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Zonation of Lithuanian Silurian graptolites and other faunal groups

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The Baltic Silurian Basin, Lithuanian Depression and other structures are shown in the map, with marked by isopachs (contour lines of equal thickness) of the Silurian beds with graptolites and fauna of other groups. The Silurian facies vary greatly in the Depression – from clayey open-sea deep shelf to carbonaceous ones of shallow shelf, and low-energy lagoon facies. The history of investigations on East Baltic area graptolites begins from 1953–1958, when 15 graptolite zones were singled out, and proceeds to 35 zones defined now. Peculiarities in the graptolite scale from *C. cyphus* to *N. lochkovensis* inclusive are discussed. Transgressions and regressions of the Silurian marine basin, as well as shorter transgressions with wedges and graptolites of clayey facies shifted towards basin shores and regressions with partial extinction of graptolites are elucidated. During these investigations the graptolite scale has been detailed and added with new zones. Graptolite evolution in the zones has been analysed. Stages of graptolite evolution are analysed in relation to the following bioevents: *Stačiūnai, Likėnai, Valgu, Ireviken, Mulde, Linde, Lau, Klev and Šilalė*. Finally, two tables present graptolite zone correlation with conodont, vertebrate and ostracod zones revealing a highly detailed stratigraphy of the Lithuanian Silurian.

Keywords: Silurian, graptolites, zones, bioevents, correlation, conodonts, vertebrates, ostracods

INTRODUCTION

Lithuanian Silurian graptolite and other extinct faunal groups occur widely in the Baltic Syneclise and south-western slope of Belarus-Mazurian Anteclise. The graptolite remains are most often found in the area of the Lithuanian Depression, as well as Kurzeme Depression and Ergli Elevation in Latvia (Paškevičius, 1997). The thickness of the Silurian beds in the area of the Baltic Syneclise, including the south-western part of the Lithuanian Depression, exceeds 1200 m and decreases to 300–600 m in the Kurzeme Depression and 50–200 m in the Ergli. Going from this syneclise to the Belarus-Mazurian Anteclise, the Silurian thicknesses decline to 300 m, and the Silurian beds wedge out at the Belarus state border south of the border with Poland (Fig. 1).

Fig. 1. Distribution of the Silurian rocks, thickness, structural tectonic and facial zonation: 1 – denudation boundary of the rocks, 2 – izopachs, m, 3 – facies boundaries, 4 – facies zones: West Lithuanian, Nadruva and Semba-Barta (1), 5 – Lithuanian–West Latvian (2), 6 – Belarus-Mozurian Anteclise slope (3), 7 – intermediate zone between syneclise clay facies and anteclise carbonaceous facies (4), 8 – northern (5a) and southern (5b) parts of the Baltic shield slope, 9 – boreholes drilled through the Silurian, 10 – boreholes without the Silurian rocks, 11 – facies of the section line, 12 – paleogeological section line, 13 – faults, 14 – supposed faults (Paškevičius, 1994).

The Silurian facies vary greatly in the structures mentioned above and their distribution is uneven, as this is related to the evolution of the Baltic Silurian Basin and tectonic movements (Paškevičius, 1997). The open-sea deep water shelf facies with graptolites occur in the western part of the Lithuanian Depression from Llandovery, Rasytė Formation, *C. cyphus* zone to Přídolí *N. lochkovensis* zone of Minija Formation inclusive. The graptolites in Latvia's Kurzeme Depression occur to the Middle Ludlow Nova beds, while in the Ergli Elevation they occur only in the Llandovery beds (later beds are denuded). Intermediate Silurian facies between the clayey and calcareous facies occur in the central parts of Lithuania and Latvia with abundant bottom fauna and graptolites becoming rarer to the Wenlock Vilkija beds. Various carbonate facies with frequent remains of bottom fauna are spread on the Belarus-Mazurian Anteclise slope and Latvian Saddle, but its eastern part is notable even for facies of fauna common for increased salinity lagoon intermediate conditions of low energy in Jočionys, Verknė, Nevėžis, Širvinta, Neris and Pabradė formations with extremely rare bottom fauna (Fig. 2).

HISTORY OF GRAPTOLITE ZONE INVESTIGATIONS

The first investigations of Lithuanian graptolites and their zones have been made in Stoniškiai-1 deep borehole cores by Aleksandr Obut (1953), where graptolites from Llandovery, Wenlock and Ludlow had been defined (Киснерюс, 1974). J. Paškevičius has been performing investigations of graptolites and their zones from 1958 to 2020. He has been especially interested in geographical and stratigraphic distribution of graptolites in Lithuanian and neighbourly borehole sections, as well as appearance and extinction of graptolite genera and species and their variability and evolution. The graptolite range zones have been most often determined, with concurrent zones manifested at the same time. Some graptolite zones have been found to form zones of communities, interval and abundance, as well as phylogenetic zones in rare cases. After the graptolite range zone index species became extinct, the interval zones among the range zones were singled out in the geological section. Much attention has been given to the interpretation of the pattern of zone changes, especially for determination of the lower boundary of the zonal index species, investigation of morphologic external and internal systematic features, observation of phylogenesis of certain species, as well as determination of graptolite complex zones, because this complex sometimes replaces the zone if there is no zonal index species. The change of the euphotic zone in the basin, water transparency and graptolite taphonomy is known to play an important role in the life of the graptolites, because they had been buried in different facies from clayey to calcareous ones. The author has been particularly interested in this, because the graptolites in Lithuania are mainly buried in the open sea deep shelf clayey deposits.

J. Paškevičius (1958) described 15 Lithuanian Llandovery, Wenlock and Ludlow graptolite zones. The boundary between Llandovery and Wenlock had been marked at the base of the *M. griestonensis* zone at that time. The number of graptolite zones in the papers of the same author (1960, 1961) increased to 19, but the boundaries of the stages did not change. The same 15 graptolite zones were discussed by J. Paškevičius (Пашкевичюс, 1963) in the paper on the Silurian stratigraphy revision, where the boundary between the Wenlock and Ludlow was marked at the base of *G. nassa* zone, which as accepted throughout Europe. Another paper (Пашкевичюс, 1965) presents a detailed analysis of graptolite zones with some new ones singled out in the Lower Silurian (Llandovery and Wenlock) section consisting of 13 graptolite zones; the borehole sections with metabentonite intermediate layers are given there. An article (Пашкевичюс, 1968) published in the book devoted to the Prague Geological Congress presents correlation of Lithuanian Silurian terrigenous deposits and 16 graptolite zones to the carbonate facies strata with zonal graptolite pictures added. At the 3rd International Silurian/Devonian Symposium in Leningrad J. Paškevičius and V. Karatajutė-Talimaa (Пашкевичюс, Каратаюте-Талимаа, 1968) discussed Downtonian stratigraphy and Ludlow graptolite zones; for the first time they distinguished the *ultimus* zone at the base of Downtonian (Přídolí) in Lithuania and so determined the lower boundary of the Přídolí. At the first colloquium in the Soviet Union held in Novosibirsk on graptolite investigations, 7 Ludlow graptolite zones explored in detail were discussed, and palaeontological description of two new species – *Pristiograptus virbalensis* sp. nov. and *P.*(?) *tauragensis* sp. nov. – were given.

