

Upper Wenlock $\delta^{13}\text{C}$ chemostratigraphy, conodont biostratigraphy and palaeoecological dynamics in the Ledai-179 drill core (Eastern Lithuania)

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Abstract. Based on the integrated chemostratigraphic and lithostratigraphic studies, as well as biostratigraphic and palaeoecological analyses of conodonts in the Ledai-179 core, we present a combined model of change in the upper Wenlock and lowermost Ludlow strata of the inner shelf settings in the eastern part of the Baltic Basin. The comparison of the $\delta^{13}\text{C}$ trend, and conodont and lithological successions confirms previous suggestions that the Birštonas and Nevėžis formations correspond to the Homerian. This is quite unexpected, however, that the chronostratigraphic position of the Širvinta Formation changed from the Gorstian to the upper part of the Homerian. The numerical biostratigraphic change-point analyses of local conodont richness, per capita immigration and also per capita extirpation rates revealed several episodes of permanent change. These episodes of dynamic states either preceded or postdated the Mulde extinction interval at the beginning of the late Homerian $\delta^{13}\text{C}$ excursion, which points to possible transient effects of this extinction event on conodonts.

Key words: $\delta^{13}\text{C}$ chemostratigraphy, conodonts, biostratigraphy, palaeoecology, Mulde Event, Eastern Baltic, Lithuania.

INTRODUCTION

The upper Wenlock is a dynamic time slice of the Silurian Period, marked by substantial environmental and biotic changes, with especially profound graptolite and conodont extinctions. These extinctions are called the *lundgreni* Event (Koren' 1987) or the 'Big Crisis' ('Große Krise') for the graptolite extinction episode (Jaeger 1991) and the Mulde Event for conodont extinctions (Jeppsson et al. 1995). Nonetheless, the exact pattern of geobiological perturbations in the late Wenlock of the Baltic region is insufficiently explored, especially in its eastern part.

The purpose of this paper is to compile the lithostratigraphy, $\delta^{13}\text{C}$ isotope data and conodont biostratigraphy of the Ledai-179 core into a coherent model of change, and using this temporal framework of integrated stratigraphy, to explain conodont palaeoecological dynamics through the upper Wenlock part of this section.

MATERIAL

The new $\delta^{13}\text{C}$ isotope data and the conodont material originate from the middle–upper Homerian and lower Ludlow parts of the Ledai-179 core section (Fig. 1). The

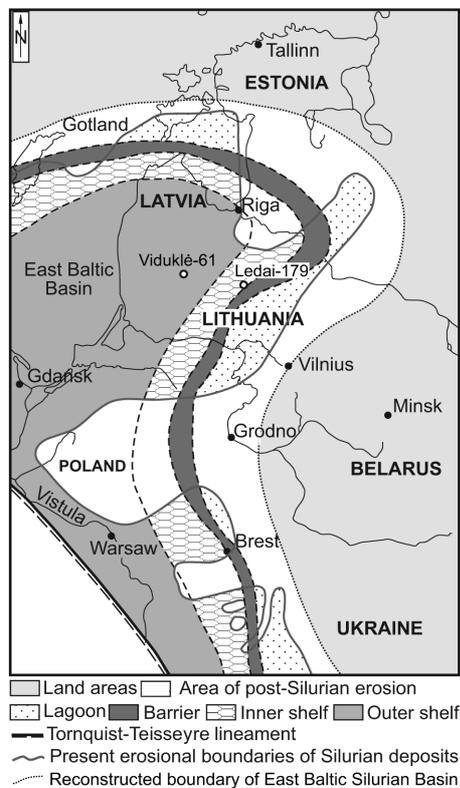


Fig. 1. Facies map of the western margin of the East European Platform (Porębska et al. 2004) and locations of boreholes.

Ledai-179 drill site is located in the eastern part of Lithuania and the succession recovered is represented by shallow marine environments (Paškevičius et al. 1994; Kiipli et al. 2011). We did not detect any graptolites in the studied part of the section. The investigated interval represents the upper part of the Jaagarahu, the entire Gėluva and the lower part of the Dubysa regional stages (Fig. 2).

