to in the text. Names of the sections from where conodonts were analysed during this study are in bold. Legend: 1, fault; 2, state boundaries; 3, core section; 4, outcrop section. The grey line corresponds to the outcrop belt of the strata of Oandu age (after *Bedrock Geological Map of Estonia*, Geological Survey of Estonia 2007).

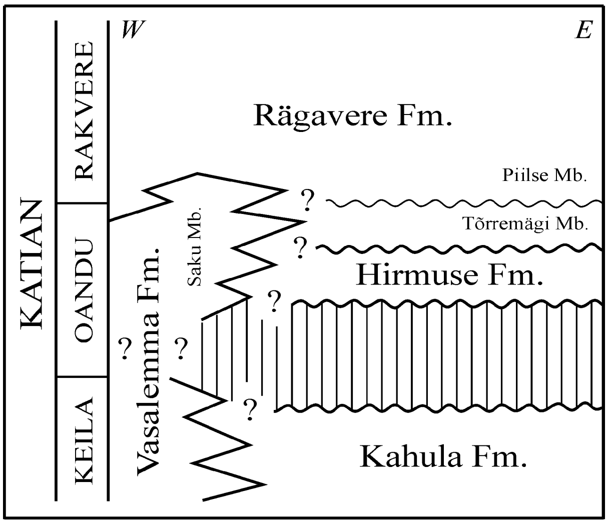


Fig. 2. Stratigraphy of the upper Keila, Oandu and lower Rakvere stages in North Estonia (modified from Ainsaar et al. 2004 and Kröger et al. 2014b). In this paper, the term 'Stage' is used in traditional for Estonia sense (e.g. Meidla et al. 2014). In Estonia, the stages are distinguished based on their content (characteristic lithology and faunas) and, as a rule, no boundary stratotypes are defined. From left to right: global stage; regional stage; probable relationship of formations and members on the western–eastern transect. Wavy lines correspond to discontinuity surfaces, vertical ruling to a gap (precise duration unknown). Question marks indicate that lateral relationships of units and the position of their boundaries are problematic. Abbreviations: *W*, West; *E*, East; Fm., Formation; Mb., Member.

surface. It coincides with the boundary between the Tõrremägi and Piilse members of the Rägavere Formation but is poorly defined biostratigraphically (Meidla 1996).

Although some faunas from the Oandu Stage in its type region are well known, the biostratigraphical correlation of this succession with sections representing other environments (e.g. reefs in the Vasalemma and Saku region; sections in southern Estonia and Central Baltic) is problematic. Problems result from differences in the composition of faunas caused by their different habitats. Additionally, sections in southern Estonia are more complete; the gaps at the stage boundaries become shorter and, towards the central part of the Palaeobaltic basin, the beds missing in the outcrop area gradually fill them. As a result, distinct changes in the faunal succession observed at the lower boundary of the stage in North Estonian sections are gradual here and there exist different possibilities of tracing the boundary in the same section (e.g. compare Meidla 2003 and Nõlvak 2003; Hints et al. 2016).

The composition and distribution of conodonts in the Oandu Stage, particularly in the succession of the type region of the stage, are poorly known. Preliminary studies of conodonts from the old Saku quarry revealed quite specific faunas from the Saku Member characterized by *Aphelognathus*? sp., *Icriodella superba*, *Phragmodus undatus* and *Plectodina* sp. (Viira 1974; Kröger et al. 2014b) which, however, are rare or not known in other sections in Estonia. In order to get a better idea about the composition of the conodont faunas in the Oandu Stage, to increase their biostratigraphical potential in this interval and to find additional criteria for the correlation of sections in different parts of the basin, five sections, located in the type region of the Oandu Stage or close to it, were sampled and processed for conodonts. The results of these studies are presented in this paper.

MATERIAL AND METHODS

This study is based on one core section, Virunurme (7721), and two outcrops, Oandu and Hirmuse, from the type region of the Oandu Stage (Fig. 1). Additionally, samples from two outcrop sections located in Rakvere (Ussimägi and Rakvere), a small town about 35 km west of the Oandu region, were studied. Samples were collected at different times and for different purposes. The samples marked as 'LH' from the lower part of the Ussimägi section were originally collected for the study of brachiopods. The main, argillaceous component of these samples was washed out using quite rough methods. Most probably, also some conodonts were lost during this process. Only calcareous leftovers of these samples, mainly small limestone nodules, were processed for conodonts. All conodont samples were dissolved in buffered acetic acid. After this procedure, residues were treated with buffered formic acid (following the method by Jeppsson & Anehus 1995) to dissolve dolomite. Insoluble residues were washed using the decanting method (no sieving) and fractionated in heavy liquid after drying at room temperature. In total, 32 samples of 0.3–0.5 kg from the Virunurme (7721) core section and 21 samples from the outcrop sections (among them 10 consisting of leftovers of brachiopod samples, weights not known), with the weight mainly from 2.4 to 4.3 kg (those from the Hirmuse section 10 and 13.8 kg), were processed for conodonts. All samples were productive. The preservation of the specimens is variable, whereas many are broken. Better-preserved specimens come from the cryptocrystalline limestone of the Rägavere Formation. The colour of conodonts is pale yellow (CAI = 1 of Epstein et al. 1977). The illustrated specimens are housed in the Institute of Geology at Tallinn University of Technology, Estonia (collection number GIT 753); the core is not preserved.

DISTRIBUTION OF CONODONTS

Virunurme (7721) core section

The sampled interval, from 17.00 to 23.90 m, corresponds (from below) to the upper Kahula, Hirmuse and lower Rägavere formations, to the upper Keila, Oandu and lower Rakvere stages (Fig. 3). The Kahula Formation consists of argillaceous limestone (mainly wackestone). The Hirmuse Formation is dominated by various marlstone with nodules and rare interbeds of argillaceous limestone. The lowermost Rägavere Formation (Tõrremägi Member) is fine-grained, bioclastic wackestone and the upper part (Piilse Member) is composed of calcareous (lime-) mudstone (cryptocrystalline limestone).