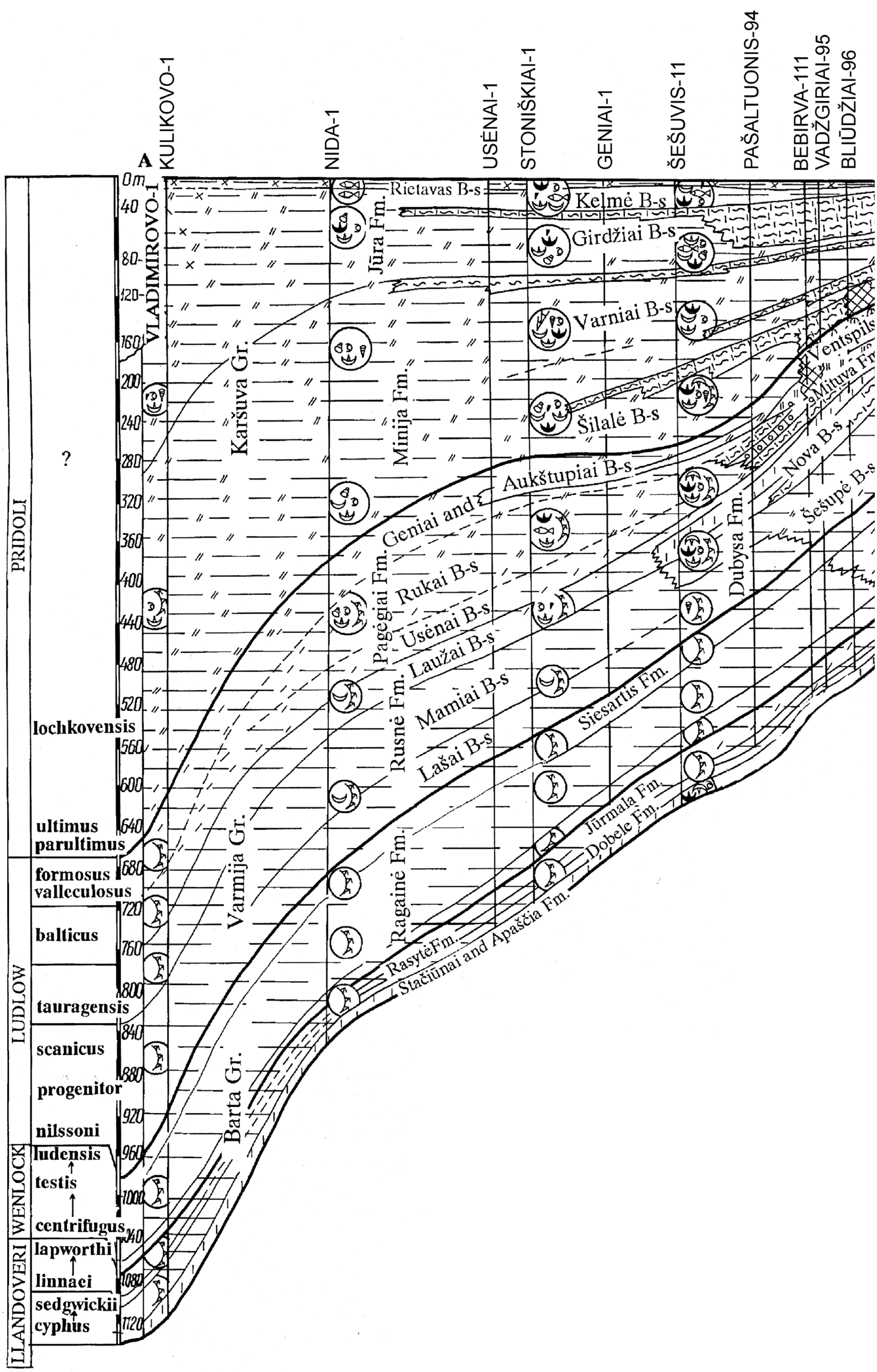
J. Paškevičius in his doctoral (habilitation) thesis (Пашкевичюс, 1972) and his study on the Silurian (Пашкевичюс, 1979) presented palaeontological description of a new genus *Lithuanograptus* gn. nov., that was revised later (Paškevičius, 2017); now two new species of *L. fusiformis* sp. nov. and *L. obuti* sp. nov. are attributed to this genus. Moreover, 65 Silurian graptolite species, including 19 news species and subspecies were explored and described in the doctoral thesis, as well as 26 graptolite zones from *C. cyphus* to *C. lochkovensis* inclusive were analysed there. The palaeontological description of the same 65 graptolite species and subspecies were given in the above-mentioned monograph with an updated zonal graptolite scale presented. J. Paškevičius (1994, 1997) in the geological transactions of the Baltic republics presented a very detailed analysis of graptolite zonal scale consisting of 35 zones and their correlation with regional and local stages. At the 24th session of the USSR Palaeontological Society, J. Paškevičius (Пашкевичюс, 1982) presented an updated stratigraphic scale of graptolite zones in the Lithuanian Silurian. The same author (Пашкевичюс 1988) explored Ludlow graptolite fauna that occurred in the Belarusian area of the Poliese-Brest Depression and compiled their zonal scale. At the 17th session of the International Geological Congress in Moscow, 1984, J. Paškevičius presented a report on the principles for graptolite zone integration with other faunal complexes; these data were published later (Пашкевичюс, 1988). Based on the Lithuanian Silurian graptolite zones, he presented chronozones in the Silurian section (Пашкевичюс, 1989). Together with co-authors (Paškevičius, Brazauskas, Musteikis, Jacyna, 1994) he published a stratigraphic revision of the upper part of the Silurian within the Baltic Silurian Basin by presenting new open-sea regional stages of Gėluva, Dubysa, Pagėgiai, Minija and Jūra with their graptolite zones. J. Paškevičius, V. Klimantavičius and S. Radzevičius (2012) performed a revision of local *P. tauragensis* graptolite zone by dividing it into 4 separate zones, as well as singled out a new *M. valleculosus* zone below the *M. formosus* zone. J. Paškevičius and S. Radzevičius (2004) took part in the National Scientific Programme 'Litosfera' and presented the systematics of the Lithuania Silurian graptolites, their pictures, evolution stages and a scale of 35 zones.

