

## The succession of Hirnantian events based on data from Baltica: brachiopods, chitinozoans, conodonts, and carbon isotopes

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**Abstract.** The Hirnantian (late Ordovician) environment was complex and dynamic. Understanding the correct order of events and their precise correlation with a time scale are extremely important for the development of different kinds of environmental interpretations. The lower boundary of the Hirnantian Stage is officially defined by “the lowest occurrence of *Normalograptus extraordinarius*, the base of major positive carbon-13 isotope excursion, and the beginning of a pronounced sea-level fall associated with onset of a major glaciation” (ICS website). Our aim is to check if these events are synchronous, particularly how the situation is with respect to the Baltic. Thus several sections were analysed using mainly East Baltic data (drill cores), but also data from elsewhere, including brachiopod, chitinozoan, and conodont biostratigraphy combined with graptolite and carbon isotope data. Brachiopod faunas of the Pirgu and Porkuni stages are rather similar to those of the Ellis Bay Formation of Anticosti Island, Quebec, but the Pirgu assemblage, as well as that of the lower Ellis Bay Fm. lack key elements of the Hirnantian faunas. The primary criterion quoted above is stable, but auxiliary data like the isotope curve are less convincing. When the latter is used, it should be specified, e.g. that the carbon isotope excursion begins usually slightly earlier (in the *Diceratograptus mirus* Biozone), but it might be conventionally placed into the *N. extraordinarius* Biozone when a biostratigraphical proxy is available. The peak of the excursion is in the lower *N. persculptus* Biozone, but the main increase in values takes place in the *N. extraordinarius* Biozone. The *Spinachitina taugourdeau* Biozone marks at many localities the bottom of the Hirnantian, and only the recent chitinozoan–graptolite data from the topmost Lousy Cove Member (on Anticosti Island) suggest a mid-Hirnantian age, which is at variance with common correlation schemes.

**Key words:** Hirnantian, Baltica, brachiopods, chitinozoans, conodonts, graptolites, carbon isotopes.

### INTRODUCTION

The Hirnantian was only a short time interval (about 2 Myr) at the very end of the Ordovician, which has received a great deal of attention due to the coincidence of several highly important global events and processes. For example, a large-scale glaciation (a short-lived phenomenon or the peak of a long-lasting one), significant biodiversity changes (mass extinction or a series of extinction phases), and notable sea level drops (two or more events) are usually listed. However, related regressions-transgressions on the continents, changes in the weathering rate of carbonate platforms, and prominent positive carbon and oxygen isotope excursions also deserve to be mentioned. These and several other less known processes, triggered primarily by climate, interacted, creating a complex and dynamic Hirnantian environment.

A correct order of events (their succession and overlap) and their accurate positions in the Hirnantian time scale are extremely important in any interpretation of the palaeogeography and palaeoclimatology of this

time slice. To emphasize that the stratigraphical order of certain facts or proxies for processes plays a crucial role in deciphering Hirnantian history, we will analyse some real data mainly from the Baltic, but also data from elsewhere, including brachiopod, chitinozoan, and conodont biostratigraphy combined with some graptolite data. These data significantly contribute to our understanding of the real Hirnantian (stage and time); we will discuss its lower boundary, refinements of chitinozoan and conodont biozonations, and dating of the carbon isotope excursion.

In general, when discussing Hirnantian events, some authors pay insufficient attention to the detailed time succession of different aspects of the phenomenon. This may partly be due to the inadequate stratigraphical framework available, but more often it is due to a rather general approach where some crucial details may be neglected. We are not going to criticize any particular paper, but our aim is to demonstrate how a study can be made more detailed.

Definitions of the boundaries of the Hirnantian Stage are available on the official IUGS ICS website with

reference to respective publications in *Episodes* (Chen et al. 2006). The principal correlative events listed for definition of the lower boundary are especially interesting in regard to our topic (word-for-word citation from ICS web): “lowest occurrence of *Normalograptus extraordinarius*, base of major positive carbon-13 isotope excursion, and beginning of pronounced sea-level fall associated with onset of a major glaciation”. Such a list suggests that all these events should be synchronous, but is this right? What is the situation in the Baltic? We will concentrate our discussion on the first two.

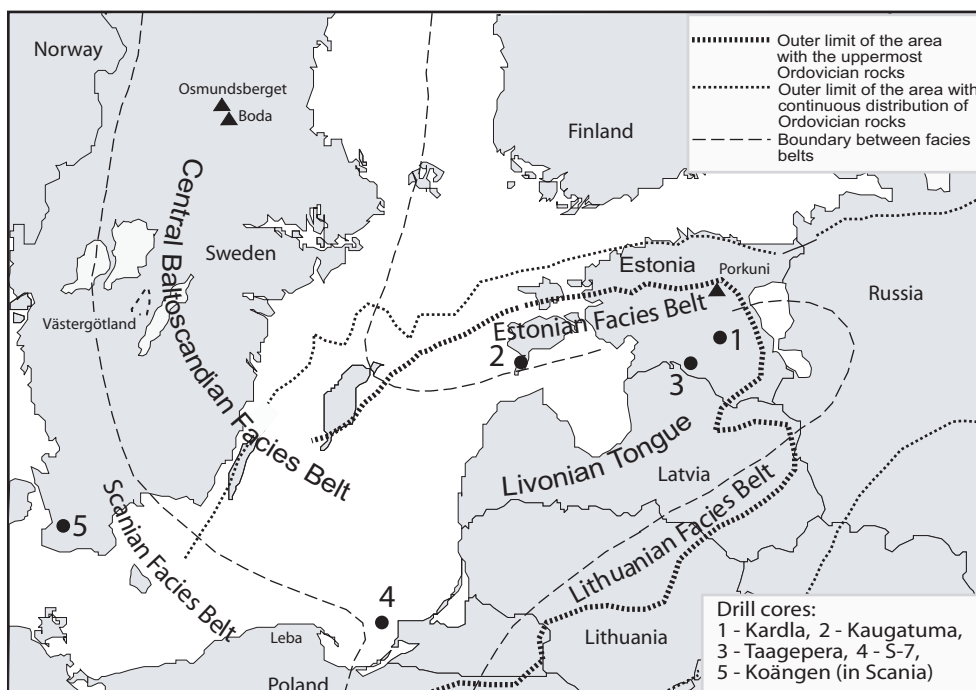
Although there has been great progress, we cannot be confident that the required precision in the dating of events has yet been achieved. For example, problems exist with the correlation of the boundary stratotype in China and the succession on Anticosti Island, Quebec, which implies that the environmental history of the Hirnantian remains problematic. Below, we present bio- and chemostratigraphical data from the East Baltic area (mainly Estonia and Latvia), which allow us to refine the dating of some crucial events and their correlation with other geological proxies. On the basis of the timing of these events, we suggest a correct, at least from a Baltic point of view, succession of the Hirnantian events that can be used for environmental studies.

The Baltic specimens of fossils and samples are housed at the Institute of Geology at Tallinn University of Technology (abbreviation GIT).

### GEOLOGICAL SETTING: FACIES AND STRATIGRAPHY

The position of the East Baltic (mainly Estonia and North Latvia) in the facies mosaic of the Palaeobaltic basin (sometimes called also the Baltoscandian basin; Jaanusson 1995), on the NW margins of the Baltica continent, is shown in Fig. 1. A more detailed background for our following discussion is readily available in a number of recent publications (e.g. Harris et al. 2004; Kaljo et al. 2004; Nestor & Einasto 1997).

An excerpt from the regional timescale, published by Nõlvak et al. (2006) and modified here for this paper (Fig. 2) forms the stratigraphical framework of the study. The chrono- and biostratigraphy is taken from the slightly modified original chart (graptolite zonation serves as a “left-hand” standard not as actual zones established in Estonia). Lithostratigraphy (formations) is from Harris et al. (2004), which also contains more general information on the facies belts. Current views



**Fig. 1.** Facies zones of the Palaeobaltic basin according to Männil (1966) and Jaanusson (1995) (modified). Scanian and Central Baltoscandian belts are pericontinental deep water facies belts with a Livonian shelf depression. Estonian and Lithuanian belts are shallower near-shore facies belts with an epicontinental extension into the mid-continent area (Moscow palaeobasin, Russia).

GLOBAL UNITS	REGIONAL STAGE	NORTH ESTONIAN FACIES BELT		CENTRAL BALTIC FACIES BELT	GRAPTOLITES ZONE	CHITINOZOANS ZONE & SUBZONE	CONODONTS ZONE
		NORTH ESTONIA	MIDDLE ESTONIA				
UPPER ORDOVICIAN	Hirnantian	Porkuni	[Stratigraphic columns for North and Middle Estonia]		Saldus	<i>N. persculptus</i>	Noixodontus fauna
			Ärina		Kuldiga	<i>N. extraordinarius</i>	
	Katian	Pirgu	Adila	Halliku	Kuili	<i>Dicellograptus anceps</i>	Amorphognathus ordovicicus
				Jelgava	Paroveja	<i>D. complanatus</i>	
	Moe		Jonstorp				
	Vormsi	Vormsi	Kõrgessaare	Tudulinna	Fjäcka	<i>Pleurograptus linearis</i>	
						<i>Acanthochitina barbata</i>	

Fig. 2. Stratigraphical framework based on the chart by Nölvak et al. (2006) (modified and with additions from Harris et al. 2004). Vertical ruling – hiatus.

(Brenchley et al. 2003; Hints et al. 2000; Kaljo et al. 2001, 2007; Nölvak et al. 2006) suggest that the Porkuni Regional Stage is a virtual equivalent of the Hirnantian Stage in the Baltic area. However, Melchin et al. (2003) and Melchin (2008) have correlated the Porkuni Stage with only the upper Hirnantian. The reasons for these contrasting correlations will be discussed below.

Two main facies belts have been distinguished in the Baltic (Fig. 1) – shallow-water facies in Central Estonia (with a gap below the Porkuni Stage and lacking its upper part) and deep-shelf facies in South Estonia and Latvia with minor hiatuses at the very top of the stage. Thus there exist two independent local stratigraphical schemes with chrono- and lithostratigraphical units (Fig. 2). The latter units are used here for demonstrating the facies distribution of fossil communities, whereas biozones are employed for their age determination. The biozonations of chitinozoans and conodonts are based on rich fossil collections, but graptolites are very rare (only single occurrences) in our part of Baltica, even if Hirnantian graptolitic rocks occur not far south of the Kurzeme Peninsula (western Latvia) in the Baltic Sea (Ulst 1992). Brachiopods belonging to the *Hirnantia* Fauna are found in the middle of the stage. The *Spinachitina taugourdeau* chitinozoan Biozone is known from the base of the stage. The last occurrences of the conodont *Amorphognathus ordovicicus* are recorded nearly from the same bed, but the main range of this species is much lower in the succession. Different other markers, including carbon isotope excursions, have been established above and below those listed, allowing a detailed dating of events. Several gaps interrupt the rock sequence of the study area, in particular on the periphery, although a reliable, nearly complete succession of biozones and carbon isotope trend has been compiled using overlapping sections, especially those from the deeper-water areas.

