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Upper Homerian (Silurian) high-resolution correlation using cyclostratigraphy: an example from western Lithuania

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ABSTRACT:

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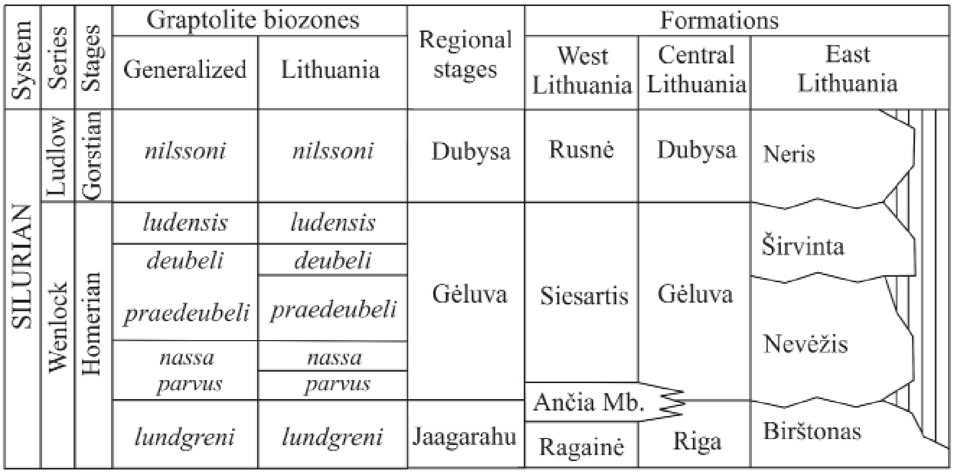
The Gėluva regional stage stratigraphically corresponds to the late Wenlock. This time interval witnessed significant graptolite extinctions and turnovers of conodont faunas, as well as a large positive Mulde carbon isotopic excursion. Thus, the development of a detailed stratigraphy is a necessary step in understanding the complex patterns of regional and global variations in the sediments accumulating during the time interval studied. Therefore, in this contribution we present a cyclostratigraphic analysis of gamma ray (GR) logs from four wells, which are located in the deep water facies belt of the Lithuanian part of the Silurian Baltic Basin of the Gėluva regional stage. The analysis was performed using REDFIT spectral estimation, continuous wavelet transform and signal filtering techniques. As a result two 4th order and five 5th order cycles were distinguished and named in all sections. The correlation of cycles between sections was calibrated with the graptolite biozones. The comparative analysis revealed that intra-basinal cyclostratigraphic correlation could achieve resolution of the order of several tens of thousands of years.

Key words: Lithuania; Silurian; Upper Homerian; Cyclostratigraphy; Graptolite biozones.

INTRODUCTION

The Silurian is the shortest but one of the most dynamic periods in the Paleozoic Era of the Earth's history. There were several biotic extinctions and radiations, with climate changes, glaciations, and sea level fluctuation episodes in this period (Jeppsson 1987, 1993, 1998; Johnson *et al.* 1991; Kiipli *et al.* 2010; Aldridge *et al.* 1993; Loydell 1998, 2007; Munnecke *et al.* 2003; Spiridonov *et al.* 2015). One of such events is documented in the middle–upper Homerian (Calner *et al.* 2006; Melchin *et al.* 2012). The middle–upper Homerian spans the stratigraphical interval from the *parvus* to *ludensis* biozones (Text-fig. 1).

Although biostratigraphic, chemostratigraphic and radiometric age dating investigations of the Silurian Period are intensive, the Silurian, as with all Paleozoic Era systems is unlucky with respect to the amount of cyclostratigraphic or astrochronologic studies performed so far (Hinnov and Ogg 2007). One of the first reports proving the Milankovitch orbital cycles for the Late Ordovician–Early Silurian is presented by G. E. Williams (1991). He, using Fourier analysis, investigated the cyclic halite and dolomite sequences of the Mallowa Salt from the Canning Basin, Western Australia. In addition, there is a magnetosusceptibility study of cyclic rock units, which links these cycles to the Earth's obliquity or eccentricity cycles at the Silurian–Devonian boundary in the Czech Republic (Crick *et al.* 2001). The ma-



Text-fig. 1. Correlation of the Lithuanian graptolite biozones with generalized graptolite biozones (Koren' *et al.* 1996) and with regional stages and formations

rine rhythmic sequences of the Riksu Formation in Estonia (Wenlock) were interpreted as being caused by Milankovitch cycles (Nestor *et al.* 2001). These studies did not use any statistical testing methods and were rather subjective in their approach. A more quantitative approach using Fischer plots analysis revealed the third order cycles in the Silurian of Siberia (Artyushkov and Chekhovich 2004). An investigation of Late Ordovician–Early Silurian tempestites in the Anticosti foreland basin (Canada) revealed evidence of astronomically caused cyclicity (Long 2007). There is a cyclostratigraphic study, which used gamma ray logs and time series techniques for the stratigraphical refinement of the Upper Wenlock in Lithuania (Radzevičius *et al.* 2014c). Also, cyclostratigraphical approaches were used recently in characterizing macroecological dynamics of conodonts in the middle–upper Pridoli of Lithuania (Spiridonov *et al.* 2016).

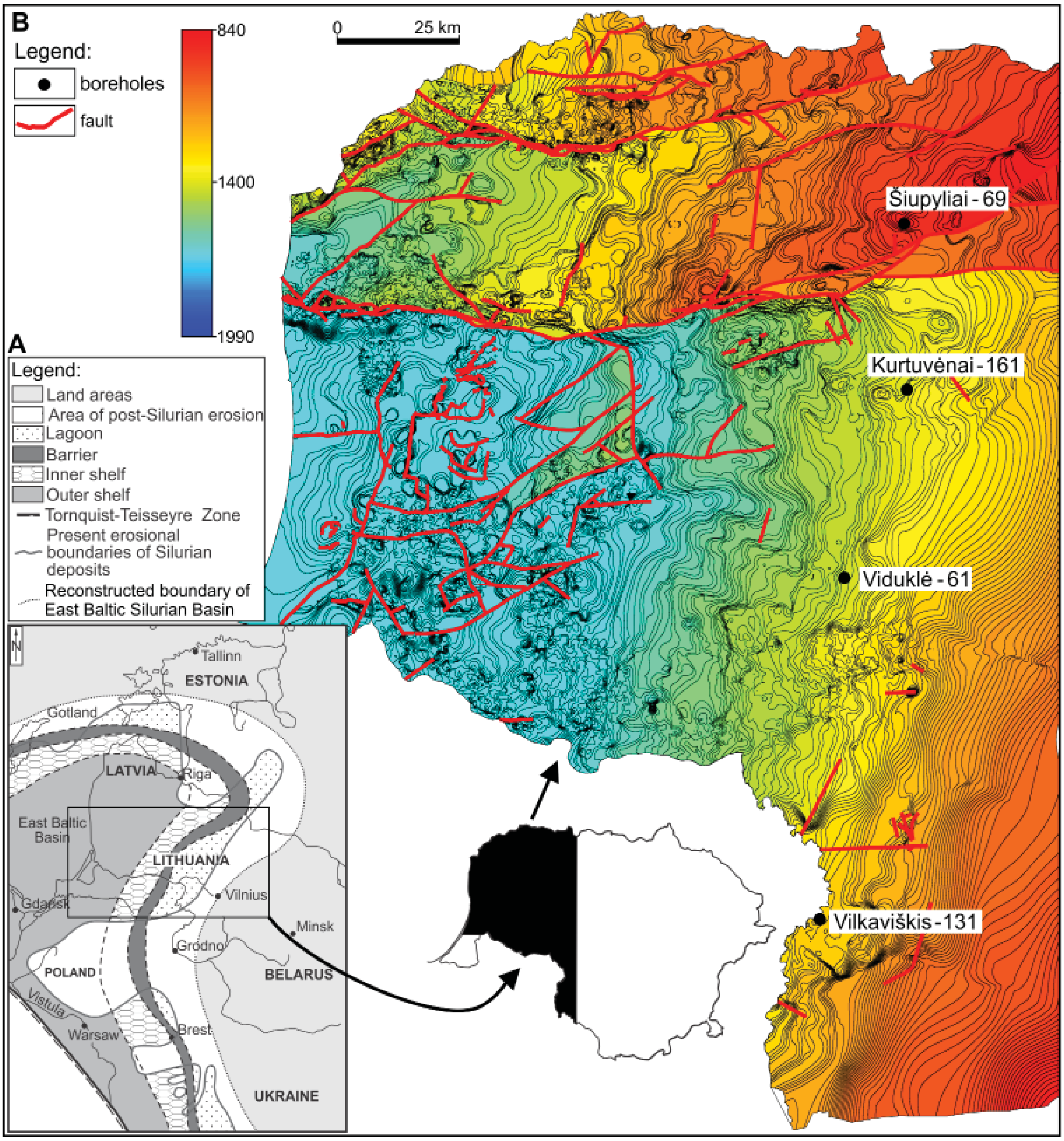
The appearance of new precise radiometric age dating (Cramer *et al.* 2012, 2015), and the latest Silurian Geochronological Scale (Melchin *et al.* 2012) allows us to distinguish and understand cyclic sedimentary patterns in the upper Homerian precisely.