Conodonts are most abundant in samples from the Kahula Formation. This interval is characterized by *Besselodus*? sp. (Fig. 4C, F–H) which, together with *Semiacontiodus* sp., disappears just below the boundary between the Kahula and Hirmuse formations. Most of the other taxa present in the formation extend into the Hirmuse Formation (Fig. 3) but, based on earlier information from other sections (Männik 2003, 2010; Männik & Viira 2005), these taxa appear below and reach the strata above the discussed interval. Few specimens of *Plectodina* sp. and *Phragmodus* cf. *undatus* appear in the uppermost part of the Kahula Formation. Both taxa are rare in the succession below and above the Oandu Stage in Estonia and occur sporadically in some intervals only (e.g. Männik & Viira 2005; Männik 2010).

The strata of the Hirmuse Formation were sampled almost bed by bed. This interval shows the practically continuous occurrence of *Ph. undatus* (Fig. 4B, J, K), *Icriodella* cf. *superba* (Fig. 4L) and *Panderodus panderi*. *Amorphognathus*, which is missing below this interval in the Virunurme (7721) core section, becomes quite common in the Hirmuse Formation. Unfortunately, it is mainly represented by fragments and cannot be identified at species level. However, in one sample from the middle part of the formation *A.* cf. *superbus* was identified. *Amorphognathus complicatus* (Fig. 4Q) appears almost at the same level but is more common in the uppermost part of the formation. Distinct faunal changes occur at the upper boundary of the formation or just above it, in the basal part of the Rägavere Formation (in the basal part of the Tõrremägi Member). Several taxa, including *I.* cf. *superba* and *Ph. undatus*, disappear in this interval in the Virunurme (7721) core section. But, based on earlier data from other sections, most of these taxa reappear higher in the succession, although some of them (e.g. *Ph. undatus*) are very rare in the strata above the interval discussed in this paper (Männik 2003, 2010; Männik & Viira 2005).

The disappearance of taxa at the base of the Rägavere Formation is evidently caused by lithological changes: at this level marlstone of the Hirmuse Formation is replaced by fine-grained bioclastic wackestone and calcareous mudstone of the Tõrremägi Member) (Fig. 3). Conodonts are known to be rare in pure calcareous mudstone (cryptocrystalline limestone). However, larger samples of mudstone processed from the Piilse Member

