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The mid-Frasnian subsidence pulse in the Lublin Basin (SE Poland): sedimentary record, conodont biostratigraphy and regional significance

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ABSTRACT:

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Most of the thickness of Frasnian sediments in the central segment of the Lublin Basin, i.e. up to 300 metres, is represented by a single transgressive-regressive Cycle VIa, developed in the carbonate-sulphate platform facies. The age of the transgressive part falls into the interval between the upper part of the Upper *hassi* Zone and the *jamieae* Zone, whereas the upper boundary runs between the upper part of the Lower *rhenana* Zone and the lower part of the Upper *rhenana* Zone. Basin architecture and conodont biostratigraphic data confirm the tectonic nature of the cycle, which represents a short-term increase in Frasnian subsidence and depositional rates. Based on the conodont data, it is plausible that the onset of the tectonic subsidence in the Lublin Basin and the incipient Pripyat Graben rifting correspond closely in age. They can thus be attributed to the common tectonic mechanism of regional extension in the south-west part of the East European Platform. The lack of any Late Devonian magmatic activity in the Lublin Basin and the synchronous development of this basin with the Pripyat Graben favour the idea that intraplate stresses were the primary factors controlling subsidence in both depocentres during the mid Frasnian to Famennian. The hypothetical mantle plume could have merely amplified the effects of crustal extension in the Pripyat Graben, thus facilitating a typical rift development.

Key words: Frasnian, Lublin Basin, Conodont biostratigraphy, Subsidence, Pripyat Graben, Rifting.

INTRODUCTION

The Lublin Basin is a part of the Variscan foreland located along the margin of the East European Platform in south-eastern Poland (Text-fig. 1). Its Devonian-Carboniferous development and latest Carboniferous inversion was controlled by a system of faults parallelling the Teisseyre-Tornquist Zone (NARKIEWICZ 2007). NARKIEWICZ & *al*. (1998a, b) noted that initiation of the basin, as recorded by a distinct pulse of subsidence, occurred in the Frasnian, roughly coeval with the initial rifting of the Pripyat Graben (Text-fig. 1A). This statement was supported by general stratigraphic data and the analysis of tectonic subsidence, albeit without description of the sedimentological record and (bio-)chronostratigraphy of the key borehole sections. The aim of this paper is to present and discuss in more detail the sedimentary evidence of the Frasnian subsidence pulse and