The purpose of this study is to test the natural gamma ray record for the presence of cycles in the upper Homerian strata of Lithuania, and using cyclostratigraphic and graptolite biostratigraphic approaches to produce high-resolution correlation of the upper Homerian strata of the same territory. In order to achieve these goals, four core sections from outer shelfal settings were studied using spectral analytical (REDFIT, continuous wavelet transform) and signal filtering techniques (Gaussian filtering).

GEOLOGICAL BACKGROUND

During the Homerian, the Baltica palaeocontinent was located in the southern hemisphere near the equator (Cocks and Torsvik 2002). The Lithuanian territory was in the eastern part of the Baltic Silurian sedimentary basin and was located on the western part of the Baltica palaeocontinent (Text-fig. 2A).

A graptolite extinction is distinguished at the end of the *lundgreni* Biozone called the *lundgreni* Event (Koren' 1987) or the Big Crisis (German *Große Krise*) (Jaeger 1991). About 95% of graptolite species became extinct during the *lundgreni* Event (Lenz and Kozłowska-Dawidziuk 2001). Only two species of the genera *Pristiograptus* and *Gothograptus* survived the *lundgreni* extinction event, and consequently it is the biggest graptolite crisis in the Silurian Period (Cooper *at al.* 2014). Based on the conodont data, this ecological perturbation is named the Mulde Bioevent (Jeppsson *et al.* 1995). The Mulde Bioevent was distinguished following detailed investigations of Gotland conodonts, which showed the conodont turnover occurring in three event levels or datum points (Calner and Jeppsson 2003; Jeppsson and Calner 2002). Acritarchs and prasinophytes experienced reorganisation in their communities (Masiak 1998, 1999; Porębska *et al.* 2004; Calner *et al.* 2006). However, recent studies have revealed that the *lundgreni* Event (the beginning of the Mulde interval) probably had a rather minor effect on the phytoplankton (Venckutė-Aleksienė *et al.* 2016). Major reductions in radiolarian biodiversity were documented during the middle Homerian of Arctic Canada (Lenz *et al.* 2006). There are well documented changes of



Text-fig. 2. A – Facies map of the western margin of the East European Platform during *Gothograptus nassa* time (after Einasto *et al*. 1986); B –Structural map of the top the Wenlock (Bitinas 2013) and location of boreholes

other biotic groups after the *lundgreni* Event as well (Kaljo *et al*. 1996).

During the discussed event there was major perturbation of the global carbon cycle in the middle–upper Homerian, which was called the upper Homerian positive carbon isotopic ($\delta^{13}C$) excursion (Kaljo *et al.* 1997). The middle–upper Homerian positive $\delta^{13}C$ excursion for the first time was identified in the Anglo-Welsh area (U.K.) (Corfield *et al.* 1992) and now is well known around the world. This excursion is characterized by two distinct positive peaks of $\delta^{13}C$ values (Cramer *et al.* 2011).

The Gėluva regional stage corresponds to the middle–upper Homerian in Lithuania and includes *parvus–ludensis* interval (Radzevičius 2013). The unit-stratotype of the Gėluva regional stage is in the Jakšiai-104 borehole in the 813–776.9 m interval (Paškevičius *et al.* 1994), and the boundary-stratotype is the Vilkaviškis-61 borehole (Kojelė *et al.* 2014). There were marked facies changes across Lithuania during the Homerian, resulting in the use of three stratal schemes for the western, central and eastern parts of the country (Text-fig. 1) In western Lithuania, the upper part of the Ančia Member (Upper Riga Formation) and the Siesartis Formation belong to the Gėluva regional stage. The Ančia Member is represented by microlaminated limestone (Lapinskas and Paškevičius 1976), and the Siesartis Formation is composed of dark grey marls (Paškevičius and Lapinskas 1978). In the central part of Lithuania, the Gėluva Formation is composed of greenish grey marls and light grey nodular limestones (Lapinskas *et al.* 1985). In eastern Lithuania, the equivalent strata comprise the Nevėžis and Širvinta formations (Text-fig. 1). The Nevėžis Formation is represented by grey marls, nodular limestones, and clayey dolostones with lenses of gypsum (Lapinskas and Paškevičius 1976). The Širvinta Formation is composed of reddish, laminated dolomitic marls with lenses of gypsum (Paškevičius 1979). Previously, the upper part of the Birštonas Formation was assigned to the Gėluva regional stage and the upper part of Nevėžis Formation, with the Širvinta Formation was assigned to the Ludlow (Paškevičius 1997). According to new biostratigraphical and geochemical ($\delta^{13}C$) data, the Birštonas Formation is now assigned to the Jaagarahu regional stage and the Nėris and Širvinta formations are assigned to the Gėluva regional stage (Radzevičius *et al.* 2014b; Radzevičius *et al*. 2016).

During the studied time interval, local paleoenvironments in the studied area changed from clayey outer shelf facies in west Lithuania to the carbonatic lagunal and sabkha facies in east Lithuania (Text-fig. 2A). Moreover, the Silurian Baltic Basin experienced a long-term (second order) trend of progressive shallowing during the Silurian. In Lithuania the lateral boundaries of facies, therefore, migrated to the west (Lazauskienė *et al*. 2003).

