Estonian Journal of Earth Sciences, 2016, **65**, 2, 85–97 doi: 10.3176/earth.2016.08

Upper Sandbian–lower Katian bio- and chemostratigraphy in the Pajevonys-13 core section, Lithuania

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Received 2 December 2015, accepted 26 February 2016

Abstract. The succession of five formations (Auleliai, Vilučiai, Alvitas, Šakiai, Jakšiai) corresponding to the upper Sandbian and lower Katian in southern Lithuania is dated based on new bio- and chemostratigraphical data from the Pajevonys-13 core section. The dating of the Auleliai and Vilučiai formations is controversial: chitinozoans suggest younger ages (Keila and Oandu) than brachiopods (Haljala and Keila) for this interval. Chemostratigraphical data ($\delta^{13}C_{carb}$ and $\delta^{13}C_{brach}$) agree better with the dating based on brachiopods: the Alvitas and Šakiai formations correspond to the Oandu Stage, the older Vilučiai Formation is of Keila age. The Jakšiai Formation is commonly dated as of Rakvere age, but it is problematic in the studied section. However, its upper boundary is well defined by the appearance of subzonal chitinozoans *Armoricochitina reticulifera* characteristic of the lowermost Nabala Stage. The *Ancyrochitina bornholmensis* and *Fungochitina spinifera* chitinozoan zones, and the upper *Amorphognathus tvaerensis*, *A. superbus* and the lowermost *A. ordovicicus* conodont zones were identified in the studied section.

Key words: Upper Ordovician, bio- and chemostratigraphy, brachiopods, chitinozoans, conodonts, East Baltic, Lithuania.

INTRODUCTION

Late Ordovician ecosystems experienced major changes in late Sandbian–early Katian time (the middle Caradoc event; Ainsaar et al. 2004; Dronov & Rozhnov 2007) and at the end of the Ordovician (glaciation event; Marshall et al. 1997). Variations in climate and sea level, which resulted in alterations in facies distribution and the geochemical composition of rocks and extinctions of faunas, are characteristic of both events. The Sandbian–Katian transition interval has been an object of numerous special studies in the East Baltic (Kaljo et al. 2007; Ainsaar et al. 2010; Kröger et al. 2014) and worldwide (Bergström et al. 2012, 2015). In Baltoscandia the Sandbian–Katian boundary correlates with a level in the Keila Stage (Nõlvak et al. 2006; Ebbestad & Högström 2007).

The aim of this study is to integrate litho-, bio- and chemostratigraphical data available from the Pajevonys-13 core section in the southern East Baltic and to update the dating and correlation of regional lithostratigraphical units of the uppermost Haljala to the lowermost Nabala stages. As the Pajevonys-13 section comes from the deeper part of the basin, it could be expected that it is more complete and the intervals missing in the stratotype region in northern Estonia are represented here. Hence, another aim of our study was to get a better idea of the faunal content of the stages in the interval studied and to find more reliable criteria for recognizing their boundaries in more complete successions. In the stratotype region the stage boundaries are largely based on lithological criteria and, as a rule, correspond to gaps in the succession. In that sense the Oandu Stage is one of the most problematic units with an extensive gap on the lower boundary in the stratotype region, interpreted as a sequence boundary (Dronov et al. 2011). The integration of different bio- and isotopic data allows evaluating the stratigraphical value of different criteria for sub- and interregional correlations. The integrated data enable us to highlight the problems, new aspects and possibilities for the correlation of sections in comparison with the stratification of the Katian deposits traditional in Lithuania.

The main focus in this study is on the stratigraphical interval from the Keila to Nabala stages, represented in the Pajevonys-13 section by the Auleliai, Vilučiai, Alvitas, Šakiai and Jakšiai formations (Paškevičius 1997; Fig. 1). These formations were earlier dated based on different groups of fossils and correlated with other sections in Lithuania (Paškevičius 1997).

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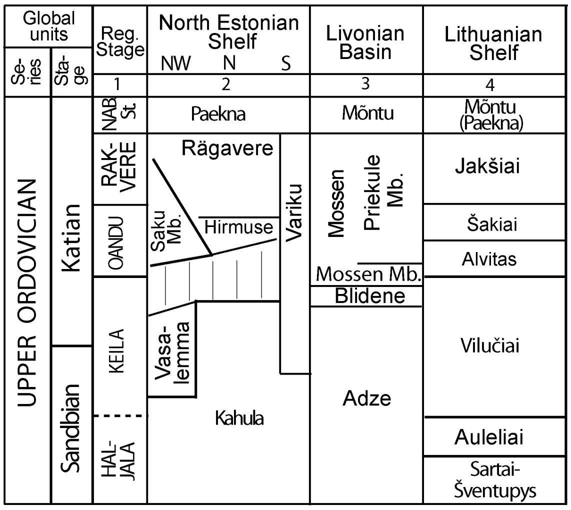

Fig. 1. Correlation of the formations and members of the Sandbian–Katian transitional interval in the East Baltic. Regional Stages (Reg. Stage) (1); correlation of formations and members (Mb.) of the Estonian Shelf and Livonian Basin (2 and 3; Ainsaar et al. 1999; Kröger et al. 2014); correlation of formations identified in the Lithuanian Shelf (Paškevičius 1997) (4); Nab. St. – Nabala Stage. For the chitinozoan and conodont biozones see Figs 3 and 4.

The set of the Ordovician lithostratigraphical units (formations and members) in Lithuania and their correlation with the Baltic stages was worked out in 1960–1970 and have been supplemented by subsequent studies (Laškovas et al. 1984; Männil & Meidla 1994; Paškevičius 1997). Paškevičius (1962) and Männil et al. (1968) presented the first information about the Pajevonys-13 core section and the succession of formations used in this paper follows the interpretation of the latter authors. However, in some papers (e.g. Sidaravičienė 1999) the boundaries of these units may be located at somewhat different levels, probably due to different interpretation of depths in the core (e.g. using the depths measured during drilling or those revised later based on the geophysical studies of the succession). The dating and exact correlation of the studied interval in Lithuania with the sections in the stratotype region are still insufficiently known due to lack of adequate data on the distribution of chitinozoans and conodonts, which are essential for the intra- and interregional correlation. The stage-level stratification, which in Lithuania is largely based on macrofossils, also needs to be compared with data by microfossils.

GEOLOGICAL BACKGROUND

The Pajevonys-13 borehole is located in southern Lithuania, close to the boundary between Lithuania and the Kaliningrad region of Russian Federation (Fig. 2). Geologically, the section represents the southwesternmost part of the distal part of the Lithuanian Shelf in the sense of Harris et al. (2004). The lowermost argillaceous limestones and mudstones (Sartai-Šventupys and Auleliai formations) in the Pajevonys-13 core section correspond to the upper Sandbian. The uppermost Sandbian–lower Katian siliciclastic deposits (clay, argillaceous marlstone, siltstone) are up to 20 m thick and belong to the Vilučiai, Alvitas, Šakiai and Jakšiai formations (Fig. 1). These units were identified (see Sidaravičienė 1999) to understand better the variation in the Katian deposits in the Lithuanian Shelf. Their faunal similarity, especially by common brachiopods and trilobites (Paškevičius 1997), with those in the Northern East Baltic enabled the general stage-level correlation of Lithuanian formations. The deposits similar to those in Lithuania have a considerably smaller thickness and correspond in the distal part of the Estonian Shelf mainly to the Variku Formation (Fm.) (Fig. 1). Maximum known thicknesses of the Variku Fm. have been measured in the Ristiküla-174 (ca 8 m) and Tartu-453 (ca 11 m) core sections (Ainsaar & Meidla 2001).