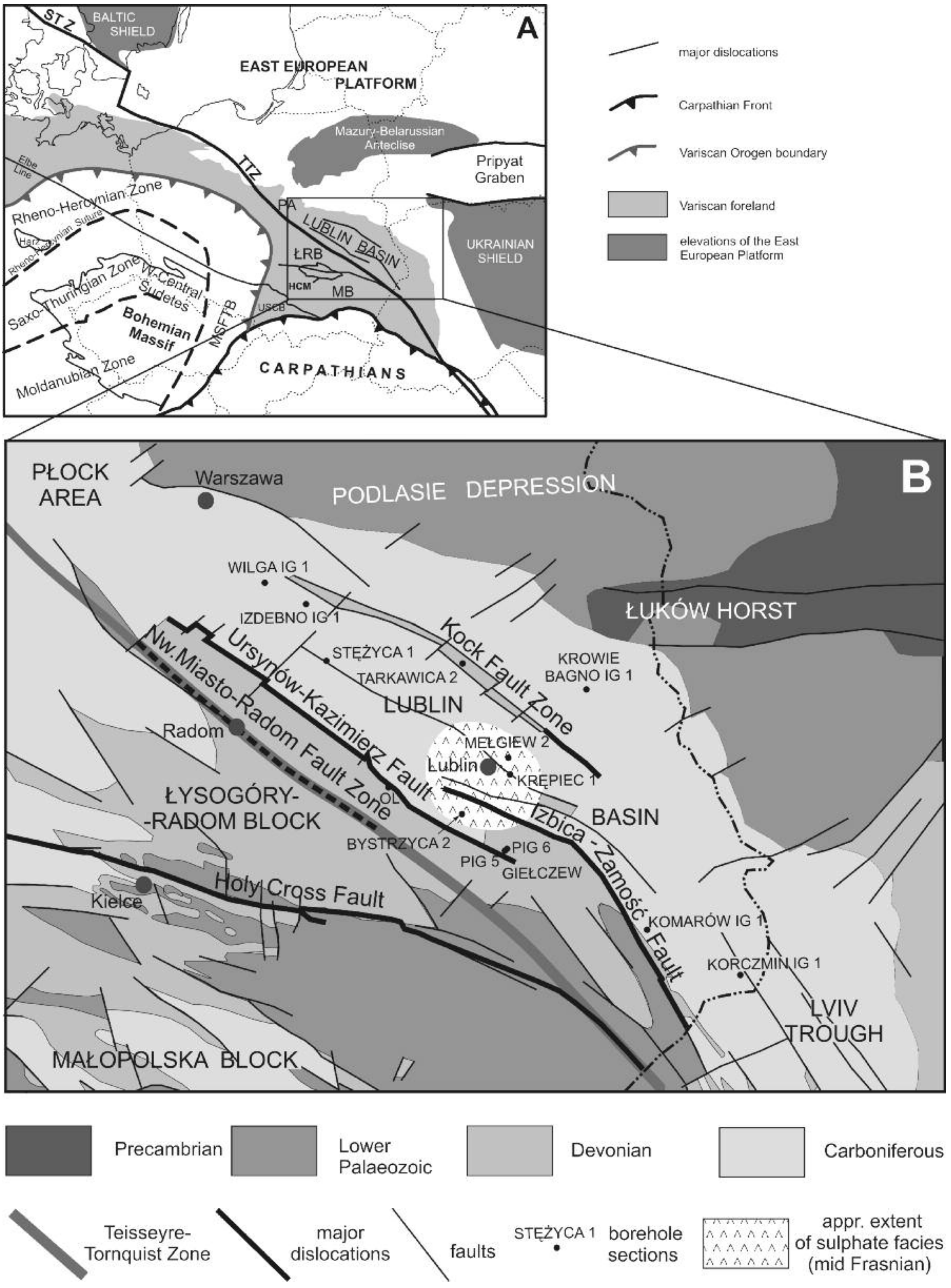

Fig. 1. **A** – Lublin Basin against the broader structural background of the Central and East European Variscan foreland. Abbreviations: HCM – Holy Cross Mountains; ŁRB – Łysogóry-Radom Block; MB – Małopolska Block; MSFTB – Moravian-Silesian Fold-and-Thrust Belt; PA – Płock Area; STZ – Sorgenfrei-Tornquist Zone; TTZ – Teisseyre-Tornquist Zone; USCB – Upper Silesian Coal Basin. **B** – Sub-Permian-Mesozoic subcrop map (after Pożaryski & Dembowski 1983, modified) with location of boreholes mentioned in the text. OL – Opole Lubelskie IG 1 borehole

to document its age constraints in the light of conodont data. This will be used as a basis for comparison between the development of the Lublin Basin and Pripyat Graben, which has important implications for explaining the tectonic framework of the Late Devonian evolution of the entire south-western part of the East European Platform.

MATERIALS AND METHODS

The present study is based on analysis of core and geophysical materials from several deep boreholes covering most of the Lublin Basin (for borehole location see Text-fig. 1B). The cores were described sedimentologically and the sections were correlated based on wireline log data and available core observations. The conodont study included successions representative of the three basin segments: north-west (Stężyca 1 borehole), central (Tarkawica 2 and Giełczew PIG 5 boreholes) and south-east (Korczmin IG 1 borehole). Text-fig. 2 shows correlation of the sections and the locations of conodont samples. The following biostratigraphic analysis is based on 22 samples which yielded a total 698 conodont specimens.