MATERIAL

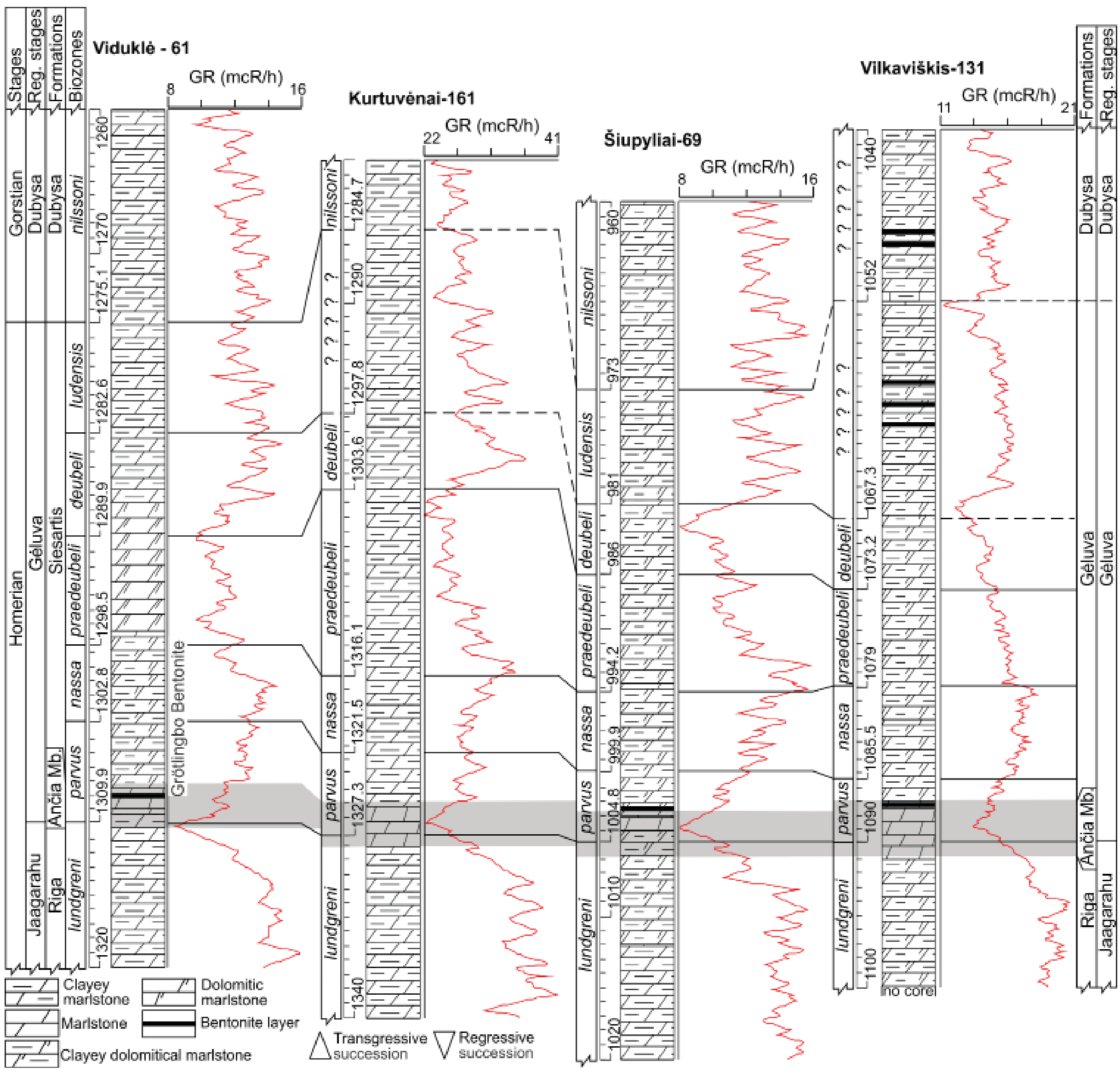
The investigated wells are located in western Lithuania (from north to the south): Šiupyliai-69 (φ 56º2'59.97"N; λ 23o5'23.99"E), Kurtuvėnai-161 (φ 55º44'36.11"N; λ 23º5'23.99"E), Viduklė-61 (φ 55º23'43.05"N; λ 22º54'37.01"E) and Vilkaviškis-131 (φ 54º45'51.94"N; λ 22º50'55.99"E). All wells were drilled in the outer shelf facies zone (Text-fig. 2B). In all investigated boreholes the upper part of the Riga Formation with the Ančia Member was recognized. The Siesartis Formation is present in the Šiūpyliai-69, Kurtuvėnai-161 and Viduklė-61 wells and the Gėluva Formation in the Vilkaviškis-131 well (Text-fig. 3). The Dubysa Formation overlaps the Siesartis and Gėluva formations. In the investigated interval, all core material studied is composed of marls with different concentrations of the clay component and different dolomitization levels. The distribution of graptolites has been studied in detail and published elsewhere (Text-fig. 3).

Several bentonites layers occur in the investigated interval of the middle–upper Homerian (Text-fig. 3). According to geochemical data, the Grötlingbo Bentonite has been identified at 1308 m depth, just above the Ančia Member, in the *parvus* Biozone in the Viduklė-61 well (Kiipli *et al.* 2008). The Grötlingbo Bentonite is an important radiometrically dated bentonite layer (Cramer *et al.* 2012) of Homerian age first described from the Gotland (Snäll 1977). There are bentonite layers at the same level in the Šiupyliai-69 and Vilkaviškis-131 boreholes. The geochemical analysis of these layers has not been done, but these bentonites in the *parvus* Biozone are interpreted as representing the Grötlingbo Bentonite.

METHODS

The gamma ray log data was used to reflect the variations in the contribution of clayey and detrital component in the time series analyses. This is a first order simplification, because the cumulative gamma signal reflects the summed contribution of gamma dosage from the radioactive isotopes of U, Th, and K, which have varying geochemical and consequently sedimentological properties (Kozłowski and Sobień 2012). Moreover, it is widely recognized that the relative amount of terrigenous and clayey material increases in the distal parts of the Silurian Baltic Basin in comparison to the proximal parts (Paškevičius 1997). Therefore, this simplification is justified in these sedimentary settings.