All conodont material used in this study, including the specimens presented in SEM pictures (Fig. 3), is stored in the Department of Geology and Mineralogy of Vilnius University.

LITHOSTRATIGRAPHY

The mid–upper Wenlock to Ludlow interval of the Ledai-179 section has been divided into the Birštonas, Nevėžis, Širvinta and Neris formations (Paškevičius et al. 1994). The Birštonas Formation (713.9–649.9 m depth) is composed of nodular wackestones. The Nevėžis Formation (649.9–628 m) consists of grey dolomitic marlstones with dolostone in its upper part. Laminated dolomitic marlstones are typical of the Širvinta Formation (628–611.3 m depth) which is of reddish colour in its lower part (628–616.1 m interval) and greyish in the upper

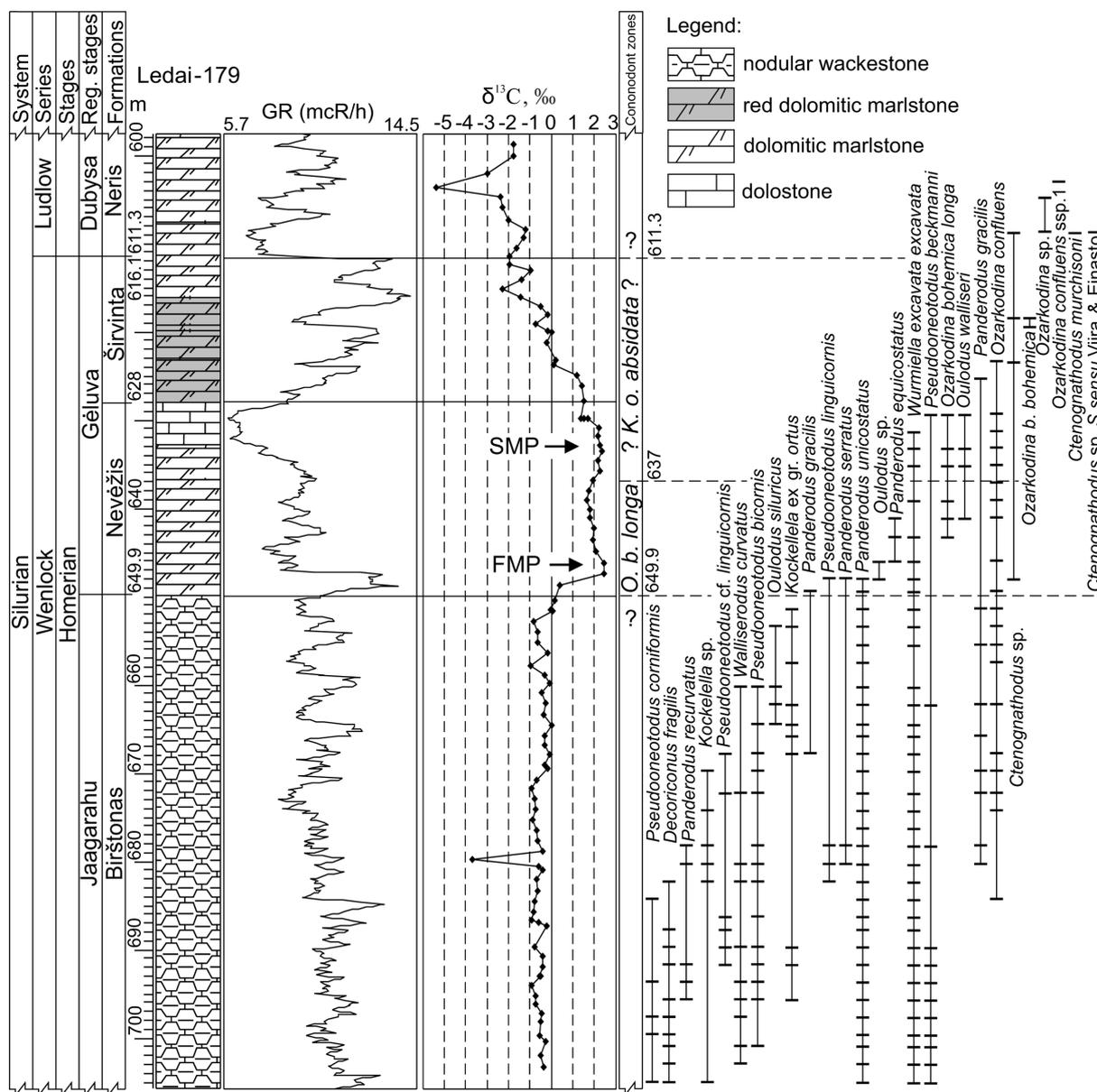


Fig. 2. Lithologies, gamma ray log, stable carbon isotopic curve and conodont distribution in the studied interval of the Ledai-179 core. FMP, first Mulde peak; SMP, second Mulde peak.