STRATIGRAPHIC FRAMEWORK AND DEPOSITIONAL RECORD

The Frasnian deposits of the south-east part of the Lublin Basin were initially attributed by MIŁACZEWSKI (1981) to the Modryń Formation, while in the remaining part of the basin they were ascribed to various informal units. Here, the concept of the Modryń Formation is extended over the entire Lublin Basin, including predominantly carbonate platform deposits with a subordinate contribution of sulphates and marly beds. The limestones as well as eogenetic dolomicrites are commonly irregularly replaced by a mesogenetic crystalline dolomite. The dolosparites are abundant mainly in the lower part of the formation, where they have been distinguished by MIŁACZEWSKI (1981) as the Werbkowice Member. The underlying Telatyn Formation comprises various shallow-water to continental deposits with a considerable proportion of clastic sediments and evaporites. The marly strata overlying the Modryń Formation are defined as the Firlej Formation in the south-east and as the Bychawa Formation in the central and north-west parts of the basin, being interpreted as deeper shelf facies of the early Famennian (MIŁACZEWSKI 1981; NARKIEWICZ & *al.* 1998b). The Modryń Formation attains a maximum thickness of ca. 400 m in the south-east and central segments of the basin, while it thins to ca. 200 m in the Stężyca area, and wedges out completely further towards the north-west. It is mostly eroded north-east of the Kock Fault Zone, where its maximum preserved thickness (Krowie Bagno IG 1 borehole) is ca. 150 m.

NARKIEWICZ & *al.* (1998b) subdivided the Devonian succession of the Lublin Basin into several transgressive-regressive cycles designated I to VII, of which cycles IV (upper part), V, VIa and VI b were distinguished within its Frasnian part. Subsequent studies (NARKIEWICZ 2005, unpublished report) allowed subdivision of cycle IV into IVa and IVb, with the boundary corresponding to the lithostratigraphic boundary between the Telatyn and Modryń formations. This boundary is widely correlatable over the entire Lublin Basin, and is reflected in a sharp vertical change in geophysical logs: a drop in the gamma-ray log values and a simultaneous increase in the neutron-gamma measurements. It represents a major turning point from mixed siliciclastic-carbonate and sulphate deposition, to “pure” early Frasnian carbonate platform development with insignificant terrigenous input. The thickness of Cycle IVb is relatively stable at around 20 metres. The overlying cycles V and VIa are also correlatable over most of the basin area, whereas cycle VIb was defined only in the north-west and central segments of the basin (Text-fig. 2). The present study is focused on Cycle VIa, which comprises more than half of the entire thickness of the Frasnian strata.

The lower part of Cycle VIa is marked by a considerable lithological contrast that is reflected in geophysical logs. The underlying regressive interval of Cycle V is composed mainly of peritidal subcycles which show two types of development: (1) dolomitic-anhydritic interlayering in the central part of the basin (e.g. Mełgiew 2, Krępiec 1 boreholes) or (2) brecciated dolomicritic horizons interpreted as solution-collapse breccias, intercalated with dolosparites at the basin margins (Giełczew PIG 6, Korczmin IG 1 boreholes – Text-fig. 3). In the Stężyca 1 borehole, the lower-order cyclicity near the top of Cycle V is exceptionally developed as alternations of wavy-bedded mudstones to wackestones with occasional marine fauna, and lighter-coloured evenly to irregularly laminated mudstones (Text-fig. 3). The laminites are devoid of skeletal content and commonly display a characteristic spotted appearance due to finely disseminated pyrite. This succession is interpreted as reflecting cyclic salinity changes in a semi-restricted carbonate platform system (“brining upward cycles”).

In the south-east segment of the basin, the thickness of undivided Cycle VI varies between 250 and 300 metres. The lowermost 70 metres is composed of a cyclic