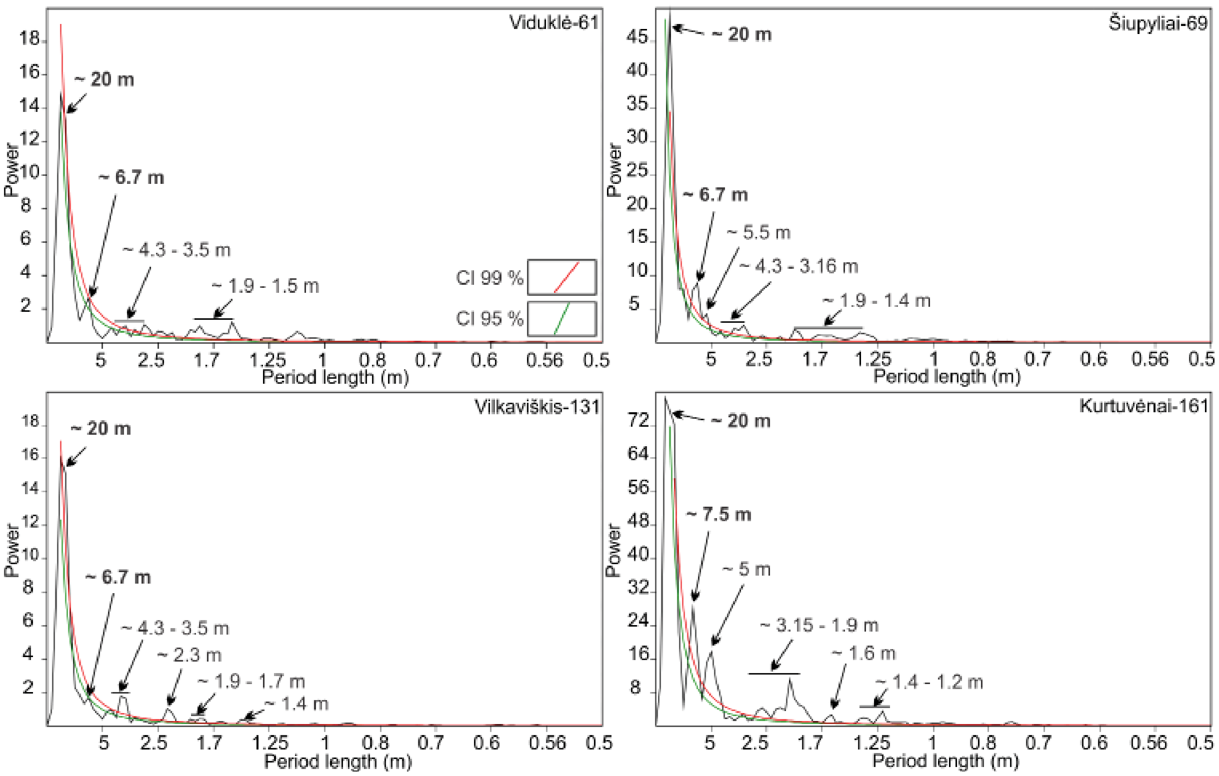
In order to reveal cyclical patterns of sedimentation in the strata of the Gėluva regional stage three complimentary spectral analytical approaches were used: (1) REDFIT amplitude spectrum estimation, (2) continuous wavelet transform, and (3) band-pass signal filtering. The REDFIT (red noise fitting) spectral estimation algorithm, which utilizes the Lomb-Scargle Fourier transform, was used because it is robust to the variations in the sampling rate (Schulz



Text-fig. 3. The correlation of the upper Homerian biostratigraphy, lithology and gamma ray log of Viduklė-61 (after Radzevičius *et al.* 2014c), Vilkaviškis-161 (after Radzevičius 2006), Kurtuvėnai-161 and Šiupyliai-69 (after Radzevičius and Paškevičius 2005)

and Mudelsee 2002). The continuous wavelet transform was used because it reveals the so called "evolutionary" spectrum of a time series, where frequency and amplitude modulation can be distinguished. Performing wavelet analyses, Morlet mother wavelet was used because of its superior characteristics in determining periodicities in the frequency domain. The REDFIT and continuous wavelet spectra were estimated using the PAST (PAlaeontological STatistics) statistical package (Hammer *et al.* 2001). Before the spectral analyses, in order to stationarize them, all stratigraphic series were detrended by subtracting the second order polynomial trend.

For the purposes of cyclostratigraphic subdivision and correlation in all three sections two longest (4^{th} and 5^{th} order) cyclicities, which were distinguished earlier in one of the investigated cores using the real part of the wavelet scalogram and Lomb periodogram, were used (Radzevičius *et al.* 2014c). Cycles as well as non-periodic features with longer duration (or stratigraphic span) are less prone to the distortions caused by the erosion, non-deposition and variations in sedimentation rates (Jerolmack and Paola 2010). In order to reconstruct the shapes of cycles from the natural gamma ray data a signal band-pass filtering procedure was performed. The natural gamma trend



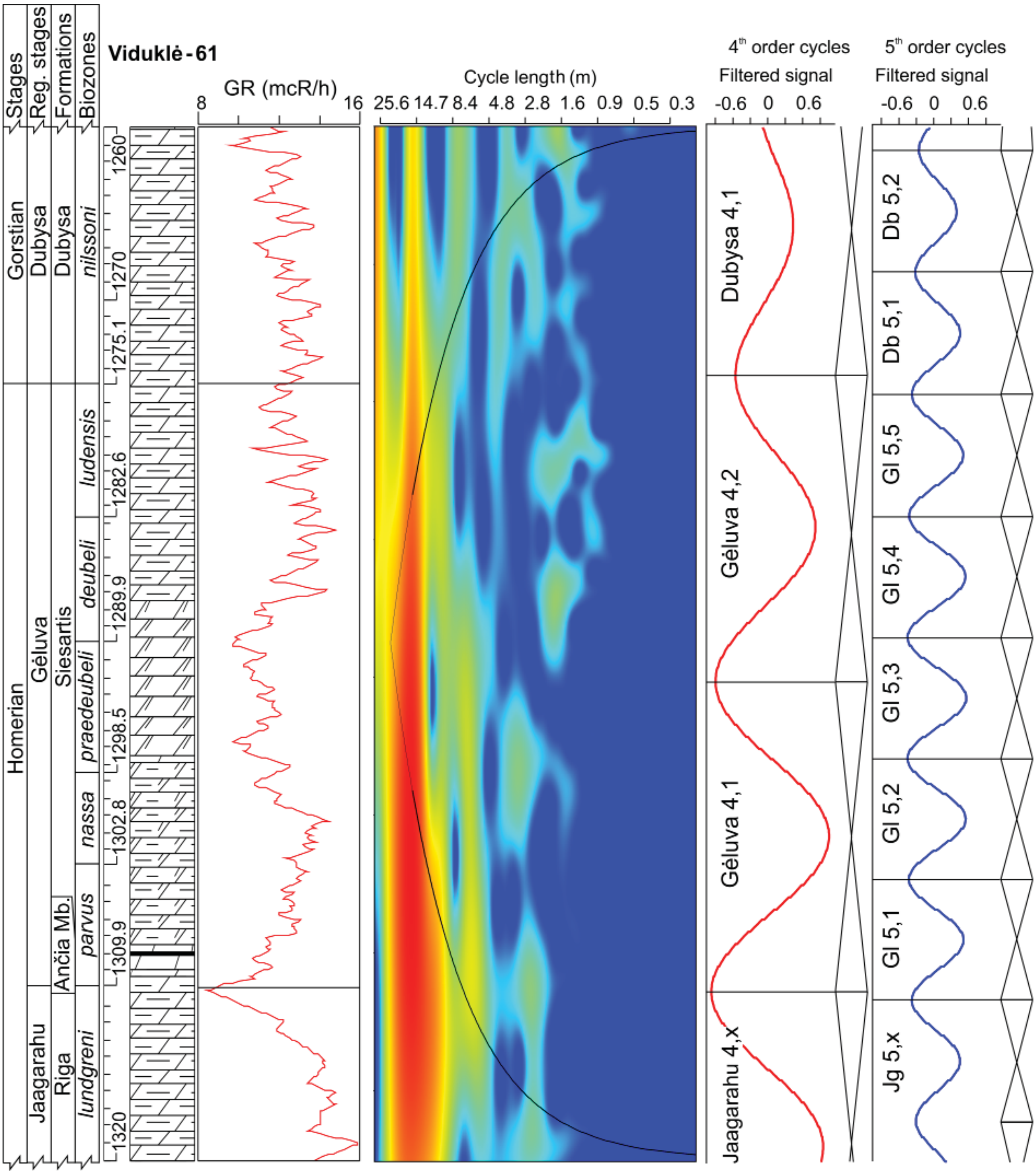
Text-fig. 4. REDFIT spectra of the gamma ray logs in the investigated wells. CI – confidence interval

was filtered in two statistically significant frequency pass bands in each core. For this purpose a Gaussian filter, which is described as a "zero phase" filter, was used (Kodama and Hinnov 2014). This filter does not distort the stratigraphic positions of heights and troughs of oscillations. The filtering of signals was performed using package "astrochron" in the R statistical computational environment (Meyers 2015; R Development Core Team 2015).