Below we give only short descriptions of the formations representing the study interval in the Pajevonys-13 core (Fig. 3). More detailed information can be found in the respective parts of the paper.

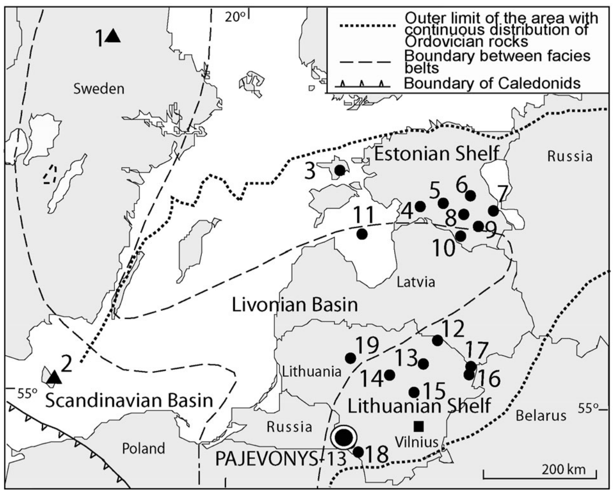

Fig. 2. Major palaeogeographic features of the Baltic Basin (modified from Harris et al. 2004) and localities in Estonia and Sweden. Outcrops (black triangles): 1, Fjäcka, main section; 2, Bornholm, outcrop in the Vasågard area; drill cores (black circles): 3, Männamaa-F367; 4, Ristiküla-174; 5, Viljandi-91; 6, Tartu-453; 7, Mehikoorma-421; 8, Kaagvere; 9, Otepää; 10, Valga-10; 11, Ruhnu-500; 12, Butkunai-241; 13, Svedasai-252; 14, Krekenava-7; 15, Ukmerge-10; 16, Drukšiai-5; 17, Kazimirovo-6; 18, Kalvaria-2; 19, Kurtuvenai-166.

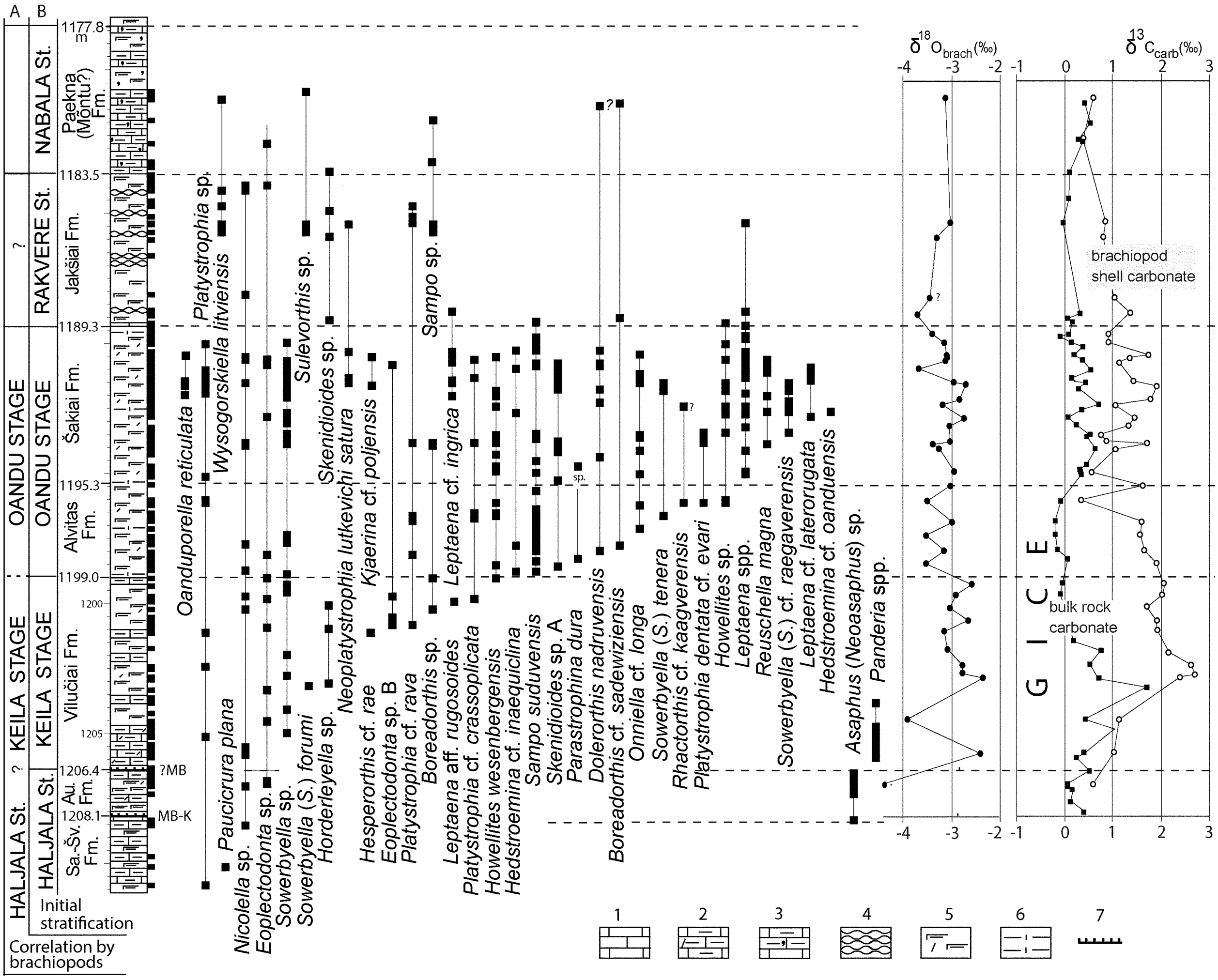

Fig. 3. Stratigraphy, lithology, distribution of brachiopods and isotope curves in the Pajevonys-13 core. S.-Š. Fm., Sartai-Šventupis Formation; Au. Fm., Auleliai Formation. Legend for the log: 1, limestone; 2, clayey limestone; 3, clayey limestone with glauconite; 4, bioclastic clayey nodular limestone; 5, clayey marl; 6, calcareous clay; 7, K-metabentonite (MB-K – Kinnekulle K-bentonite). On the left side of the log: A – correlation of the formation in terms of brachiopod data; B – age of the formation according to the stratigraphical chart of Lithuania (see Paškevičius 1997).

The **Auleliai Fm.** (interval 1208.1–1206.4 m) is represented by bioclastic marlstone with interlayers of bioclastic argillaceous limestone. A K-bentonite occurs at the base of the unit. Its possible correspondence to the Kinnekulle K-bentonite marking the lower boundary of the Keila Stage in northern Estonia is based only on chitinozoan data. The marlstone at the top of the Auleliai Fm. comprises mica, which probably indicates the occurrence of another K-bentonite. Two closely spaced K-bentonites have been identified in the lower part of the Auleliai Fm. in the Butkunai-241 (Laškovas et al. 1984) and Svedasai-252 (Paškevičius 1997) cores where the formation is respectively 15.1 and 20.1 m thick instead of 1.7 m in the Pajevonys-13 core. Possibly the Auleliai Fm. is stratigraphically incomplete in the last core and the K-bentonites in the three mentioned sections can be correlated, or they may represent K-bentonites of different age.