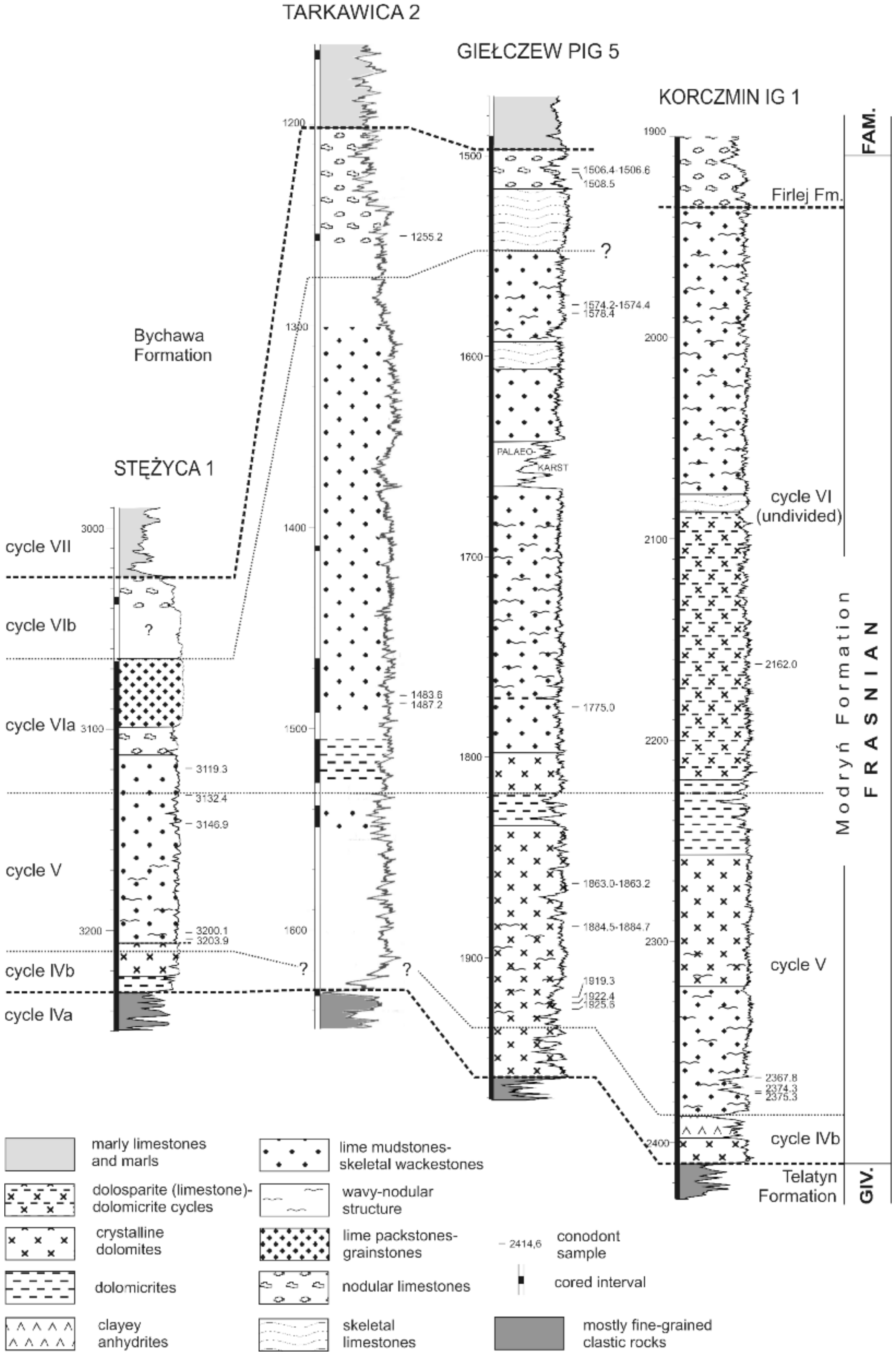

Fig. 2. Correlation of the investigated Frasnian borehole successions, with positions of the conodont samples analysed. The right-hand side of the lithological columns is a gamma-ray log reversed in order to better reflect lithological variability (minimum values to the right). Datum is the base of Cycle VIa and VI (undivided)

succession of dark-coloured, partly dolomitized mudstones with a scarce fauna of ramose stromatoporoids, interbedded with thin (10-50 cm) dolomicritic beds showing a spotted appearance. The cyclicity continues upwards, with increasingly thicker transgressive limestone intervals, while dolomites become less important. The more open-marine aspect is reflected in bioturbation and a more diverse marine fauna, including brachiopods and gastropods, and, still higher in the succession, also various rugose and tabulate corals in addition to stromatoporoids.