Filtered statistically significant cyclicities were used in the high resolution correlation of deep water (graptolite) facies of the Lithuanian part of the Baltic Basin. The order of sedimentary cycles was determined using available chronostratigraphic information and using conventional ordering nomenclature. Cycles were called 4th order when their estimated duration was of the order of several hundreds of thousands of years, and cycles were named 5th order when their estimated duration varied from several tens to a couple of hundreds of thousands of years (Miall 2010). All distinguished 4th and 5th order cycles were named using the following nomenclature: $Gl_{i,j}$. Here Gl is for Gėluva regional stage, "*i*" denotes the order of the cycle (in this case 4th or 5th) and "*j*" denotes the number of a cycle. This scheme allows us to compare cycles with other stratigraphic features in a similar manner to the event datum (Jeppsson 1998). In this way there is integration of cyclostratigraphic information into the high-resolution event stratigraphy (Cramer *et al.* 2015). Cycles are non-unique in their nature (Miall 2010) in the sense that they are distinguished using only information about their amplitude and phase relations. Thus there is a possibility of missing some cycles. In the future there is a possibility that some gaps in the record will be distinguished. Our scheme could easily accommodate such changes by interpolating new cycles between distinguished ones (i.e. if there is an additional cycle of the same order between cycles $Gl_{5,1}$ and $Gl_{5,2}$ it will be named $Gl_{5,1.1}$).

RESULTS

In this study the two cyclicities with the lowest frequencies and the highest power were focused on. According to the REDFIT analysis (Text-fig. 4), there are several additional high frequency cyclicities whose spectral power passed the 95 and 99% confidence intervals. However, high frequency features, as was mentioned in the methods section, are more sensitive to sedimentological distortion. The period lengths of 4th order cycles in all four analysed sections



Text-fig. 5. Upper Homerian biostratigraphy, lithology, gamma-ray log data, wavelet scalogram (colour intensity shows spectral strength) and filtered cycles in the Viduklė-61 well. Legend see Text-fig. 3

reached 20 m. The 5th order cycles were more variable in their period length: Viduklė-61, Šiupiliai-69, and Vilkaviškis-131 had 6.7 m long cycles; and Kurtuvėnai-161 had 7.5 m long 5th order cycles.

Cyclicities were distinguished in the Jaagarahu, Gėluva and Dubysa regional stages. In this study only the cyclicities of the Gėluva regional stage are focused on. The descriptions of the cycles of the Gėluva regional stage are given below.

Viduklė-61 well

Two 4th order cycles of the Gėluva regional stage in Viduklė-61 well were distinguished (Text-fig. 5).

The base of first 4th order cycle ($Gl_{4,1}$) coincides with the minimum values of GR in the Ančia Member in the lowermost part of the *parvus* Biozone. The $Gl_{4,1}$ ended in the upper part of *praedeubeli* Biozone. The base of $Gl_{4,2}$ cycle coincides with top of $Gl_{4,1}$ cycle. The top of the $Gl_{4,2}$ cycle coincides with the base of the *nilssoni* Biozone and the Dubysa regional stage.

Five 5th order cycles are distinguished in the Gėluva regional stage (Text-fig. 5). The base of $Gl_{5,1}$ is a little bit lower than the base of $Gl_{4,1}$ cycle in the base of the Ančia Member. The cycle $Gl_{5,1}$ ends in the topmost part of the *parvus* Biozone. $Gl_{5,2}$ cycle corresponds to the *nassa* Biozone. The base of the $Gl_{5,3}$ coincides with the *praedeubeli* Biozone. The cycle $Gl_{5,4}$ corresponds to the *deubeli* Biozone. The base of $Gl_{5,4}$ is near the base of the *ludensis* Biozone and it ends a little bit lower than the *nilssoni* Biozone and here coincides with the top of $Gl_{4,2}$ cycle boundary.

The distinguished cycles of the Viduklė-61 well are used as the typical or standards for the Gėluva regional stage. Viduklė-61 well has been chosen because it includes the boundary stratotype of the Gėluva regional stage (Kojelė *et al.* 2014), the type section of the Siesartis Formation (Paškevičius and Lapinskas 1978), and this core is well explored chemo- (Martma *et al.* 2005) and biostratigraphically (Radzevičius *et al.* 2014a).

Kurtuvėnai-161 well

Two 4th order cycles were distinguished in the Gėluva regional stage in the Kurtuvėnai-161 well (Text-fig. 6). The base of $Gl_{4,1}$ is in the Ančia Member, the *parvus* Biozone. The top of $Gl_{4,1}$ cycle is in the upper part of the *praedeubeli* Biozone. The top of $Gl_{4,2}$ cycle is near the *nilssoni* Biozone base. It is difficult to correlate the top of $Gl_{4,2}$ with the graptolite biozones because graptolites are absent in the 1297.8–1284.7 m interval, but the first appearance of *Neodiversograptus nilssoni* (Barrande) marking the beginning of the Ludlow is at a depth of 1284.7 m. Therefore the lower boundary of the *nilssoni* Biozone cannot be higher in the section.

Five 5th order cycles are distinguished in the Gėluva regional stage interval. The base of $Gl_{5,1}$ is lower than the base of $Gl_{4,1}$ cycle, near the base of the *parvus* Biozone (Text-fig. 6). The $Gl_{5,2}$ starts in the *nassa* Biozone and ends in the lower part of *praedeubeli* Biozone. The base of $Gl_{5,3}$ coincides with the top of $Gl_{5,2}$ cycle. The top of $Gl_{5,3}$ is in the upper part of the *praedeubeli* Biozone, higher than the base of $Gl_{4,2}$ cycle. The top position of $Gl_{5,4}$ is difficult to correlate with the graptolite biozones too. There are no graptolites in the interval, although the $Gl_{5,4}$, and the $Gl_{5,5}$ cycles can be related to the *deubeli* and *ludensis* graptolite biozones. The top of $Gl_{5,5}$ cycle is lower than the top of $Gl_{4,2}$ cycle, near the boundary of the Gėluva and Dubysa regional stages.

The numbers and boundary positions of the 4th and 5th order cycles of the Gėluva regional stage in the Kurtuvėnai-161 well are similar to those in the Viduklė-61 well.

