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Redefinition of the Sandbian–lower Katian conodont biozonation of Baltoscandia

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Original Article

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Abstract

Recent development in the Upper Ordovician conodont biostratigraphy of Baltoscandia highlights the mismatch between the traditionally used conodont zonation and ranges of the eponymous species. Practical application of the zonation is further complicated by the fact that the morphology of the long-ranging species *Amorphognathus tvaerensis*, the key taxon of the eponymous conodont zone, changes through its distribution interval, and its older and younger representatives are quite different. The latter one was recently described as a new species, *A. viirae*. Also, it appeared that the specimens assigned earlier to *A. ineaqualis* in the northern Baltoscandian region are conspecific with *A. tvaerensis* and *A. ineaqualis* is missing here. As a result, the *A. ineaqualis* Conodont Zone has to be abandoned from the regional zonal scheme. Restudy of conodont collections from the Bliudziai-150 (Lithuania) and Kovel-1 (Ukraine) core sections demonstrated the absence of *A. ineaqualis* and the presence of *A. viirae* also in the southern Baltoscandian area and Ukraine. This paper contains a formal description of the new, emended conodont zonation for Sandbian and the lowermost Katian of the Baltoscandian Palaeobasin and its correlation to the regional chemostratigraphic standard.

1. Introduction

Correlation of the Ordovician strata in the Baltoscandian Palaeobasin is based on various lithological, biostratigraphical and geochemical criteria. Most reliable correlations are based on K-bentonites (Bergström *et al.* 1995; Kiipli *et al.* 2015) and distribution of different faunas, for example, graptolites (Männil, 1976; Bergström, 1986; Kaljo *et al.* 1986), chitinozoans (Nõlvak & Grahn, 1993; Vandenbroucke, 2008), conodonts (Bergström & Löfgren, 2009; Paiste *et al.* 2022, 2023) and ostracods (Meidla, 1996; Meidla *et al.* 2020). During the last decades, $\delta^{13}C_{carb}$ data from different sections have been also successfully used for dating and correlation (Kaljo *et al.* 2001, 2004, 2007; Ainsaar *et al.* 2010).

The Upper Ordovician conodont zonation introduced by Bergström in 1971 and updated later by Dzik (1978) and Bergström (1983) is based on data from the Baltoscandian region and has remained unchanged until recently. However, the newest information about the composition and distribution of conodonts in the Sandbian Stage (Paiste *et al.* 2023) demonstrates that a revision of this conodont zonation is needed. It appeared that the *Amorphognathus inaequalis* Conodont Subzone, as depicted in the latest regional stratigraphic charts (Meidla *et al.* 2023; Nielsen *et al.* 2023), is missing in the region. Earlier this zone was identified in the Ruhnu-500 and Mehikoorma-421 core sections in Estonia (Männik, 2003; Männik & Viira, 2005), but the recent re-investigation of the probable specimens of *A. inaequalis* from these core section demonstrated that, in reality, they belong to *A. tvaerensis*. Additionally, a detailed study on the evolution of *A. tvaerensis* has uncovered notable morphological differences between elements in the lower and upper parts of its range and led to the erection of a new species, *A. viirae* Paiste, Männik et Meidla (Paiste *et al.* 2023). This newly established species was widespread in the Baltoscandian Palaeobasin and serves as an index species for a new, eponymous conodont zone. The revised conodont biostratigraphy allows higher precision of the conodont-based correlations of the Sandbian successions but also increases the reliability of the correlations based on the $\delta^{13}C_{carb}$ curves.

The above conclusions have been verified in the course of re-investigation of the published Ordovician conodont key successions from Estonia and Sweden (see Paiste *et al.* 2022, 2023). Moreover, as new information about conodonts in the Bliudziai-150 (Lithuania) and Kovel-1 (Ukraine) core sections revealed that *A. inaequalis*, reported earlier from these sections (Stouge *et al.* 2016 and Saadre *et al.* 2004, respectively), in reality is *A. tvaerensis* and *A. viirae* is present in both sections, it is evident that the enhanced conodont zonation is applicable also in these regions. The aims of the present paper are to update conodont biostratigraphy data in the sections from Latvia and Ukraine, to discuss correlation of these sections with those from the northern Baltoscandia and to provide formal definitions of the zones included in the proposed emended conodont zonation.

2. Geological setting

2.a. Regional palaeogeography

The Baltoscandian Ordovician Palaeobasin was located on the western shelf of the Baltica Palaeocontinent (Torsvik & Cocks, 2017). The Lower Palaeozoic deposits of this palaeobasin are well preserved and widely exposed in Eastern Europe, around Denmark, in the southern part of the Baltic Sea and smaller areas in Sweden, Norway, Finland (Åland) and the Bothnian Sea (Fig. 1). Based on the prevailing lithology of the deposits, three distinct facies belts are recognized in the palaeobasin (Fig. 1; Harris *et al.* 2004; Dronov *et al.* 2011). Limestones of nearshore facies are attributed to the Estonian and Lithuanian Shelves *sensu* Harris *et al.* (2004) (= 'North Estonian and Lithuanian Confacies' *sensu* Jaanusson, 1995). Marls and argillaceous limestones dominate the Livonian Basin (= 'Livonian Tongue' *sensu* Jaanusson, 1995) and the eastern part of the Scandinavian Basin (= 'Central Balto scandian Confacies' *sensu* Jaanusson, 1995).

2.b. Sandbian in the main study regions

Conodonts are well documented in the Sandbian of numerous sections in Estonia, whereas data about the coeval faunas from other parts around the Baltic Sea and most of Scandinavia are limited (Paiste *et al.* 2022 and references therein). The best-studied sections in Sweden are located in the Siljan district (Bergström, 2007*a*). Outside Estonia, Sandbian conodont data are available only from two core sections, one of them, Bliudziai-150, located in the central part of Lithuania (Stouge *et al.* 2016) and the other one, Kovel-1, in the western part of Ukraine (Fig. 1; Saadre *et al.* 2004).

The Fjäcka main section, the best-studied outcrop section in the Siljan district, Sweden, exposes the upper Darriwilian, Sandbian, and lower to middle Katian strata (Bergström, 2007*a* and references therein). The Siljan area is palaeogeographically located in the eastern part of the Scandinavian Basin (Fig. 1). The Furudal, Dalby, Skagen, Moldå and Slandrom limestones and the Fjäcka shale (Fig. 2) are exposed in this section. The section is located in a protected nature area and serves as the type locality for several conodont and chitinozoan (sub-) zones but also for the Dalby Limestone, Moldå Limestone and Fjäcka Shale (Jaanusson, 1982). The Sandbian in this section comprises the Dalby and |Skagen limestones separated by the Kinnekulle K-bentonite (Bergström, 2007*a*).

The Sandbian differs considerably between the Estonian Shelf and the Livonian Basin facies zones in Estonia. Weakly argillaceous to pure limestones dominate the Estonian Shelf, while argillaceous limestones are characteristic of the northern part of the Livonian Basin (Harris *et al.* 2004; Dronov *et al.* 2011). The Ordovician strata are exposed in the historical type region of northern Estonia, where the majority of the Baltic regional stages have been defined (Meidla *et al.* 2023 and references therein). The Sandbian succession in this region comprises the Pihla, Viivikonna, Tatruse and Kahula formations (Fig. 2). In southern Estonia, in the northern part of the Livonian Basin, the interval is represented by the Dreimani, Adze, Blidene, Variku and Mossen formations (Fig. 2).

In central Lithuania, the Sandbian Stage consists of various limestones of the Kriaunos, Sartai, Šventupys, Auleliai and Vilučiai formations representing the Livonian Basin (Meidla *et al.* 2023).

The Sandbian strata in the western Volyn (western Ukraine) comprise grey and mottled or nodular limestones and marls of the Pischa Formation (Meidla *et al.* 2023). Based on the lithological composition of rocks and their palaeontological characteristics (e.g. occurrence of *Platystrophia lynx lynx, Horderleyella kegelensis* and large crinoidal columnals – Pomyanovskaya, 1972; Konstantinenko, 2013), the strata in western Volyn are similar to those, characteristic of the North Estonian shelf.

3. Stratigraphic framework

The Sandbian Stage is the lowermost stage of the Upper Ordovician Series. The base of the Sandbian Stage is defined by the appearance of *Nemagraptus gracilis* (Hall; = the base of the eponymous graptolite zone), and its upper boundary by the first appearance of the *Diplacanthograptus caudatus* (Bergström *et al.* 2000). In the stratotype section of the Sandbian Stage at Fågelsång, *Nemagraptus gracilis* appears in the *Pygodus anserinus* Conodont Zone, below the First Appearance Datums (FADs) of *Baltoniodus variabilis* (Bergström) and *Amorphognathus tvaerensis* Bergström (Bergström *et al.* 2000). The lower boundary of the Katian Stage correlates with a level within the uppermost part of the *A. tvaerensis* Zone (Goldman *et al.* 2007, 2020, 2023).