### EAST BALTIC BRACHIOPODS AND THEIR BEARING ON UNDERSTANDING THE HIRNANTIAN

Ordovician and Silurian biostratigraphy is dominated by graptolites and conodonts, partly also by chitinozoans, while only in certain intervals other groups like corals, trilobites, and thelodonts are employed. Information on brachiopod communities has been more valuable for palaeoecological studies (Boucot & Lawson 1999), but their stratigraphical status, when relevant, is well accepted. Good examples are the terms *Hirnantia*, *Foliomena*, and *Holorhynchus* faunas that are widely used when investigating the environmental history and stratigraphy of the uppermost Ordovician (Brenchley & Cocks 1982; Cocks & Rong 1988; Rong & Harper 1988; Rong & Li 1999; Zhan & Jin 2005; Jin & Zhan 2008). Several aspects of the *Hirnantia* Fauna concept (the low- and high-diversity assemblages respectively in shallow- and deeper-water environments, time constraints and diachroneity of distribution) analysed by these and other authors have developed a knowledge that allows evaluation of occurrences in different provinces. Using the late Ordovician brachiopods of Anticosti Island, Copper (2001) and Jin & Copper (2008) suggested a new correlation between the Anticosti and Estonian sections, which considerably enlarged the stratigraphic scope of the Hirnantian Stage. Below we proffer a few comments relevant to the Baltic data set.

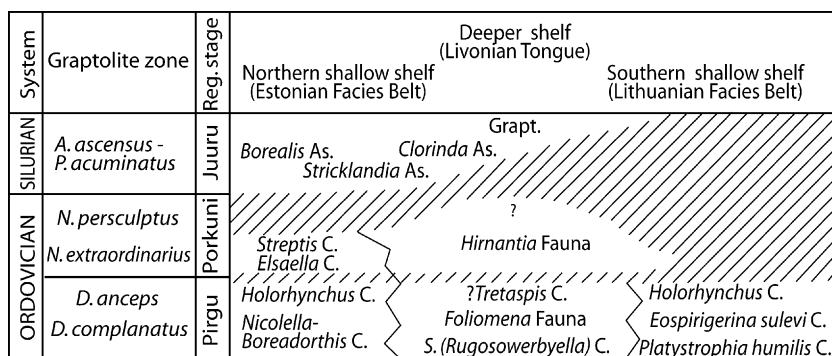
The latest Ordovician brachiopod assemblage in the East Baltic is rather diverse and the main core is well known, thus permitting the use of brachiopod data in this discussion. However, much data are scattered across a variety of stratigraphical publications (Jaanusson 1956; Männil 1966; Rõõmusoks 1967; Paškevičius 1996; Hints et al. 2000, 2005) and faunal overviews (Männil 1962; Hints & Rõõmusoks 1997), and therefore a modern taxo-

onomic revision is needed, especially of brachiopods from offshore facies. The generic composition of the latest Ordovician rhynchonelliformean brachiopod assemblages in the shallow shelf environments in the northern and southern East Baltic is essentially different from those in the deep shelf in the central part of the region (Harper & Hints 2001; Hints & Harper 2003). A community-level overview of brachiopod diversity and distribution is shown in Fig. 3; the most important taxa are illustrated in Fig. 4.

The number of species-level taxa identified in the Pirgu and Porkuni stages of the shallow shelf is about 80, 60 in the former and 20 in the latter stage. These figures show that the brachiopod diversity dropped considerably at the boundary between the stages marking the base of the Hirnantian in the Baltic (Fig. 2). In the deeper-shelf environments the low-diversity Pirgu brachiopod fauna was replaced in the Porkuni Stage by the shallower-water *Hirnantia* Fauna (BA3; Rong & Harper 1988; Rong & Li 1999).

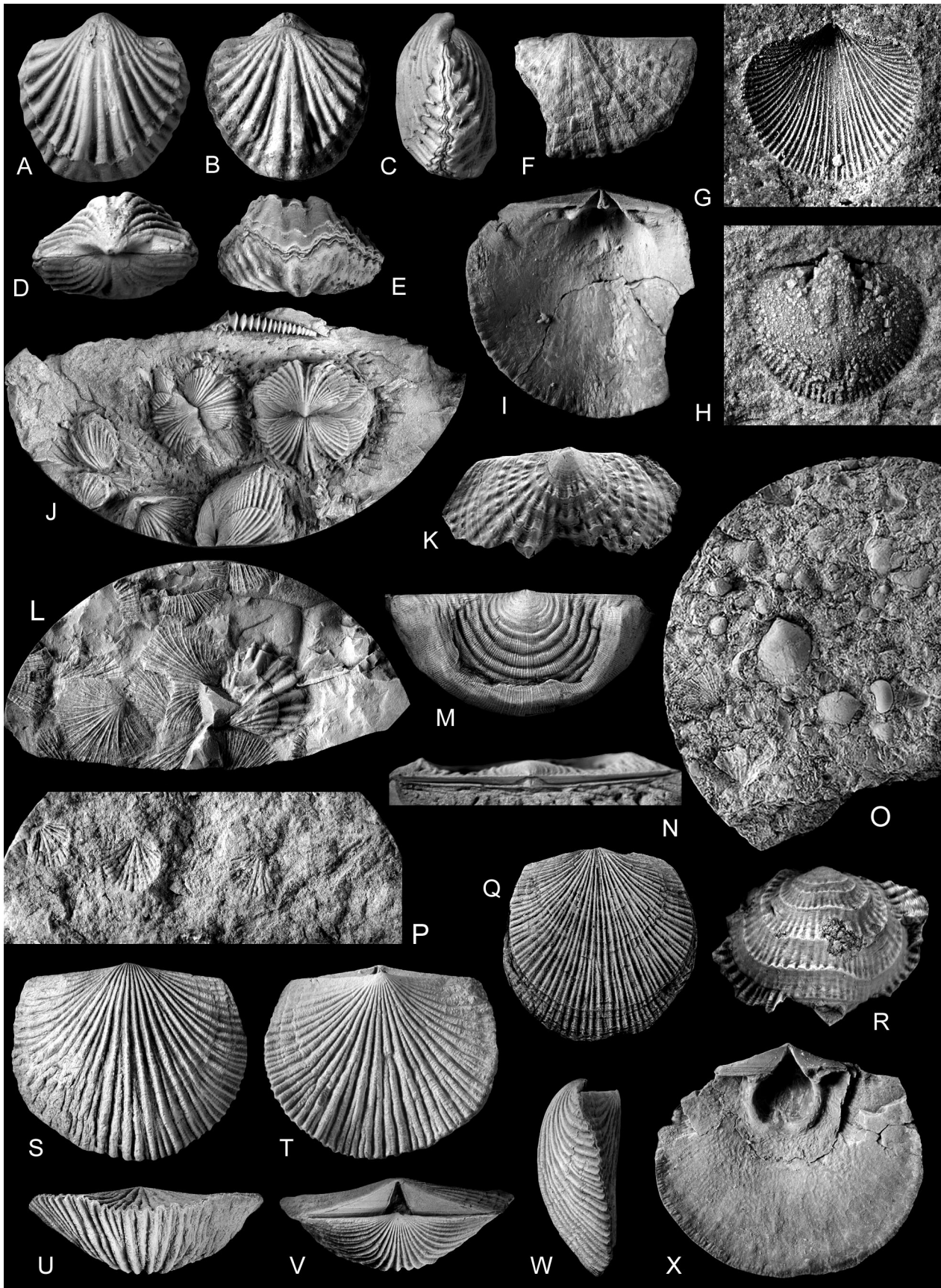
In the northern shallow-shelf environments rhynchonelliformean brachiopods of the Moe and Adila formations (further abbreviated Fms) of the **Pirgu Stage** (Fig. 2) belong to the *Nicolella–Boreadorthis* Community (“fauna” in Hints & Harper 2003), including also species of the genera *Plaesiomys*, *Platystrophia*, *Geniculina*, and *Eospirigerina*. This community occurs also in the underlying Vormsi Stage. Alikhova (1960) listed *E. sulevi* as an index species for the Pirgu Stage. It is the nominal species for the community established in the southern shallow shelf in Lithuania (Paškevičius 2000). In the last region the Vormsi–Pirgu interval comprises four communities: *Dinorthis* (= *Plaesiomys*) *solaris–Isorthis estona*, *Platystrophia humilis*, *Eospirigerina sulevi*, and *Holorhynchus*.

The *Holorhynchus* Community is distributed across a large area in the SE East Baltic, NW Belarus (Männil 1966; Ropot & Pushkin 1987; Kaljo & Hints 1996), and the westernmost Pskov region of Russia



**Fig. 3.** Distribution of the Late Ordovician – earliest Silurian brachiopod associations (As.), communities (C.), and faunas in the East Baltic. Inclined ruling – hiatus.

**Fig. 4.** Characteristic brachiopods from the Pirgu and Porkuni stages. **A–E**, *Eospirigerina sulevi* (Jaanusson in Alikhova et al. 1954), complete specimen GIT 574-1, holotype (Jaanusson 1956), views of shell exterior;  $\times 3$ ; northern Estonia, Niiby, Pirgu Stage. **F**, *Sowerbyella* (*Rugosowerbyella*) *rosettana* Henningsmoen, exterior of ventral valve GIT 542-13;  $\times 5$ ; West Latvia, Engure drill core, depth 904.1 m, Jonstorp Fm., Pirgu Stage. **G, H**, *Elsaella* sp., exterior and interior moulds of the ventral valve, GIT 542-7a and GIT 542-7b;  $\times 3$ ; western Estonia, Hiiu-maa Island, drill core K-38, dolostone of the Rõa Member of the Ärina Formation, Porkuni Stage. **I**, *Plaesiomys saxbyana* Oraspõld, interior of dorsal valve GIT 542-15;  $\times 1.2$ ; northern Estonia, Viru-Jaagupi, Vormsi Stage? **J**, sample GIT 542-3, bedding plane with shells of *Plectothyrella crassicoستا* (Dalman) and *Tentaculites*;  $\times 1$ ; West Latvia, Adze drill core, depth 838.5 m, Kuldiga Fm., Porkuni Stage. **K**, *Cliftonia* sp., incomplete ventral valve GIT 542-6;  $\times 2$ ; West Latvia, Vilcini drill core, depth 910.2 m, Kuldiga Fm., Porkuni Stage. **L**, sample GIT 542-5, bedding plane with *Eostropheodonta hirnantensis* (M’Coy) and *Plectothyrella* sp.,  $\times 1$ ; Kaliningrad region, Malinovskaya drill core, Porkuni Stage. **M, N**, *Leptaena rugosa* Dalman, ventral and posterior views of complete shell GIT 542-2;  $\times 1.2$ ; West Latvia, Vilcini drill core, depth 910.35 m, Kuldiga Fm., Porkuni Stage. **O**, sample GIT 542-4, bedding plane with ventral valve and fragments of *Hindella* sp.  $\times 1.2$ ; West Latvia, Aizpute drill core, depth 998.25 m, Kuldiga Fm., Porkuni Stage. **P**, sample GIT 574-2 with moulds of *Eospirigerina* sp.,  $\times 1$ ; easternmost Lithuania, Drukšiai (324) drill core, depth 358.4 m, Taučionys Fm., Pirgu Stage. **Q**, *Dalmanella testudinaria* (Dalman), view of dorsal valve,  $\times 2.5$ ; West Latvia, Engure drill core, depth 882.15 m, Kuldiga Fm., Porkuni Stage. **R**, *Streptis undifera* (Schmidt), view of dorsal valve GIT 230-4 (Br 4334),  $\times 1$ ; western Estonia, Kännu village, loose material in quarry, Porkuni Stage. **S–W**, *Plaesiomys saxbyana* Oraspõld, views of complete shell GIT 542-14;  $\times 1.2$ ; northern Estonia, Viru-Jaagupi, Vormsi Stage? Distribution range of *P. saxbyana* comprises the Nabala to Pirgu stages (Oraspõld 1959). **X**, *Hirnantia sagittifera* (M’Coy), interior of ventral valve GIT 542-1;  $\times 1.2$ ; West Latvia, Piltene-30 drill core, depth 938.00 m, Kuldiga Fm., Porkuni Stage.