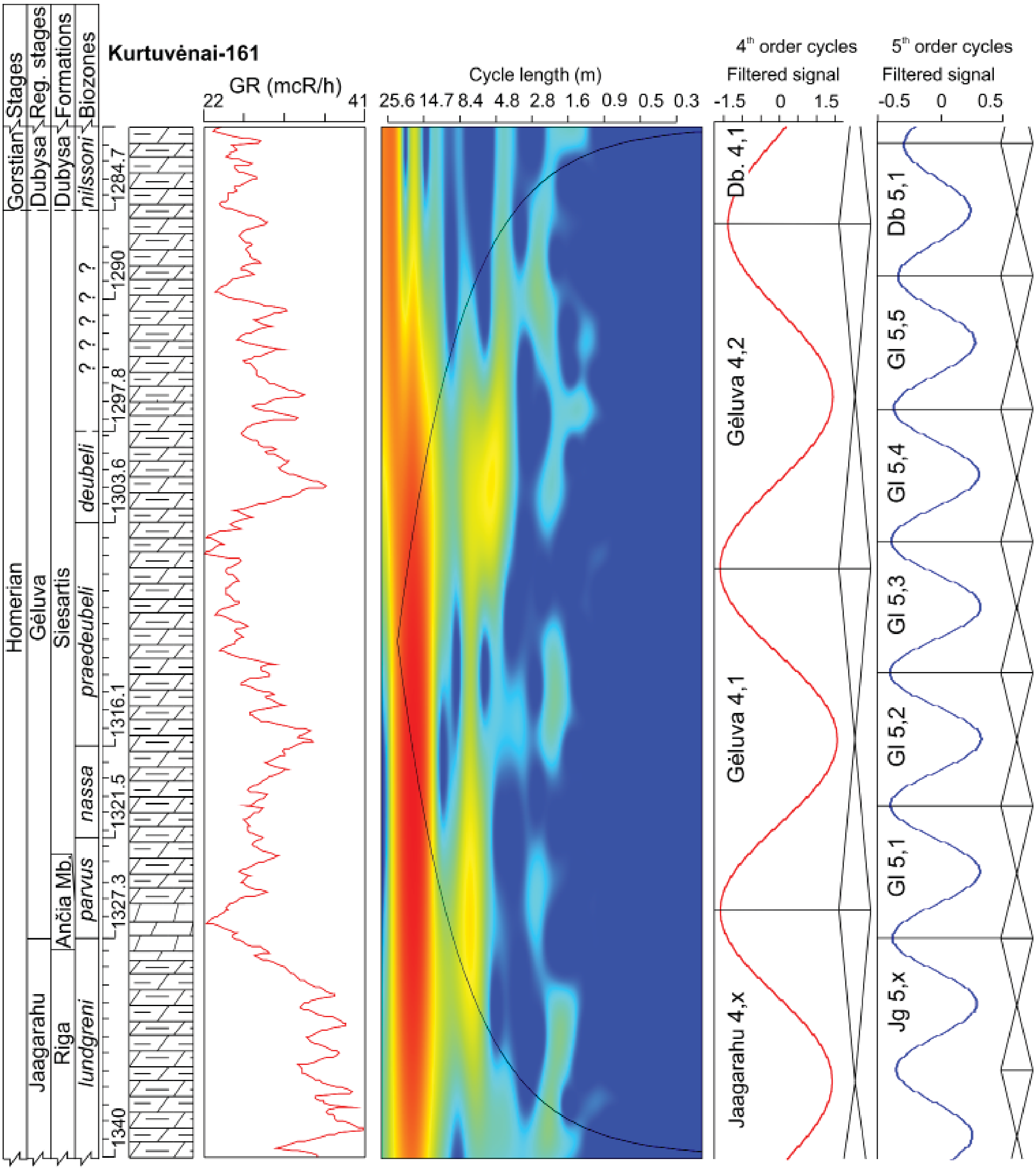
Šiupyliai-69 well

Two 4th order cycles of the Gėluva regional stage is distinguished in the Šiupyliai-69 well (Text-fig. 7). The base of $Gl_{4,1}$ cycle is in the Ančia Member, near the base of the *parvus* Biozone. The top of $Gl_{4,1}$ is in the lower part of the *deubeli* Biozone. The $Gl_{4,2}$ cycle is distinguished from the lower part of the *deubeli* Biozone to the middle *nilssoni* Biozone. The top of $Gl_{4,2}$ is about 10 m higher than the Gėluva and Dubysa regional stage boundary. Therefore significant part of the $Gl_{4,2}$ cycle is in the Dubysa regional stage. According to the described patterns, the upper boundary of $Gl_{4,2}$ in Šiupyliai-69 well is higher than in Viduklė-61 and Kurtuvėnai-161 wells.

Five 5th order cycles are distinguished in the Gėluva regional stage (Text-fig. 7). The base of $Gl_{5,1}$ is in the Ančia Member, in the the middle part of the *parvus* Biozone. It is a little bit higher than the base of $Gl_{4,1}$ cycle. The base of $Gl_{5,2}$ is in the middle part of the *nassa* Biozone. The cycle $Gl_{5,3}$ is in the middle *praedeubeli* and middle *deubeli* biozones interval. The base of $Gl_{5,4}$ cycle is in the middle part of the *deubeli* Biozone and the top in the middle of the *ludensis* Biozone. The top of $Gl_{5,5}$ is higher than the boundary of the Gėluva and the Dubysa regional stages, in the lower part of the *nilssoni* Biozone.

Vilkaviškis-131 well

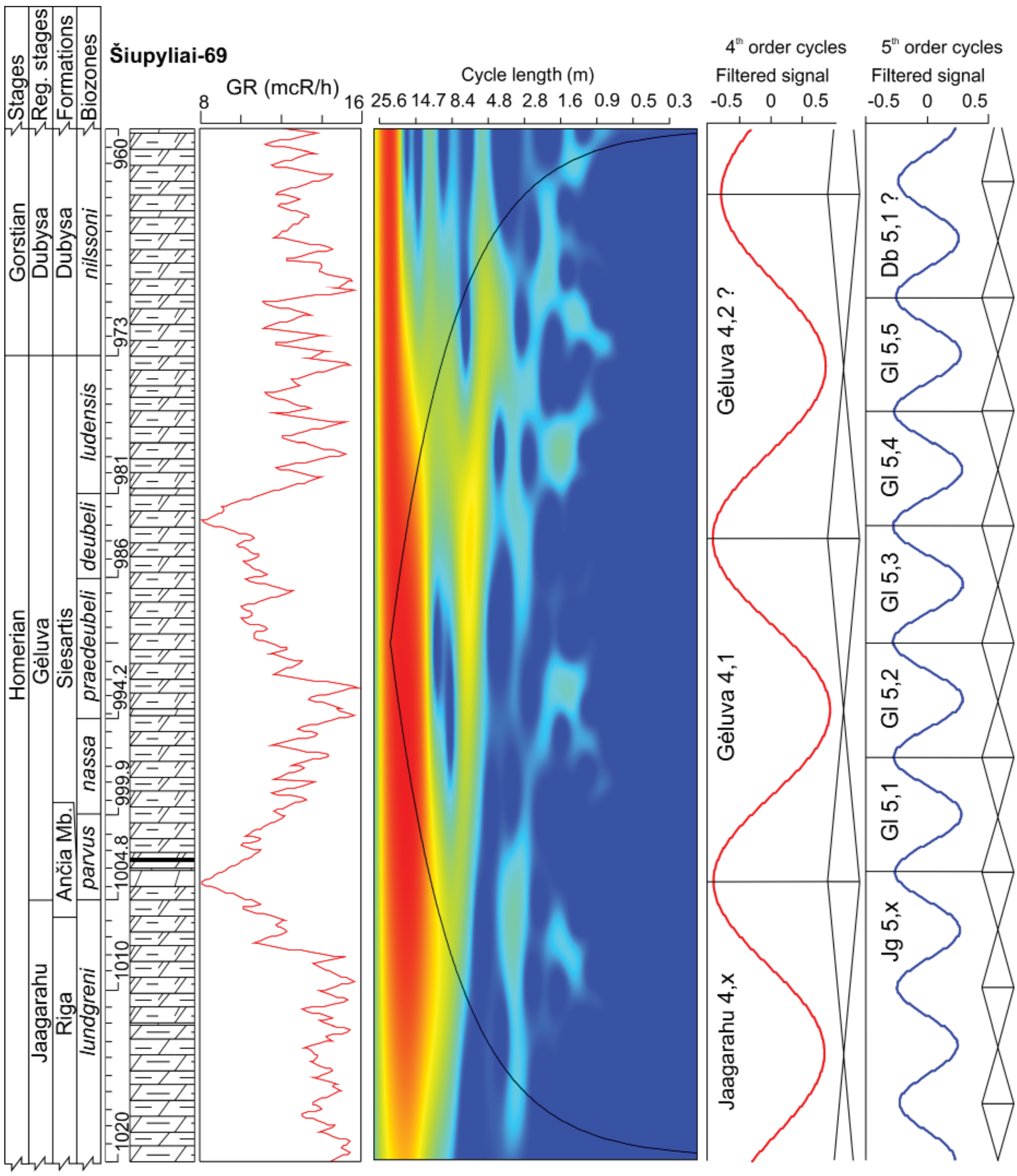
There are two 4th order cycles in the Gėluva regional stage of the Vilkaviškis-131 well section (Text-fig. 8). The base of $Gl_{4,1}$ is in the Ančia Member at the lower boundary of the *parvus* Biozone. $Gl_{4,1}$ ends in the lower part of *deubeli* Biozone. The base of $Gl_{4,2}$ is in the *deubeli* Biozone. The position of the $Gl_{4,2}$ cycle upper boundary is difficult to correlate with the graptolite biozones. In this part of the section (starting from 1067.3 m depth) graptolites are absent. Therefore the boundary between the Gėluva