Two successions of regional stages are proposed for the Ordovician in the Baltoscandian region (Fig. 3). The Estonian regional stages have been in use, with some modifications (Meidla *et al.* 2023), in the eastern part of the palaeobasin (Latvia, Lithuania, Poland, Belorus, Ukraine, NW Russia) for more than a century and were also partly adopted for Sweden (e.g., Jaanusson, 1982) and Norway (e.g., Owen *et al.* 1990). A new scheme of Scandinavian regional stages was proposed by Nielsen *et al.* (2023). According to this scheme, the Sandbian comprises the interval from the uppermost Segerstadian Regional Stage up to the top of the Dalbyan Regional Stage; in the Baltic scheme reviewed by Meidla *et al.* (2023), it comprises the Kukruse, Haljala and the lower Keila regional stages.

The Sandbian conodont zonations in these two schemes are largely identical. However, correlation of the individual zones to the global standard differs in details (Fig. 3). The lower boundary of the *A. inaequalis* Subzone is tentatively drawn at the lower boundary of the Sandbian Stage in the Scandinavian correlation chart (Nielsen *et al.* 2023). However, the lower boundary of the Sandbian Stage is drawn within this subzone in the Eastern Baltic correlation chart (Meidla *et al.* 2023).

The lower boundary of the Sandbian Stage has been suggested to lie in the transitional interval of *Baltoniodus alatus* (Hadding) *sensu* Stouge *et al.* 2024 (*B. prevariabilis* Fåhræus *sensu* Bergström) and *B. variabilis* (Bergström, 2007*b*) or near the base of the *A. inaequalis* Subzone (Goldman *et al.* 2020). However, *B. variabilis* is reported to appear as a gradual transition from its predecessor *B. alatus* (Dzik, 1978; Stouge *et al.* 2024), and because of the lack of *A. inaequalis* demonstrated in the Estonian and Scandinavian successions (Paiste *et al.* 2023), the exact position of the base of Sandbian in the Baltoscandian region remains problematic.

In the scheme by Nielsen *et al.* (2023), the lower boundary of the Katian Stage correlates with the basal *A. superbus* zone. In the scheme by Meidla *et al.* (2023), an unzoned interval is indicated for the same interval due to the scarcity of stratigraphically important taxa. The succession of *A. ventilatus* and *A. superbus* zones of the lowermost Katian overlies this interval. Possibilities of drawing this boundary within the area addressed in the present paper will be discussed in more detail below.

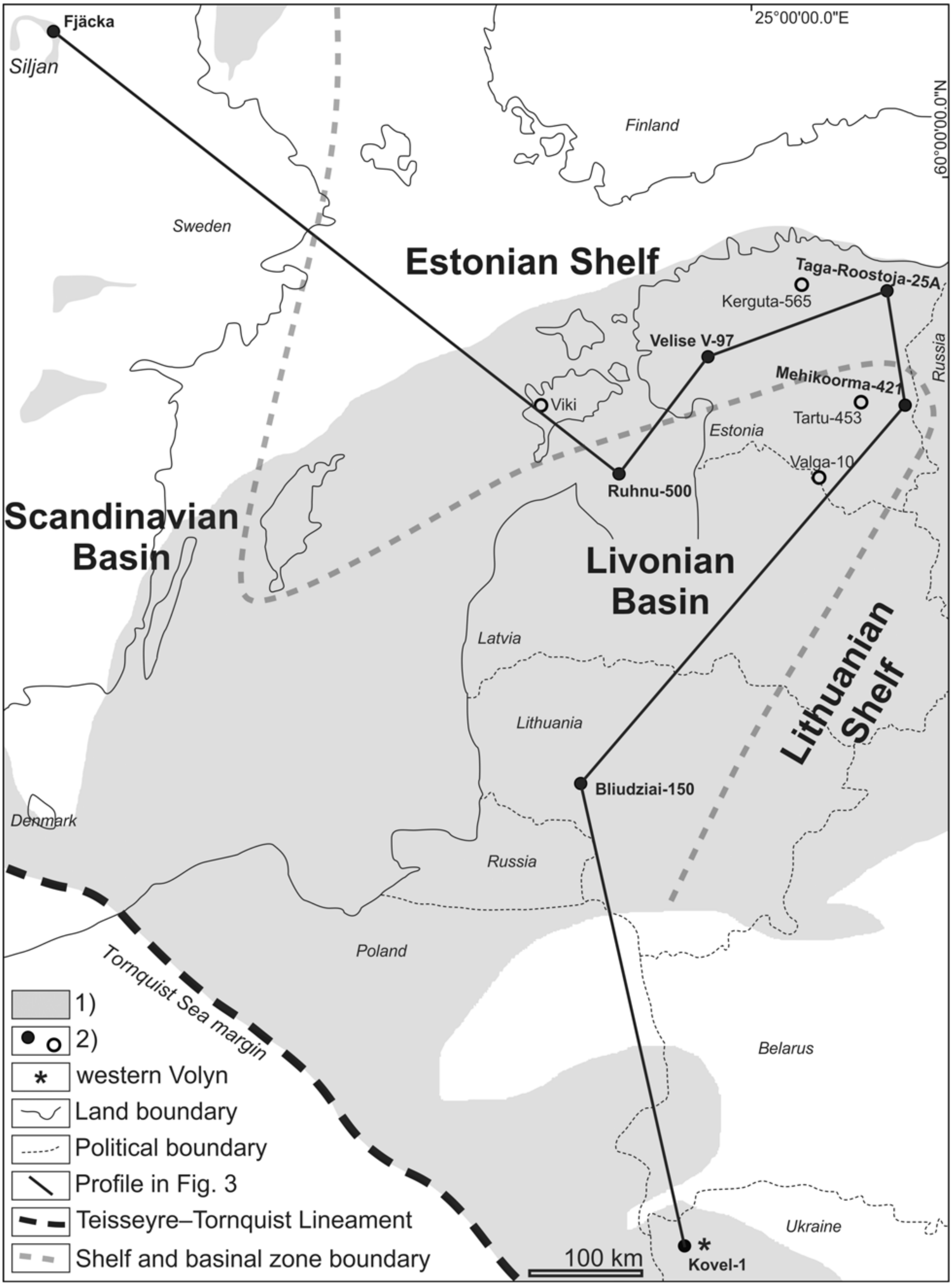

Figure 1. General Ordovician palaeogeography in the Baltoscandian Palaeobasin (modified from Harris *et al.* 2004; Saadre *et al.* 2004; Meidla *et al.* 2023). (1) Distribution of the Lower Palaeozoic strata in the eastern part of the Baltoscandian region (after Nielsen & Schovsbo, 2011); (2) circles mark the locations of the sections discussed in the text. Filled circles mark the sections along the profile in Figure 5, while empty circles mark the additional sections that correlate the Sandbian $\delta^{13}C_{carb}$ data and conodont zonation in Figure 7.

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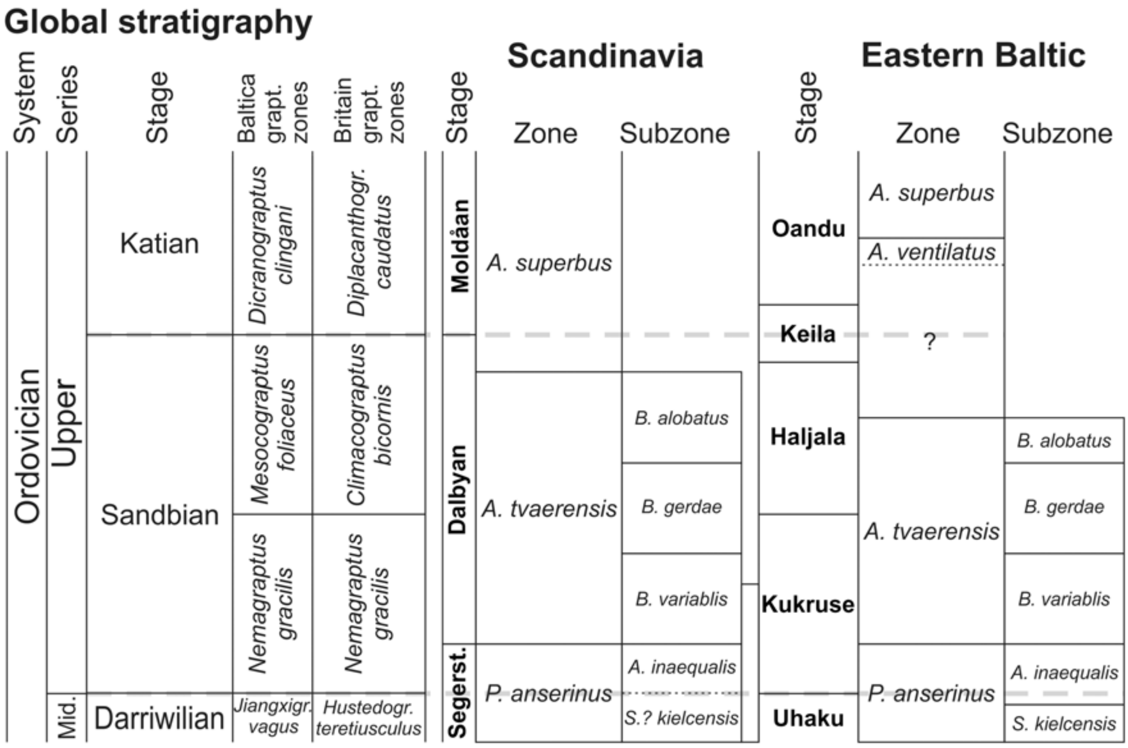