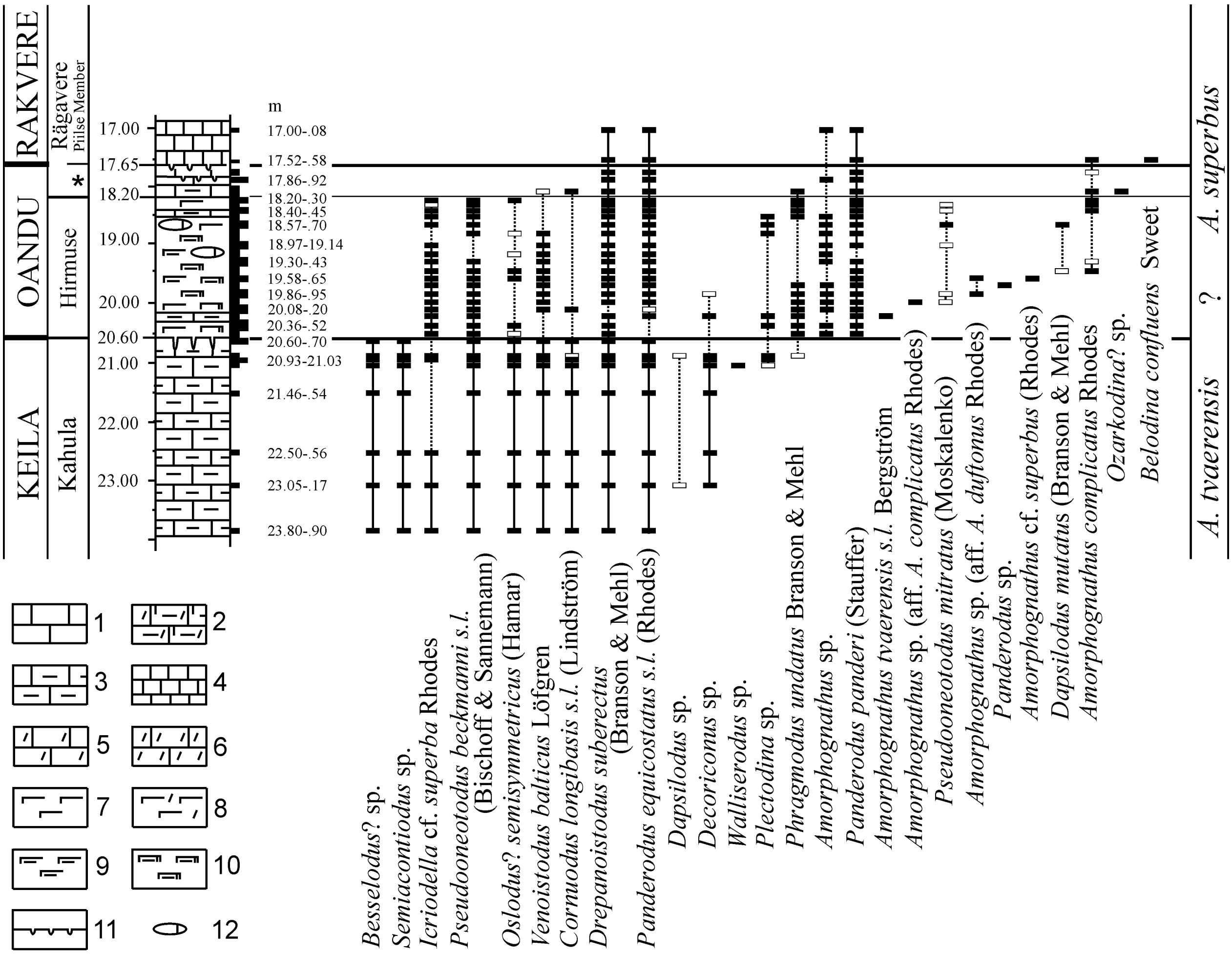
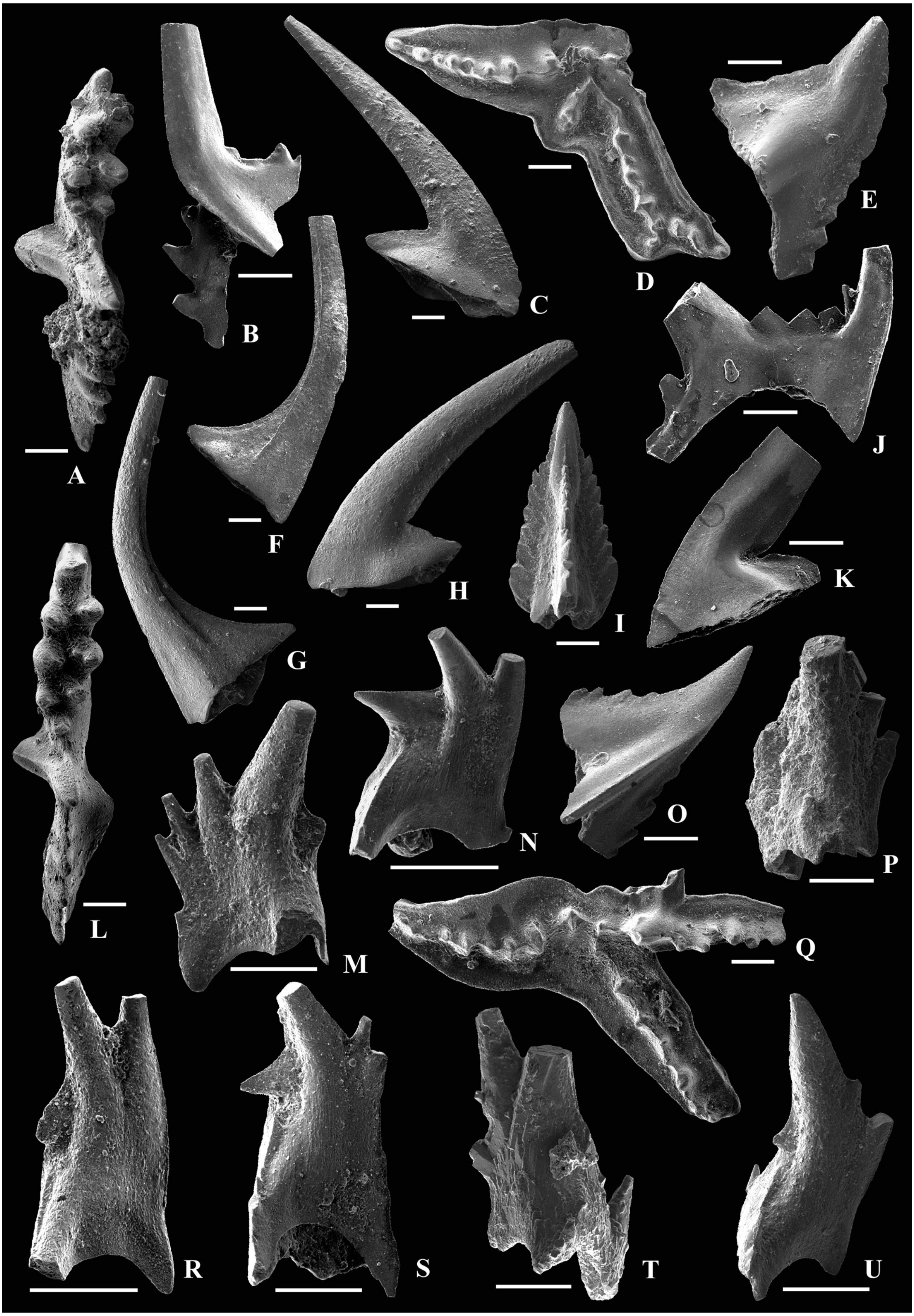


Fig. 3. Distribution of conodonts in the Virunurme (7721) core section. From left to right: stage; formation (* in the lower part of the Rägavere Formation indicates the interval of the Tõrremägi Member); depth; lithological log; samples and their intervals (in the uppermost Keila and Oandu stages only every second one is indicated); distribution of conodonts (black boxes – reliable identifications, white boxes – problematic identifications); conodont zones. Legend for Figs 3 and 6–8: 1, limestone (wackestone and packstone); 2, dolomitic argillaceous bioclastic limestone (wackestone and packstone); 3, argillaceous limestone (wackestone and packstone); 4, cryptocrystalline limestone (calcareous mudstone); 5, bioclastic limestone (packstone); 6, bioclastic limestone (grainstone); 7, calcareous marlstone; 8, calcareous marlstone with rare bioclastic material; 9, argillaceous marlstone; 10, dolomitized argillaceous marlstone; 11, pyritized discontinuity surface; 12, limestone nodule.