In the central segment of the basin, Cycle VIa has a uniform thickness of 250-300 metres. Most of the succession, except for its lowermost part, is represented by grey to dark-grey limy mudstones and wackestones commonly displaying wavy-nodular structure and a variable proportion of skeletal material, including ramose stromatoporoids, algae, brachiopods and crinoids. There also occur a few ca. 10 metres thick intercalations of stromatoporoid-renalcid biolithites presumably representing small bioherms. The base of this cycle is developed in the Giełczew PIG 5 and 6 borehole successions as a distinct erosional boundary overlain by a succession of peritidal subcycles capped by dolomicritic horizons (Text-fig. 3). In the central part of the basin (e.g. boreholes Krępiec 1, Mełgiew 2), the cycle starts with alternating limestones and massive to laminated and nodular anhydrites. The limestones are grey mudstones to wackestones, partly wavy-bedded and nodular, containing massive and ramose stromatoporoids. The extent of the sulphate-bearing facies is indicated in Text-fig. 1B.

Towards the north-west, cycle VIa thins gradually, attaining ca. 200 m in the Opole Lubelskie IG 1 borehole, 70 m in the Stężyca 1 borehole, 55 m in the Izdebno IG 1 borehole and probably less than 20 metres in the Wilga IG 1 borehole (compare borehole locations in Text-fig. 1). Wavy-bedded to nodular mudstones-wackestones predominate in the lower part, whereas the upper part is composed of massive packstones to grainstones.