Figure 2. Comparison of the global (Goldman *et al.* 2020), Scandinavian (Nielsen *et al.* 2023) and Eastern Baltic (Meidla *et al.* 2023) stratigraphic schemes. Abbreviations: *Jiangxigr.* – *Jiangxigraptus*, *Hustedogr.* – *Hustedograptus*, *Diplacanthogr.* – *Diplacanthograptus*, grapt. – graptolite, *P.* – *Pygodus*, *A.* – *Amorphognathus*, *B.* – *Baltoniodus*, *S.* – *Sagittodontina*.

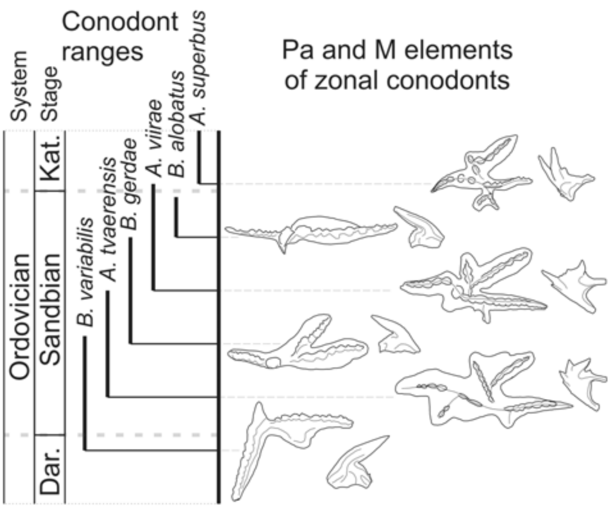

Figure 3. Diagnostic elements and ranges of the zonal taxa used in this study. Outline drawings of Pa elements of *Baltoniodus* are from Bergström, 1971, plate 2 and M elements are from Paiste *et al.* 2022, figure 5. Pa element of *Amorphognathus tvaerensis* is from Bergström, 1962, plate 4, *A. viirae* from Paiste *et al.* 2023, figure 4 and *A. superbus* from Bergström, 1971, plate 2. M elements of *Amorphognathus* are from Paiste *et al.* 2023, figures 3–5.

4. Material

Information from the Kovel-1 (Saadre *et al.* 2004) and Bliudziai-150 (Stouge *et al.* 2016) core sections was re-examined. For comparison, collections from the Kerguta-565 (Viira *et al.* 2006*a*), Mehikoorma-421 (Männik & Viira, 2005; Paiste *et al.* 2023), Ruhnu-500 (Männik, 2003), Taga-Roostoja-25A (Viira & Männik, 1999), Tartu-453 (Stouge, 1998), Valga-10 (Männik, 2001), Velise-V97 (Paiste *et al.* 2022), Viki (Männik, 2010; Hints *et al.* 2014) core sections from Estonia and Fjäcka main outcrop section from Sweden (Bergström, 2007*a*) were also inspected.

5. Results of re-investigation of the conodont successions in Lithuania, Ukraine, Estonia and Sweden

Occurrence of *A. inaequalis* in the Bliudziai-150 and Kovel-1 core sections was not confirmed. The oldest specimens of *Amorphognathus* in these core sections, previously identified as *A. inaequalis*, in reality belong to *A. tvaerensis*. Currently, no elements of *A. inaequalis* are identified from the Baltica successions.

Occurrence of *A. viirae* was confirmed in the Bliudziai-150 and Kovel-1 core sections. All known successions from the Baltica where upper range of *A. tvaerensis* has been previously described have yielded elements of *A. viirae*.

The FAD of *A. superbus* in the Hirmuse Formation, in the Estonian part of the Baltoscandian palaeobasin, is based on M elements known to appear along with other typical Katian taxa (e.g., *A. complicatus* Rhodes) in the Hirmuse Formation (Männik, 2017).

In the Fjäcka main section, the reappearance of the genus *Amorphognathus* is recorded at 1.5 m above the base of the Kinnekulle K-bentonite (Fig. 2). The M elements present are morphologically similar to some of the M elements occurring in the Mehikoorma-421 core section in the interval 292.8–294.4 m together with typical M elements of *A. superbus* (Paiste *et al.* 2023, Supplementary File, Fig. S13e, j).

Distribution and correlational remarks of zonal species are covered in the discussion below. The FADs and LADs of the zonal species are provided in Table 1. Diagnostic elements of zonal species are illustrated in Figure 2. More detailed representations of diagnostic elements are provided in Paiste *et al.* 2022, 2023.

6. Discussion

6.a. Revised Sandbian conodont zonation of Baltoscandia

A tentative revised version of the Baltoscandian conodont zonation was proposed by Paiste *et al.* (2023). Formal definitions of the zones in this emended zonation were not provided in that paper but are given below in this chapter. The main changes compared to the traditional approach are (1) abandoning of the *A. inaequalis* Subzone, (2) the inclusion of a new, *A. viirae* Zone, corresponding to the upper part of the former *Baltoniodus gerdae* Subzone, and (3) redefinition of the former *B. variabilis*, *B. gerdae* and *B. alobatus* subzones as zones. A major difference between the proposed approach and the old biozonation is uniform definition of zones: all zones are defined as interval zones, with their lower boundaries drawn according to FADs of the eponymous taxa (Fig. 4). This improves clarity of the conodont zonation and supports its unequivocal implementation during future studies.

6.a.1. *Baltoniodus variabilis* zone

Definition. The FAD of *B. variabilis* marks the base of the zone.

Reference section. The Fjäcka main section in Dalarna, south-central Sweden, where the FAD of *B. variabilis* coincides with the lower boundary of the Dalby Limestone (Bergström, 2007*a*). The zone corresponds to the lowermost 6.05 m of the Dalby Limestone. It is overlain by the *A. tvaerensis* Zone (Figs. 4 and 5).

Description. Additionally to *B. variabilis*, characteristic of the zone are *Pygodus anserinus*, *Complexodus puginifer* and *Sagittodontina kielcensis* which range into the zone from below; the FAD of *Eoplacognathus elongatus* occurs within the zone.

Remarks. The zone corresponds to the lower part of the total range of *B. variabilis*. The base of the redefined *B. variabilis* Zone is remarkably older than the base of the *B. variabilis* concurrent range Subzone of the *A. tvaerensis* Zone *sensu* Bergström (1971; Fig. 4). The *B. variabilis* Subzone *sensu* Bergström (1971) corresponds only to a part of the range of the eponymous species between the appearance of *A. tvaerensis* and that of *B. gerdae.* The same interval corresponds to the redefined *A. tvaerensis* Zone herein (see below).

Stratigraphic age. The *B. variabilis* Zone represents the upper part of the Darriwilian Stage and the lowermost part of the Sandbian Stage; it correlates with the uppermost part of the Segerstadian Regional Stage in Scandinavia; it comprises the upper Uhaku and lower Kukruse regional stages in the eastern Baltic region (Fig. 6).

6.a.2. *Amorphognathus tvaerensis* zone

Definition. The FAD of *A. tvaerensis* marks the base of the zone.

Reference section. The Fjäcka main section in Dalarna, south-central Sweden, where the FAD of *A. tvaerensis* is recorded 6.05 m above the base of the Dalby Limestone (Bergström, 1971, 2007). The zone is 4.45 m thick and is overlain by the *B. gerdae* Zone (Figs. 4 and 5).

Description. The zone is characterized by *A. tvaerensis*; *B. variabilis* and *E. elongatus* range into it from below.

Remarks. Initially, the lower boundary of the *A. tvaerensis* Zone was drawn 5.25 m above the base of the Dalby Limestone (Bergström, 1971). Restudy of the same collection from the Fjäcka main section did not confirm the appearance of *Amorphognathus* at this level. The first true elements of *A. tvaerensis* were found 6.05 m above the base of the Dalby Limestone. As the specimens of *A. inaequalis* reported from the sections of the Baltoscandian region are conspecific with *A. tvaerensis,* the former *A. inaequalis* Zone comprises a lower part of the revised *A. tvaerensis* Zone.