(Brenchley et al. 1997). In Estonia it has a restricted distribution, occurring in the Pirgu rocks below the reef complex of the Porkuni Stage (Hints 1993). In Sweden (Siljan) *Holorhynchus* was found in the flank deposits of the Boda Limestone in Osmundsberget (Jaanusson 1982a), where it is characterized, as in the East Baltic and Norway, by low values of  $\delta^{13}\text{C}$  indicating a pre-Hirnantian age of the strata yielding this brachiopod (Brenchley et al. 1997).

The deep shelf mottled and red-coloured marl- and limestones of Pirgu age (Jonstorp and Kuili Fms) with a light-coloured limestone unit (Paroveja Fm.; Fig. 2) contain a low-diversity fauna. A specific association of brachiopods including *Sowerbyella* (*Rugosowerbyella*), *Sampo?*, and several *Tretaspis* group trilobites (Ulst et al. 1982) is characteristic of a facies with the red varieties of rocks. Roughly contemporaneous strata in Sweden (Jonstorp Fm. in Västergötland, Jaanusson 1982b; Jerrestad Mudstones in Scania, Sheehan 1973) contain the *Foliomena* Fauna brachiopods. In contrast to the absence of organic-walled fossils (chitinozoans, graptolites, scolecodonts) in red-coloured sediments (Nölvak 2001), the light limestones of the Paroveja Fm. (Fig. 2) contain several species of graptolites [*Climacograptus angustus* (Perner), *Rectograptus gracilis* (Roemer), *R. pauperatus* (Elles & Wood); Ulst et al. 1982].

The brachiopod fauna of the marls and argillaceous limestones (Tootsi and Halliku Fms; Fig. 2) in the shallow to deep shelf transition is dominated by small-shelled taxa like *Sampo?*, *Eospirigerina*, *Sulevorthis*, *Dicoelosia*, *Skenidioides*, and *Kullervo* (Hints & Harper 2003). In showing similarity to the deep-water *Dicoelosia*–*Skenidioides* Community (Boucot 1975; Sheehan 1987), this fauna seems to be closely related to the geographically widespread *Foliomena* Fauna (Harper 1979; Rong et al. 1999; Zhan & Jin 2005; Jin & Zhan 2008). Faunal turnover at the end of Pirgu time led to the disappearance of many taxa in both the shallow and deep shelf areas (Kaljo et al. 1988; Nestor et al. 1991).

In the shallow shelf environments of central Estonia the topmost Ordovician **Porkuni Stage** is represented by a complex of stromatoporoid-coral patch reefs with inter-reef rocks, which overlie dolostones of restricted thickness. At some localities the complex is capped by sandstone and/or oolitic limestone beds constituting all together the Ärina Fm. (Oraspöld 1975; Hints et al. 2000). The fauna is comprised of separate associations (Fig. 3) which are made up of two components – survivors from the Pirgu Stage [*Barbarorthis porkuniensis* Oraspöld, *Thaerodonta nubila* Rõõmusoks, *Pirgumena martnai* Rõõmusoks (= *Eostropheodonta martnai* of Cocks & Rong 2000)] and some specific, short-lived species like *Elsaella bekkeri* a.o., restricted to some part of the Porkuni

Stage. Brachiopods of the genus *Elsaella*, in association with *Thaerodonta*, crinoids, and corals, make up the *Elsaella* Community (Fig. 4) in the early Porkuni dolostones. The *Streptis undifera* Community with leptaeninids, strophomeninids, and the last clitambonitids *Vellamo* and *Ilmarinia* occurs in different lithological varieties of the reef complex, where the carbon isotopes show increase in values upwards up to about 4‰ (Hints et al. 2000). *Streptis undifera* (Schmidt) is known also in Norway in somewhat older strata (in unit 5a correlated with the Pirgu Stage) than in Estonia (Wright 1965). According to recent  $\delta^{13}\text{C}$  and conodont data by Schmitz & Bergström (2007), the uppermost Boda Limestone together with the overlying Glisstjärn Fm. is of Hirnantian age (Ebbestad & Högström 2007a). That is also consistent with the early Hirnantian age of the rocks forming the Porkuni Stage in central Estonia (see below).

A transition from the shallow shelf carbonate rocks of the Porkuni Stage in the north (Fig. 1) to the deeper shelf sections is insufficiently known due to the scarcity of fossils in the southern periphery of the Ärina Fm. (Kaljo & Hints 1996) and/or complete absence of those transitional strata (Oraspöld 1975). Siliciclastic carbonates of the Kuldiga and Saldus Fms (Fig. 2; Oraspöld 1975; Ulst et al. 1982) in the central East Baltic, which are correlated with the shallow shelf sections mainly by chitinozoans and isotope data, contain a rather different macrofauna. There occur several key elements of the *Hirnantia* Fauna – *Hirnantia sagittifera* (M'Coy) and *Dalmanella testudinaria* (Dalman), but also representatives of the genera *Plectothyrella*, *Hindella*, *Leptaena*, and some others (Hints & Harper 2003), whose detailed taxonomic composition and distribution of species require additional study. Hirnantian brachiopods appear in the lowermost Porkuni Stage, in or above the *Spinachitina taugourdeaui* chitinozoan Biozone. The drill core data show that the maximum diversity of fossils, such as rhynchonelliformean and lingulate brachiopods, gastropods, tentaculitids, and calcareous algae, is in the lower half of the Kuldiga Fm., which is also characterized by high carbon isotope ( $\delta^{13}\text{C}$ ) values. Noteworthy is the occurrence of nautiloid conchs and specific echinoderm columnals (Fig. 4) in the lowermost Kuldiga Fm. at the same stratigraphical level in several sections. Large numbers of nautiloids are known from the Glisstjärn Fm. (Ebbestad & Högström 2007b), however, there is no biostratigraphic proof for their contemporaneous abundance in different parts of the Baltic basin.

Brachiopods have not been found in the youngest Ordovician dolomitic sandy and oolitic limestones in the uppermost Ärina Fm. in Estonia and of the Saldus Fm. in the Central East Baltic (Fig. 2). The latest Ordovician is biostratigraphically dated in the westernmost Baltic

section (drill core S-7; Ulst 1992), where strata with some *Hirnantia* brachiopods are overlain by graptolite-bearing rocks, most likely of the *Normalograptus extraordinarius* Zone (Fig. 5). Podhalanska (2003) reported the same sequence of beds and fossils from the Leba area (North Poland).

### Comparison of the latest Ordovician brachiopod assemblages of the East Baltic and Anticosti Island

The rich and diverse shelly fauna of brachiopods, stromatoporoids, corals, bryozoans, molluscs, and trilobites in the Ellis Bay Fm. of Anticosti Island has long attracted the interest of scientists. Recently Jin & Copper (2008) analysed the response of brachiopod communities to environmental changes at the very end of the Ordovician and reached some paradoxical conclusions (their expression). Their conclusions urged us to check how these appear in the Baltic.

Outlining briefly the main results of the Jin & Copper (2008) paper, we can note the following: (1) The Ellis Bay brachiopod assemblage differs from preceding associations and, based on the taxonomical and community structure, can be subdivided into two parts. The lower Ellis Bay is rich and diverse (cf. fig. 2 in Jin & Copper 2008), strongly contrasting with the

poorly diverse upper Ellis Bay beginning with the Lousy Cove Member (Mb.). (2) Eight associations have been identified: *Onniella* occurring through the whole of the Ellis Bay Fm., while most of the other associations – *Plaesiomys*, *Hindella*, *Parastrophinella*, and *Barbarorthis* – are limited to the lower Ellis Bay, the short-lived *Gnamptorhynchos* and *Orthorhynchyllion* associations are confined to the top of the lower Ellis Bay, and the *Mendacella* Association appears in the Lousy Cove Mb. (3) The taxonomic content (species and genera) of brachiopods by members is very much in the same line as by associations, but the difference between the lower and upper Ellis Bay is perhaps less drastic because six taxa are from the lower Ellis Bay within the *Onniella* Association (Jin & Copper 2008, table 1, sample A94).

The entire picture seems to be in great harmony with the environmental changes recorded at the end of the Ordovician, and only the dating of the lower Ellis Bay Fm. as of Hirnantian age should be reconsidered. New results of Ordovician studies in Anticosti reported at Lille IGCP 503 meeting (Achab et al. 2008; Desrochers et al. 2008) make it clear that the problems in dating the Ellis Bay and other formations will be soon solved. A comparison with the Baltic late Ordovician including brachiopods can be informative and may help to achieve a well-defined stratigraphical classification and correlation.

Several brachiopod associations identified in the Ellis Bay Fm. include the genera *Hindella* and *Eospirigerina*, which Jin & Copper (2008) considered as indicators of Hirnantian age. Both genera are well known also in the Baltic, even if previously some different names were applied. The species *Plectatrypa* (= *Eospirigerina*) *sulevi* (see Jaanusson 1956) (Fig. 4A–E) was formally described and published by T. N. Alikhova in Alikhova et al. (1954) from the Pirgu Stage. However, that species first appears in the lowermost part of the Vormsi Stage (Aulepa old quarry; Meidla et al. 1990). *Eospirigerina* *sulevi* is not found in the reefs of the Porkuni Stage in northern Estonia, but the genus *Eospirigerina* occurs in the central East Baltic, in red-coloured rocks of the Pirgu Stage and in the lowermost part of the Kuldiga Fm. of the Porkuni Stage (Hints et al. 2005). Brachiopods of the genus *Hindella* (Fig. 4O) are common in the central East Baltic (southern Estonia, western Latvia and Lithuania) in siliciclastic carbonate rocks of the Kuldiga Fm. containing brachiopods of the *Hirnantia* Fauna. Rare occurrences have been reported also from the pre-Hirnantian Adila Fm. in North Estonia (Jaanusson 1956). In conclusion, in the East Baltic the brachiopods *Eospirigerina* and *Hindella* belong most commonly to associations dwelling in different environments and their main distributional ranges are not contemporaneous.

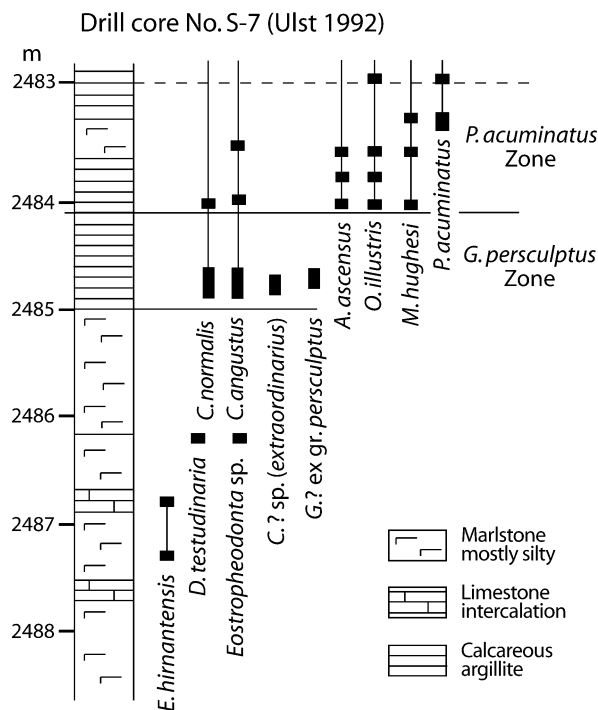


Fig. 5. Relationships of the *Hirnantia* Fauna and graptolitic Hirnantian in the drill core S-7 in the south of the Baltic (according to Ulst 1992). Original nomenclature is retained.