Based on explorations done by J. Paškevičius in 32 graptolite zones, D. Kaljo, J. Paškevičius and R. Ulst (Кальо, Пашкевичюс, Ульст, 1984) presented the Llandovery, Wenlock, Ludlow and Přídolí zonal scale for the entire Eastern Baltic region. S. Radzevičius and J. Paškevičius (2000, 2005), under the guidance of the latter, performed an investigation of adaptive types of the Upper Wenlock *Pristiograptus* genus, presented their distribution and biostratigraphy, and later S. Radzevičius (2013) published a paper on the Lithuanian Silurian graptolite biozones.

PECULIARITIES OF GRAPTOLITE ZONAL SCALE

At the present stage of graptolite investigations, 35 graptolite zones have been explored in Lithuania and neighbourly countries in correlation with the zones of other faunal groups, communities and complexes (Table 1). There are no *P. acuminatus* and *C. vesiculosus* graptolite zones in Lithuania, they correspond to the formations of Stačiūnai and Apaščia carbonate facies. Although *Dimorphograptus confertus* species pretending to indicate the presence of *C. vesiculosus* zonos is found in Estonia, however this is not yet sufficient for zone delimitation. Graptolites are also absent in the Jūra Formation of the upper part of the Lithuanian Silurian. This interval without graptolites would most likely consist of two zones – *M. bouceki* and *I. transgredients*.

Graptolites in the Baltic basin had been forming basically from the Llandovery *C. cyphus* phase to the Ludlow marine transgression east-southeastwards with the occurrence of clayey facies, although short-term regressions also took place. At the second half of the Silurian, however, irreversible sea regression began from Ludlow, when the basin with graptolites was becoming shallower and carbonate facies migrated west-southwestwards. Beside the general transgression and regression, J. Paškevičius found also transgressions and regressions of lower extent. This is shown by the east-southeast spreading of wedges of clay facies with graptolites. Formation of such transgressive wedges took part in the *C. cyphus*–*S. sedgwickii* and *M. griestonensis*–*O. spiralis* zones


A
KULIKOVO-1
VLADIMIROVO-1
NIDA-1
USĖNAI-1
STONIŠKIAI-1
GENIAI-1
ŠEŠUVIS-11
PAŠALTUONIS-94
BEBIRVA-111
VADŽGIRIAI-95
BLIŪDŽIAI-96
0m
40
80
120
160
200
240
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640
680
720
760
800
840
880
920
960
1000
1040
1080
1120
PRIDOLI
LUDLOW
WENLOCK
LLANDOVERI
?
lochkovensis
ultimus
parultimus
formosus
valleculosus
balticus
tauragensis
scanicus
progenitor
nilssoni
ludensis
testis
centrifugus
lapworthi
linnaei
sedgwickii
cyphus
Rietavas B-s
Kelmė B-s
Girdžiai B-s
Jūra Fm.
Varniai B-s
Karšuva Gr.
Minija Fm.
Šilalė B-s
Ventspils
Mituva Fm.
Aukštupiai B-s
Geniai and
Nova B-s
Šešupė B-s
Pagėgiai Fm.
Rukai B-s
Dubysa Fm.
Usėnai B-s
Laužai B-s
Mamiai B-s
Siesartis Fm.
Rusnė Fm.
Lašai B-s
Jūrmala Fm.
Dobele Fm.
Varmija Gr.
Ragainė Fm.
Rasytė Fm.
Apaščia Fm.
Stačiūnai and Apaščia Fm.
Barta Gr.