The Auleliai Fm. is included in the Jõhvi Substage of the Haljala Stage in geological practice in Lithuania (Paškevičius 1997). In our study, however, it described as a possible lower part of the Keila Stage, as it was interpreted by Männil & Meidla (1994).

The **Vilučiai Fm.** (interval 1206.4–1199.0 m) is represented by greenish-grey thin-bedded bioturbated marlstone with thin interlayers of dolomitic clay. The marlstone in the lower half of the formation (below a depth of 1201.5 m) comprises interlayers of grey argillaceous microcrystalline to micritic limestone (5–15 cm thick). Stylolites occur at some levels. The marlstone contains unevenly distributed microcrystalline pyrite. The Vilučiai Fm. is correlated with the Keila Stage (Paškevičius 1997). Our bio- and chemostratigraphical studies (see below) of the formation suggest somewhat controversial interpretations of its age.

The **Alvitas Fm.** (interval 1199.0–1195.3 m) is represented by greenish-grey thin-bedded marlstone with rare interbeds of dolomitic calcareous clay. Brown films and small (0.5–1.0 cm in diameter) lenses rich in fine-grained pyrite are common. Fragments of macrofossils are abundant in some beds. The marlstone consists predominantly of clay minerals (60%) together with quartz grains (25%), chlorite (3%), pyrite (2%) and rare grains of feldspar and hydrogoethite. The Alvitas Fm. comprises brachiopods, among them *Howellites wesenbergensis* characteristic of the Oandu Stage. However, in spite of the faunas unusual for the Keila Stage, this part of the section is sometimes correlated with that stage (compare the Krekenava-7 section: Männil 1966; Paškevičius 1997). The lower boundary of the formation corresponds to the top of the uppermost limestone bed, above which the section is represented by marlstone without limestone interlayers. Some new taxa appear in the shelly fauna at this level (Fig. 3).

The **Šakiai Fm.** (interval 1195.3–1189.3 m) is represented by fossiliferous marlstone with rare interbeds of dolomitic calcareous clay. The rock is rich in brachiopods, which may form coquinas or at some levels occur together with numerous small colonies and fragments of bryozoans (e.g. at 1191.0 m, 1193.5 m). Rugose corals are also found at several levels. The brachiopod fauna of the formation is similar to that known from the Oandu Stage in northern Estonia (Rõõmusoks 1970; Põlma et al. 1988; Paškevičius 1997; Hints 1998). The formation, together with the underlying Alvitas Fm., is correlated on the basis of similar shelly fauna with the Oandu Stage in northen Estonia (Paškevičius 1997).

The **Jakšiai Fm.** (interval 1189.3–1183.5 m) consists of massive greenish-grey marlstone with interlayers (3–7 cm, one bed up to 30 cm thick) and/or nodules of grey clayey micritic limestone. The limestone includes thin wavy layers of marlstone with brownish films, whereas one of them contains small lenses (0.5–1.0 cm in size) rich in microcrystalline pyrite. The marly layers contain stem ossicles of echinoderms, small bryozoan colonies, fragments of trilobites and brachiopods. Based on its position in the succession, the Jakšiai Fm. has been considered to correspond to the Rakvere Stage (Laškovas et al. 1993).

The Jakšiai Fm. is overlain by a unit of argillaceous and/or bioclastic limestone with glauconite grains. In the Lithuanian stratigraphical chart this unit has been indicated as the Paekna Fm. in the sense of the Mõntu Fm. of Männil & Meidla (1994) of the Nabala Stage. The latter term is used here because the Paekna Fm. is non-glauconitic in northern Estonia.

MATERIAL AND METHODS

Deep boreholes in southwestern Lithuania were drilled by the Lithuanian Geological Survey. The Pajevonys-13 drill core was described and sampled in the late 1960s for palaeontological studies by our late colleagues V. Korkutis and N. Sidaravičienė from Lithuania, and R. Männil and L. Põlma (and some others) from the Institute of Geology in Tallinn, Estonia. The mineralogical–petrographical composition of rocks was analysed in the Lithuanian Geological Survey.

Palaeontological–biostratigraphical studies in this paper are based on 311 samples. Brachiopods were identified by J. Paškevičius and L. Hints from two separate series of samples. One of them is housed at Vilnius University (Lithuania) and the other at the Institute of Geology at Tallinn University of Technology (Estonia). When needed, hydrogen peroxide (H_2O_2) was used to clean brachiopods of the soft clayey matrix.

Leftovers of earlier collected macrofossil samples were processed in buffered acetic acid to study microfossils (chitinozoans and conodonts). Additionally, earlier published data about chitinozoans (Männil et al. 1968) were considered and revised. Thirty-five samples were processed for chitinozoans, whereas conodonts were picked from 12 of these. All samples were productive. The specimens are relatively well preserved, however, about half of the chitinozoans are flattened. Some of the samples were too small to provide enough specimens, particularly of conodonts, to allow reliable identification of taxa. Moreover, evidently several biostratigraphically valuable taxa were not found because of the limited sample size.

Carbon isotopes were measured in 57 bulk rock and 22 brachiopod (shells) samples collected from the interval 1185–1208 m. The specimens of different taxonomic groups available were used for brachiopod analyses. Oxygen isotopes were also studied in brachiopod shells. The analyses were performed with the GasBench II preparation line connected to the Thermo Scientific Delta V Advantage mass spectrometer. The results are given in the usual δ-notation, as per mil deviation from the VPDB standard. The reproducibility of duplicate analyses was generally better than ±0.1‰.

BIOSTRATIGRAPHY

Brachiopods and notes on some trilobites

The Auleliai Fm. of restricted thickness and the Vilučiai Fm. yield relatively few brachiopods in the Pajevonys-13 core (Fig. 3). The long-ranging plectambonitid brachiopods *Sowerbyella* and *Eoplectodonta* together with orthide brachiopods *Nicolella* and *Platystrophia* are found in both formations. Relatively large dalmanellides (*Horderleyella*? sp.), possibly related to *Horderleyella*? *kegelensis oanduensis* Hints in northern Estonia, and *Leptaena* (*L.*) aff. *rugosoides* Oraspõld in the upper part of the Vilučiai Fm. (interval 1199.8–1202.8 m) indicate Keila age. Two trilobites, *Asaphus* (*Neoasaphus*) cf. *ludibundus* Törnquist and *Panderia* sp. mentioned by R. Männil (Männil et al. 1968), refer to the Haljala and Keila stages. The former species has various stratigraphical ranges in different parts of the basin and disappears in the Haljala (Ulst et al. 1982; Paškevičius 1997) or Keila Stage (Männil 1966; Rõõmusoks 1970). Trilobites of the genus *Panderia* are distributed in the deeper parts of shelves and occur most frequently in the Haljala Stage but also in the Keila Stage (Männil 1966). The Auleliai–Vilučiai boundary cannot be dated by shelly fossils in the Pajevonys-13 core.