Stratigraphic age. The *A. tvaerensis* Zone corresponds to the lower part of the Sandbian Stage; to the lowermost part of the Dalbyan Regional Stage in Scandinavia; to the middle part of the Kukruse Regional Stage in the eastern Baltic (Fig. 6).

6.a.3. *Baltoniodus gerdae* zone

Definition. The FAD of *B. gerdae* marks the base of the zone.

Reference section. The Fjäcka main section in Dalarna, south-central Sweden, where the first appearance of *B. gerdae* is recorded in the middle part of the Dalby Limestone, 10.05 m above the base of the unit. The zone is 3.25 m thick and is overlain by the *A. viirae* Zone (Figs. 4 and 5).

Description. The zone is characterized by *B. gerdae*; *A. tvaerensis* and *E. elongatus* range from below into the zone.

Remarks. The lower boundary of the *B. gerdae* Zone was initially marked at 9.5 m above the base of Dalby Limestone by Bergström (1971). Restudy on the same collection from the Fjäcka main section did not confirm the presence of this species in the lowermost 0.55 m above this depth. The original *B. gerdae* Subzone *sensu* Bergström (1971) was equivalent to the total range of *B. gerdae* (Fig. 4), whilst the revised interval zone version corresponds only to the lower part of the range of this species (Fig. 4).

Stratigraphic age. The *B. gerdae* Zone represents the middle part of the Sandbian Stage; the lower part of the Segerstadian Regional Stage in Scandinavia; comprises the upper part of the Kukruse and the lower part of the Haljala regional stages in the eastern Baltic (Fig. 6).

6.a.4. *Amorphognathus viirae* zone

Definition. The FAD of *A. viirae* marks the base of the zone.

Reference section. The Fjäcka main section in Dalarna, south-central Sweden, where the first appearance of *A. viirae* is recorded 13.3 m above the base of the Dalby Limestone. The zone is 1.05 m thick and overlain by the *B. alobatus* Zone (Figs. 4 and 5).

Description. The zone is characterized by *A. viirae*; *B. gerdae* ranges from below into the zone.

Remarks. The holotype of *A. viirae* comes from the interval 314.9–315 m of the Mehikoorma-421 core section, Estonia (Paiste *et al.* 2023). No outcrop section suitable for use as a stratotype of *A. viirae* Zone is available in Estonia. The reference section for all Sandbian conodont zones proposed by Bergström (1971; Fig. 4) is the Fjäcka main section in Dalarna, Sweden. The particular value of this locality was created by extensive excavations in 1945–1946 that opened an almost complete succession through the uppermost Middle and Upper Ordovician. The section was intensively studied during subsequent decades and serves as the type section for several conodont and chitinozoan zones (Bergström, 1971; Nõlvak & Grahn, 1993), lithostratigraphic units (Jaanusson, 1982) and regional stages (Nielsen *et al.* 2023). Considering the possibility of cleaning this heavily overgrown section in future, we tentatively keep the Fjäcka main section as the reference section for all Sandbian conodont zones, including the *A. viirae* Zone. However, as information about conodonts from the Fjäcka main section is based on a limited collection (Bergström, 2007*a*; Paiste *et al.* 2023; Fig. 5), a detailed restudy of the succession is strongly advised.

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Table 1. FADs and LADs of stratigraphically important conodont species in the studied sections. Revised ranges of first (FAD) and last appearance datums (LAD) of species are shown in italics

Species	Section	Distribution interval	FAD	LAD	Species	Section	Distribution interval	FAD	LAD
B. variabilis	Kerguta-565	Kõrgekallas/Viivikonna	*169.88*	147.75	*A. viirae*	Kerguta-565	Tatruse	144.94	144.83
Bergström, 1962	Taga-Roostoja-25A	Kõrgekallas/Viivikonna	*93.7*	*71.7*	Paiste, Männik et. Meidla, 2023	Taga-Roostoja-25A	Tatruse/Kahula	65.9	60.6
	Velise-V97	Kõrgekallas/Pihla	215.25	*205.04*		Velise-V97	Tatruse/Kahula	202.54	196.4
	Viki	Kõrgekallas/Pihla	*348*	340.2		Viki	Tatruse/Kahula	338.33	334.2
	Mehikoorma-421	Kõrgekallas/Dreimaņi	*334*	317.95		Mehikoorma-421	Tatruse/Kahula	316.1	310.6
	Tartu-453	Kõrgekallas/Dreimaņi	*341.48*	*327.3*		Tartu-453	Tatruse/Kahula	325.03	320.5
	Ruhnu-500	Taurupe/Dreimaņi /Adze	*669.7*	658.8		Ruhnu-500	Adze	656.8	653.8
	Valga-10	Taurupe/Dreimaņi /Adze	*418.04*	401.15		Valga-10	Adze	397.9	396.75
	Fjäcka main	Dalby	0.00	*9.85*		Fjäcka main	Dalby	13.30	17.85
	Bliudziai-150	Kraštai	1382.75	*1373.9*		Bliudziai-150	Sartai	1372.79	1370.92
	Kovel-1	Pishcha: V	*276.5*	*262*		Kovel-1	Pishcha: IX	261	256
A. tvaerensis	Kerguta-565	–	–	–	*B. alobatus*	Kerguta-565	Kahula	143.47	143.32
Bergström, 1962	Taga-Roostoja-25A	Viivikonna	77.97	*67.95*	Bergström, 1971	Taga-Roostoja-25A	Tatruse/Kahula	*64.6*	57.5
	Velise-V97	Pihla/Tatruse	211.37	*202.95*		Velise-V97	Tatruse/Kahula	200.45	*194.2*
	Viki	Pihla/Tatruse	343.8	*338.95*		Viki	Tatruse/Kahula	337.3	*331.5*
	Mehikoorma-421	Dreimaņi /Tatruse	*328.7*	*316.4*		Mehikoorma-421	Tatruse/Kahula	315	*308.95*
	Tartu-453	Dreimaņi /Tatruse	*335.83*	*325.4*		Tartu-453	Tatruse/Kahula	*322.85*	*318.08*
	Ruhnu-500	Dreimaņi /Adze	*664.8*	*657.8*		Ruhnu-500	Adze	655.8	652.8
	Valga-10	Dreimaņi /Adze	*405.22*	*400.05*		Valga-10	Adze	397.9	395.8
	Fjäcka main	Dalby	*6.05*	*13.10*		Fjäcka main	Dalby	14.35	19.34
	Bliudziai-150	Kraštai	*1378.87*	*1372.93*		Bliudziai-150	Sartai	*1372.31*	1369.66
	Kovel-1	Pishcha: VI	*272.9*	*262*		Kovel-1	Pishcha: XII	257	256
B. gerdae	Kerguta-565	–	–	–	*A. superbus*	Kerguta-565	Hirmuse/Rägavere	122.25	121.18
Bergström, 1971	Taga-Roostoja-25A	Viivikonna/Tatruse	*69.9*	65.3	Rhodes, 1953	Taga-Roostoja-25A	Hirmuse/Rägavere	*37.4*	*34.8*
	Velise-V97	Tatruse	204.38	201.5		Velise-V97	Hirmuse/Rägavere	*176.75*	173
	Viki	Tatruse	339.9	338.18		Viki	Hirmuse	*328.45*	328.35
	Mehikoorma-421	Dreimaņi /Tatruse	319.85	315.5		Mehikoorma-421	Variku	*296.4*	288.2
	Tartu-453	Tatruse	*326.76*	*323.21*		Tartu-453	–	–	–
	Ruhnu-500	Adze	657.8	656.8		Ruhnu-500	Blīdene/Mossen	*646.3*	642.05
	Valga-10	Adze	400.23	400.05		Valga-10	Blīdene/Mossen	*388.85*	384.4
	Fjäcka main	Dalby	10.05	14.10		Fjäcka main	Moldå	*27.2*	*27.3*
	Bliudziai-150	Sartai	1373.9	1372.51		Bliudziai-150	–	–	–
	Kovel-1	–	–	–		Kovel-1	–	–	–