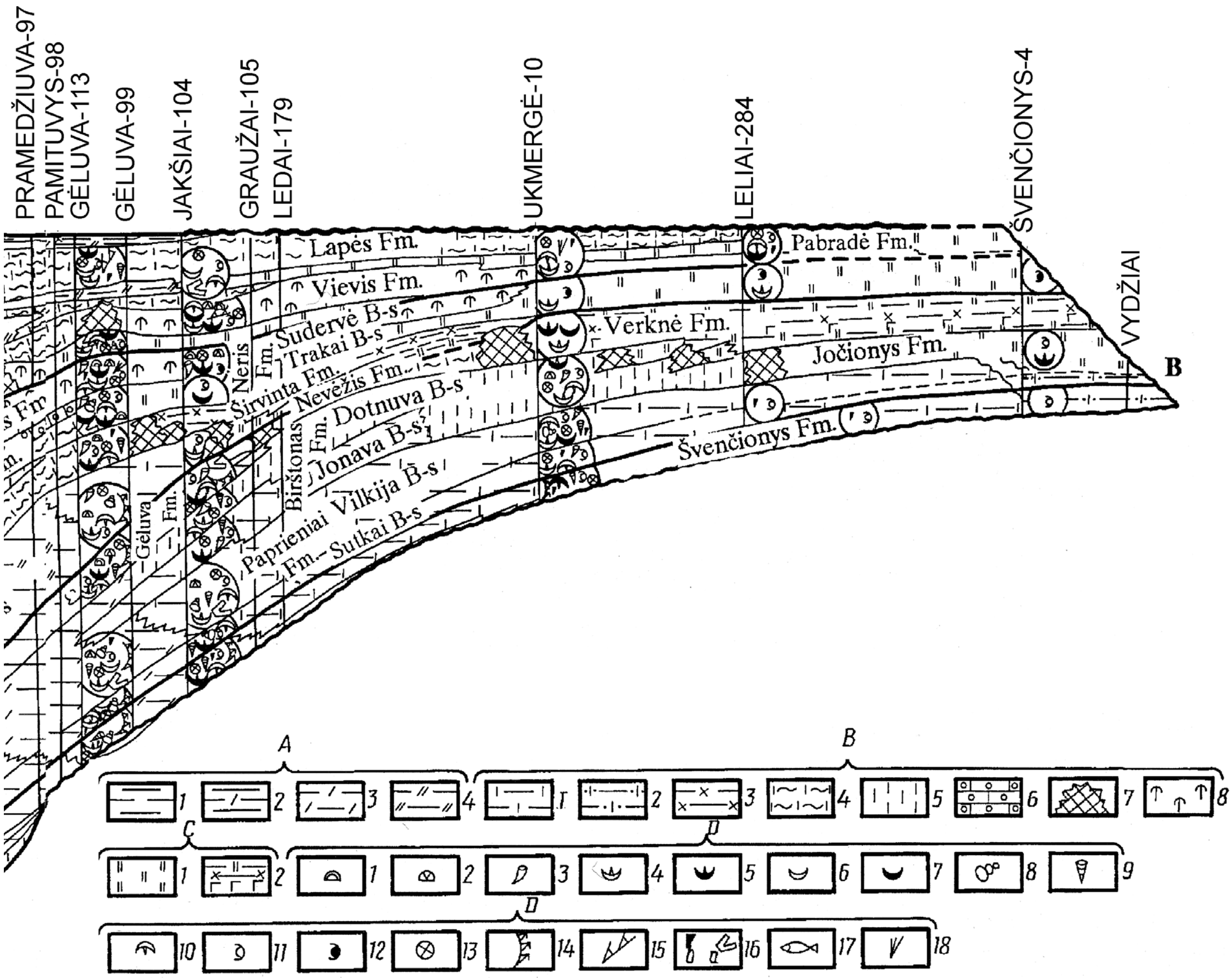

Fig. 2. A smoothed section of the Silurian facies the Baltic Syneclise and Belarus-Mosurian Anteclise. A – marine facies group formed in the areas of low energy under the anaerobic conditions: 1 – black organics – rich clay with graptolites, 2 – black and grey clay with graptolites, 3 – gray clay with graptolites, 4 – carbonaceous clayey silt (carbonaceous clay and marl with biomorphous limestone interlayers) with graptolites; B – marine facies group formed in the areas of high energy under the aerobic conditions: 1 – clayey carbonaceous silt (marl) with low and high detritus contents, 2 – sandy aleuritic, clayey carbonaceous silt, 3 – red clayey carbonaceous silt, including dolomitic ones, 4 – detritic limestone deposits (nodular detritic limestone and marl), 5 – limestone detritic deposits (large nodules limestone), 6 – oolitic-oncolithic limestone deposits, 7 – biomorphous clastic rocks (reefs), 8 – dark grey and yellowish grey carbonaceous silt (marl and nodular limestone) with corals (carbonate-rich lagoons); C – increasid salinity lagoon facies group in low energy areas under intermediate conditions: 1 – dolomitic silts (dolomite) in the plains affected by medium floods, 2 – grey dolomitic and dolomitic clayey silt with gypsum (dolomite, dolomitic marl and gypsum) in the lagoons with high flood level; D – fauna and flora: 1 – stromatoporoids, 2 – tabulates, 3 – rugoses, 4 – thin- walled brachiopods, 5 – thick-walled brachipods, 6 – thin-walled bivalves, 7 – thick-walled bivalves, 8 – gastropods, 9 – cephalopods, 10 – trilobites, 11 – ostracodes, 12 – large ostracodes (leperditiid lagoons), 13 – crinoids, 14 – graptolites, 15 – dendroids, 16 – bryozoans, 17 – conodonts, 18 – vertebrata, 19 – primitive vegetation (Paškevičius, 1994)

Table 1. **International generalized and Lithuanian graptolite, conodont zones, correlation and bioevents**

Table 1

System	Series	Stage	Reg. Stage	Generalized Graptolite zones (Koren' et al., 1996)	Lithuania Graptolite zones (Paškevičius, 1972, 1997, 2004; Radzevičius 2006, 2013)	Lithuanian Conodont zones (Brazauskas, 2004)	Bioevents
SILURIAN	Přidoli			*Istrograptus transgrediens*	?	*O. e. remscheidensis*	Klonk 10
				Monograptus bouceki	?		
				Neocolonograptus lochkovensis *Neocolonograptus branikensis*	*Neocolonograptus lochkovensis*		Šilalė 9
				Neocolonograptus ultimus *Neocolonograptus parultimus*	*Neocolonograptus ultimus*	*O. e. eosteinhornensis*	
					Neocolonograptus parultimus		
	Ludlow	Ludfordian	Pagėgiai	*Formosograptus formosus*	*Formosograptus formosus*	*O. crispa*	Klev 8
					Monograptus valleculosus	*O. s. scanica - O. wimani*; *P. aequicotatus*	
				Neocucullograptus kozlowskii	*Monograptus balticus*	*C. dubius*	Lau 7
			Dubysa	*Bohemograptus b. tenuis*	*Ps. tauragensis*: *Bohemograptus b. tenuis*	*P. siluricus*	
					Bohemograptus cornutus		
					B. praecornutus		Linde 6
				Saetograptus leintwardinensis	*Saetograptus incipiens*		
		Gorstian		*Lobograptus scanicus*	*Lobograptus scanicus*	? *K. variabilis*	
					Lobograptus progenitor		
				Neodiversograptus nilssoni	*Neodiversograptus nilssoni*	*O. b. bohemica*	
	Wenlock	Homerian	Gėluva	*Colonograptus ludensis*	*Colonograptus ludensis*	*O. b. longa*	
				Colonograptus deubeli	*Colonograptus deubeli*		
				Colonograptus praedeubeli	*Colonograptus praedeubeli*		
				Gothograptus nassa	*Gothograptus nassa*		
				Pristiograptus parvus	*Pristiograptus parvus*		Mulde 5
			Jaagarahu	*Cyrtograptus lundgreni*	*Cyrtograptus lundgreni*	*O. s. sagita-P. linguliformis*	
		Sheinwoodian		*Cyrtograptus perneri* *Cyrtograptus rigidus*	*Cyrtograptus perneri*	*K. amsdeni*	
				Monograptus belophorus	*Monograptus belophorus*	*K. walliseri*	
			Jaani	*Monograptus riccartonensis*	*Streptograptus antennularius*	*K. ranuliformis*	Ireviken 4
					Monograptus riccartonensis		
				Cyrtograptus murchisoni	*Cyrtograptus murchisoni*		
	Llandovery	Telychian	Adavere	*Cyrtograptus centrifugus*	*Cyrtograptus centrifugus*	*P. a. amorphognathoides*	
				Cyrtograptus insectus *Cyrtograptus lapworthi*	*Cyrtograptus lapworthi*		
				Oktavites spiralis interval	*Oktavites spiralis*	*P. a. lithuanicus*	
				Monoclimacis crenulata	*Monoclimacis crenulata*	*P. celloni*	
				Monoclimacis griestonensis	*Monoclimacis griestonensis*		Valgu 3
				Streptograptus crispus	*Streptograptus crispus*	*A. latus*	
				Spirograptus turriculatus	*Spirograptus turriculatus*		
				Spirograptus guerichi	*Rastrites linnaei*	*D. tricavus*	
		Aeronian		*Stimulograptus sedgwickii*	*Stimulograptus sedgwickii*		
			Raikküla	*Lituigraptus convolutus*	*Lituigraptus convolutus*		Likėnai 2
				Monograptus argenteus	*Campograptus millepeda*		
				Demirastrites pectinatus	*Demirastrites pectinatus*		
		Rhuddanian		*Demirastrites triangulatus*	*Demirastrites triangulatus*		
				Coronograptus cyphus	*Coronograptus cyphus*		
			Juuru	*Cystograptus vesiculosus*	?	*D. siluricus*	Stačiūnai 1
				Parakidograptus acuminatus	?		