The faunal renovation, marked by the appearance of the Oandu-type brachiopods of the genus *Boreadorthis* together with *Platystrophia* cf. *rava* Oraspõld, starts in the topmost Vilučiai Fm. Several other new species [*Howellites wesenbergensis* (Wysogorski), *Hedstroemina* cf. *inaequiclina* (Alichova), *Sampo suduvensis*, *Dolerorthis nadruvensis* (Paškevičius & Hints 2016), *Skenidioides* sp. A, *Parastrophina* sp., *Onniella* cf. *longa* Hints] appear in the Alvitas Fm. A similar renovation of brachiopod fauna in the Alvitas Fm. has been described from other sections in Lithuania (e.g. Krekenava-7: Paškevičius 1997; Kazimirovo-6 and Drūkšiai-5: Laškovas et al. 1993). The brachiopod association characteristic of the Alvitas Fm. occurs also in the overlying Šakiai Fm. In the latter formation the fauna is supplemented by a number of new taxa, including *Oanduporella reticulata*, *Reuschella magna* Hints and several species of the genus *Leptaena* (represented by frequent specimens). The brachiopod fauna achieves the highest diversity in the Šakiai Fm. and is identified as the *Howellites wesenbergensis–Hedstroemina subaequiclina–Reuschella magna* community of the open shelf facies BA4 (Paškevičius 2000). In the high diversity of taxa and abundance of specimens the fauna of the Šakiai Fm. in the studied section is most similar to that known as the *Sowerbyella–Howellites* fauna in the sense of Harper & Hints (2001) occurring in the Oandu Stage in northern Estonia (Põlma et al. 1988). However, several brachiopods (*Sampo suduvensis*, *Dolerorthis nadruvensis*, *Reuschella magna*, *Skenidioides* sp. A) are known only from the deeper parts of the shelves in Lithuania. The last two brachiopods occur also in central and southern Estonia (Mehikoorma-421 section: Hints 2005; Kaagvere and Otepää sections: Männil 1966).

In comparison with the underlying Šakiai Fm., brachiopods are rare in the Jakšiai Fm. (Fig. 3). *Sampo* cf. *hiiuensis* Öpik and small-shelled *Skenidioides* sp. appear in the lowermost and *Wysogorskiella litviensis* Hints is first found in the upper part of the Jakšiai Fm. The last species is probably an indicator of the appearance of a new brachiopod fauna in the basin. Its meaning for biostratigrapy is not clear. The age of the Jakšiai Fm. is based on the occurrence of the *Boreadorthis sadewitziensis–Rafinesquina* (= *Hedstroemina* in Cocks & Rong 2000) *inaequiclina* community (BA3) (Paškevičius 2000) in several sections in Lithuania (Krekenava-7, Svedasai-252: Paškevičius 1997; Kazimirovo-6, Drukšiai-5: Laškovas et al. 1993). This community comprises mostly the species common with the underlying Alvitas Fm. (Paškevičius 1997) and represents together with the *Howellites wesenbergensis–Hedstroemina subaequiclina–Reuschella magna* community the succession of ecologically similar biofacies.

Chitinozoans and graptoloids

Two K-bentonites, at depths of 1206.4 and 1208.1 m, are recognized in the Auleliai Fm. The chemical composition and the content of sanidine in these K-bentonites have not been analysed. The K-bentonite bed corresponding to the Kinnekulle K-bentonite is geochemically proven in northern Lithuania in the Kurtuvenai-166 drill core (Kiipli et al. 2007 and Tarmo Kiipli pers. comm. 2016). The correlation of K-bentonites, including the Kinnekulle K-bentonite (Bauert et al. 2014) on the lower boundary of the Keila Stage, is most probable in Lithuania. The chitinozoan species *Angochitina multiplex* (Shallreuter), which occurs exactly above the Kinnekulle K-bentonite in Estonia (Hints & Nõlvak 1999; Nõlvak 2008, fig. 6), is not found in the Pajevonys-13 section. However, the occurrence of *Belonechitina jaanussoni* Grahn & Nõlvak below the K-bentonite at a depth of 1208.1 m suggests that this bed might be the Kinnekulle K-bentonite (Bergström et al. 1995) and mark the lower boundary of the Keila Stage (Fig. 4). Up to now, *B. jaanussoni* has not been found above the Haljala Stage in the East Baltic sections (e.g. Männamaa-F367: Nõlvak 2008 and references therein). The occurrence of a graptoloid similar to *Amplexograptus maxwelli ukmergensis* Paškevičius in two samples at depths of 1207.8 and 1208.1 m (the lower Auleliai Fm.) supports the Keila age of the beds above the mentioned K-bentonite. This graptoloid has