Text-fig. 6. Upper Homerian biostratigraphy, lithology, gamma-ray log data, wavelet scalogram and filtered cycles in the Kurtuvėnai-161 well. Legend see Text-fig. 3

and the Dubysa regional stages are distinguished based on the lithological changes (Gėluva–Dubysa formations).

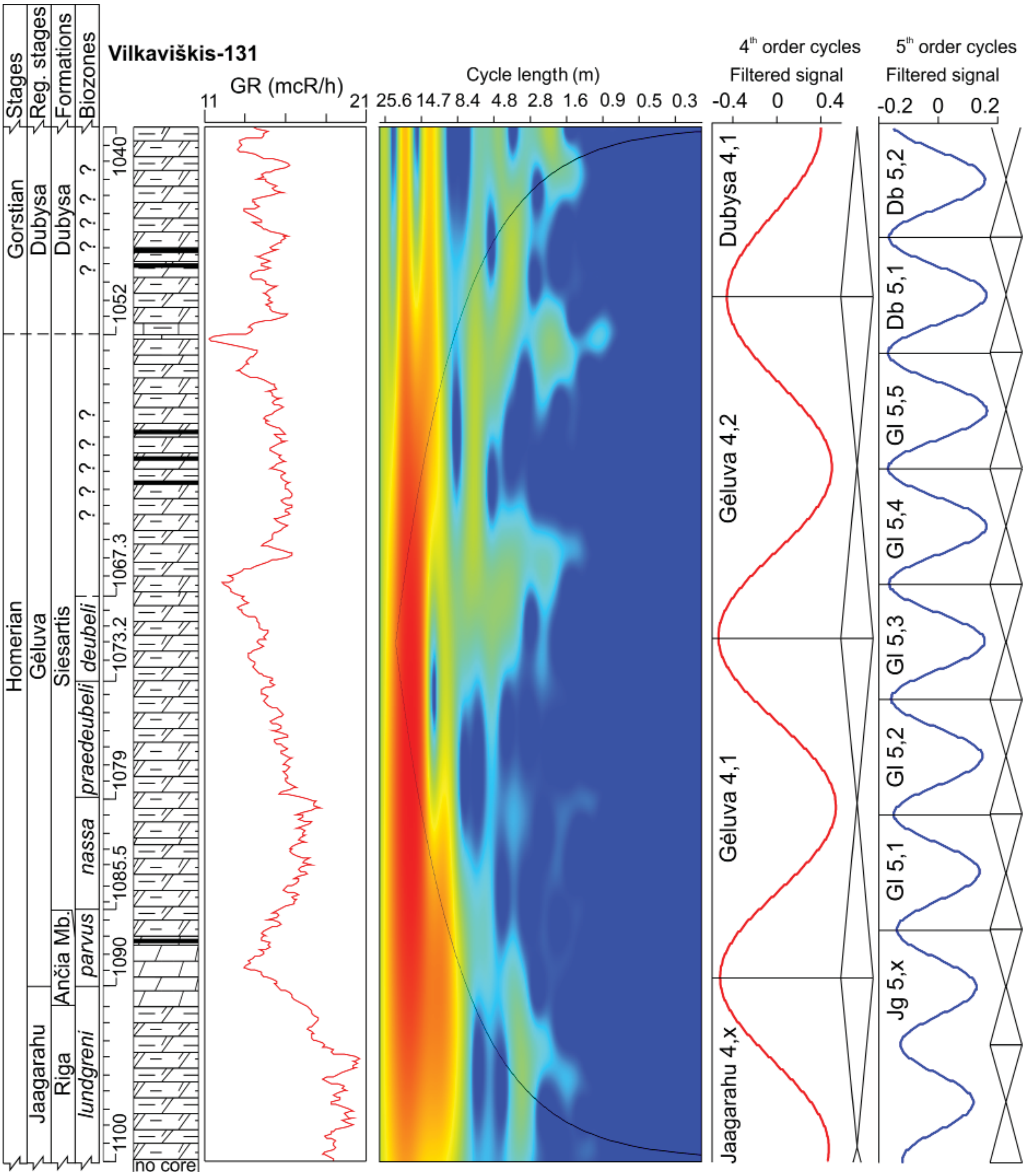
There are five 5th order cycles in the studied interval (Text-fig. 8). The base of $Gl_{5,1}$ is in the upper part of the *parvus* Biozone, a little bit higher than the base of the $Gl_{4,1}$ cycle. The base of $Gl_{5,2}$ is located in the upper part of the *nassa* Biozone. The $Gl_{5,3}$ corresponds to the *deubeli* Biozone. There is no possibility of correlating $Gl_{5,4}$ and $Gl_{5,5}$ with the graptolite biozones because graptolites are absent there. However, the upper boundary of $Gl_{5,5}$ is lower than the upper boundary of the $Gl_{4,2}$ cycle, near the Gėluva and Dubysa regional stages boundary.



Text-fig. 7. Upper Homerian biostratigraphy, lithology, gamma-ray log data, wavelet scalogram and filtered cycles in the Šiupyliai-69 well. Legend see Text-fig. 3