Brachiopods of the former genus were more common in pre-Hirnantian and the latter genus in Hirnantian time.

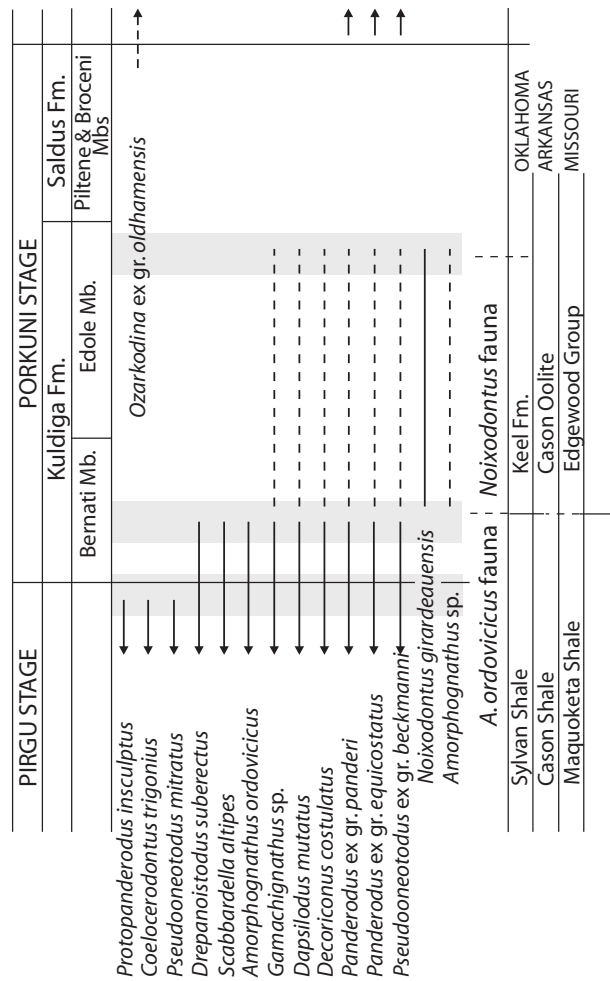
The Pirgu Stage in northern Estonia has several genera in common with the Ellis Bay Fm. Besides *Eospirigerina* there occur *Plaesiomys* (known also under the name *Dinorthis*, Fig. 4I, S–W), *Vellamo*, *Thaerodonta*, *Barbarorthis*, *Platystrophia*, *?Hebertella*, and *?Mendacella* (Öpik 1934; Oraspõld 1959; Rõõmusoks 1964, 1981). These genera do not belong to the typical *Hirnantia* Fauna. Some of the common taxa have been considered as opportunistic, appearing suddenly in the lower Ellis Bay from offshore regions (Jin & Zhan 2008). An essentially narrowed Iapetus ocean (Fortey & Cocks 2003) presumably was not a too serious barrier for brachiopod migration, however, the timing of brachiopod appearance in another region depends of the correlation of sections.

High biodiversity and the lithofacies successions of Pirgu time in the Baltic Basin and in the Anticosti Basin during the formation of the Ellis Bay rocks indicate a marked similarity in environments. Considering also the common brachiopod genera, two different conclusions can be reached: (1) the lower and middle parts of the Ellis Bay Fm. are of pre-Hirnantian age, or (2) similar environments and faunas developed in different basins in different, pre-Hirnantian and Hirnantian times. Because several data, among them the carbon isotope and other data discussed below, but also acritarchs reported by Delabroye et al. (2008) indicate the possibility that most of the Ellis Bay Fm. (below the upper Lousy Cove Mb.) is of pre-Hirnantian age, we would prefer the first interpretation.

**PIRGU–PORKUNI CONODONTS: BIOZONATION AND SOME CORRELATIONS**

The youngest Ordovician strata have been studied in two core sections of Estonia, Valga-10 and Ruhnu-500 (these are the official names but below we have removed the numbers), located, respectively, in the S and SW parts of the region (Männik 2001, 2003). The distribution of the latest Ordovician conodonts in these sections is summarized in Fig. 6 and the detailed occurrences in the Valga section are shown in Fig. 7. Some key taxa from the latter section are figured in Fig. 8.

The Pirgu Stage (Upper Katian) is characterized by rich faunas. The ranges of taxa are relatively continuous up to the lowermost Porkuni Stage (up to the lower Bernati Mb. of the Kuldiga Fm.; Fig. 7). Above this level, in the Edole Mb., the number of conodont specimens in samples decreases considerably, occurrences of taxa

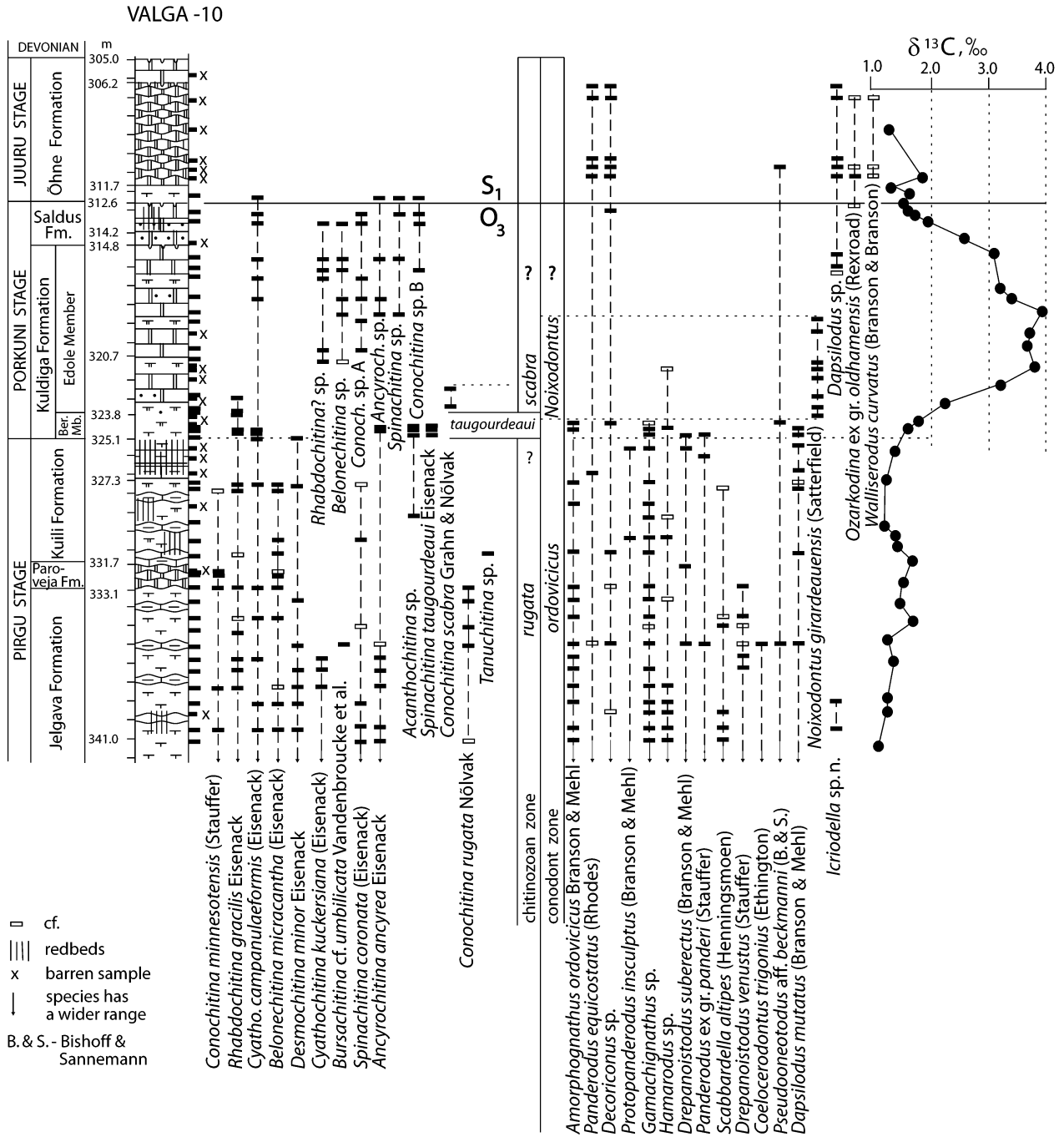


**Fig. 6.** General distribution of selected taxa and main levels of changes in the uppermost Ordovician conodont succession in Estonia correlated with data of Barrick (1986) from the central United States. Grey intervals – intervals where main changes (events) in conodont succession are recorded. Arrows indicate that a taxon occurs also below and/or above the illustrated interval. Dashed lines – occurrences are sporadic.

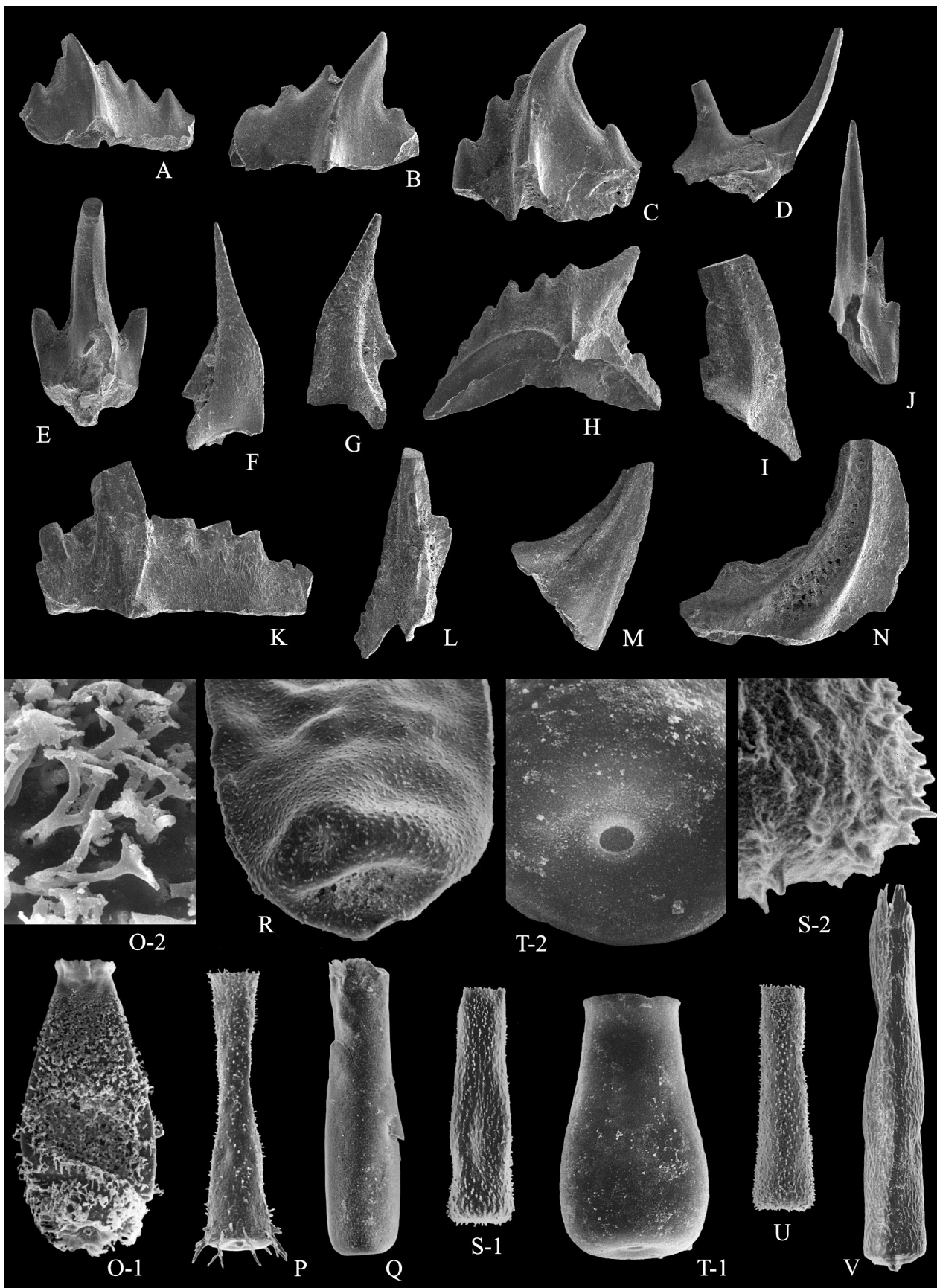
become sporadic (Fig. 6), and the preservation of specimens is often too poor to allow reliable identification of species. Sedimentologically, the Edole Mb. formed during a continuous shallowing of the basin, as part of a major Late Ordovician regression. According to Harris et al. (2004), this interval corresponds to the HST of the Upper Ordovician Sequence 7 in Estonia.