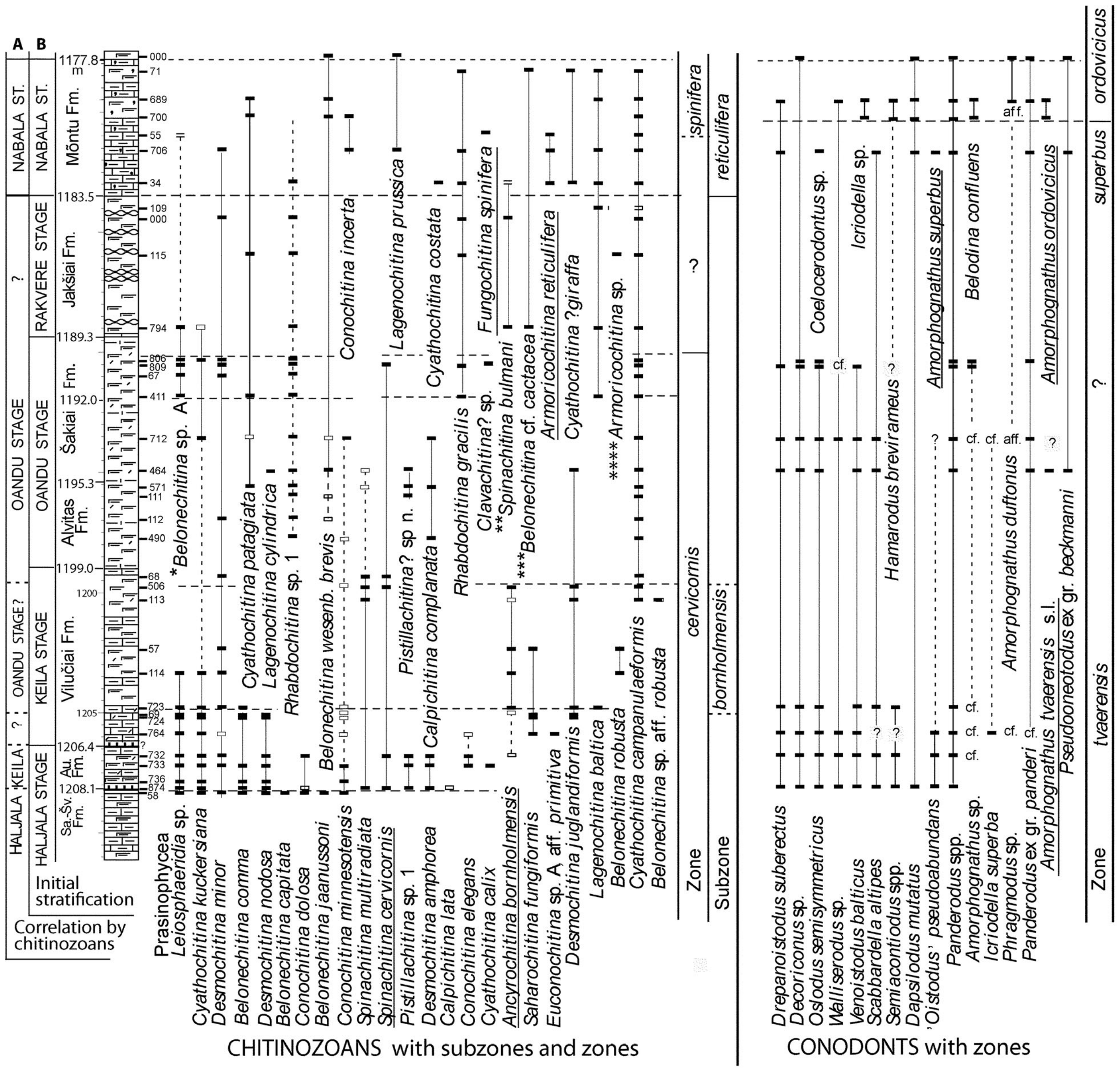

Fig. 4. Distribution of chitinozoans and conodonts, biozones and subzones in the Pajevonys-13 core. On the left side of the log: A, correlation of formations in terms of chitinozoans; B, as in Fig. 3. Chitinozoan species identified *sensu* Vandenbroucke et al. (2013) * *Belonechitina* sp. A as specimen in pl. 3, fig. i; ** *Spinachitina bulmani* as in pl. 2, figs h–m; *** *Belonechitina* cf. *cactacea* as in pl. 4, figs a, d; **** *Armoricochitina* sp. as in pl. 5, fig. h. For the lithological legend refer to Fig. 3.

been recorded from the stratigraphical level considered to be of Keila age (Paškevičius 2011, p. 55).

The chitinozoan fauna of the lowermost Vilučiai Fm. (interval 1206.4–1205.0 m) yields *Desmochitina nodosa* Eisenack, *Belonechitina comma* (Eisenack) – a specific curved form – and *Cyathochitina kuckersiana* Eisenack together with abundant prasinophycean *Leiosphaeridia* sp. Such an assemblage is characteristic of the Keila Stage and disappears in the Estonian Shelf just below the upper stage boundary, which is marked by a gap of some duration and a distinct faunal change (see Meidla et al. 1999). Therefore this interval could also belong to the Keila Stage, but is dated here with a question due to the occurrence of curved and slender forms of *Conochitina* cf. *minnesotensis* (Stauffer) and *Euconochitina* sp. A (aff. *primitiva*), which according to earlier data are not known from the Keila Stage. At the same time, mainly because of the absence of widely distributed *Belonechitina robusta* (Eisenack), these beds seem to be older than those of the Blidene Fm.

of the Keila Stage (Ainsaar et al. 2004) in South Estonia and Latvia. *Desmochitina juglandiformis* Laufeld and *Saharochitina fungiformis* (Eisenack) appear in the upper part of this interval, in the lowermost Vilučiai Fm. However, rare specimens of both species are found earlier, already in the Haljala Stage (Nõlvak 2001, 2008; Bauert et al. 2014).

No time-indicative taxa were found from a depth of 1200.3–1205.0 m (main part of the Vilučiai Fm.), therefore this interval can be dated here only tentatively. These beds contain *Ancyrochitina bornholmensis* Vandenbroucke & Nõlvak (= *Ancyrochitina* sp. 1 in Nõlvak 2001, 2003, 2008). The species is known also from poorly dated marls and black shales of the Blidene and Mossen formations, from the interval corresponding to the upper Keila and Oandu stages in southern and southwestern Estonia (Nõlvak 2001, 2003). However, it has not been found in the strata of Oandu age in northern Estonia (Nõlvak 2008). Most probably, this interval in the Pajevonys-13 core section represents strata which are older than the Hirmuse Fm. in North Estonia and correspond to the interval of a gap marking the boundary between the Keila and Oandu stages.

The chitinozoan assemblage in the uppermost Vilučiai to the lower Šakiai formations (interval 1192.0–1200.3 m), together with *Rhabdochitina* sp. 1 appearing here, is typical of the Oandu Stage (Hirmuse Fm.) in North Estonia, indicating that these beds correspond to the *Spinachitina cervicornis* chitinozoan Zone (ChZ), correlated with beds not younger than late Oandu in Estonian sections (Nõlvak & Grahn 1993; Nõlvak et al. 2006). However, rare specimens of *Pistillachitina*? sp. n. appearing in the middle part of this interval (Fig. 4) could be interpreted as a specific species of the Lithuanian Shelf.

Higher in the section the interval 1183.5–1192.0 m (upper Šakiai and Jakšiai formations) yields an assemblage of chitinozoans unknown in Estonian and Latvian sections. A similar assemblage occurs in the middle part of the *Dicellograptus* Shales on Bornholm Island, where black shale, evidently representing deeper-water environments than those in the East Baltic, are interpreted as belonging to the lowermost *Fungochitina spinifera* ChZ (Vandenbroucke et al. 2013, text-fig. 3: interval 3.5–4.5 m). Hence, the strata between 1183.5 and 1192.0 m could here represent a younger part of the Oandu Stage compared to Estonia and, most probably, correspond also to the *F. spinifera* ChZ. The absence of *Belonechitina robusta*, but particularly of zonal *Cyathochitina angusta* Nõlvak & Grahn, which are both very common in aphanitic limestones of the Rakvere Stage in Estonia, supports this interpretation. The chitinozoan data do not prove the Rakvere age of the Jakšiai Fm. in this section.

The base of the Nabala Stage (at a depth of 1183.5 m) is biostratigraphically well dated by the appearance of *Armoricochitina reticulifera* (Grahn) and some other species (Fig. 4). This boundary is easy to recognize in the entire East Baltic region (Männil & Meidla 1994; Nõlvak et al. 2006).

In general, according to chitinozoan data, the bases of the Keila and Nabala stages can be defined relatively precisely, but the base of the Oandu Stage and the presence or absence of analogues of the Rakvere Stage in the studied section remain problematic. The data available seem to suggest that the strata of Rakvere age are missing in the Pajevonys-13 core section. Based on chitinozoans, it is possible that the Vilučiai and Jakšiai formations are of Oandu age. This means that the lower and upper parts of the Oandu Stage might be represented here by beds that are missing (correspond to gaps) in North Estonia.

Conodonts

Conodonts were studied in 12 samples (Fig. 4). Although the samples were small (weights mainly between 100 and 200 g), all of them were productive. The fauna is dominated by long-ranging taxa [e.g. *Decoriconus* sp., *Drepanoistodus suberectus* (Branson & Mehl), *Panderodus* spp.], whereas age-diagnostic taxa are poorly represented and often difficult to identify. The occurrence of a younger form of *Amorphognathus tvaerensis* Bergström (*A. tvaerensis s.l.* in Fig. 4; earlier identified as *A. ventilatus* Ferretti & Barnes: Männik & Viira 2005, 2012) in the sample from 1194.9–1195.0 m (in the lowermost Šakiai Fm.) suggests that the interval below this level corresponds to the upper part of the *A. tvaerensis* conodont Zone (CZ). Rare occurrence of *Amorphognathus* and lack of *Baltoniodus* in that interval support this interpretation. In Estonia, *A.* '*ventilatus*' is characteristic of the Oandu Stage.