(Llandovery), *M. riccartonensis* and *C. lundgeni* (Wenlock), *L. scanicus* and *M. formosus* (Ludlow) as well as *C. parultimus–ultimus* zones (Přídolí) (Пашкевичюс, 1991).

Throughout the entire period of investigations, the zonal scale of Lithuanian graptolites was being improved and added from 15 zones in 1958 to 35 ones at present. Two zones, i.e. *D. pectinatus* and *C. millipeda*, have been distinguished in Llandovery between the *D. triangulatus* and *L. convolutus*, and one more zone of *C. centrifugus* fixed at its end. The name of *M. flexilis* species was replaced by its original one – *M. belophorus.* The Wenlock zone of *M. testis* was renamed as *C. lundgreni* with its base boundary lying a bit lower than that of *M. testis* zone. In the lower part of the *G. nassa* zone, there is a smaller zone of *P. parvus* identified, which coincides with the lower limit of the Siesartis Formation. The local Wenlock zone of *P. virbalensis* is divided into two zones accepted in Europe, i.e. *C. praedeubeli* and *C. deubeli*. A large local *P. tauragensis* zone being between the zones of *L. scanicus* and *M. balticus* is divided into 4 autonomous zones: *S. incipiens*, *B. praecornutus*, *B. cornutus* and *B. bohemicus tenuis*. A new Ludlow zone of *M. valleculosus* is identified between the *M. balticus* and *F. formosus* zones.

The graptolite scale of Lithuanian Silurian was compared to the internationally recognised Generalised Graptolite Zonal Sequence (Koren', Lenz, Loydell et al., 1996). The only difference is that two lower Llandovery zones and two upper Přídolí zones are absent in Lithuania.

Composition of the Baltic Silurian graptolite taxa in the zones described varied greatly, especially in Llandovery, as the numbers of genera and species depended on still intensive development of diplograptids, while evolution of monograptids was differentiated throughout the Silurian mainly due to biological development and less because of changes in environment conditions of a marine basin.

SILURIAN GRAPTOLITES, DEVELOPMENT OF THEIR ZONES AND BIOEVENTS

At the end of the Ordovician, the Baltic Sea basin is known to become significantly shallower due to global glaciation of the Earth. Detritic and oolitic limestone deposits had been formed in it. The shallowed sea basin penetrated also into the Silurian sea basin of the Lithuanian Depression. At the beginning of the Stačiūnai time period, the Rovėja Member marls of a still slightly deeper sea origin were formed, later during the course of Stačiūnai period the conditions of a shallow archipelago basin with arid climate formed and nodular aphanitic limestones containing no graptolites were settled with very rare conic nectobenthic conodonts and also rare benthic fauna of brachiopods and ostracods. Full temporal extinction of Lithuanian graptolites should be noted, although graptolites were still met among the Ordovician and Silurian deposits in the Baltic Sea boreholes. This is the first bioevent in the development of the Silurian graptolites in Lithuania and it can be named *Stačiūnai* 1 Bioevent (graptolite crises are marked by numbers in Table 1).

C. cyphus–C. millipeda Stage. From the *C. cyphus* phase a powerful sea transgression began resulting in deep-shelf clayey deposits with rich buried organic matter (up to 20%) and extremely abundant species of *C. cyphus–C. millipeda* zones. This is the stage of graptolite prosperity notable for very good trophic (feeding) conditions. Diplograptids also developed with 31 species counted in Lithuania, as well as 26 species of monograptids, including 10 new species. At the end of the *C. millipeda* phase, even 30 species extincted. This is the highest number of emerged and extincted graptolite species throughout the Silurian. During the *L. convolutus* phase, numbers of diplograptid and monograptid species declined to 15 and 17, correspondingly. The general trend in biological evolution is marked by increase in diplograptid extinction rate. The authors propose to name this period of graptolite prosperity and extinction the *Likėnai* 2 Bioevent, because it wears the boreholes of Likėnai-396 and Parovėja-9 where the highest numbers of graptolite species and partial die-out have been detected.

The *R. linnaei–C. lapworthi* Stage took place when, due to activation of marine transgression in the Baltic Sea Basin, marl wedges formed with slight increase in graptolite species. Only four species lived of diplograptids *Petalolithus*, *Retiolites*, *Stomatograptus* and *Pseudoplegmatograptus*, while the number of monograptid species *Pristiograptus*, *Monograptus, Streptograptus*, *Monoclimacis*, *Oktavites*, *Campograptus* and other genera reached 22, including 13 new species. At the end of *S. crispus* phase, 13 species died out. During the *M. griestonensis* phase, 7 and 12 species emerged and died out, correspondingly. The above-mentioned extinction of graptolite species most likely is related to changes in environmental conditions. The beds below the upper limit of *S. crispus* contain 4 metabentonite interlayers of buried volcanic ash notable for increased carbonate content in the deposits. This indicates changes in the chemical composition of basin's water unfavourable for graptolite life. This extinction of graptolites from *S. crispus* to *M. griestonensis*, compared to the *Valgu* 3 Bioevent (Männik et al., 2005), is an important evolutionary event known for many faunal groups throughout the world.

On the basis of the above, one can say that during Llandovery in the Baltic Basin there were three obvious crises in graptolite evolution: *Stačiūnai*, *Likėnai* and *Valgu*, but some smaller crises happened as well.