Due to the rare and sporadic occurrence of taxa, events in the conodont succession (real LADs of taxa) are difficult to locate. Nevertheless, three levels of changes (LADs) are noted in the latest Ordovician conodont succession: (1) At the top of the Pirgu Stage *Protopanderodus*, but probably also *Coelocerosodus* and





**Fig. 7.** Distribution of conodonts and chitinozoans in the Valga core section, their zones and relationship with the carbon isotope curve. Lithologic symbols as for Fig. 9. Chitinozoans from the interval 312.5–320.7 m are poorly preserved and special study is needed. These include (possible reworking should be considered) a few forms passing into the lowermost Silurian (*Cyathochitina*, *Ancyrochitina*), others are limited to the Ordovician. Note that barren samples are confined to redbeds (e.g. uppermost Pirgu) or caused by dolomitization. Ber. Mb. – Bernati Member.



*Pseudooneotodus mitratus* (Moskalenko), disappeared. (2) In the Bernati Mb. (lowermost Porkuni Stage) conodonts of the so-called *Amorphognathus ordovicicus* Fauna, which is characteristic of the Pirgu Stage, became rare or disappeared. However, due to the limited size of samples it is difficult to tell which taxa (if any) really became extinct during this event. In both the studied sections *Noixodontus girardeauensis* appears just above this level. (3) In the upper part of the Edole Mb. most of the typical Ordovician conodonts, including *Noix. girardeauensis*, disappeared. The end-Ordovician event was survived mainly by some simple-cone taxa (e.g. *Panderodus* ex gr. *equicostatus*, *P.* ex gr. *panderi*, *Pseudooneotodus* ex gr. *beckmanni*).

Conodonts are very rare in the uppermost Porkuni Stage, probably due to unsuitable ecological and/or sedimentological (preservation) conditions. Lithologically highly variable rocks (oolites, sandstones, microlaminated siltstones with mud cracks) of the Saldus Fm. originated during a general sea level lowstand (= LST of sequence S1 *sensu* Harris et al. 2005) in the basin. Only a couple of conodont specimens (*Decoriconus* sp., *Dapsilodus?* sp.) were found in these strata in the Valga core (Fig. 7). Also the oldest specimens of *Ozarkodina* ex gr. *oldhamensis* come from this formation.

In terms of the conodont biostratigraphy, the strata above the level of disappearance of identifiable *Am. ordovicicus* in Estonia correspond to the “*Noixodontus* fauna” (Nölvak et al. 2006). A sparse fauna characterized by *Noix. girardeauensis* was identified by Barrick (1986) from the lower oolitic-skeletal and laminated beds of the

Keel Limestone in southern Oklahoma and the Cason oolite in northern Arkansas. Barrick (1986) noted the co-occurrences of *Noix. girardeauensis* and the Hirnantian shelly faunas in the central United States and, considering also the position of *Noix. girardeauensis* in the Yukon graptolite sequence, concluded that most probably *Noix. girardeauensis* is restricted to the Hirnantian interval.

In Anticosti Island, the strata up to the middle part of the Laframboise Member (Member 7; top of the Ellis Bay Fm.) are correlated with the *Am. ordovicicus* conodont Zone, followed by the *Ozarkodina hassi* Zone above (Bergström et al. 2006). However, the uppermost specimens of *Am. cf. ordovicicus* are from the lower part of the Velleda Mb. (Member 3) of the Ellis Bay Fm. (McCracken & Barnes 1981). Above this level, up to the appearance of Silurian-type conodont faunas [with *O. hassi* (Pollock, Rexroad & Nicoll), *O. oldhamensis*, etc.] *Oulodus*, *Aphelognathus* (both missing in Estonia), and *Gamachignathus* become the most common conodonts. *Noixodontus* has not been found in this region. Due to the faunal differences, detailed correlation based on conodonts between Anticosti Island and Estonia is difficult. Based on the data above, but also these in Bergström et al. (2006), most probably at least part of the Laframboise Mb. of the Ellis Bay Fm. on Anticosti Island corresponds to the Saldus Fm. in Estonia. This agrees with carbon isotope data (see below), but chitinozoans only bracket the Laframboise Mb. at the bottom and the top (Soufiane & Achab 2000; Achab et al. 2008). The occurrences of *Gamachignathus*, low in the Grind-

**Fig. 8.** Selected conodonts (all from the Valga-10 core section) and chitinozoans. **A–E, J**, *Noixodontus girardeauensis* (Satterfield). **A**, GIT 573-1, outer lateral view of dextral Pa element, 323.35–323.50 m,  $\times 100$ . **B**, GIT 573-2, outer lateral view of sinistral Pa element, 323.80–323.95 m,  $\times 100$ . **C**, GIT 573-3, outer lateral view of sinistral Pb? element, 323.80–323.95 m,  $\times 100$ . **D**, GIT 573-4, inner lateral view of sinistral Sc element, 323.80–323.95 m,  $\times 100$ . **E**, GIT 573-5, posterior view of Sa element, 321.35–321.50 m,  $\times 100$ ; **J**, GIT 573-6, posterior view of dextral Sb element, 323.80–323.95 m,  $\times 100$ . **F–H**, *Amorphognathus ordovicicus* Branson & Mehl. **F**, GIT 573-7, inner lateral view of sinistral M element, 324.00 m,  $\times 100$ ; **G**, GIT 573-8, inner lateral view of dextral M element, 324.00 m,  $\times 100$ . **H**, GIT 573-9, outer lateral view of sinistral Pb element, 324.00 m,  $\times 100$ . **I, K, L**, *Gamachignathus* sp. **I**, GIT 573-10, inner lateral view of sinistral M element, 324.95–325.05 m,  $\times 70$ . **K**, GIT 573-11, outer lateral view of dextral Pa element, 324.95–325.05 m,  $\times 100$ . **L**, GIT 573-12, posterior view of dextral Sb element, 324.95–325.05 m,  $\times 70$ . **M**, *Scabardella* cf. *altipes* (Henningsmoen), GIT 573-13, lateral view, 324.00 m,  $\times 70$ . **N**, *Protopanderodus insculptus* (Branson & Mehl), GIT 573-14, lateral view, 325.50–325.60 m,  $\times 70$ . Chitinozoans (from different core sections). **O-1**, *Acanthochitina* sp. GIT 573-15, Elva core, 272.6 m, partly flattened specimen (from the *taugurdeau* Zone),  $\times 140$ . **O-2** same specimen, detail of ornamentation,  $\times 675$ . **P**, *Spinachitina taugurdeau* (Eisenack), GIT 306-14, Undva core, 152.4 m,  $\times 165$ . **Q, R**, *Conochitina scabra* Grahn & Nölvak. **Q**, GIT 573-16, Tartu core, 188.7–188.8 m,  $\times 165$ . **R**, GIT 573-17, Ohesaare core, 448.0 m, detail of the basal part,  $\times 420$ . **S, U**, *Belonechitina gamachiana* Achab. **S-1**, GIT 573-18, Kaugatuma core, 346.9 m,  $\times 145$ . **S-2**, same specimen, detail of the basal part,  $\times 360$ . **U**, GIT 573-19, Kaugatuma core, 344.4 m,  $\times 145$ . **T-1**, *Bursachitina umbilicata* Vandenbroucke, GIT 573-20, Kaugatuma core, 352.6 m,  $\times 430$ . **T-2**, same specimen, detail of the base,  $\times 1050$ . **V**, *Conochitina rugata* Nölvak, GIT 573-21, Hagudi core, 24.3 m, with partly broken aperture,  $\times 150$ .

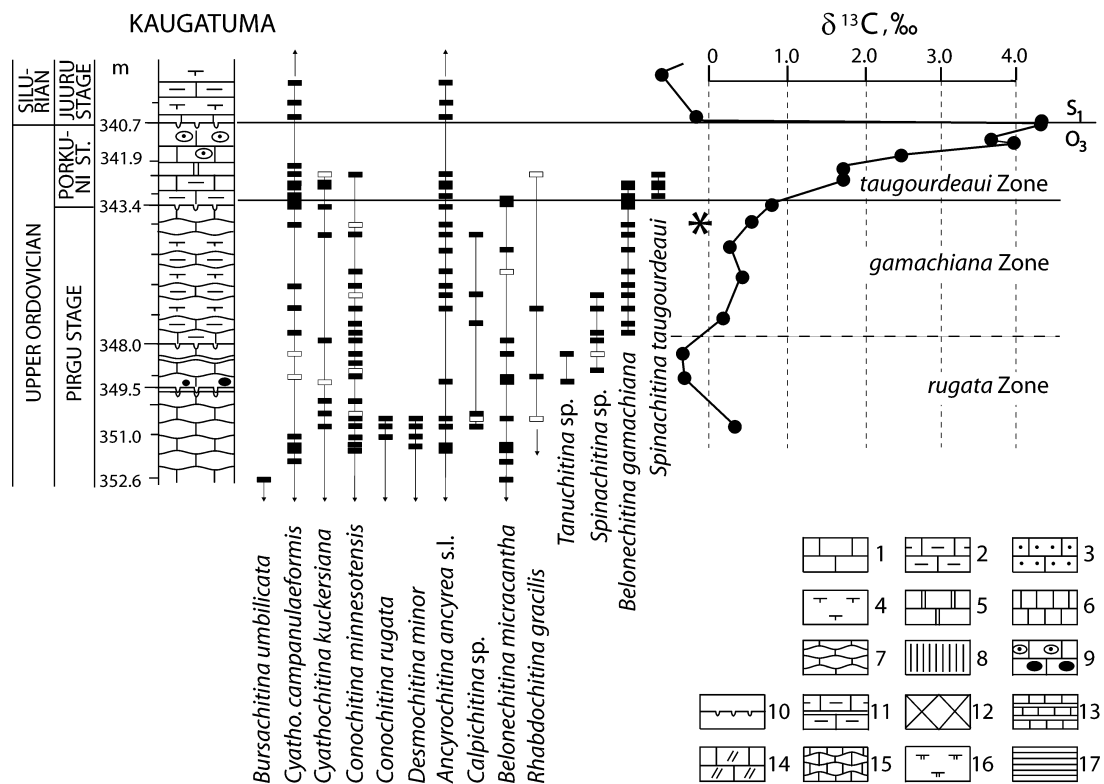
stone Mb., are not convincing evidence for an Hirnantian age for the entire Ellis Bay Fm. (Jin & Copper 2008). In Estonia *Gamachignathus* occurs both in the Hirnantian Porkuni Stage and in the pre-Hirnantian Pirgu Stage.