Fig. 4. Selected conodonts from the Virunurme (7721) and Ussimägi sections. As positional homology of elements in an apparatus has been determined only for few taxa, traditional Pa, Pb, Pc, M, Sa, Sb, Sc notation introduced by Sweet & Schönlaub (1975) is followed here and also in Fig. 5. Scale bar represents 100 µm. **A**, **E**, **I**, **L**, **O**. *Icriodella* cf. *superba* Rhodes: A, L, Pa elements, GIT 753-1 and GIT 753-2; E, M element, GIT 753-3; I, Sa element, GIT 753-4; O, Pb(?) element, GIT 753-5. A, E, I, O from Ussimägi section: A and I from sample LH-13, E and O from sample LH-11; L from Virunurme (7721) core section, interval 19.69–19.82 m. **B**, **J**, **K**, *Phragmodus undatus* Branson & Mehl: B, Pb element, GIT 753-6; J, Sc(?) element, GIT 753-7; K, M element, GIT 753-8. All from Virunurme (7721) core section, interval 20.36–20.52 m. **C**, **F**–**H**, *Besselodus*? sp.: C, H, geniculate coniform elements, GIT 753-9 and GIT 753-10; F, G, coniform elements, GIT 753-11 and GIT 753-12. All from Virunurme (7721) core section, interval 22.50–22.56 m. **D**, *Amorphognathus* sp. (aff. *A. complicatus* Rhodes), Pa element, GIT 753-13. Virunurme (7721) core section, interval 19.95–20.08 m. **M**, **R**, **S**, **U**, *Amorphognathus* sp. (aff. *A. duftonus* Rhodes), M elements GIT 753-14, GIT 753-15, GIT 753-16 and GIT 753-17. M and R from Virunurme (7721) core section, interval 19.58–19.69 m; S and U from Ussimägi section, S from sample LH-13, U from sample LH-7. **N**, *Amorphognathus tvaerensis s.l.* Bergström, M element, GIT 753-18. Virunurme (7721) core section, interval 20.20–20.36 m. **P**, *Amorphognathus* cf. *superbus* (Rhodes), M element, GIT 753-19. Ussimägi section, sample M-347. **Q**, *Amorphognathus complicatus* Rhodes. Pa element, GIT 753-20. Virunurme (7721) core section, interval 18.40–18.45 m. **T**, holodontiform (M) element A Ferretti, Bergström & Barnes, GIT 753-21. Ussimägi section, sample M-347.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(Hirmuse section) revealed that also this type of rock yields taxonomically rich faunas.

The uppermost part of the studied section, the lower Piilse Member of the Rägavere Formation, includes only *Drepanoistodus suberectus*, *Pand. equicostatus s.l.*, *Pand. panderi* and *A. complicatus*. *Belodina confluens*, a conodont known to appear in the Rakvere Stage in Estonia (Männik & Viira 2012), has been found in the lowermost Piilse Member.

Oandu section

In this section, about 0.3 m of strongly argillaceous limestone (wackestone–packstone), very rich in various fossils (e.g. brachiopods, bryozoans, trilobites), is exposed. The single sample processed from this outcrop (2.6 kg) was collected in 1983. It yielded *Besselodus*? sp., *Cornuodus longibasis s.l.*, *D. suberectus*, *I.* cf. *superba*, *Oslodus*? *semisymmetricus*, *Semiacontiodus* sp., *Venoistodus balticus* and very rare specimens of *Dapsilodus* sp. This assemblage is similar to that occurring in the Kahula Formation in the lower part of the Virunurme (7721) core section (Fig. 3).

Hirmuse section

The samples were collected from this section in 2015, from the riverbed about 30 m downstream and 15 m upstream, respectively, of a bridge across the Hirmuse River in Sirtsi village. Here, some beds of the Piilse Member (Rägavere Formation), consisting of pyrite-rich (forms an irregular cloudy pattern in the rock) calcareous mudstone (cryptocrystalline limestone) with rare fine-grained bioclastic material, are exposed as extensive surfaces several square metres in size. The samples from this section are the largest processed for this study (10 and 13.8 kg) and yield exceptionally rich fauna for this kind of rock: *Amorphognathus* sp. (aff. *A. duftonus*) (Fig. 5K), *Cornuodus longibasis s.l.*, *D. suberectus*, *Decoriconus costulatus* Rexroad, *I.* cf. *superba* (Fig. 5M, R), *O.*? *semisymmetricus*, *Pand. equicostatus s.l.*, *Pand. panderi*, *Pand.* aff. *unicostatus*, *Protopanderodus liripipus* (Fig. 5O), *Pseudooneotodus beckmanni s.l.*, *Ps. mitratus* and *V. balticus*. Also, few specimens of *Aphelognathus*? sp. (Fig. 5C, G, I) and *Yaoxianognathus*? *tunguskaensis* (Fig. 5J), both extremely rare in Estonia, were found. The only other section in the region yielding *Aphelognathus*? sp. is the old Saku quarry (Kröger et al. 2014b). One specimen of *Y.*? *tunguskaensis* has been found also in the Ussimägi section.

Ussimägi section

In this outcrop section, located just east of the town of Rakvere, an about 2.9 m succession corresponding to the upper Hirmuse and lower Rägavere (Tõrremägi and lower Piilse members) formations was exposed in 1983, when the section was studied and sampled. At present the section is partly covered by soil.

The lowermost 1.10+ m of the section is represented by argillaceous and calcareous marlstone (with nodules of argillaceous limestone) of the Hirmuse Formation (detailed description of the section is available in Põlma et al. 1988). Eleven samples from this interval yield rich conodont faunas (Fig. 6). The most characteristic taxa of the Hirmuse Formation are *I.* cf. *superba* (Fig. 4A, E, I, O), *D. suberectus*, *Pand. equicostatus s.l.*, *Pand. panderi*, *C. longibasis s.l.* and *Amorphognathus* sp. The lowermost sample provided specimens of *Amorphognathus* that are preserved well enough to allow the recognition of *A. tvaerensis s.l.*, its upper morph, which in earlier publications (Männik 2003, 2010; Männik & Viira 2005) has been identified as *A. ventilatus*. *Plectodina* sp. has been identified in the upper half of the interval and *A. complicatus* (Fig. 5A) and *Pand.* cf. *serratus* appear in the uppermost Hirmuse Formation.

In the Tõrremägi Member of the lower Rägavere Formation, the number of specimens per sample drops considerably. Several taxa characteristic of the Hirmuse Formation below (e.g. *I.* cf. *superba*, *Plectodina* sp.) are missing here.