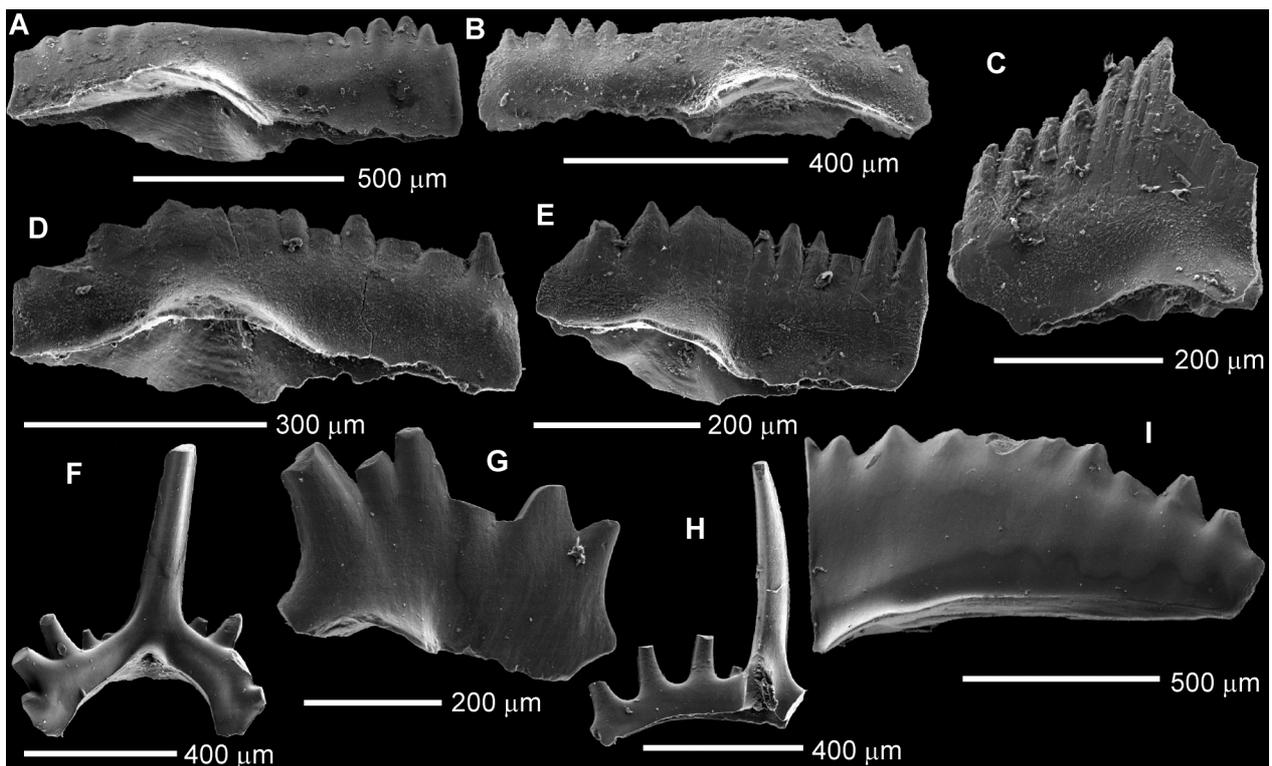


Fig. 3. SEM pictures of stratigraphically significant conodonts from the Ledai-179 core. **A–C**, *Ozarkodina bohemica longa*, Wenlock, Gėluva Regional Stage, Nevėžis Formation; **A**, Pa element, VU-CON-L179-001, depth 641.7 m; **B**, Pa element, VU-CON-L179-002, depth 635.7 m; **C**, incomplete Pb element with partially broken ventral process, VU-CON-L179-003, depth 635.7 m; **D, E**, *Ozarkodina bohemica bohemica*, Pa elements, Wenlock, Gėluva Regional Stage; **D**, VU-CON-L179-004, depth 619.9 m; **E**, VU-CON-L179-005, depth 618.9 m; **F–H**, *Ctenognathodus* sp. S (*sensu* Viira & Einasto 2003), Ludlow, Dubysa Regional Stage, Neris Formation, depth 608.5 m; **F**, Sb element, VU-CON-L179-006; **G**, almost complete Pa element without dorsal process, VU-CON-L179-007; **H**, incomplete Sa element, VU-CON-L179-008; **I**, *Ctenognathodus munchisoni*, Ludlow, Dubysa Regional Stage, Neris Formation, depth 608.5 m, dorsal part of Pa element, VU-CON-L179-007. Anatomical notations *sensu* Purnell et al. (2000).

part. Finally, the Neris Formation, ranging from 611.3 m to 582.9 m, is composed by greyish, laminated dolostones.

All formations are composed of carbonates with varying clay content. We used gamma log data as an additional source of information which reflects the clay content of the rocks with respect to the formations and numerical analysis of conodont dynamics. Specific minerals such as glauconite are absent in the investigated interval. Therefore, the gamma log mirrors the relative concentrations of clayey and organic material in the carbonates and presumably reflects cyclic and episodic patterns of sedimentation.

CARBON ISOTOPE ($\delta^{13}\text{C}$) CHEMOSTRATIGRAPHY

For the purpose of chemostratigraphy, samples for stable carbon isotope analysis were collected from the

703.3–598.7 m interval, approximately at every metre (Fig. 2). The $\delta^{13}\text{C}$ composition of the samples was analysed in the Department of Geology, University of Tartu, Estonia.