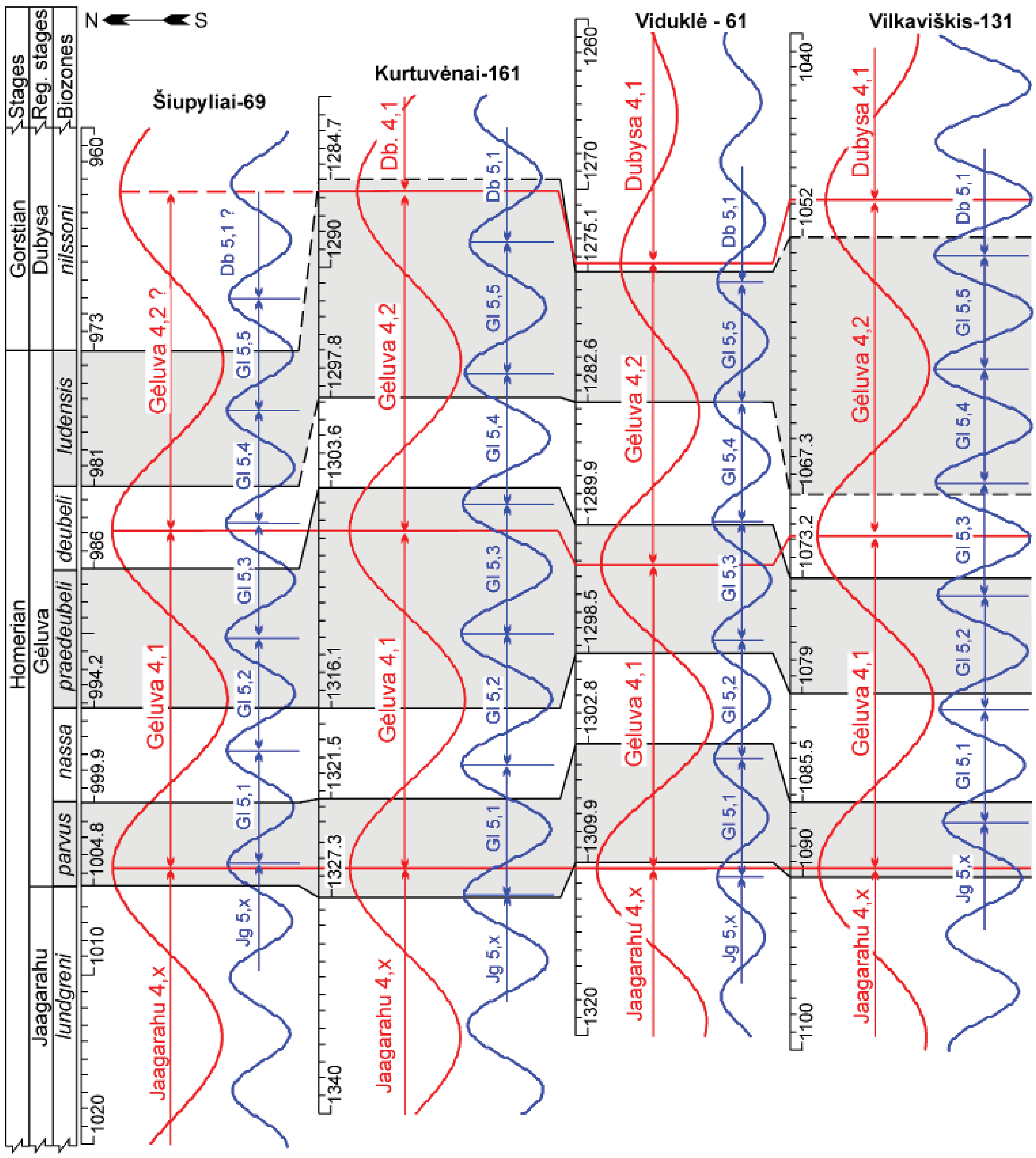
DISCUSSION AND CONCLUSIONS

All studied middle–upper Wenlock sections yielded the same set of 4th and 5th order cycles: two long and five shorter cycles each (Text-fig. 9). Lower (4th) order cycles ($Gl_{4,1}$ and $Gl_{4,2}$) are broadly comparable to the Ho2 and Ho3 sequences recognized in different sections of Europe and North America (Barrick 1997; Calner 1999; Cramer *et al.* 2011; Cramer *et al.* 2012; Marshall *et al.* 2012; Ray and Butcher 2010). However, according to the precise cyclostratigraphical placement, based on the spectral analysis and sig-



Text-fig. 8. Upper Homerian biostratigraphy, lithology, gamma-ray log data, wavelet scalogram and filtered cycles in the Vilkaviškis-131 well. Legend see Text-fig. 3

nal filtering, the base of the Gl$_{4,2}$ cycle is stratigraphically lower than that proposed for the comparable sequence Ho3. In our case the maximum regression is observed in the *praedeubeli* or *deubeli* biozones and not in the *ludensis* Biozone as was shown by Cramer *et al*. (2011). The differences could be of a double nature. Firstly, a difference could arise because of different scaling schemes for graptolite zones. Secondly, stratigraphical sequences are distinguished based on mainly qualitative observations and typological schemes, (e.g., maximum regressive surface), which could conflate dynamic features that belong to dif-



Text-fig. 9. Correlation of 4th and 5th order cycles with graptolite biozones in the studied boreholes

ferent hierarchical orders when they superpose each other (Catuneanu 2006). Spectral analyses, on the other hand, are based on the Fourier theorem, which states that the studied continuous signal could be decomposed into the sum of independent components (simple functions), representing amplitude contributions of different frequencies of the signal.

It should be noted that the occurrence of two 4th order cycles in the Gėluva regional stage corresponds well to the bentonite based correlation of the lower two sedimentary cycles (Iide Beds and Viita+Kuusnõmme Beds) in the Rootsiküla Stage of the shallow water Estonian sections in the upper part of the Homerian (Kiipli *et al.* 2011).

The 4th order cycles revealed could be correlated between the different wells studied with high accuracy and precision. However, some features, especially in the upper part of the section, have a lower stratigraphic time significance potential. The base of the $Gl_{4,1}$ cycle corresponds approximately to the lower boundary of the *parvus* Biozone. The base of the $Gl_{4,2}$ cycle in the type section (Viduklė-61) and also in the Kurtuvėnai-161 section is distinguished in the middle of the *praedeubeli* Biozone. In the more near-shore successions of the Šiupyliai-69 and the Vilkaviškis-131 wells the base of the $Gl_{4,2}$ cycle is observed stratigraphically higher – in the *deubeli* Biozone. Similarly in those two sections the upper boundary of the $Gl_{4,2}$ cycle is offset further into the Ludlow. This phase delay of cycles in shallower sections in comparison to deeper sections is also observed in the patterns of the 5th order cycles. For example, in the Vilkaviškis-131 succession 5th order cycles are significantly (by 180°) displaced in phase in comparison to the Viduklė-61 section.

There could be several possible reasons for differences in phase relations between cycles, which are driven by the same forcing mechanism, i.e., Milankovitch mechanisms (Herbert 1994; Hinnov and Hilgen 2012). One of the possible sources of non-in-phase responses of sedimentary systems is progressive variation in the potential of carbonate production on the offshore-nearshore gradient. This could be related to the variations in pH and also in the availability of light for photosymbiotic carbonate building organisms. This could result in non-linear fluxes of carbonates as a response to possibly linear external forcing. It was shown that the sensitivity of carbonate content (which is approximately inversely reflected in the gamma ray curves) as a palaeoclimatic proxy strongly depends on the average carbonate concentrations in the studied section (Herbert 1994). Changes in accommodation spaces due to eustatic variations also could cause out of phase sedimentation patterns in different parts of a basin (Kidewell 1988), as well as spatial colonization dynamics of carbonate material producing organisms, which react to the sea level perturbations in a lagged manner (Tipper 1997).

The patterns of cyclic sedimentation revealed, which are constrained by high-resolution graptolite stratigraphy, undoubtedly show a great potential of spectral method based cyclostratigraphy in the correlation of offshore strata of the Silurian Period. Based on the previous estimations of the durations of the cycles of the Gėluva regional stage (Radzevičius *et al.* 2014c), core sections could be correlated with the stratigraphic precision in order of ~ 70 Ka (approximately half of a 5th order cycle). The combination of cyclostratigraphy with other tools, such as biostratigraphy and $\delta^{13}C$ chemostratigraphy could reduce this correlation error even further.

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