Fig. 5. Selected conodonts from the Virunurme (7721), Ussimägi and Hirmuse sections. Scale bar represents 100 μm. **A**, *Amorphognathus complicatus* Rhodes, Pa element, GIT 753-22. Ussimägi section, sample M-347. **B**, **F**, *Plectodina* sp.: B, Sc(?) element, GIT 753-23; F, Pa element, GIT 753-24. Both from Ussimägi section, sample LH-6. **C**, **G–I**, **P**, *Aphelognathus*? sp.: C, Sb element, GIT 753-25; G–I, Pa elements, GIT 753-26, GIT 753-27 and GIT 753-28; P, Pb element, GIT 753-29. C, G and I from Hirmuse section, sample C15-1; H from Virunurme (7721) section, interval 17.68–17.84 m; P from Ussimägi asection, sample M-347. **D**, **J**, *Yaoxianognathus*? *tunguskaensis* (Moskalenko), Sc(?) elements, GIT 753-30 and GIT 753-31. D from Ussimägi section, sample M-347; J from Hirmuse section, sample C15-1. **E**, *Protopanderodus* sp., GIT 753-32. Ussimägi section, sample M-347. **K**, *Amorphognathus* sp. (aff. *A. duftonus* Rhodes), M element, GIT 753-33. Hirmuse section, sample C15-1. **L**, holodontiform (M) element A(?) Ferretti, Bergström & Barnes, GIT 753-34. Hirmuse section, sample C15-1. **M**, **R**, *Icriodella* cf. *superba* Rhodes: M, M element, GIT 753-35; R, Pa element, GIT 753-36. Both from Hirmuse section, sample C15-1. **N**, **Q,** *Belodina confluens* Sweet: N, compressiform element, GIT 753-37; Q, eobelodiniform element, GIT 753-38. Both from Ussimägi section, sample M-346. **O**, *Protopanderodus* cf. *liripipus* Kennedy, Barnes & Uyeno, GIT 753-39. Hirmuse section, sample C15-1.


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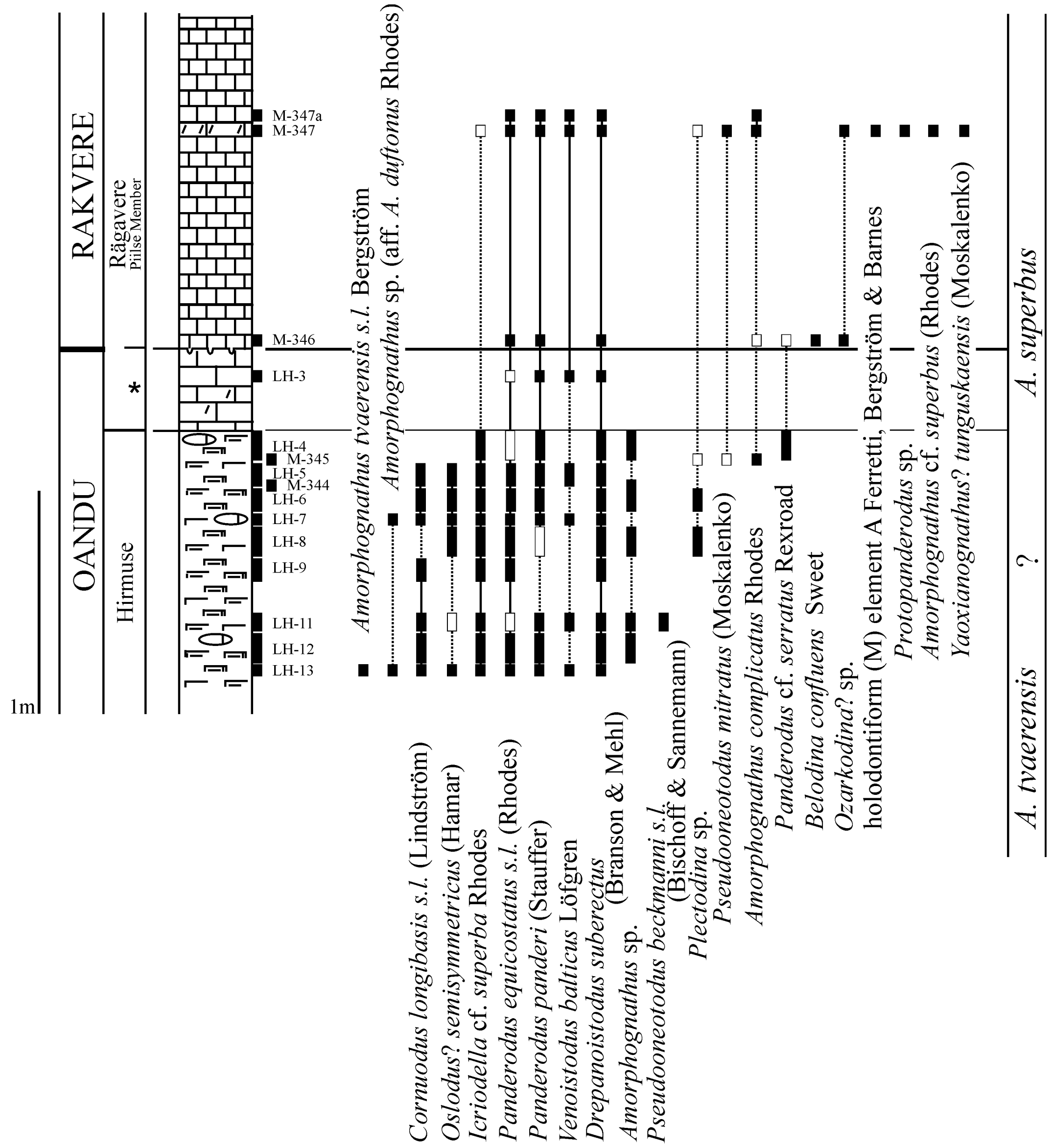

Fig. 6. Distribution of conodonts in the Ussimägi section. For the explanation and legend refer to Fig. 3. Just to the right of the log sample numbers are indicated instead of depths.