The $\delta^{13}\text{C}$ values are moderately stable and range from -0.95‰ to 0.18‰ in the Birštonas Formation, but rise rapidly to 2.47‰ at 650.4–646.1 m depth in the lower part of the Nevėžis Formation and decrease to 1.66‰ at 639 m (middle part of the Nevėžis Formation). The $\delta^{13}\text{C}$ ratios rise again to a value of 2.21‰ at 630.8 m. This double peak in the isotopic curve of the Nevėžis Formation is followed by a drop to low $\delta^{13}\text{C}$ values in the uppermost part of the Nevėžis Formation. The $\delta^{13}\text{C}$ values gradually fall from 1.54‰ (at 627.7 m) to negative values at 621.2 m and decrease further to -1.95‰ at 612.3 m in the Širvinta Formation. The Neris Formation is characterized by negative $\delta^{13}\text{C}$ values fluctuating between -5.39‰ and -1.96‰ .

CONODONT BIOSTRATIGRAPHY

Based on our taxonomic work, we distinguish two conodont biozones in the upper part of the studied section (see Fig. 2 and the ‘Discussion and Conclusions’ section).

The lower part of the section corresponding to the Birštonas Formation (Jaagarahu Regional Stage) is depauperate of short-ranging conodont species, which precludes conodont-based biozonation of this interval. Most of the species belong to deep-water and open-sea genera, such as *Panderodus*, *Pseudooneotodus* and *Decoriconus*. These genera are accompanied by the environmentally omnipresent species *Wurmiella excavata excavata* (Branson & Mehl) and more restricted *Kockelella ex gr. ortus* (Walliser), *Oulodus siluricus* (Branson & Mehl) and *Ozarkodina confluens* (Branson & Mehl).

In the analysed portion of the section we found remains of just one conodont zonal species, *Ozarkodina bohémica longa* Jeppsson (Fig. 3A–C), at a depth of 643.7–629.9 m. Considerable changes in the lithology are recorded in the upper part of the section. This fact indicates possible truncation of apparent stratigraphic distributions of this species.