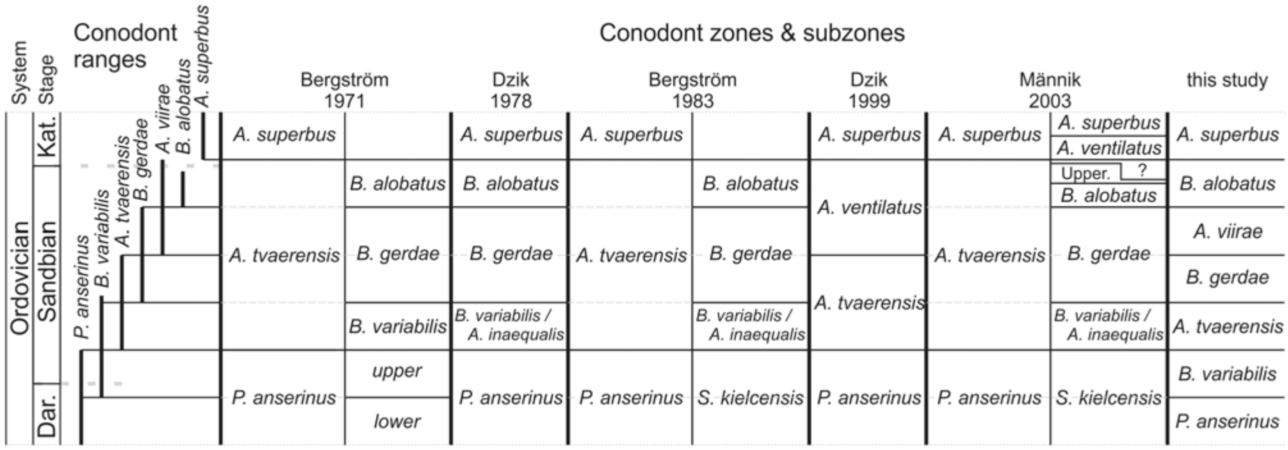

Figure 4. Conodont zonations used in the Baltoscandian region. In the left-hand side of the figure, ranges of the key taxa used to define the zones in this study are indicated. Upper. – Uppermost *B. alobatus* range.

Outside the Baltoscandian region, *A. viirae* has been recognized in the sections of Oklahoma, USA, and Holy Cross Mountains, Poland, based on the illustrations published by Goldman *et al.* (2007) and Dzik (1994), respectively. The *A. viirae* Zone corresponds to the upper part of the *B. gerdae* Subzone of the former *A. tvaerensis* Zone of Bergström (1971; Fig. 4). The *A. ventilatus* Zone (Fig. 4; Dzik, 1999) was based on the elements later reidentified as *A. viirae* (Paiste *et al.* 2023).

In the Fjäcka main section, *A. viirae* is not very common (Fig. 5; Bergström, 2007*a*; Paiste *et al.* 2023), but its FAD is distinct and easily identifiable based on the morphological changes in the lineage of *Amorphognathus* (Paiste *et al.* 2023, fig. 7).

Stratigraphic age. The *A. viirae* Zone corresponds to the upper part of the Sandbian Stage; to the middle part of the Dalbyan Regional Stage in Scandinavia; to the middle part of the Haljala Regional Stage in the eastern Baltic (Fig. 6).

6.a.5. Baltoniodus alobatus zone

Definition. The FAD of *B. alobatus* marks the base of the zone.

Reference section. The Fjäcka main section in Dalarna, south-central Sweden, where the first appearance of *B. alobatus* is recorded in the upper part of the Dalby Limestone, 14.35 m above the base of Dalby Limestone. The zone is 12.85 m thick and is overlain by the *A. superbus* Zone (Figs. 4 and 5).

Description. The zone is characterized by *B. alobatus*. However, the recorded *B. alobatus* range does not extend up to the FAD of *A. superbus* (Figs. 4 and 5). *A. viirae* ranges from below into the zone. *Icriodella superba* appears within the zone (Männik, 2017).

Remarks. Lower boundary of the *B. alobatus* Zone equals that of the *B. alobatus* Subzone *sensu* Bergström (1971). In all studied sections, *B. alobatus* disappears near but still below the Kinnekulle K-bentonite (Fig. 2). The 'Uppermost *B. alobatus* range' by Männik (2003; Fig. 4) marks the interval barren of *Amorphognathus* elements in the sections of the Baltoscandian region (Fig. 5).

Stratigraphic age. The *B. alobatus* Zone corresponds to the upper part of the Sandbian Stage and the lowermost part of the Katian stages; to the upper part of the Dalbyan Regional Stage in Scandinavia; to the upper part of the Haljala and the lowermost part of the Keila regional stage in the eastern Baltic (Fig. 6).

6.a.6. Amorphognathus superbus zone

Definition. The FAD of *A. superbus* marks the base of the zone.

Reference section. The Fjäcka main section in Dalarna, south-central Sweden, where the first appearance of *A. superbus* is recorded in the lower part of the Moldå Limestone at the depth of 27.2 m (Fig. 5). The zone is 12.3 m thick and corresponds to the main part of the Moldå Limestone and major part of the Slandrom Limestone. It is overlain by the *A. ordovicicus* Zone (Bergström, 2007*a*).

Description. The zone is characterized by *A. superbus*. The FADs of *A. complicatus*, *A. ventilatus*, *Belodina confluens* and *Hamarodus brevirameus* are characteristic of the zone.

Remarks. The lower boundary of the *A. superbus* Zone was initially located at the top of the Dalby Limestone by Bergström (1971). Restudy of the Fjäcka main section did not confirm the presence of elements of *Amorphognathus* at this level. The first diagnostic elements of *A. superbus* were found 0.9 m above the base of the Moldå Limestone (in the sample labelled as '131; 4.9–5.0 above base unit'). In a later paper (Bergström, 2007*a*), the lower boundary of the *A. superbus* Zone was drawn in the middle of the Moldå Limestone. The definition of the *A. superbus* Zone is still the same as in Bergström (1971), but additional findings of characteristic M elements (Paiste *et al.* 2023) shift the boundary downwards. The previous *A. ventilatus* Zone indicated as underlying the *A. superbus* Zone (Männik, 2003) is abandoned because the revised FAD of *A. superbus* occurs below the FAD of *A. ventilatus* in Mehikoorma-421, Ruhnu-500 and Valga-10 core sections (Paiste, 2023).

Stratigraphic age. The *A. superbus* Zone corresponds to the lower part of the Katian Stage; to the upper part of the Dalbyan and to the lower part of the Moldåan regional stages in Scandinavia; in the eastern Baltic area it comprises the interval from the upper part of the Keila Regional Stage up to the lower part of the Nabala Regional Stage (Fig. 6; Meidla *et al.* 2023, Nielsen *et al.* 2023).

6.b. Revised conodont correlation

The first conodont zonation based on the phylogenetical successions of species in the genera *Amorphognathus* and *Baltoniodus* was introduced by Bergström (1971) and, with some later modifications (Dzik, 1978; Bergström, 1983; Dzik, 1999;