It should be noted that the uppermost identifiable *Am. ordovicicus* specimens in Estonia come from the lowermost Porkuni Stage, from the Bernati Mb. of the Kuldiga Fm., and have not been found from the younger strata (Figs 6, 7). However, in Missouri *Am. ordovicicus* is reported from the Leemon Fm. (Thompson & Satterfield 1975) which lies above the Girardeau Fm. that contains *Noixodontus* fauna. According to Bergström et al. (2006), the Leemon Fm. appears to represent the end of the Hirnantian isotopic event. Hence, in that region *Am. ordovicicus* reaches high up into the Hirnantian. It may be the case also in Estonia but additional studies of conodonts from the upper Porkuni Stage are required to identify the rare specimens of *Amorphognathus* occurring there.

### CHITINOZOAN BIOZONES AND SOME CORRELATIONS

A modern chitinozoan biozonal scheme for the Baltic Ordovician was recently published by Nõlvak et al. (2006). This is reproduced here with some modifications as part of Fig. 2. The key fossils are illustrated in Fig. 8. Actual chitinozoan occurrences in a few drill core sections are documented in Figs 7 and 9, along with conodont and isotope data from the same sections.

A typical and most complete sequence of chitinozoan biozones at the junction of the Pirgu and Porkuni stages has been established in the Kaugatuma core (Fig. 9), plotted against the  $\delta^{13}\text{C}$  excursion. This section fills in the gaps in chitinozoan occurrences caused by the barren beds below the Pirgu/Porkuni boundary in the Valga (Fig. 7) and Ruhnu core sections (Brenchley et al. 2003). This succession of chitinozoan biozones also removes the problem regarding the doubt about the precise position



**Fig. 9.** Chitinozoan ranges and biozones in the Kaugatuma core, and relationship with the  $\delta^{13}\text{C}$  trend (modified from Brenchley et al. 2003) dating the beginning of the HICE in terms of chitinozoan biozones. Approximate position of *Climacograptus supermus* occurrences in the Eikla core, Saaremaa, Estonia (Männil 1976) is shown by a star. Lithologic symbols: 1, limestone; 2, argillaceous limestone; 3, limestone with sandy admixture; 4, carbonaceous marlstone; 5, dolostone; 6, micritic limestone; 7, nodular limestone; 8, red limestone or marl; 9, upper: oolites and lower: intraclasts; 10, discontinuity surface; 11, argillaceous limestone with marly interbeds; 12, mud mounds; 13, laminar micritic limestone; 14, calcarenites; 15, nodular micritic limestone; 16, dolomitic marlstone; 17, dolomitic clay. Open symbols in the fossil ranges represent taxa referred to as cf.

of the lower boundary of the *Spinachitina taugourdeui* Biozone (Nölvak 2001, 2003).

The *Spinachitina taugourdeui* Biozone marks the lowermost beds of the Porkuni Stage in the Baltic (Nölvak et al. 2006), occurring in the deeper shelf area (in the lower Kuldiga Fm.) as well as in the shallow-water Ärina Fm. (mainly below or at the outside of the reefs, Kaljo et al. 2001). It was recently reported from the lowermost Hirnant Limestone at the Cwm Hirnant quarry, Wales (Vandenbroucke et al. 2008) together with the *Hirnantia* brachiopods. On Anticosti Island the zone was identified in the uppermost part of the Lousy Cove Mb. of the Ellis Bay Fm. but no chitinozoans were found in the Laframboise Mb. (Achab et al. 2008). The next lower chitinozoan biozone (*Belonechitina gamachiana* Achab), which occurs in the uppermost Pirgu Stage of Estonia and in the Lousy Cove Mb. of Anticosti (below the range of *S. taugourdeui*), provides a useful hint for the correlation of sections in both areas. The *S. taugourdeui* Biozone is also useful for linking shelly and graptolite-bearing rocks thanks to the discovery of Hirnantian graptolites in the uppermost Lousy Cove Mb. by Melchin (2008; see discussion below) and for dating the Hirnantian carbon isotope excursion (HICE) through correlation of the bio- and chemostratigraphical data. In the last sense the East Baltic drill cores seem to be the most promising despite some heard criticism.

A modification should be stressed that concerns the *Conochitina scabra* Biozone – the highest chitinozoan biozone established so far in the Hirnantian of Baltoscandia. However, it should be noted that, at least in drill

cores of Estonia and North Latvia, no well-preserved and identifiable (Fig. 7) chitinozoans are known from the topmost Ordovician – the Saldus Fm. For this reason the corresponding interval is left blank in the biozonal scheme (Fig. 2). The situation seems to be similar in Scania (Sweden), as demonstrated in a recent paper by Grahn & Nölvak (2007). In that paper several new occurrences of *C. scabra* Grahn & Nölvak from the uppermost Lindegård Mudstone to the lowermost beds of the Tommarp Fm. were presented. The latter beds are correlated with the lower part of the *N. persculptus* Biozone, which may be correct, but other relationships are difficult to recognize due to the highly condensed succession.

*Conochitina scabra* is not known from Anticosti Island and the British Isles. The top of the Hirnantian sequence in the schemes of these regions is occupied by the *Ancyrochitina ellisbayensis* Biozone (Soufiane & Achab 2000; Bergström et al. 2006; Verniers & Vandenbroucke 2006). This biozone was defined for the first time (Soufiane & Achab 2000) in the beds covering the bioherms of the Laframboise Mb. and this time was referred to the top of the Ordovician. Recently Achab et al. (2008) corrected the previous assignment, stressing that these strata with *Anc. ellisbayensis* Soufiane & Achab belong to the Becscie Fm., not to the Ellis Bay Fm. This correlation may require a more detailed explanation, because Melchin (2008) has found lower, but perhaps not the lowest Rhuddanian graptolites in the lower Becscie Fm. (see below). At the Dob's Linn GSSP section (Fig. 10) the *Anc. ellisbayensis* Biozone ranges

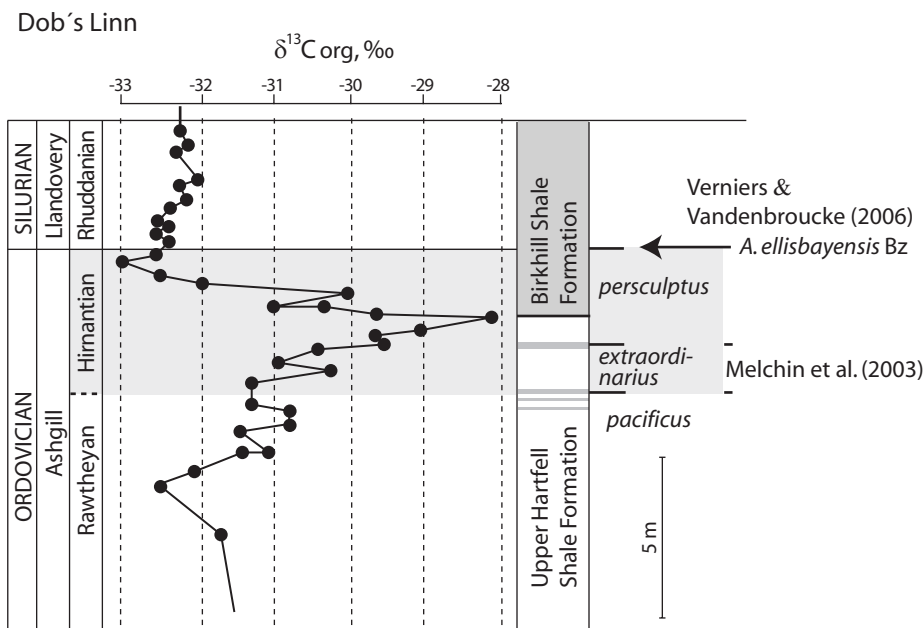


Fig. 10. Refinements to the bio- and chemostratigraphy of the Dob's Linn GSSP (modified from Underwood et al. 1997; see text).

across the O/S boundary (Verniers & Vandenbroucke 2006). Thus a question remains, whether the Ordovician part of this zone is also represented on Anticosti or not, but nevertheless this zone is an important marker. *Ancyrochitina ellisbayensis* has not been found yet in East Baltic sections. This might be caused by the hiatus at the top of the Saldus Fm. and/or difficulties in species identifications among *Ancyrochitina*, often due to poor preservation of specimens: morphologically important spines can be easily broken. On the other hand, we still do not know how to correlate the *Spinachitina oulebsiri* Biozone with Baltic successions. The latter biozone was established from the uppermost Ordovician in Algeria (Paris et al. 2000) and new data by Vandenbroucke et al. (2008) from Wales seem very intriguing, but still insufficient for solving this problem.

Summarizing the above discussion, we would emphasize that chitinozoans provide two exact datums relevant to the uppermost Ordovician stratigraphy under discussion. The first is the uninterrupted succession of the *Belonechitina gamachiana* and *Spinachitina taugourdeaui* biozones at the lower boundary of the Porkuni Stage, the second is the range of the *Ancyrochitina ellisbayensis* Biozone through the O/S boundary at Dob's Linn. Both are clearly useful criteria for tracing the boundaries of the Hirnantian Stage.

#### DISCUSSION INCLUDING GRAPTOLITE AND CARBON ISOTOPE EVIDENCE FROM THE BALTIC AND ELSEWHERE

As stated in the introduction, our paper has two main aims: establishing the correct succession of events in the Hirnantian and tracing the lower boundary of that stage in Baltica and Laurentia. It is obvious that these two are interrelated aspects of one complex dating problem having also different implications for palaeogeography, biodiversity studies, and stratigraphical practice. Let us formulate the difficulties arising in the dating more precisely.

1. Onset of the Hirnantian glaciation (irrespective of earlier coolings). The most balanced viewpoint is summarized by Brenchley (2004), but evidence for the accurate timings of these events are scarce and indirect proxies (sea-level fall, shift of carbon and oxygen isotope values) controversial (which came first?). In general, it seems possible to conclude that the glaciation commenced in the "earliest Hirnantian", i.e. within the lowest *Normalograptus extraordinarius* Biozone.
2. Sea level. Most authors have discussed a lowstand interval with a change to a rising trend in the mid-Hirnantian (Brenchley 2004 – before the mid-

*persculptus* Biozone; Ross & Ross 1995); pre-Hirnantian gaps are known in the Baltic (Einasto 1995; Nölvak 1997) and Laurentia (New York, Illinois, Ohio; Ross & Ross 1995). Nielsen (2004) has also provided a sea-level curve, but it is not clear how these results were achieved. His Fig. 10.2 shows that the Kuldiga Fm. is correlated with the Adila Fm. within the Pirgu Stage and the Ärina Fm. with the Saldus Fm. in the top of the Porkuni Stage. This construction is possible only if virtually all bio- and chemostratigraphical data from the Baltic Ordovician are ignored. This case is not unique; analogous concerns are expressed also elsewhere, but it demonstrates that a correct stratigraphy helps to avoid elementary mistakes.