The genus *Ctenognathodus* (Fig. 3F–I) in the Ledai-179 section is represented by specimens unassigned at the species level as well as representatives of two recognized species *C. purchisoni* and *Ctenognathodus* sp. S *sensu* Viira & Einasto (2003). Remains of the last two species are confined to the uppermost portion of the section in the beds of the Neris Formation (lowermost Ludlow) near the boundary of the Širvinta Formation, at a depth of 609.2 m. *Ctenognathodus purchisoni* was previously used as a zonal index species, marking the uppermost Homerian beds (Calner & Jeppsson 2003). However, later findings confirmed a significantly earlier occurrence of this supposed zonal species (Radzevičius et al. 2014), which constrained its use in high-resolution biostratigraphy. To our knowledge the species *Ctenognathodus* sp. S has only been found in the Vesiku and Anikaitse beds of Estonia (Viira & Einasto 2003), which in most recent studies are assigned to the Lower Ludlow (Kiipli et al. 2011). Our recovery of this species in the boundary beds of the lowermost Ludlow confirms its short stratigraphic range, even if a final conclusion about its temporal distribution cannot be drawn. Near-shore strata that developed during regression are the most prone settings for the development of such large stratigraphic gaps (Patzkowsky & Holland 2012).

DYNAMICS OF CONODONT PALAEOECOLOGICAL TURNOVER

In this study, in addition to biostratigraphy, we analysed conodonts in a palaeoecological context. Based on the occurrence data of the recognized species in the form of the presence–absence matrix (coded in ‘0’ for absence and ‘1’ for presence), we calculated three metrics describing biodiversity turnover processes, namely, the observed species richness (a), per capita immigration rates (I) and per capita extirpation rates (E). Species richness shows local levels of conodont species diversity, which is an important factor describing the complexity of palaeocommunities. The other two parameters (extirpation and immigration rates) reflect changes in the stability of species composition in local palaeocommunities and reflect patterns of turnover in a wider regional metapopulation context. Therefore, the listed metrics were tested for the changes in their parameter values in the constructed time series.

The observed species richness (a) was calculated as the number of species in the sample. The calculation of other two metrics was more complicated. Raw numbers of appearances or disappearances of species in consecutive samples could be strongly dominated by absolute values of standing diversity (they are biased in this respect). Because of this problem, the per capita metrics are more preferred.

The first step in calculating per capita immigration rates was the transformation of the occurrence matrix into the immigration matrix, by applying the following operation to all species (I):

$$\begin{cases} 1 & \text{if } (p_{ji} - p_{ji-1}) > 0, \\ 0 & \text{otherwise.} \end{cases}$$

Here ‘0’ and ‘1’ are values of the immigration matrix, p_{ji} is a state of species ‘j’ in the presence–absence matrix in the current sample ‘i’ and p_{ji-1} is a state of the same species in the presence–absence matrix in the preceding sample (i.e. ‘i–1’).

The extirpation matrix was calculated in an analogous way (II):

$$\begin{cases} 1 & \text{if } (p_{ji} - p_{ji-1}) < 0, \\ 0 & \text{otherwise.} \end{cases}$$

The per capita immigration rates (I) were calculated as a sum of all immigration events over all species at a time ‘i’ divided by a number of species (n) present at a

time ‘ $i - 1$ ’ (the last number represents potential for species immigrations at a given time from the standpoint of a time step before). It was assumed that a species existed in a regional pool between its first and last appearances in the studied portion of the section (for the estimation of diversity at any given time, during the calculation of per capita rates, we used interpolated diversity). The per capita extirpation rates (E) were calculated similarly, except that in the place of immigration events we summed extirpation events. During the calculation of I and E , if apparent standing diversity reached zero levels, in order to avoid arithmetic errors (dividing by zero), we substituted zero values with the smallest positive integer (‘1’).