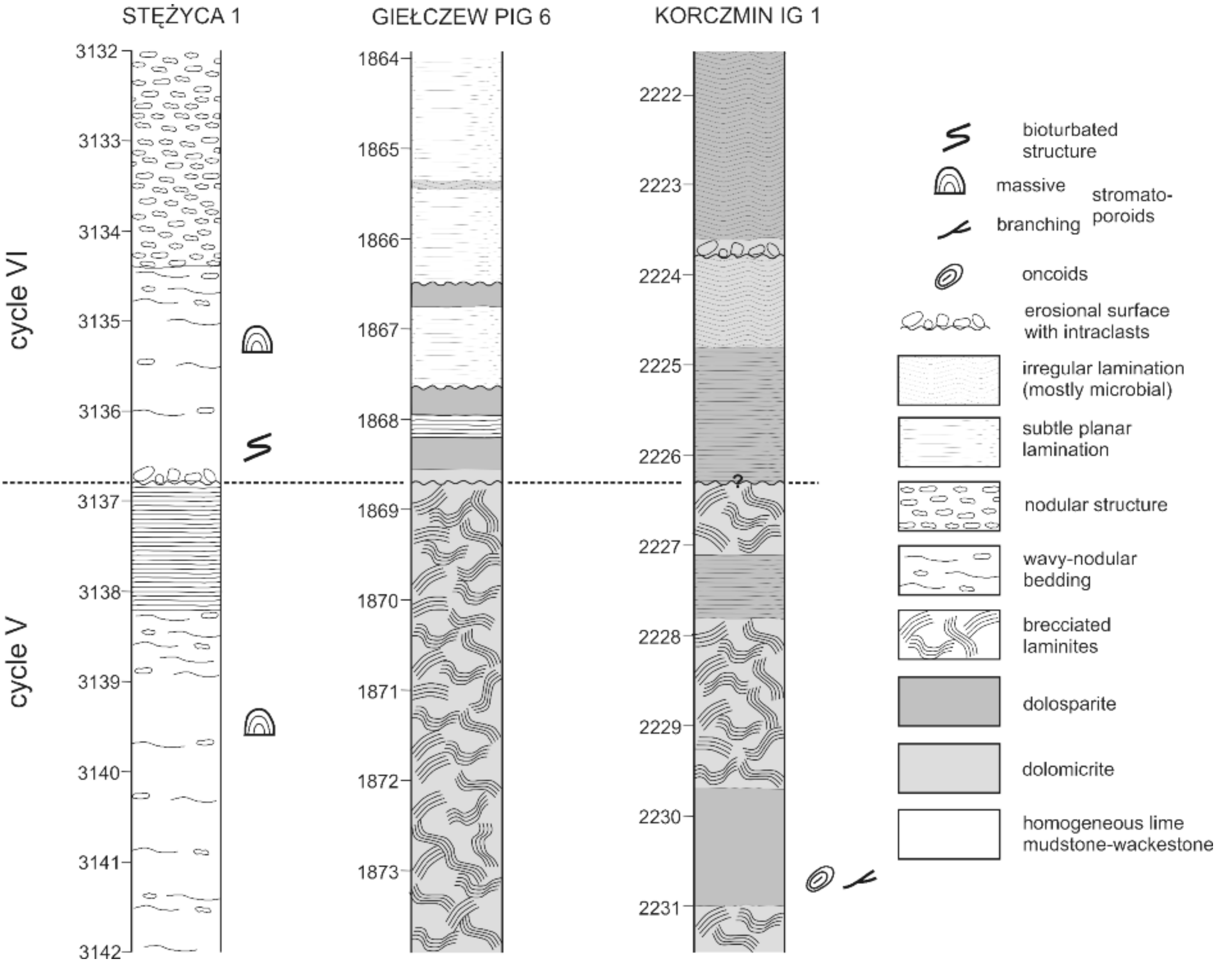

Fig. 3. Lithological details of the boundary between cycles V and VIa (undivided VI in Korczmin IG 1 borehole) in three cored sections

Cycle VIb is 35 to 70 metres thick and displays a complex internal depositional architecture. Data from a few well-cored boreholes from the central segment of the Lublin Basin allowed subdivision of this succession into several subcycles. They comprise a wide range of lithofacies, including dark marly mudstones, nodular and bioclastic limestones, stromatoporoid-algal bindstones and fenestral mudstones.

CONODONT BIOSTRATIGRAPHY

Conodonts in the borehole successions were yielded by particular lithological levels, which alternated with barren intervals. The specimen frequency per sample varies widely, ranging from 3 to 107. The highest abundances were noted in the Giełczew PIG 5 and Korczmin IG 1 borehole successions (Tables 1-2), which were also the most densely sampled. These sections provided the main body of evidence for the biostratigraphic conclusions. The supplementary data are from the Stężyca 1 and Tarkawica 2 boreholes (Table 3).

Frasnian conodont zonation

The assemblages studied are dominated by polygnathids, which are usually interpreted as representing marine environments shallower than those attributed to palmatolepids (SANDBERG & *al*. 1988, 1989). Unfortunately, Frasnian Polygnathidae are still rather poorly known, requiring further taxonomic, stratigraphic and palaeoecological studies. The only Frasnian zonation based on *Polygnathus*, as proposed by OVNATANOVA & KONONOVA (2001) for the shallow-water carbonate platform facies of the central East European Platform, cannot be applied to the Lublin Basin sections, due to a lack of index taxa. Consequently, the standard Frasnian conodont zonation of ZIEGLER & SANDBERG (1990), based on a succession of deeper-marine forms of the genus *Palmatolepis*, is applied here. Also used is the zonation worked out by KLAPPER (1988) for the Devonian succession of Montagne Noire (MN), based on deeper-water taxa; its correlation with the standard zonation follows KLAPPER & BECKER (1999).

Because of the controversy regarding the position of the middle-upper Frasnian boundary, it is marked as tentative in Text-fig. 4.

Stratigraphic range of *Polygnathus aequalis*

KLAPPER (1997) reported the first appearance of *Polygnathus aequalis* near the top of the MN 6 Zone, which corresponds to the upper part of the *punctata* Zone (KLAPPER & BECKER 1999). GOUWY & BULTYNCK (2000), however, noted this species distinctly earlier, in the upper part of the *transitans* Zone (see Text-fig. 4),