3. Biodiversity changes (mass extinction or a series of extinction phases). Many publications (see Brenchley et al. 2003; Webby et al. 2004) commonly accept two main phases – at the very beginning and in the middle of the Hirnantian. From the Estonian point of view, the first phase may be even pre-Hirnantian, because several fossil groups (brachiopods, stromatoporoids, ostracodes, and conodonts) were most diverse in the Pirgu Stage. In Porkuni time the extinctions continued in all groups and in summary only a very limited number of Hirnantian taxa continued into the Silurian (Nestor et al. 1991). In analysing diversity changes in the acritarch and chitinozoan assemblages, Kaljo et al. (1996) showed that their disappearance rate began to increase in the mid-Katian and reached a peak in the late Katian (Pirgu). This means that the two phases mentioned above were not sudden events, but the results of longer environmental processes.
4. Major carbon and oxygen isotope excursions commencing in the earliest Porkuni Stage in the Baltic or earliest Hirnantian elsewhere are correlated with the base of the *N. extraordinarius* Biozone. Sometimes the beginning of an isotope excursion is not very clear or is rather arbitrary and this is the case, as will be shown below, also at the base of the Hirnantian.

In the section above, we have discussed mainly East Baltic data (brachiopod, conodont, and chitinozoan biostratigraphy) with some additions from elsewhere and have presented several positions for further discussion. Here we check these in the light of some graptolite and carbon isotope data in order to confirm our conclusions.

#### Graptolite evidences

##### *Age of the Pirgu Stage*

A few pre-Hirnantian graptolite occurrences have been reported from carbonate rocks of the Pirgu Stage in

Estonia (Männil 1976). *Rectograptus gracilis* (Roemer) is most common in the lower part of the stage and in the underlying Vormsi rocks. In the top of the Pirgu Stage several specimens of *Climacograptus* (= *Appendispinograptus*) *supernus* Elles & Wood have been found in the Eikla core, Saaremaa, Estonia (approximate position of these finds is shown in Fig. 9). Most probably these occurrences indicate a late Katian age, but the latter species is known also from the *N. extraordinarius* Biozone together with *Paraorthograptus pacificus* (Ruedemann) (e.g. at Vinini Creek, Nevada; Finney et al. 1999 and in the GSSP in China; Chen et al. 2006). Ulst et al. (1982) listed four long-ranging graptolites from the Pirgu Stage in Latvia, which are distributed across Scandinavia within or below the *Dicellograptus complanatus* graptolite Zone (Skoglund 1963).

Ulst (1992) reported Hirnantian graptolites from deep shelf rocks, penetrated by wells for offshore oil prospecting. *Normalograptus* ex gr. *persculptus* Salter and some other graptolites occur just above beds with the *Hirnantia* Fauna and are followed first by *Akidograptus ascensus* Davies and then *Parakidograptus acuminatus* Nicholson, etc. (Fig. 5). The identifications of the graptolites occurring below the *A. ascensus* Biozone are uncertain, but are still referred to the upper Hirnantian. Podhalanska (2003) reported more exact data about the same general situation from the Leba area, and there was found also *Normalograptus avitus* Davies, suggesting an interregnum between *N. persculptus* s.str. and *A. ascensus* ranges like that in Scania (Koren et al. 2003).

The graptolite data quoted above are consistent with the current stratigraphical correlation (Fig. 2; Nölvak et al. 2006), and correlate most probably the Pirgu Regional Stage with its rich shelly faunas (brachiopods included) with the uppermost Katian Stage. This means also that we must reject the correlation of the Estonian section suggested by Jin & Copper (2008), resulting from their enlarged scope of the Hirnantian.

### Dating the carbon isotope curve

#### *Dob's Linn*

Revising graptolite occurrences in the stratotype section (GSSP) for the base of the Silurian, Melchin et al. (2003) found that the lower boundary of the *N. extraordinarius*–*N. ojsuensis* Biozone should be placed at 2.2 m and that of the *N. persculptus* Biozone 1.2 m below the base of the Birkhill Shale. This means that the peak of the  $\delta^{13}\text{C}_{\text{kerogen}}$  excursion established by Underwood et al. (1997) in the top of the *N. extraordinarius* Biozone should be now placed into the *N. persculptus*

Biozone (1.08 m from the bottom). Correspondingly, the ascending limb of this excursion remains mainly in the former biozone (Fig. 10).

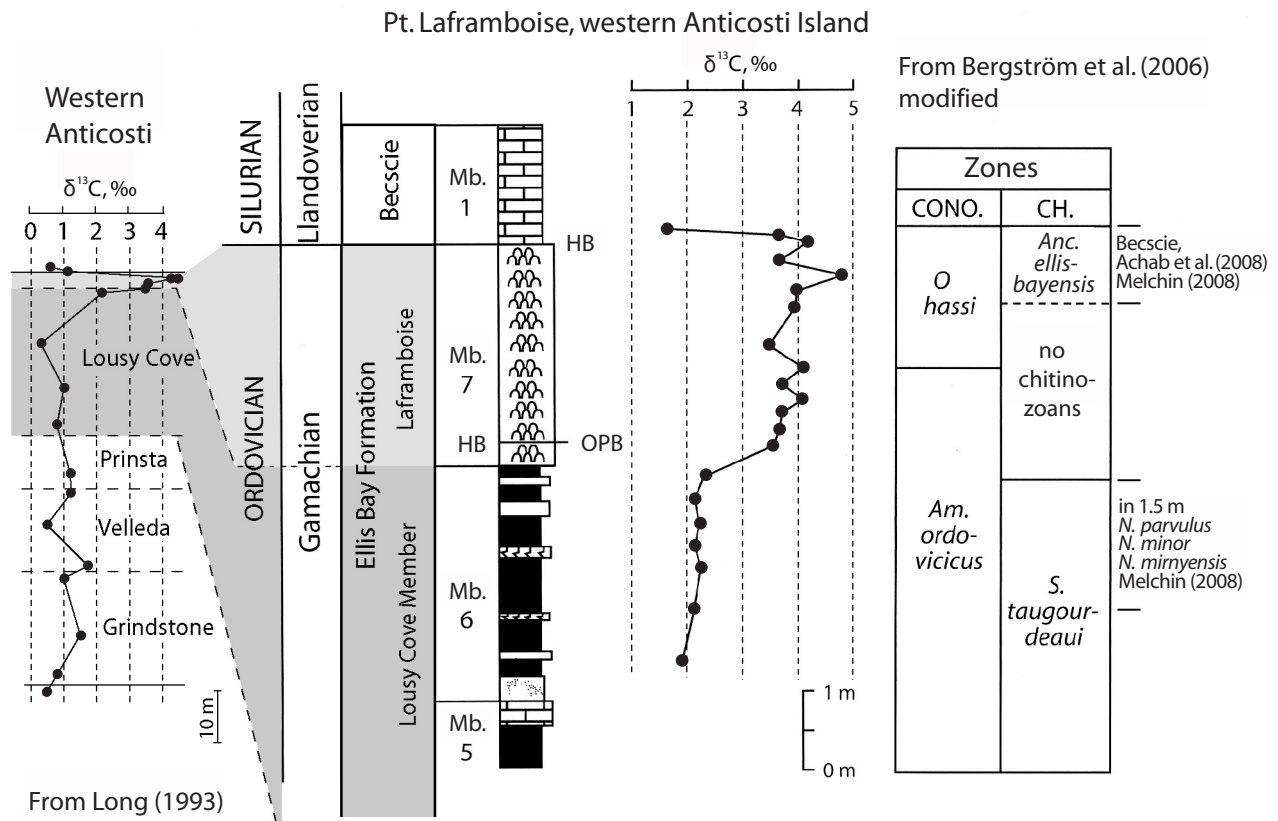
#### *Nevada*

Finney et al. (1999) published two  $\delta^{13}\text{C}$  curves: (1) The Vinini Creek section in the Robert Mountains is better dated by graptolites, but the carbon isotope excursion is rather short. It shows a rapid rise of values in the *N. extraordinarius* Biozone, follows a variable plateau between 2 and 2.5‰, and reaches a few metres into the *N. persculptus* Biozone before the succession is ended by an erosion surface. (2) The Monitor Range section shows a well-defined isotope trend, but graptolites date the excursion only before the *N. extraordinarius* Biozone, and *N. persculptus* occurs above the erosion surface. We follow Finney et al. (1999) in that the ascending limb of the  $\delta^{13}\text{C}$  curve and most of its slightly falling plateau is of *N. extraordinarius* time, but perhaps the beginning of the *N. persculptus* Biozone could be lowered several metres below the erosion surface as in the Vinini Creek section. Considering also the Dob's Linn data (Fig. 10), it seems probable that the appearance of *N. persculptus* is delayed at Monitor Range due to environmental reasons. The Monitor Range isotope curve has been interpreted by Saltzman & Young (2005) and correlated with Baltic sections (Ruhnu and Valga cores, respectively) by Brenchley et al. (2003) and Kaljo et al. (2007), consistent with the conclusions above regarding its ascending limb and relationship with the *N. extraordinarius* Biozone.

#### *Anticosti*

Recent revision of graptolite occurrences in the Ellis Bay and Becscie Fms by Melchin (2008) noted several biostratigraphically important species (Fig. 11). From the upper half of the Ellis Bay Fm. (uppermost 1.5 m of the Lousy Cove Mb.) he identified *Normalograptus parvulus* (Lapworth) (as cf. in the Laframboise Mb.), *N. minor* (Huang), and *N. mirnyensis* (Obut & Sobolevskaya). These graptolites, occurring on Anticosti together with the last representatives of *Spinachitina taugourdeaui*, were known earlier from the *N. persculptus* Biozone and lower Rhuddanian, the last species is also recorded from the *N. extraordinarius* Biozone. From the “basal Becscie” Melchin identified *N. imperfectus* (Legrand), a species that in Algeria and China is limited to the *P. acuminatus* Biozone.

These graptolite data allow us to conclude that the uppermost Ellis Bay Fm. (beginning at the top of the Lousy Cove Mb.) is contemporaneous with a part of the



**Fig. 11.** Bio- and chemostratigraphy of the uppermost Ellis Bay Fm. in western Anticosti Island based on Bergström et al. (2006) and Long (1993) with additions included. Note the big difference in vertical scales for the  $\delta^{13}\text{C}$  curves, which changes the shape of the trend. Member (Mb.) 1 is represented mainly by limestones; Mb. 7 by biohermal limestones with a lowstand level or gap (HB) at the top of the member and another lowstand (HA) at the Oncolite Platform Bed (OPB); Mbs 6 and 5 consist of mudstones with limestone intercalations.