In order to characterize time-dependent evolution in the described palaeoecological parameters, we implemented so-called multiple change point analyses of time series, using ‘changepoint’ package in R statistical computing environment (Killick & Eckley 2013; R Core Team 2014). This type of analysis estimates exact locations in a time series where statistical parameters (i.e. means or/and variances) change (Killick & Eckley 2013). The change in species richness (a) was modelled as a Poisson process with one parameter, by describing stochastic occurrences of rare discrete events (in this case, the presence of species in samples). On the other hand, because per capita extirpation (E) and immigration rates (I) are ratios, their time series were modelled as sequences of Gaussian variables described by two parameters (means and variances).

All time series were evaluated for statistically significant changes in both means and variances, using an approximate binary segmentation algorithm. This algorithm has an advantage over others presented in the package, by requiring setting the maximum number of changepoints in a time series. In this way we lowered the probability of overfitting (that is, finding false positive changes in parameter values) (Auger & Lawrence 1989; Killick & Eckley 2013). In all three analyses, we set the maximum number of changepoints to five.

The results of analyses showed that the observed species richness (a) experienced two episodes of permanent change from higher to lower values of standing conodont species diversity (Fig. 4A). The first drop of standing local diversity occurred at a depth of 660.8 m in the late Jaagarahu Regional Stage, the second drop at a depth of 629.9 m in the Géluva Regional Stage at the top of the Nevėžis Formation. Per capita immigration rates also experienced two episodes of permanent change (Fig. 4B). The first change to higher values occurred at a depth of 698.3 m in the Birštonas Formation, though it was very small and possibly an artefact of overfitting. The other change occurred at a depth of 637.7 m to the regime of much

higher volatility of per capita immigration rates. Changes in the per capita extirpation rates were very similar to those in immigration rates (Fig. 4C), although they experienced just one shift to the higher volatility in the upper portion of the section, at a depth of 629.9 m, at the exactly same point as the last drop in species richness.

The pattern of local conodont palaeoecological turnover, revealed by changepoint analysis of three metrics (a , I and E), shows that the main controlling mechanisms of their change were environmentally controlled changes in habitats. The first drop in species richness was associated with the disappearance of most deep sea species (i.e. *Waliserodus curvatus*, *Pseudooneotodus bicornis*), shortly after the depositional regime

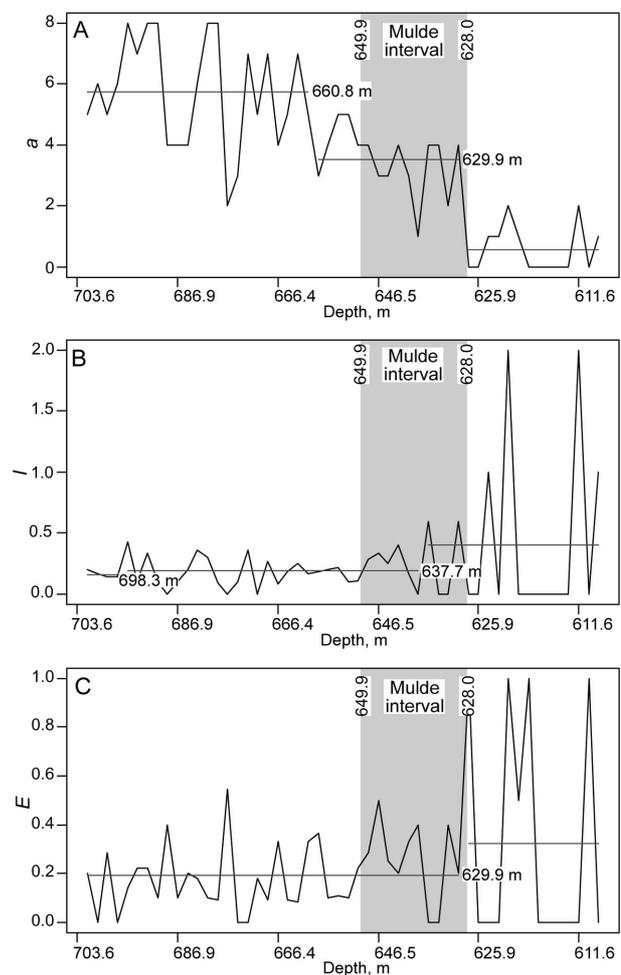


Fig. 4. Change point analyses of conodont palaeoecological time series in the Ledai-179 core section. **A**, stratigraphic series of local species richness estimates (a); **B**, dynamics of per capita immigration rates (I); **C**, dynamics of per capita extirpation rates (E). Dashed horizontal lines denote statistically differing dynamic states.