In the course of Wenlock graptolite evolution, two stages can be identified: the early stage of *C. murchisoni–S. antennularius* and the later one *M. belophorus–C. ludensis*.

The *C. murchisoni–S. antennularius* Stage began with active evolution of graptolites, when 12 new species of Wenlock genera developed, such as *Pristiograptus*, *Monograptus*, *Monoclimacis*, *Streptograptus*, *Barrandeograptus*, *Cyrtograptus*, and *Retiolites*. Especially active development should be noted for cyrtograptids and pristiograptids, as well as the species of Monoclimacis genera. Mere *C. murchisoni* zone is found to contain up to 20 species. Extinction of 7 species is detected in the *S. antennularius* zone. Such evolution of graptolites has been partly determined by biological development, but, in my opinion, sharp increase of phytoplankton in *C. murchisoni* and *M. riccartonensis* zones after its Llandovery decrease played a role in this. Generally, Wenlock deposits are rich in organic matter, however only 12 species survived in the *S. antennularius* zone, with most dramatic reduction in the number of *Monograptus* and *Monoclimacis* species. However, the number of individuals of the same species rose, and those of monotype species prospered due to their adaptation to the altered conditions, especially in the *Monograptus riccartonensis* zone. Bioevents of this stage should be compared to a widely known in Europe *Ireviken* 4 Event (Jeppsson et al., 1995). So, regular change in the above-mentioned graptolites took place in the Baltic Basin.

The *M. belophorus–C. ludensis* Stage witnessed again the enhance of evolution rate during the *M. belophorus* and later phases till *P. parvus*. Even 38 graptolite species of the same genera as in the earlier Wenlock stage spread. Biological evolution until *P. parvus* time was determined by stable environmental conditions. Sedimentation of deposits changed substantially only from the *P. parvus* phase. Micro-varved carbonaceous clays and marls were formed indicating seasonal short-term settling of phytoplankton and rise in carbonates in the microlayers thus causing the micro-varved pattern. Namely, these unstable conditions of the basin's environment caused decline of *Monograptus* and *Monoclimacis*, as well as final extinction of cyrtograptids and species of other genera, especially at the end of *C. lundgreni* and during the *P. parvus* phase. Only the parvus species of the conservative genus *Pristiograptus* adapted to the changed environment conditions, but it diminished greatly, although later 6 species of this genus were still evolving. The number of graptolite species in the *G. nassa* zone began to restore gradually, and at the end of the stage a new *C. ludensis* genus and species appeared. This marked extinction of graptolite species, genera and families is named *Mulde* 5 Event (Jeppsson et al., 1995) after a geographical area on the island of Gotland.

One may single out four stages in graptolite zone evolution during the Ludlow and Přídolí epochs: *N. nilssoni–S. incipiens*, *B. paecornutus–B. b. tenuis*, *M. balticus–M. formosus* and *N. parultimus–C. lochkovensis*.

The *N. nilssoni–S. incipiens* Stage, during its first half, is notable for restoration of graptolite genera and species. Before the *S. incipiens* phase 27 new graptolite species emerged and evolved further belonging to such genera as *Holoretiolites*, *Neodiversogratus*, *Colonograptus*, *Saetograptus*, *Lobograptus*, *Cucullograptus* and *Pseudomonoclimacis*, as well as species of old *Monograptus* and

Pristiograptus genera. They reached their extinction peak at the end of the leintwardinensis phase. This graptolite crisis period may be juxtaposed with the *Linde* 6 Event (Melchin et al., 2012).

Later during the *B. praecornutus–B. b. tenuis* phase, or local *P. tauragensis* phase, a small activation of graptolite evolution is observed followed by a regression, when partial die-out of species of such genera *Pristiograptus*, *Monograptus*, *Polonograptus*, *Cucullograptus*, *Bohemograptus*, *Saetograptus*, *Pseudomonoclimacis*, etc. took place. Their number declined to 7, and this should be related to biological evolution that partly depended on instability of environmental conditions, regression of the basin, water turbulence, depth of wave base, increased rate of carbonate sedimentation, variations in red-ox potential, water transparency and, at last, changes in salinity (Musteikis, 1991; Musteikis, Paškevičius, 1999). The late part of this graptolite evolution stage at the end of the *leintwardinensis* phase and further phases most likely coincide with the already known Lau 7 Event (Jeppson et al., 2000) that caused crises not only for graptolites but also conodonts (Brazauskas, 2004).

M. balticus–F. formosus Stage. Renewal of monograptids in the zones of this stage is not so marked as that during the previous stage. Generally, with development of the basin's regression, graptolite fauna becomes rarer. Nevertheless, the renewal of the mentioned graptolites is indicated by new species of such genera as *Monograptus*, *Pristiograptus*, *Formosograptus*, *Neocullograptus*, and *Neocolonograptus*, but the number of these species is small, reaching 8 ones in Lithuania. During the *F. formosus* phase, the number of graptolite species declined significantly, representatives only of *Formosograptus* and *Linograptus* genera, as well as *P. dubius* developed further. According to A. Urbanek (1997), the instability of *M. spineus* fauna and its partial die-out was lower than during the *S. leintwardinensis* or *N. kozlowskii* phases. Extinction of such specialised forms as *F. formosus* marks the limits of Ludlow and Přídolí. This stage of graptolites and their crises is proposed to be compared to the Klev 8 Event (Jeppsson et al., 2000). For the first time *F. formosus* species in the Baltic marine basin had been explored on the Sambian Peninsula.

The *N. parultimus–N. lochkovensis* Stage took place already in Přídolí. The number of graptolite species declined eminently. New species of such genera as *Neocolonograptus*, *Monograptus*, etc. appeared. Typical *F. formosus* phase species vanished. Specialised species of the *C. parultimus-ultimus* line were being formed, but with a scanty composition, as this should be related to irreversible regression of the Baltic marine basin. Deposition of carbonates prevailed; it favoured changes of environment conditions and extinction of graptolite fauna after the *N. lochkovensis* phase (Пашкевичюс, 1972; Paškevičius, 2004). This was an irreversible regression of the Eastern Baltic Silurian Basin that caused extinction of graptolite fauna; therefore, these crises should be compared to the *Šilalė* 9 Bioevent, the area where graptolites from Šešuvis-11 and Viduklė-61 boreholes were explored and $^{13}C_{carb}$ izotopes valued (Kaljo Dimitri et al., 2012).

In Lithuania there are no graptolites of the *I. transgrediens* zone detected, therefore data about the crisis referred to as *Klonk* 10 Event are lacking.