Three samples were processed from the Piilse Member. In the sample just above the lower boundary of the member there appear *Belodina confluens* (Fig. 5N, Q) and *Ozarkodina*? sp. Two samples from the upper part of the Piilse Member were taken from an almost the same level, from the interval where an about 3 m long and up to 10 cm thick lens of bioclastic packstone occurs in the calcareous mudstone (cryptocrystalline limestone) characteristic of the member. One of the samples (M-347, Fig. 6) comes from the bioclastic lens and the other (M-347a) from the mudstone. The number of specimens in the sample from the bioclastic rock exceeds that from the mudstone sample by almost 20 times. The number of taxa is also higher in the former sample. At this level, in addition to the taxa occurring already in the strata below, there appear *Protopanderodus* sp. (Fig. 5E), *A.* cf. *superbus* (Fig. 4P) and *Y.*? *tunguskaensis* (Fig. 5D).

Rakvere section

The section in a temporal ditch in the eastern part of the town of Rakvere was also studied and sampled in 1983. The exposed interval is almost identical to that in the Ussimägi section (Figs 6, 7). Three samples, each from a different unit, were processed. They yielded only taxa

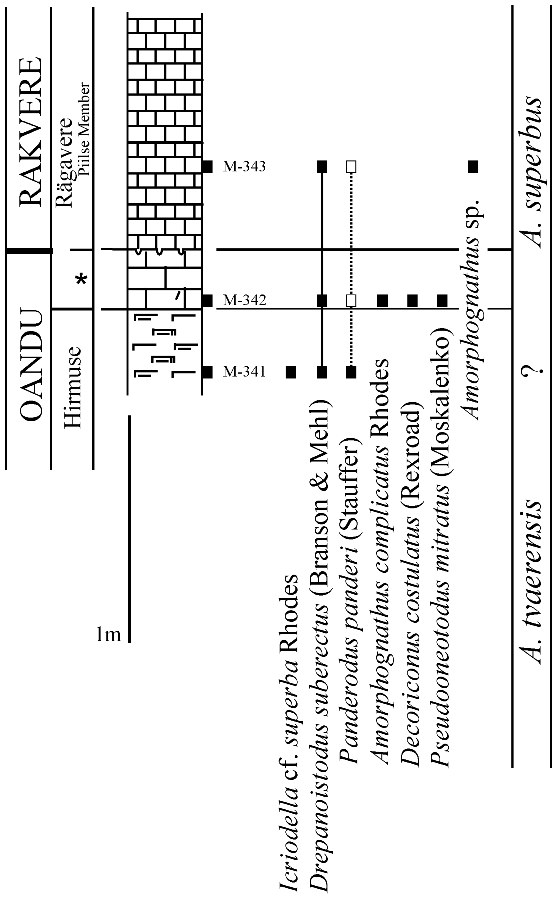

Fig. 7. Distribution of conodonts in the Rakvere section. For the explanation and legend refer to Fig. 3. Just to the right of the log sample numbers are indicated instead of depths.

most common in the stratigraphic interval discussed in this paper. As in the Ussimägi section, *I.* cf. *superba* is constrained to the Hirmuse Formation. The only identifiable specimen of *A. complicatus* in the Rakvere section was found in the lowermost Rägavere Formation (in the sample from the Tõrremägi Member).

DISCUSSION

The complete succession of the Oandu Stage, including also strata below and above it, was studied in the Virunurme (7721) core section (Fig. 3). The conodont assemblage of the stage is characterized by the (1) disappearance of *Semiacontiodus* sp. and *Besselodus*? sp. at the same level, just below the lower boundary of the stage, (2) continuous occurrence of *Amorphognathus* sp., *I.* cf. *superba*, *Pand. panderi* and *Ph. undatus* in (most part of) the stage and (3) appearance of *A.* cf. *superbus* and *A. complicatus* in the middle part of the stage (Figs 3, 6). *Amorphognathus* sp. and *Pand. panderi* are missing in the strata below the Oandu Stage (in the Kahula Formation); a probable specimen of *Ph. undatus* was found just below the lower boundary of the stage (Fig. 3). The number of specimens per sample, and conodont diversity, decrease in the upper part of the Oandu Stage, in the fine-grained bioclastic wackestone and calcareous mudstone of the Tõrremägi Member of the Rägavere Formation (Figs 3, 6). Still, as demonstrated by earlier data, most of the taxa disappearing in the studied sections at this level occur also higher in the succession (Männik 2003, 2010; Männik & Viira 2005). Conodonts become even more rare (the number of specimens per sample drops considerably) at the boundary between the Tõrremägi and Piilse members of the Rägavere Formation, at the upper boundary of the Oandu Stage. However, as data from the Hirmuse section (see above) suggest, poor faunas from the calcareous mudstone of the Piilse Member in most of the studied sections are caused by too small sizes of samples processed. Evidently, the accumulation of calcareous mud was much faster (and its compaction minimal? because of early cementation) than of other types of rocks. This is well demonstrated by two samples (M-347 and M-347a) from the Ussimägi section, one from calcareous mudstone of the Piilse Member containing rare conodonts and the other from a lens of bioclastic packstone with much richer faunas (Fig. 6; see above). A higher yield of conodonts in the latter sample evidently resulted from the condensation of sediment as the calcareous mud was washed out during the deposition of this bed.

The interval of the upper boundary of the Oandu Stage in the studied sections is poorly represented by conodonts, mainly because of too small samples. However, in both the Virunurme (7721) and Ussimägi sections, *Belodina confluens* appears in the lowermost Piilse Member, just above the boundary between the Oandu and Rakvere stages. So far, this conodont has been found only in the strata of Rakvere age or younger (Männik & Viira 2012).