in shelfal environments changed to a more volatile state with higher-amplitude regression–transgression cycles as reflected in the geophysical gamma log (Fig. 2). This change could indicate the transition to a climatically less stable state, which influenced local dynamics related to species presence and absence. The second drop in local species richness coincides with the increase in the volatility of both the per capita rates of extirpation and per capita rates of immigration. The change in immigration rates slightly precedes changes in the other two metrics. This transition approximately coincides with a regression, evidenced also by facies changes (Fig. 2). The transition to very shallow environments coincides with the absence of open-ocean and deep-water taxa. The uppermost part of the section (Širvinta and Neris formations) contains species of only two genera, *Ctenognathodus* and *Ozarkodina*. Very high volatility of immigration and extirpation rates indicates intercalation of very restricted environments. The most probable factor that caused the punctuational drop in the local diversity (a) and increase in volatility levels in I and E was the change in the tectonically driven sediment accommodation regime, together with the change in the shoreline position. The increase in the volatility of immigrations and extirpations could be caused by a higher sensitivity of foreshore environments to sea level perturbations than shown by deeper subtidal settings.

DISCUSSION AND CONCLUSIONS

The two peaks in $\delta^{13}\text{C}$ values within the Nevėžis Formation are interpreted as corresponding to the Global Middle Homerian double peak in carbon isotope ratios.

The pattern of occurrences and the shape of the stable carbon isotopic curve indicate that the interval between 649.9 and 639 m should be assigned to the *Ozarkodina bohémica longa* Biozone. The upper part of the curve (between 639 and 611.3 m), corresponding to the second Mulde excursion peak, most possibly corresponds chronostratigraphically to the *Kockelella ortus absidata* Biozone (based on the patterns of conodont occurrences and stable isotopic records presented in Cramer et al. 2012; Radzevičius et al. 2014). The lack of the later species is possibly caused by the unfavourable shallow-water environments. This kind of environment dominated the proximal part of the basin during the latest Wenlock. This conclusion is strengthened by the observation of episodic appearances of the shallow-water genus *Ctenognathodus* starting from the lowermost parts of the Gėluva Regional Stage (Fig. 2). Additionally, the time correspondence to the *K. o. absidata* Biozone, of the discussed interval of the upper part of the Gėluva Regional Stage, is confirmed

by the presence of the subspecies *O. b. bohémica* at a depth of 618.9 m, which is often associated with the former zonal subspecies (data from Brazauskas 1993).

Based on the stratigraphic distribution of conodont taxa and the shape of the stable carbon isotopic curve, the presence of an interval coeval with the following two conodont biozones in the strata of the Gėluva Regional Stage may be suggested: strata time-equivalent to the *O. bohémica longa* Biozone in the lower part of the Nevėžis Formation and the *K. ortus absidata* Biozone in the upper part of the Nevėžis and entire Širvinta formations. According to $\delta^{13}\text{C}$ and biostratigraphical data, the Širvinta Formation most probably corresponds to the upper part of the Gėluva Regional Stage. The lower part of the analysed section is depauperate of zonal conodont species and isotope data are not representative, which makes an exact stratigraphic subdivision of this part of the core impossible.

The time series analyses of palaeoecological parameters describing species richness, per capita immigration rates and per capita extirpation rates reveal an episodic character in the change in local conodont diversity and turnover levels. The first drop in diversity followed the change to a more volatile sedimentation in the upper part of the Jaagarahu Regional Stage, probably forced by climate changes. The second sudden drop in standing diversity and increase in the volatility of both per capita immigration and extirpation rates was associated with the development of shallow-water settings. Most probably this change was caused by a tectonically controlled regression. Surprisingly, none of the episodes of permanent change in the studied parameters occurred during the interval postulated for the Mulde extinction event at the beginning of the Homerian carbon isotopic excursion.

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