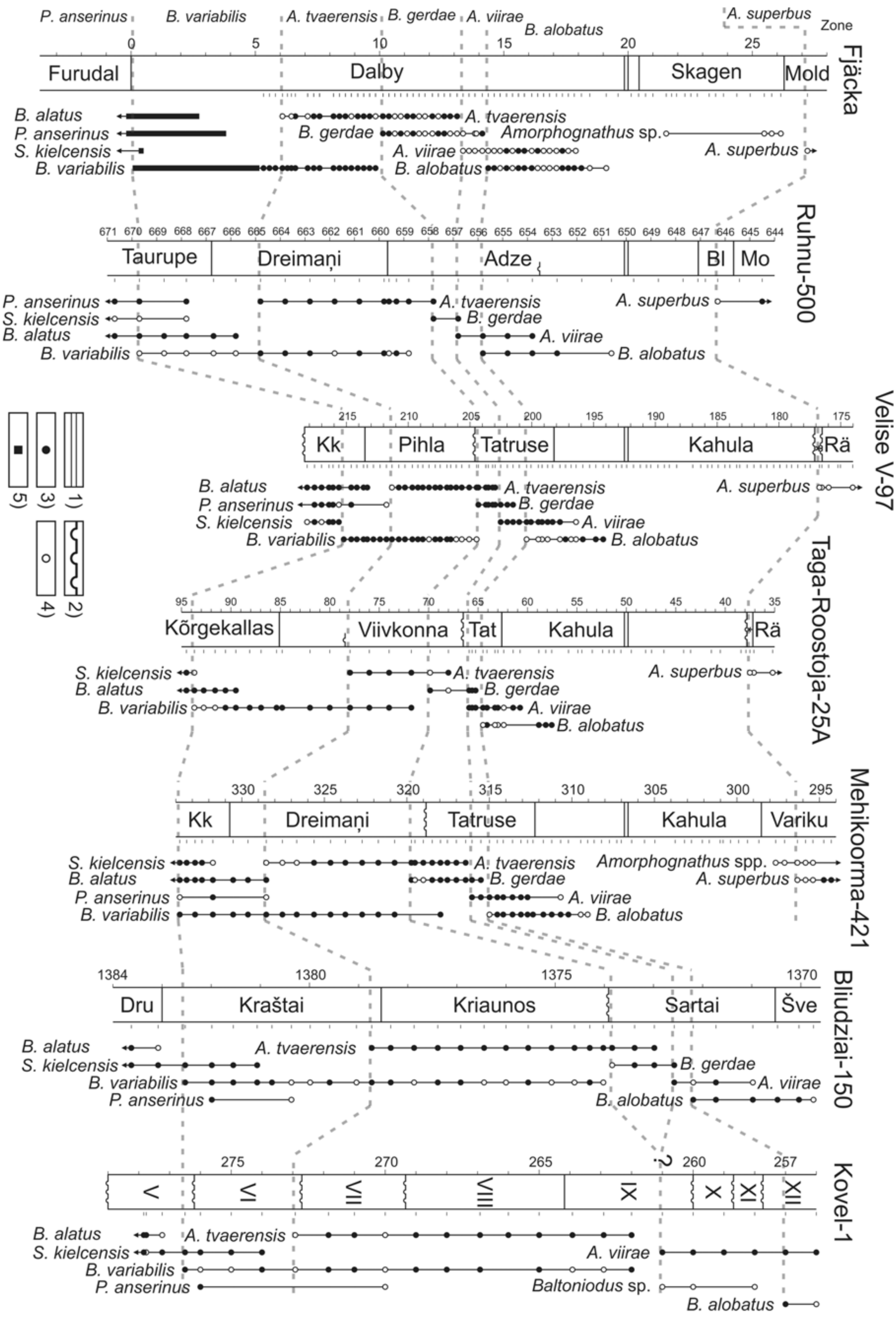

Figure 5. Updated distribution of stratigraphically important conodonts and correlation of the sections. Legend: (1) Kinnekulle-K bentonite; (2) discontinuity surface = prominent sedimentary hiatus in the succession; (3) species identification of a taxon based on recognizable Pa element; (4) identification of a taxon based on other than Pa element; (5) distribution data from Bergström, 2007*a*. Abbreviations: Mold – Moldå; Bl – Blīdene; Mo – Mossen; Kk – Kõrgekallas; * – Hirmuse; Tat – Tatruse; Rä – Rägavere; Dru - Drukšiai; Šve - Šventupys.

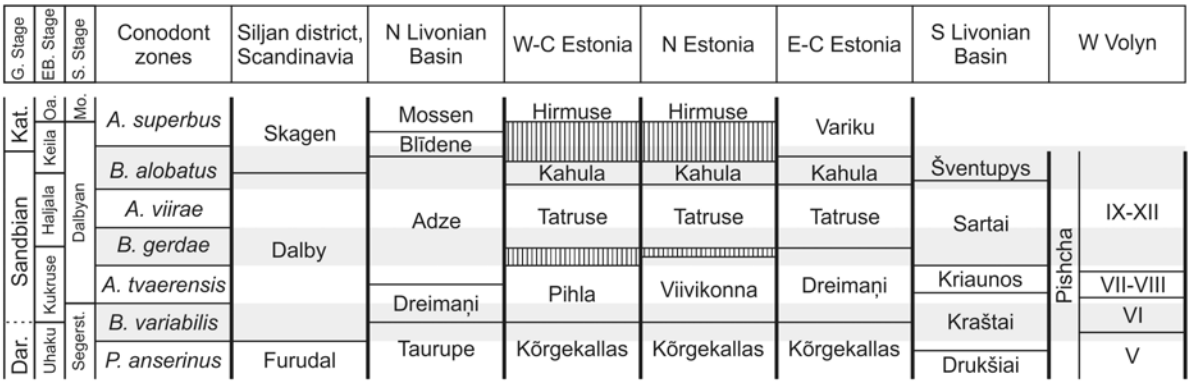

Figure 6. Sandbian correlation chart of the Baltoscandian region. Correlation of the Siljan district is based on the Fjäcka main section, N Livonian Basin on the Ruhnu-500 and Valga-10 sections; W-C Estonia on the Viki and Velise-V97 sections; N Estonia on Kerguta-565 and Taga-Roostoja-25A sections; E-C Estonia on the Tartu-453 and Mehikoorma-421 sections; S Livonian Basin on the Bliudziai-150 section; W Volyn region on the Kovel-1 section. Boundaries of the RSs are drawn according to the results of the discussion below and in the chapter 'Sandbian-early Katian conodont zones and Regional Baltoscandian stages'. Abbreviations: G. Stage – Global Stage; EB. Stage – East Baltic Stage; S. Stage – Scandinavian Stage; Dar. – Darriwilian; Kat. – Katian; Oa. - Oandu Segerst. – Segerstadian; Mo. - Moldåan.

Männik, 2003), was applied during many decades. The probable earliest species of *Amorphognathus*, *A. inaequalis*, has not been found in the Baltoscandia. The oldest representative of the genus in this area is *A. tvaerensis*. The origin of the *Amorphognathus* lineage is currently unknown (Dzik, 2024). However, as *A. inaequalis* is known from Avalonia only, it is possible that the *Amorphognathus* lineage originated in that region and, after some time, migrated to the other palaeocontinents. So far, *A. inaequalis s.s.* is reliably identified from the sections located on Avalonia only (Ferretti & Bergström, 2022).

The correlations in the Figure 5 are based on the FADs of *B. variabilis*, *A. tvaerensis*, *B. gerdae*, *A. viirae*, *B. alobatus* and *A. superbus* in Baltoscandia. Although details of morphological changes during the transition from *B. alatus* to *B. variabilis* require a further taxonomic study, the transition level still represents a usable marker, like also suggested in earlier publications (Saadre *et al.* 2004; Bergström, 2007*b*). The usability of the transition level as a stratigraphic marker is also supported outside Baltoscandia (Bagnoli & Qi, 2014; Albanesi & Ortega, 2016).

The redefined conodont zonation also harmonizes the practice of using Ordovician conodont zones on a global scale. For example, Goldman *et al.* (2020) use *B. variabilis* as a zonal taxon for correlating the sections in Baltica and South China Platform. This correlation is misleading as the *B. variabilis* Subzone *sensu* Bergström (1971) represents the upper part of range of the eponymous species in Baltica (Bergström, 1971), whilst the *B. variabilis* Zone in South China is defined by the FAD of B. variabilis (Wang *et al.* 2019) and thus comprises the lower part of the range of this species. Redefining the *B. variabilis* Subzone and raising it into rank of a zone support the use of *B. variabilis* Zone as a global correlation marker and facilitate the stratigraphic correlation of the successions of Baltica with Scotland (Armstrong, 1997), Wales (Bergström & Ferretti, 2018), South China (Zhang *et al.* 2019), North America (Bergström, 1971) and Argentina (Albanesi & Ortega, 2002).

The late appearance of *P. anserinus* in the Kovel-1 and Bliudziai-150 core sections requires additional comment. The FAD of *P. anserinus* above the FAD of *B. variabilis* in these sections suggests that the real FAD of *P. anserinus* was not recorded. The late appearance of *P. anserinus* in the Kovel-1 core section may be due to gaps, particularly considering the numerous discontinuity surfaces recorded in the core section (Saadre *et al.* 2004). An alternative explanation for this section could be facies difference. According to Saadre *et al.* (2004), the strata in the Kovel-1 section represent shallow shelf or even shoal facies and *P. anserinus* is not common in shallow facies (Viira & Männik, 1999; Viira *et al.* 2006*a*; Hints *et al.* 2007; Viira, 2008).

Amorphognathus viirae has been identified in all studied sections, and its FAD provides a reliable level for basin-wide correlation (Table 1; Fig. 5). An exception is the appearance of *A. viirae* in the *Eisenackitina rhenana* Chitinozoan Subzone, clearly below the *Lagenochitina dalbyensis* Chitinozoan Zone (Stouge *et al.* 2016), in the Kovel-1 core section. This discrepancy remains currently unexplained.

The FAD of *A. tvaerensis* (Table 1) falls within the *E. rhenana* Chitinozoan Subzone in all Baltoscandian sections where both taxa are identified (Tartu-453 – Männik, 1998; Taga-Roostoja-25A – Põldvere, 1999; Valga-10 – Põldvere, 2001; Kovel-1 – Saadre *et al.* 2004; Ruhnu-500 – Põldvere, 2003; Kohtla/Viru – Hints *et al.* 2007; Mehikoorma-421 – Põldvere, 2005; Fjäcka – Grahn & Nõlvak, 2010; Viki – Hints *et al.* 2014; Bliudziai-150 – Stouge *et al.* 2016). In the majority of the studied section (Tartu-453, Taga-Roostoja-25A, Mehikoorma-421, Fjäcka, Viki, Bliudziai-150), the FAD of *A. viirae* lies within the *L. dalbyensis* Chitinozoan Zone. However, as identified in the Valga-10 core section (Põldvere, 2001), the FAD of *A. viirae* coincides with the base of *Belonechitina hirsuta* Chitinozoan Zone. Latter discrepancy may result from about a 2+ m unsampled interval below the FADs of these taxa.