The conodont zonation in the Upper Ordovician is mainly based on the evolutionary lineage of *Amorphognathus*. Previous studies have shown that there is an interval corresponding to the upper Haljala and Keila, but probably also to the lowermost Oandu stages in Estonia where *Amorphognathus* is extremely rare or missing (Männik 2003, 2010; Männik & Viira 2005). In sense of conodont biostratigraphy, this interval corresponds to the middle part of the *A. tvaerensis s.l.* conodont Zone and has been referred to as the 'Mid-Caradoc Event' in some earlier publications (Männik 2003, 2004; Männik & Viira 2005).

In the Virunurme (7721) core section *Amorphognathus* appears and is continuously present in most part of the Oandu Stage (Fig. 3). However, mainly because of the rare occurrence of the diagnostic M element, the identification of its species is mostly not possible. Still, the finds of identifiable *A. tvaerensis s.l.* in the lower Hirmuse Formation and of *A.* cf. *superbus* and *A. complicatus* in its upper part indicate that the boundary between the *A. tvaerensis* and *A. superbus* conodont zones surely lies within the Oandu Stage. This agrees with earlier results demonstrating that *A. complicatus* and *A. superbus* appear at closely spaced levels in that stage, both just above the uppermost identifiable specimen of *A. tvaerensis s.l.* in a section (Männik 2003, 2010; Männik & Viira 2005).

The lower boundary of the Oandu Stage in the stratotype region, as identified in the Virunurme (7721) section (e.g. Põlma et al. 1988), is well defined in the conodont succession. The boundary is marked by the disappearance of *Besselodus*? sp. and *Semiacontiodus* sp. Additionally, *Amorphognathus* sp. and *Pand. panderi* reappear at the same level and, together with *I.* cf. *superba* and *Ph. undatus*, become common in the strata above. Based on earlier data, also the composition of many groups of other fossils changes sharply at this level, making it one of the most distinct biostratigraphic boundaries in Estonia (Rõõmusoks 1970; Põlma et al. 1988; Hints et al. 1989; Meidla 1996; Ainsaar et al. 1999). However, this boundary is marked by a discontinuity surface and distinct changes in lithology, indicating that an interval of time is not represented by rocks in the sections in North Estonia. This suggests that faunal changes at this level are artefacts resulting from the incomplete preservation of strata. Distinct changes in faunas occurring at the boundary in North Estonia become gradual in sections located closer to the central part of the Palaeobaltic basin (Ainsaar et al. 2004; Hints et al. 2016). Besides, as the boundary is characterized only generally (as a level of sharp changes in the composition of many groups of fossils; see above) and not defined properly as a level of the appearance or disappearance of a certain taxon (or taxa), it is not possible to tell which of these events marks it.

Unfortunately, the information about conodonts available for the time being does not help to solve the problem either. The events (appearances/disappearances of conodont taxa at the lower boundary of the Oandu Stage in eastern North Estonia) occur at different levels in more complete sections in South Estonia. One of the best-studied core sections in sense of biostratigraphically useful fossils is Ruhnu (500), which has yielded detailed data on the distribution of ostracods, conodonts, chitinozoans, but also acritarchs. Ostracods suggest that the lower boundary of the Oandu Stage lies in the middle of the Mossen Formation, at the level of about 642 m (Meidla 2003). According to chitinozoans, the boundary is close to 647.1 m, based on acritachs at 645.7 m (corresponds to the lower and the upper boundary of the Blidene Formation, respectively) (Nõlvak 2003). The situation with conodonts is more complicated. Restudy of the collection from the Ruhnu (500) core revealed that *Besselodus*? sp. (appears in this section at 652.8 m, in the middle of the Adze Formation, in the middle of the Haljala Stage) disappears at 646.8 m, in the lower Blidene Formation, i.e. close to (between) the levels suggested for the lower boundary of the Oandu Stage by chitinozoans and acritachs (Fig. 8). *Semiacontiodus* sp. disappears in the Ruhnu (500) core section at 644.5 m (in the lower Mossen Formation), *Panderodus panderi* and *Phragmodus undatus* both become common at 642.1 m in the middle of the Mossen Formation, almost at the level suggested for this boundary by ostracods. The bounday between the *A. tvaerensis s.l.* (identified as *A. ventilatus* in Männik 2003) and *A. superbus* conodont zones lies at about 640.5 m, in the upper Mossen Formation. Hence, based on conodonts the lower boundary of the Oandu Stage as identified in eastern North Estonia occurs between 646.8 and 642.1 m, in the interval from the lower Blidene Formation below to the upper Mossen Formation above. It is also evident that, at least, the strata between these two levels correspond to the gap marking this boundary in eastern North Estonia.

Hence, there are no biostratigraphic criteria for defining the lower boundary of the Oandu Stage as identified in its type region in more complete sections in South Estonia but also in the Central Baltic. For the time being such dating could only be possible by the comparison of the $\delta^{13}C$ curves recorded from sections located in different parts of the basin (Hints et al. 2016) but it is problematic without good biostratigraphical control.

CONCLUSIONS

The Oandu Stage in its type region is best characterized by the occurrence of *Phragmodus undatus*, *Icriodella* cf. *superba* and *Plectodina* sp., i.e. taxa that are rare or missing below and above this stratigraphic interval in Estonia.

The lower boundary of the Oandu Stage in northern Estonia is marked by the disappearance of *Semiacontiodus* sp. and *Besselodus*? sp. *Amorphognathus* sp. and *Panderodus panderi* reappear at the same level and, together with *I.* cf. *superba* and *Ph. undatus*, become common in the strata above.