Conodont zones	Lower *hassi-jamieae*						L. *rhenana-linguiformis*			U. *rh-lin.*
Depth (m)	1925.6	1922.4	1919.3	1884.7-1884.5	1863.2-1863.0	1775.0	1578.4	1574.4-1574.2	1508.5	1506.6-1506.4
Palmatolepis cf. *Pa. bogartensis*										1
Polygnathus krestovnikovi							1	1		1
Polygnathus cf. *P. krestovnikovi*								1		
Icriodus alternatus alternatus							1			
Polygnathus morgani							1			
Polygnathus seraphimae	8									
Polygnathus cf. *P. seraphimae*	3									
Polygnathus aff. *P. seraphimae*					2					
Polygnathus pseudoxylus	2					1				
Polygnathus aequalis			7	20		1				
Polygnathus angustidiscus	6		1	1						
Polygnathus cf. *P. angustidiscus*		1								
Polygnathus aff. *P. angustidiscus* (1)	2	2								
Mehlina cf. *M. gradata*			1							
Icriodus subterminus	3									
Icriodus subterminus (2)				1						
Polygnathus alatus	1									
Polygnathus xylus				1						
Belodella sp.										1
Polygnathus sp. indet.	39		8	13	2	1	2			
coniform elements									2	
ramiform elements	15	6	9	12	3	4	3	1	1	2
total number of elements	79	9	26	48	7	7	8	3	3	5

Tab. 1. Conodont occurrences in the Giełczew PIG 5 borehole. Explanations: (1) *sensu* KLAPPER & LANE (1985); (2) *sensu* SEDDON (1970). Abbreviations: L. – Lower, U. *rh.-lin*. – Upper *rhenana - linguiformis*

Conodont zones	Upper *hassi* - *jamieae*			
Depth (m)	2375.3	2374.3	2367.8	2162.0
Icriodus prealternatus	7			
Polygnathus zinaidae				2
Polygnathus aspelundi			2	
Polygnathus seraphimae	4	4	17	
Polygnathus aff. *P. seraphimae*			2	
Polygnathus sp. *F* (1)				3
Polygnathus elegantulus		1		
Polygnathus robustus			2	
Polygnathus aequalis	17			3
Polygnathus pseudoxylus	11	4		
Polygnathus pollocki		1		
Polygnathus angustidiscus			4	
Polygnathus aff. *P. angustidiscus* (1)			3	
Mehlina gradata		5		
Mehlina sp.		7		
Icriodus subterminus	20	10		
Icriodus cf. *I. subterminus*			2	
Icriodus aff. *I. subterminus*		7		
Polygnathus alatus	9		4	2
Tortodus aff. *T. variabilis* (2)		1		
Icriodus sp. indet.	11	7		
Polygnathus sp. indet.	34	10	34	11
ramiform elements	14	27	25	6
total number of elements	127	84	95	27

Tab. 2. Conodont occurrences in the Korczmin IG 1 borehole. Explanations: (1) *sensu* Klapper & Lane (1985); (2) *sensu* Norris & Uyeno (1998)

and consequently this latter date is accepted herein.

The species ranges to the *jamieae* Zone (Klapper & Lane 1985; Klapper 1997). Its exceptionally high last occurrences, in the Lower *rhenana* Zone, reported by Matyja (1993, pl. 19, figs 10, 11) and Ziegler & *al*. (2000, pl. 7, figs 13, 14), are not confirmed. Matyja (1993) reported *P. aequalis* from the Chojnice 3 borehole (Pomerania, northern Poland) from the depth interval 2553-2786 m. She ascribed this interval to the Lower *rhenana* Zone, based on the presence of *Polygnathus brevilaminus* Branson & Mehl, 1934, which first appears in this zone (Matyja 1993, fig. 6); *P. brevilaminus* appears at 2798 m depth and ranges upwards. The only specimen illustrated from this section (from depth interval 2742-2743 m; Matyja 1993, pl. 19, fig. 2) does not display, however,