The only identifiable specimen of *A. superbus* (Rhodes) comes from the middle part of the Mõntu Fm. (sample 1181.7 m). The boundary between the *A. tvaerensis* and *A. superbus* CZs cannot be defined precisely in the Pajevonys-13 section because an interval of about 9 m between the uppermost *A. tvaerensis* and the lowermost *A. superbus* did not yield identifiable *Amorphognathus*. However, if the probable specimen of *Hamarodus brevirameus* from sample 1190.5–1190.6 m really belongs to this species, the boundary between these two biozones lies below that sample. Based on the current data from Estonia, *H. brevirameus* appears in the *A. superbus* CZ. In Estonia *A. superbus* appears in the upper Oandu Stage and occurs also in the Rakvere and lower Nabala stages (Männik & Viira 2012). The appearance of *A. ordovicicus* (Branson & Mehl) in the upper Mõntu Fm. correlates the topmost part of the studied interval in the Pajevonys-13 core with the *A. ordovicicus* CZ and suggests not older than the late Nabala age.

ISOTOPES

Carbon isotopes

General $\delta^{13}C$ changes in the Pajevonys-13 section (Fig. 3) are quite similar to those described earlier from the sections of the Estonian Shelf (Ainsaar et al. 2010). The main difference is that the Rakvere (Kope) excursion is evidently missing in the Pajevonys-13 section. However, in that sense this section is not an exception: the Rakvere excursion has not been identified also in sections located in the deeper part of the Estonian Shelf (Tartu-453, Ristiküla-174 and Viljandi-91: Ainsaar et al. 2010). As is known from earlier studies, the maximum values (up to 1.5‰) of the Guttenberg Isotope Carbon Excursion (GICE) have been detected in the uppermost Keila Stage (Baltic carbon isotopic zone BC6; Ainsaar et al. 2010). The $\delta^{13}C_{carb}$ excursion that starts in the lowermost Vilučiai Fm. in the Pajevonys-13 core section reaches its maximum values (1.57‰) in the upper half of the same formation, at a depth of 1203.3 m. The fast falling limb of the isotope excursion terminates in the uppermost Alvitas Fm. Higher up to the lowermost Mõntu Fm., the $\delta^{13}C$ values vary between 0.5‰ and 0‰.

The $\delta^{13}C$ curve that was revealed from the brachiopod shell carbonate has a somewhat different configuration, especially in the GICE interval, whereas the maximum values (2.68‰) occur at a depth of 1202.3 m. The peak values in both the $\delta^{13}C_{carb}$ and $\delta^{13}C_{brach}$ curves occur in a one metre interval, however, in the latter curve the falling limb of the GICE has higher values, is longer and reaches low background values in the uppermost Alvitas Fm. (Fig. 3). Based on these differences, two types of the GICE can tentatively be identified: (1) a relatively short one (corresponding to the Vilučiai Fm.) in the $\delta^{13}C_{carb}$ curve and (2) the excursion in the $\delta^{13}C_{brach}$ curve which is about two times longer than in the $\delta^{13}C_{carb}$ curve and has more than two times higher values. Lower values related to the bulk rock samples might be of diagenetic origin (Brenchley et al. 2003) and/or result from the high content of siliciclastic material in the samples. Our $\delta^{13}C$ data suggest that the Vilučiai Fm. (or most of it) in the Pajevonys-13 section is of Keila age, and the Alvitas and Šakiai formations are of Oandu age.

The Jakšiai Fm. is poorly studied for carbon isotopes. The data currently available indicate that the values in the $\delta^{13}C_{carb}$ curve start to increase in the upper part of the formation, whereas in the $\delta^{13}C_{brach}$ curve the falling trend continues through it. Too few isotope analyses are available for the interpretation of such controversial data.

In general, the $\delta^{13}C$ curve in the Pajevonys-13 core section is similar to that described from the Mehikoorma-421 section (Martma 2005). The falling limbs of the GICE in the $\delta^{13}C_{carb}$ curve in the Mehikoorma-421 section and in the $\delta^{13}C_{brach}$ curve in the Pajevonys-13 section reach the Oandu Stage. In both curves the lower boundary of this stage lies close to a level with somewhat lower values in the middle part of the falling limb. Analysing the Baltic data, Bergström et al. (2010) reached the same conclusion: the GICE ends in the middle part of the Oandu Stage. If the interval with strongly oscillating $\delta^{13}C_{brach}$ values in the Šakiai Fm. (Fig. 3) corresponds to the plateau recognized between the GICE and Rakvere excursions in the Mehikoorma-421 section, the Šakiai Fm. in Lithuania, middle part of the Variku Fm. in southern Estonia and the strata of Oandu age in the stratotype region of the stage in northern Estonia are approximately of the same age.

The shape of the $\delta^{13}C_{carb}$ curve in the Fjäcka section (Sweden; Bergström et al. 2011) (Fig. 5) is similar to

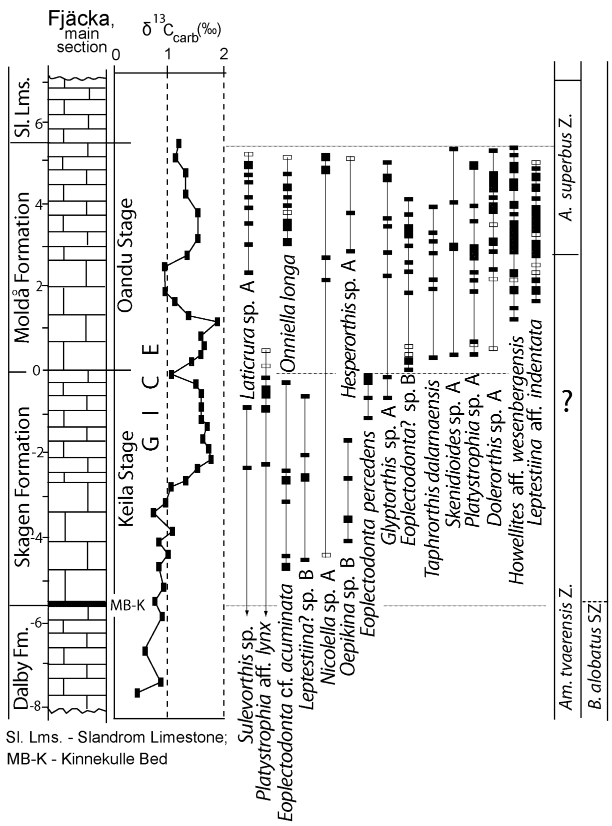

Fig. 5. Carbon isotopes, distribution of brachiopods and conodont biozones and subzones in the Fjäcka section, Sweden after Bergström et al. (2010, 2011) and Jaanusson (1982). MB-K, Kinnekulle K-bentonite.

that of the $\delta^{13}C_{brach}$ curve in the Pajevonys-13 section (Fig. 3). In the Fjäcka section the GICE has clearly two peaks with lower values between them at a level corresponding to the boundary between the Skagen and Moldå formations. In the Pajevonys-13 section the upper interval with higher values is poorly developed but still recognizable in the uppermost Vilučiai–lowermost Alvitas formations. The lower values in this curve, separating two parts of the GICE, occur in the uppermost Vilučiai Fm. The faunal data (see below) support the assumption about similar geochemical events in southern Lithuania and Sweden.