Based on the data above (Fig. 5; Table 1), an updated correlation chart of the Sandbian in Baltoscandia was compiled (Fig. 6).

This chart (Fig. 6) also reflects the recent data about conodonts from the Oandu Regional Stage (Männik, 2017; Paiste *et al.* 2022). The lower boundary of the stage is based on a significant change in the faunal succession (Männil & Meidla, 1994) in the lower parts of Variku and Mossen formations or corresponds to the sedimentary hiatus at the base of the Hirmuse Formation (Fig. 5; Jaanusson, 1976; Meidla, 1996; Ainsaar *et al.* 2004). A restudy of elements of *Amorphognathus* in the lower Katian revealed that the FAD of *A. superbus* occurred earlier than previously suggested, in the Blīdene Formation and in the lower part of the Variku Formation of the Keila Regional Stage (Fig. 6) but not in the Oandu Regional Stage as suggested earlier (Männik, 2017; Paiste *et al.* 2022). Following Bergström (1971) and Nielsen *et al.* (2023, figs. 3 and 5), correlation of *A. superbus* Zone with the Skagen Topoformation

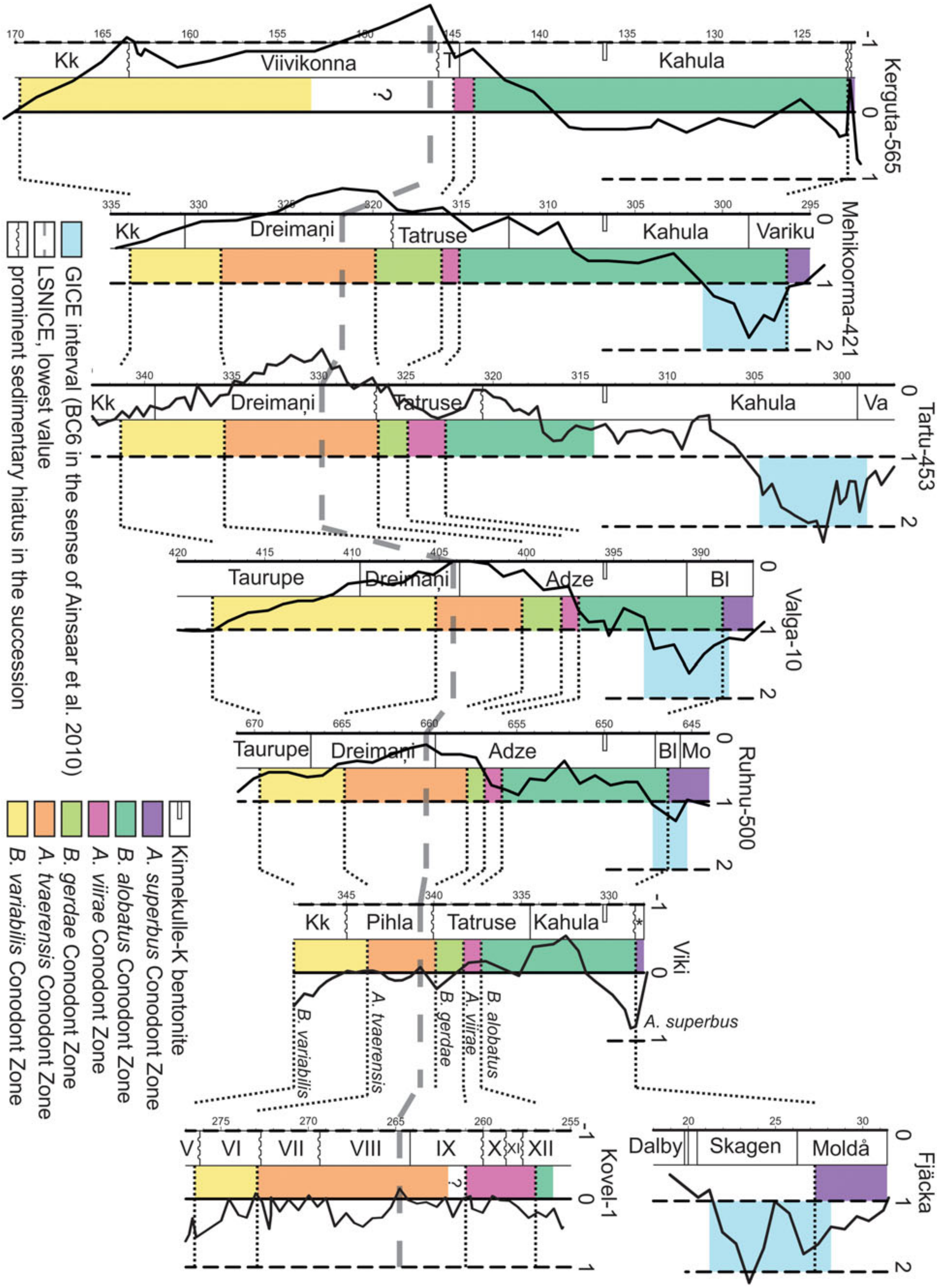

Figure 7. Correlation of the Sandbian $\delta^{13}C_{carb}$ curves and conodont zonation. Kk. – Kõrgekallas; * – Hirmuse; T – Tatruse; Va – Variku; Bl – Blīdene; Mo – Mossen.

(Fig. 6) is tentatively accepted here, although these papers provide no direct information which supports this statement.

6.c. The bases of the Sandbian and Katian stages in the conodont succession

The lower boundaries of the Sandbian and Katian stages are based on the FADs of graptolites and cannot be determined precisely in the conodont succession (Paiste *et al.* 2022). In its stratotype section at Fågelsång, the base of the Sandbian Stage lies within a 4-m interval that is barren of conodonts (Bergström, 2007*b*). Conodonts below and above this interval point at some levels within the *P. anserinus* range. As *B. alobatus* occurs below and *B. variabilis* is identified above the barren interval, the real FAD of *B. variabilis* and its relationship to the lower boundary of the Sandbian Stage cannot be identified directly in this section.

According to Vandenbroucke (2004), the base of Sandbian corresponds to a level in the lower part of the *E. rhenana* Chitinozoan Subzone in the Fågelsång section. Available information from sections where conodonts and chitinozoans occur together (Tartu-453 – Männik, 1998; Taga-Roostoja-25A – Põldvere, 1999; Valga-10 – Põldvere, 2001; Ruhnu-500 – Põldvere, 2003; Kovel-1 – Saadre *et al.* 2004; Mehikoorma-421 – Põldvere, 2005; Kerguta-565 – Põldvere, 2006; Smedsby Gård – Bergström *et al.* 2011, Grahn & Nõlvak – 2010; Viki – Põldvere, 2010, Hints *et al.* 2014; Bliudziai-150 – Stouge *et al.* 2016; see also Table 1) shows that the FAD of *B. variabilis* is always below the FAD of *E. rhenana*. Hence, it can be concluded that the lower boundary of the Sandbian Stage lies within the lower part of the *B. variabilis* Zone.

In the stratotype section of the base of the Katian Stage, the boundary lies 4.0 m above the base of the Bigfork Chert (Goldman *et al.* 2007). This level falls within the uppermost range of the *A. tvaerensis*, being located 1.7 m below the appearance of *Amorphognathus* sp. cf. *A. superbus* (Goldman *et al.* 2007). Section D, the supplementary stratotype section also indicates that the base of the Katian Stage falls within the range of *A. tvaerensis*. Here, the FAD of *Diplacanthograptus caudatus* lies within the upper range marked by *A. tvaerensis*? (Goldman *et al.* 2007, fig. 11). Revised identifications of some conodonts from the stratotype section of the Katian Stage are possible using the specimens illustrated by Goldman *et al.* (2007, fig. 7: 17–22). The Pa element 0.3 m below the top of the Womble Shale (Goldman *et al.* 2007, fig. 7: 18) does not show the extra posterolateral process on the outer side of its posterior process. Absence of the extra posterolateral process is the primary feature distinguishing Pa elements of *A. viirae* from those of *A. tvaerensis* (Paiste *et al.* 2023). Additionally, the small lateral lobe on the outer side of the posterior process and the similar lengths of the anterior process and the anterior branch on the inner lateral process are the characteristic features of *A. viirae* (Paiste *et al.* 2023). This suggests that the specimens identified as *A. tvaerensis* by Goldman *et al.* (2007) in reality belong to *A. viirae,* and the stage boundary falls within the range of *A. viirae*. Furthermore, illustrated specimen of *Amorphognathus* sp. occurring 5.7 m above the base of the Bigfork Chert was suggested to represent *A. superbus* (Goldman *et al.* 2007, fig. 7: 15–16). A re-examination of these photos confirms the absence of the extra posterolateral process and shows an almost straight main denticle row with its distal end pointing towards the outer side, and the equal lengths of the anterior process and the anterior branch on the inner lateral process. All these are characteristic features of *A. superbus* (Bergström, 1971). This suggests that the base of the Katian cannot be younger than the *A. viirae* Zone in terms of the zonation proposed in the present paper. This level occurs in the upper part of the *B. alobatus* Zone in Figure 20.2 by Goldman *et al.* (2020), where the previous definition of this zone was applied.