For the time being, defining the lower boundary of the Oandu Stage outside the outcrop area is highly problematic. The events, i.e. appearances/disappearances of conodont taxa (but also other faunas) characteristic of that boundary in eastern North Estonia, occur at different levels in more complete sections in South Estonia, in an interval corresponding to the gap at the lower boundary

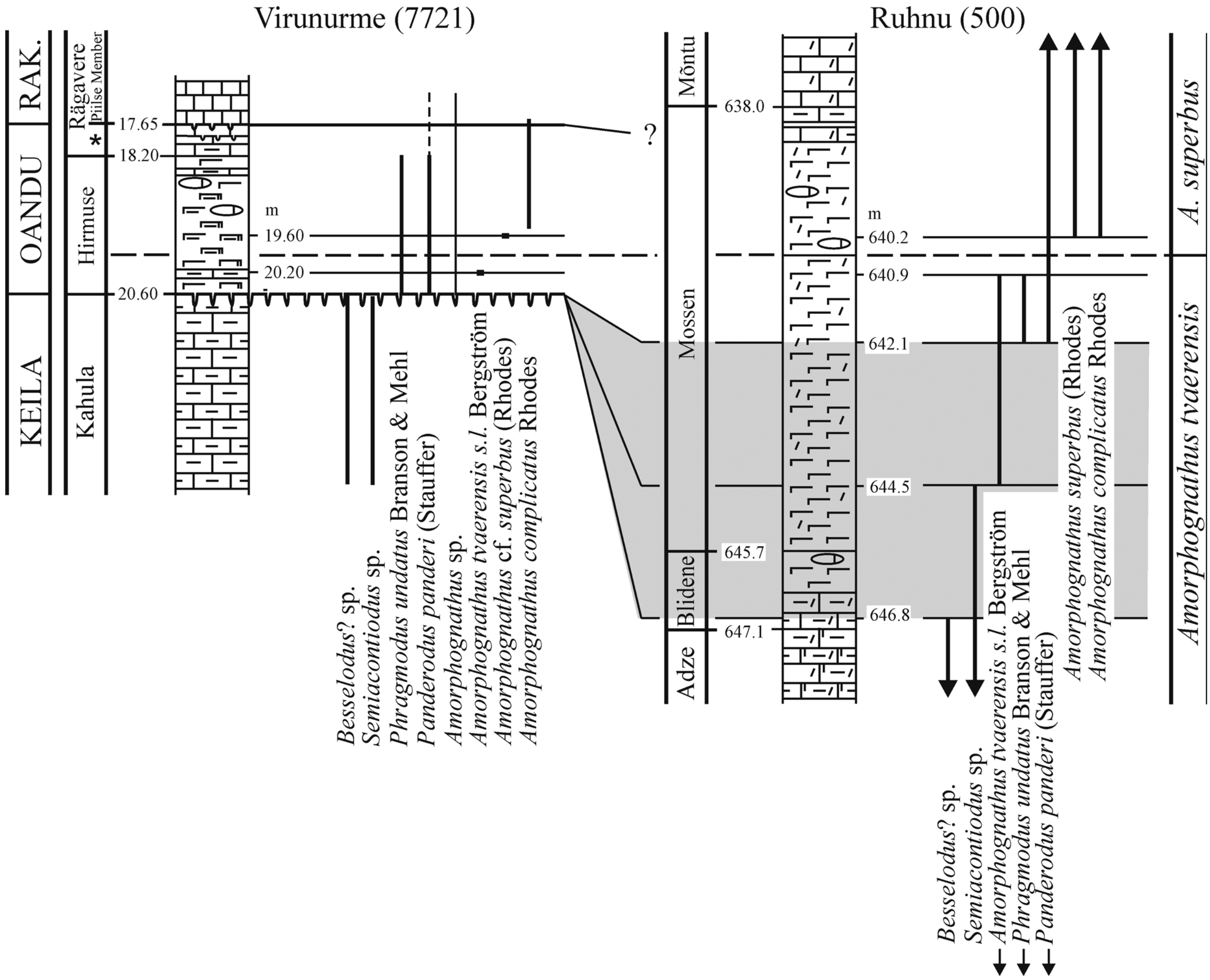

Fig. 8. Conodont-based correlation of the Virunurme (7721) and Ruhnu (500) core sections. The lithological log of Ruhnu (500) is modified from Põldvere (2003). For the lithological legend of sections refer to Fig. 3. Stages are indicated on the left-hand side of the figure and conodont zones on the right-hand side. In both sections, from left to right: formation (* in the lower part of the Rägavere Formation indicates the interval of the Tõrremägi Member); depth of the boundaries of lithological units; lithological log; depth of the appearance and/or disappearance levels of taxa (indicated only when these levels do not coincide with the unit boundaries); generalized distribution of selected conodonts. The arrows at the ends of distribution lines indicate that these taxa occur also below and/or above the studied interval. '?' at the end of the line marking the boundary between the Oandu and Rakvere stages in the Virunurme (7721) core section means that the position of this boundary in the Ruhnu (500) core section is not known. The strata corresponding to the grey interval in the Ruhnu (500) core section are missing in the Virunurme (7721) core section (correspond to the gap at the lower boundary of the Oandu Stage).

of the stage in its type region. Additional study of faunas, particularly based on complete sections from the deeper part of the Palaeobaltic basin, is needed in order to find reliable criteria for the identification of this boundary.

Besselodus? sp. and *Semiacontiodus* sp. recognized in the sample from the Oandu section indicate that the strata corresponding to the Kahula Formation (Keila Stage) in the Virunurme (7721) core section are represented in Oandu.

The boundary between the *A. tvaerensis* and *A. superbus* conodont zones lies within the Oandu Stage.

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Oandu lademe (Kati, Ülem-Ordoviitsium) konodontidel põhinev biostratigraafia Ida-Eestis

Peep Männik

Uuritud läbilõigetes tähistab Oandu lademe alumist piiri konodontide *Semiacontiodus* sp. ja *Besselodus*? sp. kadumine. Lademele on iseloomulik perekondade *Phragmodus*, *Icriodella* ja *Plectodina* esinemine. Esialgne konodontide leviku võrdlus Põhja- ja Lõuna-Eesti läbilõigetest näitab, et Põhja-Eestis on säilinud ainult lademe ülemine osa. Lademe alumisele poolele vastavad kihid puuduvad.