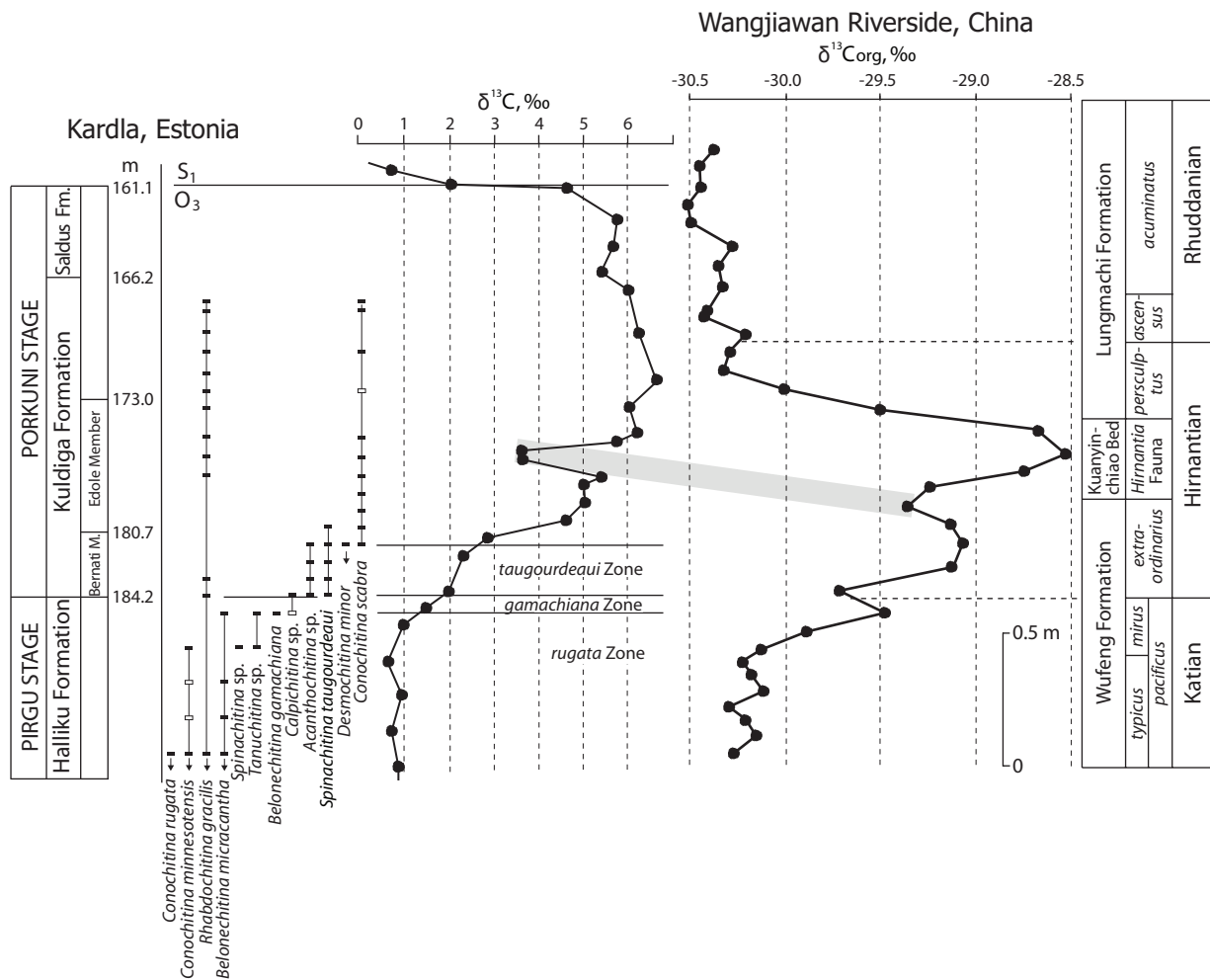
*N. persculptus* Biozone. This dating is made just below the Laframboise Mb., with the high values of  $\delta^{13}\text{C}$  indicating that the excursion should be identified as the HICE. Lower down in the Lousy Cove Mb. the values drop rapidly ca 1.5‰ and remain close to 1–2‰ (Fig. 11, respectively according to data by Long 1993 and Bergström et al. 2006) and the shape of the curve allows various possibilities for correlation that will be discussed below.

#### Chinese sections

The Wangjiawan Riverside section that is located close to the GSSP section shows a trend with most positive  $\delta^{13}\text{C}_{\text{org}}$  values (–28.5‰) in the middle of the Kuanyinchiao Bed bearing the *Hirnantia* Fauna. The bed lies between the *N. extraordinarius* and *N. persculptus* biozones. According to a graphic correlation, the base of the latter

biozone is within the above bed, i.e. the peak is placed into the lower part of the *N. persculptus* Biozone as in Dob’s Linn (Chen et al. 2006). The Kuanyinchiao Bed marks a shallowing event in a deep-sea facies succession. It is rather common that positive carbon isotope peaks are linked to the sea level lowstands and in this sense the connection with a shelly fauna bed is supporting the observation mentioned. On the other hand, this situation is also a reason why commonly not all  $\delta^{13}\text{C}$  peaks are represented in some sections; they are missing due to gaps caused by sea level drops. The range of a eustatic sea level change in a basin depends on local geology, and even in deep-sea settings like both GSSPs the presence of some smaller hiatuses is not excluded, although gaps known from shallower sea deposits are not very probable to occur here. The Dob’s Linn and Wangjiawan Riverside (see Figs 10 and 12) sections are both highly condensed (the latter in particular) and the





**Fig. 12.** Correlation of the carbon isotope trends of the Wangjiawan Riverside section (Chen et al. 2006) and Kardla drill core section (Brenchley et al. 2003). When comparing the trends, consider also the difference in the vertical scale demonstrated in Fig. 11.

carbon isotope excursions are rather similar. However, at least a few per mill difference in the  $\delta^{13}\text{C}_{\text{org}}$  values requires discussion. Regarding the beginning of the HICE excursion in the Wangjiawan Riverside section, Fig. 12 shows that it would be more reasonable to place the origination of the excursion into the *Diceratograptus mirus* Biozone where the values begin to increase from the pre-excursion plateau. Placing the beginning in the *N. extraordinarius* Biozone, it would be somewhere midway in the rising  $\delta^{13}\text{C}$  limb, and may cause uncertainty. The same is true in the Estonian cores (Figs 7, 9, and 12), where we do not have graptolites but the  $\delta^{13}\text{C}$  curves are well dated by chitinozoans and conodonts (see above), and can be easily correlated based on their shape.

### Correlation of isotope trends and the age of the *S. taugourdeui* Biozone

The interval occupied by the HICE is 1 m thick in the Wangjiawan Riverside section, 4 m at Dob's Linn, 23 m at Kardla, and ca 40 m at Monitor Range, but the  $\delta^{13}\text{C}$  curves are similar. Of course, the general shape is different – the first two, which occur in condensed deep-water sedimentary rock successions, are narrow, peak-like excursions with some jags, whereas the other two are also jagged but wide and plateau-like. However, Fig. 11 demonstrates how a tenfold difference in the scale can change the shape – a peak becomes a plateau or vice versa. In Fig. 12 we correlate the Chinese and Estonian  $\delta^{13}\text{C}$  trends, whereas the highlighted correlation

line helps to see details of the excursion allowing such a correlation. This correlation emphasizes that despite some differences in the general shape of the carbon isotope trend in different localities, the main details can be identified if these are preserved in the section. It would be proper to note that rather often  $\delta^{13}\text{C}_{\text{carb}}$  and  $\delta^{13}\text{C}_{\text{org}}$  curves are much less similar than demonstrated here. In such cases the correlation by shape might be impossible or only a very general trend is recognizable.

We performed the same correlation with the other sections discussed herein and used earlier, analogous results published by Brenchley et al. (2003) and Bergström et al. (2006). The latter authors also emphasize the presence of gaps in the corresponding sections and, as shown by Achab et al. (2008), accepting them may largely contribute to the proper understanding of the Anticosti Island sections. Nevertheless, the interpretation of the Anticosti  $\delta^{13}\text{C}$  curve is complicated due to controversial graptolite and chitinozoan data – representatives of the *N. persculptus* and *S. taugourdeai* biozones occur together in one bed as specified above. According to all correlations except that of Anticosti (Fig. 11, upper part of the Laframboise Mb.), the FAD of the former index species is just below the peak isotope values (Figs 10, 12). The FAD of the second key species is usually tied to the lower part of the HICE with its increasing values at the very beginning of the *N. extraordinarius* Biozone (Fig. 12). We do not know why the Anticosti sequence does not fit the others, but the actual relationship indicates that the range of *S. taugourdeai* might be extraordinarily long in the Anticosti sections. There may also be some other more reasonable explanations.

## CONCLUSIONS

1. The utility of the primary criterion, which defines that the base of the Hirnantian is the FAD of *Normalograptus extraordinarius*, is confirmed.
2. Secondary criteria (e.g. isotope curves, sea level changes) are less convincing. When used for correlation, these should be specified: the carbon isotope excursion usually begins slightly earlier (in the *Diceratograptus mirus* Biozone of China), but might be conventionally placed into the *N. extraordinarius* Biozone, especially when biostratigraphical criteria are available. The peak of the excursion is in the lower *N. persculptus* Biozone, and main increase in values takes place in the *N. extraordinarius* Biozone.
3. Combination of graptolite and chitinozoan biozonations with carbon isotope shifts allows a reliable correlation of the Hirnantian lower boundary level in different facies. The peak of the carbon isotope trend is also a correlation level close to the base of the upper Hirnantian.
4. The base of the *Spinachitina taugourdeai* Biozone marks at many localities the base of the Hirnantian, and only recent data from the topmost Lousy Cove Mb. (Anticosti Island) suggest the mid-Hirnantian. This problem should be solved by additional study.
5. Brachiopod faunas from the Pirgu and Porkuni stages are rather similar to those of the Ellis Bay Fm. of Anticosti, but the Pirgu assemblage together with that of the lower Ellis Bay Fm. contains no key elements of the Hirnantian fauna.
6. Similar to diversity changes in the brachiopods of the Ellis Bay Fm., a marked disappearance event occurred at the end of the lower Ellis Bay Fm. and at the end of the Pirgu Stage. This extinction in the latest Katian, i.e. before the Hirnantian, is documented also in several other fossil groups.

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## Sündmuste järjestus Hirnantia eal Baltica andmete alusel: brahhiopoodid, kitiinikud, konodondid ja süsiniku isotoobid

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Hirnantia ea keskkond oli mitmekesine ja dünaamiline. Keskkonnatingimuste ja nende arengu tuvastamisel kivimite uurimise alusel on väga oluline teada eri sündmuste korrektset järjestust ning paigutust ajaskaalal. Hirnantia lademe alumine piir on ametlikult määratletud graptoliidi *Normalograptus extraordinarius*'e esmailmumise, süsiniku isotoopide suhte kõvera positiivse muutuse ja jääumisest tingitud ookeani veetaseme olulise langusega. Artikli eesmärgiks on selgitada, kas Balti materjal toetab oletatud sündmuste üheaegsuse ideed. Mitmetes puurläbilõigetes uuriti pealkirjas märgitud fossiilide koosseisu ja levikut ning võrreldi neid graptoliitide ja süsiniku isotoopide andmetega nii Baltikumist kui ka muudelt aladelt. Pirgu ja Porkuni lademe brahhiopoodid on väga sarnased Anticosti saare (Québec) Ellis Bay kihistust leiduvatega, kuid mõlemas faunas puuduvad Hirnantiale iseloomulikud elemendid. Sama näitab ka mõlema ala konodontide võrdlus. Eespool märgitud esmane Hirnantia lademe alumise piiri kriteerium on usaldusväärne, kui see graptoliit on leitud.  $\delta^{13}\text{C}$  kõver on vähem kindel tunnus ja peab olema tõendatud biostratigraafiliste andmetega. Isotoopkoosseisu muutuse algus on tavaliselt pisut varasem kui *N. extraordinarius*'e ilmumine, kuid kitiiniku *Spinachitina taugourdeau*i levik Porkuni lademe alguses võimaldab õige momendi fikseerimist. Isotoopkõvera tipp paikneb *N. persculptus*'e tsooni alumises osas. Korrelatsiooni Anticosti läbilõikega komplitseerib viimase tsooni graptoliitide leid Ellis Bay kihistu riffide alt ning vastuolude selgitamiseks on vajalikud täiendavad uuringud.