6.d. Sandbian conodont distribution and C stable isotopic data

Two distinct $\delta^{13}C_{carb}$ excursions are known in the Sandbian of Baltoscandia. The Lower Sandbian Negative Isotopic Carbon Excursion (LSNICE; Bauert *et al.* 2014; Upper Kukruse Low by Kaljo *et al.* 2007) is a negative excursion during which $\delta^{13}C_{carb}$ values decrease to about 0‰ in the upper part of the Kukruse Regional Stage. The Guttenberg Isotopic Carbon Excursion (GICE), recognized in the upper Keila Regional Stage (Ainsaar *et al.* 1999), is characterized by an increase of $\delta^{13}C_{carb}$ values close to or higher than +2% in Estonia for a short time interval, followed by a decline to about +1% (Ainsaar *et al.* 2010). The GICE was originally recognized in North America (Harch *et al.* 1987) and is also recorded in the stratotype of the Katian Stage (Goldman *et al.* 2007), directly above the base of the stage. In the stratotype section (the Black Knob Ridge section: Goldman *et al.* 2007; Fig. 4), the GICE starts below the FAD of *Amorphognathus* sp. cf. *A. superbus*. Further studies of this interval in the type region are clearly needed as Carlucci *et al.* (2015) have alternatively proposed, based on the occurrences of trilobites and chitinozoans, that the isotopic excursion in this area may represent a younger excursion, 'the Kope excursion' by Bergström *et al.* (2010). If this hypothesis would be confirmed, the lower boundary of the Katian Stage in the whole Baltoscandian region may require a revision.

Conodont and $\delta^{13}C_{carb}$ data from the strata of the Sandbian are available from several Baltoscandian sections: Ruhnu-500 (Kaljo *et al.* 2004; Ainsaar *et al.* 2004), Kerguta-565 (Kaljo *et al.* 2007), Mehikoorma-421 (Kaljo *et al.* 2007), Valga-10 (Kaljo *et al.* 2007), Tartu-453 (Bauert *et al.* 2014) and Viki (Hints *et al.* 2014) core sections in Estonia, the Fjäcka main section in Sweden (Ainsaar *et al.* 2010) and the Kovel-1 core section in Ukraine (Hints, O., Martma, T., unpublished data, Supplementary Table S1, see also Fig. 7).

The LSNICE correlates with the *A. tvaerensis* Zone in all studied sections (Fig. 7). In the Kerguta-565 and Viki sections, the GICE interval is evidently cut off by a gap at the lower boundary of the Hirmuse Formation (Fig. 7), but it is preserved in the Tartu-453, Mehikoorma-421, Valga-10, Ruhnu-500 and Fjäcka sections. In the latter successions, the lower boundary of the GICE interval (in sense of Ainsaar *et al.* 2010) lies above the Kinnekulle K-bentonite and the lower boundary of the *A. superbus* Zone lies within the GICE interval, near the GICE peak (Fig. 7). This agrees with the data from the Katian stratotype (Goldman *et al.* 2007) where the first appearance of *Amorphognathus* sp. cf. *A. superbus* is recorded within the GICE interval, above the K-bentonite.

6.e. Sandbian-early Katian conodont zones and regional stages in Baltoscandia

In Estonia and adjacent areas, the Ordovician succession contains numerous sedimentary hiatuses. The historical boundaries of regional stages defined in the Ordovician outcrop belt in Estonia were often confined to more prominent discontinuities. Gaps in the succession made these boundaries biostratigraphically clear and distinct. In order to improve the chronostratigraphic correlation between the type region and more complete offshore

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sections, numerous attempts, mainly based on the distribution of microfossils, have been made during the last decades. Although conodonts represent a useful correlation tool, they cannot be effectively used for tracing the stage boundaries in the studied interval as not a single one of the zonal boundaries in the Sandbian strata correlates with a boundary of a regional stage in the eastern Baltic area (Meidla *et al.* 2014; Meidla *et al.* 2023).

The lower boundary of the Kukruse Regional Stage lies distinctly below the FAD of the *A. tvaerensis* (Fig. 6) in the stratotype area of the stage (Viira *et al.* 2006*b*), within the *B. variabilis* Zone (Hints *et al.* 2007). The zonal graptolite *Nemagraptus gracilis*, the generally accepted primary marker of the base of the Sandbian Stage, has been recorded in the Mehikoorma-421 (at the depth 319.5–324.7 m; Männik *et al.* 2021), Valga-10 and Ruhnu-500 drillcores (at the depths 407.8 and 662.8 m, respectively; Nõlvak & Goldman, 2007). The FAD of *A. tvaerensis* is located below the first *N. gracilis* in the Mehikoorma-421 and Ruhnu-500 sections (Fig. 5) and above it in the Valga-10 section (Männik, 2001). This fact seems to point at a discrepancy between the eastern Baltic succession and the GSSP of the Sandbian Stage, where the FAD of the *A. tvaerensis* is located distinctly higher than the first *N. gracilis*. However, as the finds of *N. gracilis* in Estonian sections are very rare, their real positions within the range of this species, but also in relation to the base of Sandbian, are unknown. Most probably, this explains this apparent discrepancy. The lower boundary of the Haljala Regional Stage in North Estonia is marked by a remarkable gap corresponding to a part of the *B. gerdae* Zone (Hints & Meidla, 1997).

In the recently proposed succession of the Ordovician regional stages for the Scandinavian part of the basin, the lower boundary of the Dalbyan Regional Stage, by definition, corresponds to the FAD of *A. tvaerensis* (Nielsen *et al.* 2023, p. 288). Results of the recent restudy of conodonts from the Fjäcka main section (Paiste *et al.* 2023) suggest that the lower boundary of the Dalbyan Regional Stage in this section actually lies 6.05 m above the base of the Dalby Limestone, 0.8 m higher than stated in the original definition of the boundary stratotype by Nielsen *et al.* (2023).

The lower boundary of the overlying Moldåan Regional Stage is marked by the appearance of trilobite *Toxochasmops extensus* (*sensu lato*) within the Freberga Formation, at the hiatus between the Skagen Limestone and Moldå Limestone in the Fjäcka main section (Nielsen *et al.* 2023). The current correlation of the base of the Katian with the base of the Moldåan Regional Stage (Nielsen *et al.* 2023) is based on indirect evidence, considering ties between the conodont and graptolite successions in the Scandinavian region as indicated by Bergström (1986, tie 41 referring to Bergström, 1973, ties 17, 18). The latter ties conflict with the current Ordovician timescale (Goldman *et al.* 2020) and the faunal evidence from the Katian boundary stratotype section (Goldman *et al.* 2007). Comparison of our data with that from the Katian stratotype section (Goldman *et al.* 2007) suggests that the base of Katian is older than the FAD of the *A. superbus* and the starting point of GICE. As a result, the base of the Katian Stage correlates with a level in the upper part of the Dalbyan Regional Stage but does not coincide with the base of the Moldåan Regional Stage as suggested by Nielsen *et al.* (2023, fig. 3).

7. Conclusions

- *A. inaequalis* is missing in the Baltoscandia as well as in the western Ukraine; hence, the use of the eponymous conodont zone in these regions is misleading and should be avoided.

- Base of the Sandbian Stage correlates with a level within the *B. variabilis* Zone. However, the exact position of the FAD of *B. variabilis* is still problematic. Further taxonomic study of specimens from the transitional interval between *B. alatus* and *B. variabilis* is needed to clarify differences between these taxa.

- The presence of *A. viirae* is confirmed in all studied sections within the Baltoscandian region. Study of the published illustrations of conodonts from the Katian stratotype section indicated that the base of the Katian Stage corresponds to a level in the upper part of the range of *A. viirae*, below the FAD of the *A. superbus*.

- Based on the previous considerations, the Sandbian conodont zonation of Baltoscandia was redefined. The emended zonation includes the following zones (from below): *B. variabilis*, *A. tvaerensis*, *B. gerdae*, *A. viirae* and *B. alobatus*. Lower boundaries of all zones are defined as FADs of the eponymous taxa. This improves clarity of the conodont zonation and supports its unequivocal implementation during future studies.

- The available data indicate that the lowest $\delta^{13}C_{carb}$ value of the LSNICE falls within the *A. tvaerensis* Zone, below the FAD of the *B. gerdae*, and the lower boundary of the *A. superbus* zone lies in the GICE interval (in sense of Ainsaar *et al.* 2010), close to the level of its highest values.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0016756825100241

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