ZONAL CORRELATION BETWEEN GRAPTOLITES AND OTHER FAUNAL GROUPS

The stratigraphy of Lithuanian Silurian is among the most complete and detailed ones in the Baltic countries. It relies upon palaeontological, stratigraphic, lithologic and geochemical and other investigation methods applied composing stratigraphic schemes and scales of particular faunal groups. Especially detailed and rather complete is the graptolite stratigraphic scale that is a cornerstone in the Lithuanian Silurian stratigraphy. Beside the zonal scale of graptolites, the present work presents zonal scales of conodonts, vertebrates and ostracods, as well as their correlation.

Conodont zones and their correlation. The first biostratigraphical zonal scale of conodonts was constructed by A. Brazauskas (1987, 1963). Later, based on new conodont investigation data, his original conodont zones were being revised and changed. The zones of *O. nathani*, *O. siluricus*, *D. kentuckyensis*, and *O. tillmani* were rejected and replaced by such zones widely spread in the world and Lithuania as *D. siluricus*, *D. tricavus*, *P. amorphognathoides lithuanicus*, *O. s. sagitta–P. linguliformis*, *O. bohemica longa*, *O. b. bohemica*, and *P. equicostatus* (Brazauskas, 2004).

The Juuru Regional Stage is compared to the conodont zone of *Distamodus siluricus* that in Lithuania is common in Stačiūnai Formation and the lower part of the Apaščia Formation.

Raikkiula–Adavere regional stages are correlated with the *Distamodus tricavus* zone and the lower part of *Pteraspathodus a. amorphognatoides*, as well as with the upper part of the *C. cyphus* zone and *C. lapworthi* graptolite zones. These stages compose the Llandovery series (Table 1).

Jaani–Jaagarahu regional stages are compared to the conodont zones from the upper part of the *P. a. amorphognathoides* to *Ozarkodina s. sagitta–Pseudoonetodus linguliformis* and inclusive *C. murchisoni–C. lundgreni* graptolite zones in the Wenlock.

Gėluva–Pagėgiai regional stages are correlated with the conodont zones from *Ozarkodina longa* to the top of the *Panderodus equicostatus*. The *Lau* Event is defined in the *N. kozlowskii* zone or the upper part of the *B. b. tenuis*, where changes in the dynamics of conodonts take place with changes in composition of complex morphological conodont species, and only the dominant species of the community remains (Brazauskas, 2004). The stages mentioned and their conodont zones are compared to the graptolite zones of *P. parvus–M. balticus*.

The upper part of Pagėgiai, Přídolí regional stages in the formations of Ventspils and Minija contains conodonts of Ozarkodina *e. scanica–Ozarkodina e. eosteinhornensis* zones, which are correlated with *M. valleculosus–N. lochkovensis* graptolite zones. The Jūra Formation in Lithuania contains no graptolites.

Vertebrate zones and their correlation. The vertebrate fauna and their zones in the Baltic countries have been investigated by V. Karatajūtė-Talimaa (Каратаюте-Талима, 1978) and T. Märss (Мярсс, 1986). Beside the eastern Baltic area, the vertebrate fauna and their zones were explored in many regions, such as Scandinavia, British Islands, Timan-Pechora, Central Urals, Novaya Zemlya and Severnaya Zemlya. Based on the data from these regions, the zones of extinct vertebrate fauna were constructed and correlated with the zones of conodonts and graptolites (Märss, Feedholm, Talimaa et al., 1995).

The Silurian rock section from the base upwards begins with a vertebrate zone of *V. crista*. It occurs in the Rhuddani Regional Stage and is correlated with the *D. kentuckyensis* conodont zone and the upper part of the *P. acuminatus* graptolite zone, as well as with the zones of *vesiculosus* and cyphus. Eleven vertebrate zones occurring higher comprise the entire Silurian geological section; moreover, they are matched with the conodont and graptolite zones. At the very top of the Silurian, V. Karataiute-Talimaa (1978) explored and published two vertebrate species: *Katoporodus lithuanicus* and *K. timanicus* occurring in the top zone of the Silurian that is correlated with the Rietavas beds of Jūra Formation in West Lithuania (Paškevičius, Bitinas, 2014). Boundaries of all vertebrate zones are dotted, since they can be changed in the future (Table 2).

Ostracod zones and their correlation. The ostracods of the Lithuanian Silurian were explored by A. Pranskevičius (Пранскевичус, 1972), Estonian by L. Sarv (Сарв, 1963, 1977) and N. Sidaravičienė (Сидаравичене, 1986). In Latvia detailed investigations were performed and ostracod zones presented by L. Gailitė et al. (Гайлите и др., 1974; Гайлите, 1986). The ostracod scale constructed by her is partly used in Lithuania. It should be mentioned that the ostracods of Lithuanian Silurian yet are not explored in detail. So, for instance, only their communities in the lower part of the Silurian are presented, their zones are not defined. Two communities are detected in the Stačiūnai and Apaščia Formations, as well as in the Rasytė Formation up to the top of the *M. crenutata* graptolite zone. Namely, *M. flabeformis* and other ostracod species are found to occur up to the middle of the *C. cyphus* zone, while *L. elongata* and other species occur up to the top of the *crenulata* zone. The *R. vitrica* and *Th. valensis* zone defined in the upper part of the Rasytė Zone is compared to the *O. spiralis* and *C. lapworthi* zones (Table 2).

Beside the above-mentioned ostracod communities, in the Silurian geological section, there are 15 ostracod zones distinguished, which are correlated with the graptolite, conodont and vertebrate zones. The boundary between the Ragainė and Siesartis formations is marked in the middle part of *C. incurvata*, *L. quadriplicata* zone, or at the base of the *P. parvus* zone. The boundary of Siesartis