Oxygen isotopes

As demonstrated by earlier studies, the $\delta^{18}O$ profiles based on brachiopod shells are strikingly parallel to the $\delta^{13}C$ curves from the same sections and, hence, provide an additional tool for correlation (Brenchley et al. 1996, 2003; Marshall et al. 1997). This is also the case in the Pajevonys-13 section (Fig. 3). In all curves the excursion starts in the middle Vilučiai Fm., reaches maximum values in the upper part of the formation, falls to low values in the middle of the Alvitas Fm. and has another interval of higher values in the Šakiai Fm.

Oxygen isotopes have also been used as a proxy for sea-surface temperature (Trotter et al. 2008 and references therein) but, as demonstrated by e.g. Wenzel et al. (2000), the $\delta^{18}O$ data measured from brachiopod bioclasts are not suitable for such studies. The main reason is that shell calcite is prone to diagenetic alteration that is very difficult to detect even by means of special microstructural or geochemical investigations. Still, although our data evidently do not allow the identification of sea-surface temperature, the $\delta^{18}O_{brach}$ curve in Fig. 3 might give an idea about general trends in temperature changes. Overall continuous decrease in $\delta^{18}O_{brach}$ values starting from the Vilučiai Fm. evidently suggests a weak gradual warming of the sea surface water. The established $\delta^{18}O_{brach}$ values from –4‰ to –3‰ are considered to correspond to the temperatures 25–30 °C (Grossmann 2012; Brand et al. 2013), which is expected for the relatively stable equatorial temperature of the middle and late Ordovician. This agrees with data by Trotter et al. (2008) according to which, on the background of a general cooling trend in the Ordovician, the mid-Darriwilian–mid-Katian interval was a time of minor warming.

DISCUSSION

The dating of the late Sandbian–early Katian strata in the Pajevonys-13 core section using different biostratigraphical criteria allows no unequivocal identification of the boundaries of stages. Differences from the earlier interpretations and those suggested by brachiopods and chitinozoans concern the lowermost part of the studied interval, from the Haljala to Keila stages (Sartai-Šventupys, Auleliai and Vilučiai formations). Chitinozoans indicate that the interval from the uppermost Sartai-Šventupys Fm. to the upper Šakiai Fm. corresponds to the *Spinachitina cervicornis* ChZ. In Estonia this zone correlates with the uppermost Haljala, Keila and most part of the Oandu stages (Nõlvak et al. 2006). The occurrence of *Belonechitina jaanussoni* below the K-bentonite at a depth of 1208.1 m (in the lower boundary of the Auleliai Fm.) suggests that this K-bentonite might correspond to the bentonite marking the base of the Keila Stage in Estonia and, hence, the Auleliai Fm. might be of Keila age. However, the brachiopods *Porambonites schmidti* and *P. baueri*, together with *Bekkerina anijana anijana* reported from the Auleliai Fm. by Paškevičius (1997) in other sections, commonly occur in the Haljala Stage (Rõõmusoks 1970), although Männil (1966) has mentioned *P. schmidti* also from the Keila Stage in the Kalvaria-2 section in Lithuania.

Chitinozoans suggest the correlation of the lowermost Vilučiai Fm. (below 1205.0 m) with the Keila Stage (Fig. 4). However, the main part of this formation (up to 1200.3 m) yields a specific chitinozoan assemblage, which is probably younger than Keila in age (taxa characteristic of the Keila Stage are missing) but differs also from that characteristic of the Oandu Stage in northern Estonia. Earlier, a similar assemblage was recovered in the Valga-10 and Ruhnu-500 core sections in the Blidene and (lower) Mossen formations, tentatively correlated with the upper Keila and Oandu stages (Nõlvak 2001, 2003). Most probably the strata yielding this assemblage (characteristic of the *Ancyrochitina bornholmensis* ChZ) are missing (correspond to the gap between the Keila and Oandu stages) in northern Estonia.

The lowermost range of *A. bornholmensis* in the Pajevonys-13 section overlaps the distribution interval of *Leiosphaeridia* sp. (Prasinophycae), which disappears in the middle Vilučiai Fm. (Fig. 4). In the stratotype region in northern Estonia, *Leiosphaeridia* sp. always disappears below (or at) the lower boundary of the Oandu Stage. But, as in northern Estonia this boundary corresponds to a gap of considerable duration, and only the upper part of the stage is represented, the real disappearance level of abundant *Leiosphaeridia* sp. has been problematic. However, data from the Pajevonys-13 section suggest that *Leiosphaeridia* sp. does not reach the Oandu Stage also in deeper-water environments, or it disappears below the level of maximum $\delta^{13}C$ values. According to earlier investigations (Kaljo et al. 2007;

Ainsaar et al. 2010), the peak values of the GICE occur in the upper Keila Stage. This agrees with the brachiopod data suggesting that (most of) the Vilučiai Fm. corresponds to the Keila Stage. The occurrence of the ostracode *Sigmoopsis rostrata* (Krause) below 1202.0 m in the section (Männil et al. 1968) indicates also the Keila age (Meidla 1996). As is evident from above, the distribution of brachiopods and geochemical data, but also ostracodes, show that the Vilučiai Fm. (probably its uppermost part excluded, see below) corresponds to the Keila Stage. Chitinozoans from the lower part of the formation do not prove this dating but higher in the formation there appear species known from the Oandu Stage in the northern Baltic.

Rich brachiopod fauna characteristic of the Oandu Stage (e.g. *Howellites wesenbergensis*, *Hedstroemina* cf. *inaequiclina*, *Parastrophina* sp., *Onniella longa*) occurs in the Alvitas Fm. (Fig. 3). This agrees with earlier data suggesting that the faunal renovation usually takes place close to (just above) the peak values of the GICE. The chitinozoan assemblage characteristic of the Oandu Stage in northern Estonia (e.g. *Calpichitina complanata*, *Rhabdochitina* sp. 1, *Belonechitina wesenbergensis brevis*) also appears in the Alvitas Fm. The overlying Šakiai Fm. comprises the most diverse brachiopod fauna which, based on the occurrence here of e.g. *Kjaerina poljensis* (Alichova) and *H. wesenbergensis* (Fig. 3), is comparable with the fauna recognized in the Hirmuse Fm. (Oandu Stage) in northern Estonia (Rõõmusoks 1970). Hence, it is most probable that the Alvitas Fm. corresponds to an interval of Oandu age, which is not represented in northern Estonia. The lowermost part of the Šakiai Fm. has yielded *Amorphognathus tvaerensis s.l.* (Bergström) (earlier identified as *A.* '*ventilatus*'), known to occur in the Oandu Stage (Fig. 4).