Table 2. **Lithuanian graptolite, vertebrate, ostracod zones and correlation**

Table 2

System	Series	Stage	Reg. Stage	Lithuania Graptolite zones (Paškevičius, 1972, 1997, 2004; Radzevičius 2006, 2013)	Vertebrate zones (Märss et al. 1995)	Lithuanian oatracodes zones and communities[x] (Sidaravičienė, 1986; Pranskevičius, 1972; Sarv, 1963, 1977; Gailite, 1974, 1986)	Formations with graptolites
SILURIAN	Přidoli			?	*K. timanicus* *K. lithuanicus*	*Amigdalella* sp. nov.	Jūra
				?	*K. punctatus*	*N. tuberculata*; *N. postulosa*	
				Neocolonograptus lochkovensis	*N. gracilis*		Minija
				Neocolonograptus ultimus	*T. sculptilis*	*F. groenvalia*	
				Neocolonograptus parultimus			
	Ludlow	Ludfordian	Pagėgiai	*Formosograptus formosus*		*N. margaritae, N. alia*	Pagėgiai
				Monograptus valleculosus			
				Monograptus balticus		*H. balticum, N. otenopora, N. lauensis*	
			Dubysa (*Ps. tauragensis*)	*Bohemograptus b. tenuis*	*A. hedei*	*H. pulchrivalata* *C. eserensis*	Rusnė / Dubysa
				Bohemograptus cornutus			
				B. praecornutus			
		Gorstian		*Saetograptus incipiens*	*P. elegans*	*C. percurrens* *C. lietuvensis* *A. curvata*	
				Lobograptus scanicus	*P. ortata*		
				Lobograptus progenitor	*P. murchisoni*		
				Neodiversograptus nilssoni			
	Wenlock	Homerian	Gėluva	*Colonograptus ludensis*		*B. susrotunda*	Siesartis
				Colonograptus deubeli			
				Colonograptus praedeubeli			
				Gothograptus nassa		*C. incurvatus* *L. qudricuspidata*	
				Pristiograptus parvus			
			Jaagarahu	*Cyrtograptus lundgreni*	*L. grossi*		Ragainė / Riga
		Sheinwoodian		*Cyrtograptus perneri*		*A. bovina* *M. vuriolis*	
				Monograptus belophorus		*P. rectellaformis* *R. confinis* *S. acer*	
			Jaani	*Streptograptus antennularius*			
				Monograptus riccartonensis			
				Cyrtograptus murchisoni	*L. avonia*		
	Llandovery	Telychian	Adavere	*Cyrtograptus centrifugus*		*Th. walensis* *P. vitrica*	Rasytė / Jūrmala
				Cyrtograptus lapworthi	*L. scotica* *J. sibirica*		
				Oktavites spiralis			
				Monoclimacis crenulata		*L. elongata*[x] *P. fusoidia* *A. cornuta*	
				Monoclimacis griestonensis			
				Streptograptus crispus			
				Spirograptus turriculatus			
				Rastrites linnaei			
		Aeronian		*Stimulograptus sedgwickii*			
			Raikküla	*Lituigraptus convolutus*			Dobele
				Campograptus millepeda			
				Demirastrites pectinatus			
		Rhuddanian		*Demirastrites triangulatus*			
				Coronograptus cyphus	*V. crista*		Stačiūnai / Apaščia
			Juuru	? ?		*M. flabeformis*[x] *M. edita* *A. sineclivula*	

and Rusnė formations is defined by the *C. perrcurens*, *C. lietuvensis* and *A. curvata* zone base. The boundary of Rusnė and Pagėgiai formations is marked by the base of the *N. ctenophora*, *N. lauensis* zone. This boundary coincides with that of the graptolite zones *B. bohemicus tenuis* and *M. balticus*. The boundary of Pagėgiai and Minija formations is defined by the base of the ostracod zone *F. groenvaliana*. The latter occurs widely in Scandinavian and Baltic countries. This boundary coincides with the base of the graptolite zone *N. parultimus* and boundary between Ludlow and Přídolí. The boundary between the Minija and Jūra formations is marked by the base of the ostracod *N. pustulosa* zone. The last zone of the Silurian ostracods is still understudied, but N. Sidaravičienė (Сидаравичене, 1986) singled out and named it *Amigdalella* sp. nov. that is most likely matched to the Rietavas beds of the Jūra Formation.

CONCLUSIONS

Graptolites and their zones are widely common in different facies: clayey deposits of open sea deep shelf and carbonaceous deposits of shallow shelf. The history of graptolite zone investigations from 1958 up to now is presented. The graptolite zones were being perfected over time, and their number grew from 15 to 35. The peculiarities of the zones have been discussed. The transgressions and regressions of the Silurian marine basin and related biological peculiarities of graptolite evolution have been given. The analysis has been done about the stages of graptolite development and their bioevents: *Stačiūnai, Likėnai, Valgu, Ireviken, Mulde, Linde, Lau, Klev and Šilalė*. The marked bioevents of Lithuanian graptolite evolution have been based on appearance and extinction of species and partly genera, on the Baltic Basin water regime reconstructing it according to the facies and changes in environmental conditions. There are 7 international and 2 local names of the bioevents given. The correlation between the zones of graptolites and other faunal groups is given in two Tables.

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LIETUVOS SILŪRO GRAPTOLITŲ IR KITŲ GYVŪNIJOS GRUPIŲ ZONACIJA

Santrauka
Baltijos silūro baseino, Lietuvos įdaubos ir kitos struktūros pateiktos žemėlapyje, jos išreikštos silūro sluoksnių izopahitomis (storio linijomis) su graptolitų ir kitų grupių fauna. Silūro facijos įdauboje labai įvairios – nuo molingų, atviros jūros, gilaus šelfo iki karbonatinių seklaus šelfo, mažos energijos lagūninių facijų. Baltijos kraštų graptolitų tyrimo istorija prasideda 1953–1958 metais. Tada buvo išskirta 15, o iki šių dienų jau 35 graptolitinės zonos. Aptarti Lietuvos graptolitinės skalės nuo *C. cyphus* iki *N. lochkovensis* imtinai ypatumai. Pateiktos silūro jūrinio baseino transgresijos ir regresijos, taip pat trumpesnės transgresijos su molingų facijų pleištais ir graptolitais, pasistūmusios baseino kranto kryptimi, ir regresijos su iš dalies išmirštančiais graptolitais. Per šį tyrimo laiką graptolitinė skalė buvo detalizuota ir papildyta naujomis zonomis. Nagrinėjama graptolitų evoliucija zonose, analizuojami graptolitų raidos etapai, susiję su svarbesniais bioįvykiais, pažymėti *Stačiūnų, Likėnų, Valgu, Irevikeno, Muldės, Lindės, Lau, Klevo* ir *Šilalės* vardais. Lentelėse pateikta graptolitinių zonų koreliacija su konodontų, stuburinių ir ostrakodų zonomis, kurios atskleidžia itin detalią Lietuvos silūro stratigrafiją.

Raktažodžiai: silūras, graptolitai, zonos, bioįvykiai, koreliacija, konodontai, stuburiniai, ostrakodai