A continuous gradual increase in brachiopod diversity upwards in the section takes place also in the Fjäcka outcrop, Sweden. Here the Skagen Fm. is of Keila age (Bergström et al. 2010), and its upper part corresponds to the lower half of the two-peaked GICE. The uppermost Skagen Fm. contains, for example, *Estoniops maennili* (Jaanusson & Ramsköld 1993) known from the Blidene Fm. (Keila Stage) in the East Baltic. The first brachiopods (*Howellites* aff. *wesenbergensis*, *Skenidioides* sp. A, *Dolerorthis* sp. A; Fig. 5) appear above the boundary between the Skagen and Moldå formations, in the interval corresponding to the upper part of the GICE. Brachiopod diversity also increases gradually and continuously upwards in the Fjäcka outcrop section of Sweden. The similarities of isotope curves and brachiopod faunas in the Fjäcka and Pajevonys-13 sections suggest that the lowermost Moldå Fm. and the Alvitas Fm. could be of the same age. The frequent and diverse brachiopod fauna in the upper part of the Moldå Fm. is comparable with that in the Šakiai Fm. in the Pajevonys-13 section. If the correlation above is correct, the Moldå Fm. in the Fjäcka section corresponds to the Oandu Stage as recognized in the Pajevonys-13 section, and its upper, post-GICE interval is of the same age as the strata of the stage exposed in northern Estonia.

As noted above, both chitinozoans and brachiopods allow the correlation of the Alvitas Fm. and main part of the Šakiai Fm. with the Oandu Stage but the dating of the Jakšiai Fm. is ambiguous. Earlier, the Jakšiai Fm. was correlated with the Rakvere Stage, although the brachiopod assemblage in this formation does not differ essentially from that occurring in the older strata (Paškevičius 1997). The Pajevonys-13 core section stands out for the low diversity of the brachiopod fauna in the Jakšiai Fm., in comparison with some other sections (Krekenava-7 and Svedasai-252) (Paškevičius 1997). The appearance of some brachiopods (*Wysogorskiella litviensis*, *Sulevorthis* sp., *Sampo* spp.) seems to indicate the beginning of the formation of a new brachiopod fauna in the middle of the Jakšiai Fm. Chitinozoans from the upper Šakiai Fm. and the Jakšiai Fm. represent an assemblage unknown in Estonian and Latvian sections. However, considering data from Bornholm (Vandenbroucke et al. 2013), this interval probably correlates with the lowermost *Fungochitina spinifera* ChZ and could represent a younger part of the Oandu Stage which is also missing in northern Estonia. The chitinozoan data available suggest that the strata of Rakvere age are missing in the Pajevonys-13 core section. This conclusion is supported by lack of any trace of the Rakvere excursion in the δ^{13}C curve.

The base of the Nabala Stage at a depth of 1183.5 m is well dated by chitinozoans (marked by the appearance of *Armoricochitina reticulifera* and some other species) in the lower Paekna (Mõntu) Fm. within the *Amorphognathus superbus* CZ (Fig. 4). This boundary is easy to recognize in the East Baltic region. In the upper part of the formation *Amorphognathus ordovicicus*, known to appear in the upper Nabala Stage in Estonia, was identified.

CONCLUSIONS

The presented overview of the late Sandbian–early Katian in the Pajevonys-13 drill core from the southern East Baltic revealed several problems in the stratification of the Katian deposits and questions about dating and faunal development which need future research. Based on our study, the following conclusions can be drawn.

1. Brachiopods and chitinozoans suggest different ages for the lower part of the studied interval, for the Auleliai and Vilučiai formations. Based on chitinozoans, the Auleliai Fm. is of Keila and the Vilučiai Fm. of Oandu age (Fig. 4). Based on brachiopods (Fig. 3), the Auleliai Fm. could be included in the Haljala Stage, as it has been used in stratigraphical practice in Lithuania.
2. According to chitinozoans, the strata of Rakvere age are probably missing in the studied section (Fig. 4). This conclusion is supported by $\delta^{13}C$ data: the Rakvere excursion that is known in the Rakvere Stage (in the Rägavere Fm.) has not been recorded in the Pajevonys-13 core (Fig. 3).
3. Chitinozoans suggest the probable occurrence of early and latest Oandu age strata, which are missing in the stratotype region in northern Estonia.
4. Only analogues of the Šakiai Fm., of the fossiliferous strata above the GICE with varying isotope composition, are preserved in northern Estonia, in the stratotype region of the Oandu Stage.
5. The magnitudes of the carbon isotope excursions compiled by bulk rock samples and brachiopod shell calcareous material differ essentially by up to 2‰ (Fig. 3).
6. The interval of the formation of the 'Oandu-type' brachiopod fauna correlates with the falling limb of the GICE.
7. Similarities in the brachiopod distribution and geochemical characteristics of the Pajevonys-13 section with the Fjäcka sections in Sweden (Fig. 5) allow the correlation of the Moldå Fm. with the Oandu Stage.
8. The *Ancyrochitina bornholmensis* and *Fungochitina spinifera* ChZs and *Amorphognathus tvaerensis* (upper part), *A. superbus* and *A. ordovicicus* CZs were identified.
9. Overall continuous decrease in $\delta^{18}O_{brach}$ values starting from the Vilučiai Fm. evidently suggests gradual warming of the sea-surface water. This agrees with data by Trotter et al. (2008) according to which, on the background of the general cooling trend in the Ordovician, the mid-Darriwilian–mid-Katian interval was a time of minor warming.

Acknowledgements. The authors thank D. Kaljo and the referees A. Dronov and L. R. M. Cocks for valuable comments and suggestions. T. Kiipli is acknowledged for useful information on K-bentonites. The study was financially supported by the Estonian Research Council projects PUT611 (for T. M.), PUT378 (for P. M. and J. N.) and Institute of Geology at Tallinn University of Technology (for L. H.). This study is a contribution to IGCP591.

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Ülem-Sandbi – Alam-Kati bio- ja kemostratigraafia Leedu Pajevonys-13 puursüdamikus

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On analüüsitud kolme faunarühma – käsijalgsete, kitiinikute ja konodontide – levikut ning neid esindavate liikide biostratigraafilist tähtsust Sandbi ja Kati globaalsete lademete piirialale vastavate Keila, Oandu ja Rakvere regionaalsete lademete identifitseerimisel Pajevonys-13 puursüdamikus Lõuna-Leedus. On esitatud läbilõikes eraldatud kihistute lühikesed kirjeldused. Biostratigraafilisi sündmusi, liikide koosseisu muutumist ja uuenemist on võrreldud paleokeskkonda iseloomustava hapniku ning süsiniku isotoopkoosseisu muutustega. Liikide ja isotoopkoosseisu muutused võimaldavad järeldada, et Leedus on Oandu lade stratigraafiliselt täielikum kui Põhja-Eestis, see tähendab, et uuritud piirkonnas on esindatud kihid, mis käsijalgsete ja kitiinikute koosseisu arvestades võiksid vastata Oandu lademe kõige vanemale osale, mis Põhja-Eestis puudub. Käsijalgsete ja kitiinikute andmed lubavad siiski teha mõnevõrra erinevaid järeldusi kihtide lademelise kuuluvuse kohta. Uuritud läbilõikes on kõige vähem andmeid Rakvere lademe kohta, samas on aga kitiinikute ja konodontide iseloomulike liikide ilmumisega markeeritud tase, mis tavaliselt märgistab Rakvere ja sellel lasuva Nabala lademe vahelist piiri. Kemostratigraafiliselt oluline nn Guttenbergi isotoopgeoloogiline sündmus (GICE) hõlmab Keila ja Oandu lademe piirikihte, sarnaselt Moldå kihistu Fjäcka paljandi läbilõikega Rootsis.