Borehole	Tarkawica 2			Stężyca 1				
Conodont zones	L. *h.* - *j*.	U. *h.* - *j.*	L. *rhenana*	U. *hassi* - L. *rhenana*		U. *hassi* - *linguiformis*		
Depth (m)	1487.2	1483.6	1255.2	3203.9	3200.1	3146.9	3132.4	3119.3
Palmatolepis hassi (1)			1					
Polygnathus brevis			2					
Polygnathus krestovnikovi			22					
Pelekysgnathus planus			13					
Polygnathus seraphimae	1				1			
Polygnathus aequalis		3						
Polygnathus politus		1	2	1		1	3	1
Polygnathus alatus	2	3					1	
Ozarkodina brevis			3					
Belodella sp.						1		
Polygnathus sp. indet.		3	37	3	2	1	2	5
ramiform elements	5	4	25	3	3	1	5	7
total number of elements	8	14	107	7	6	4	11	13

Tab. 3. Conodont occurrences in the Stężyca 1 and Tarkawica 2 boreholes. Explanations: (1) *sensu* Klapper & Foster (1993). Abbreviations: L. – Lower, U. – Upper, *h*. – *hassi*, *j*. – *jamieae*, *rh*. – *rhenana*

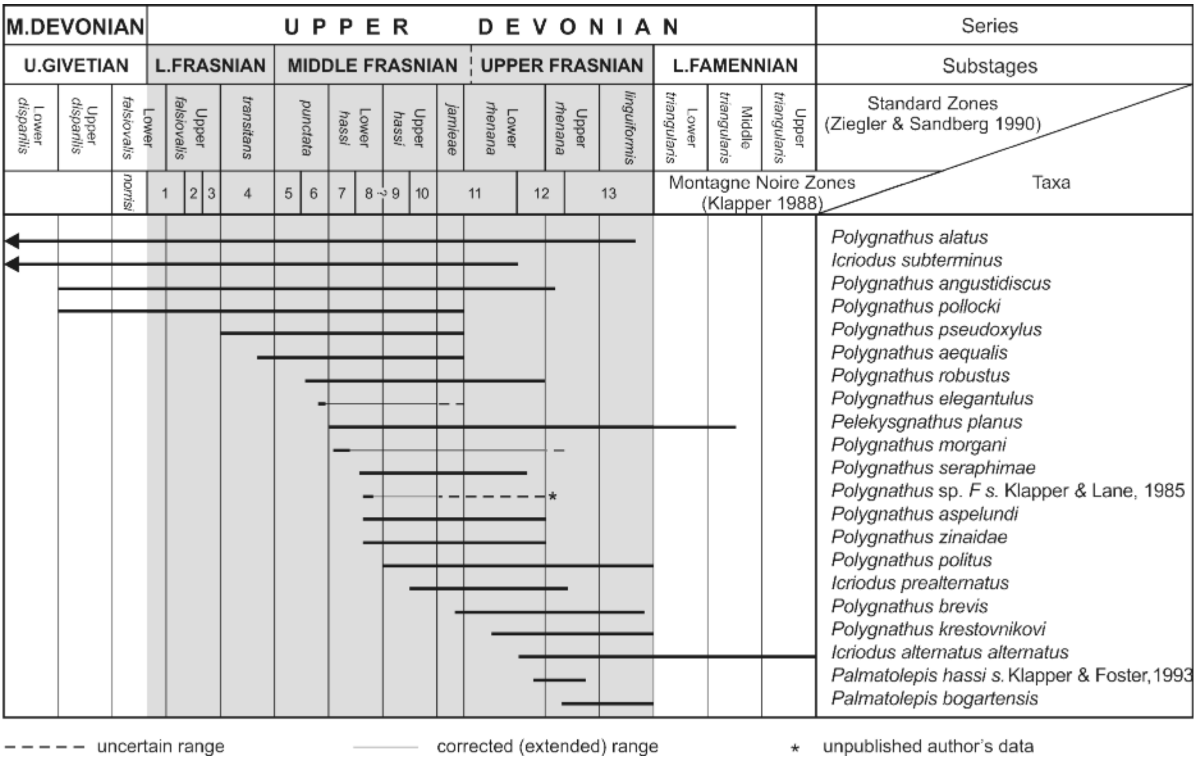

Fig. 4. Stratigraphic ranges of the investigated conodont taxa according to ZIEGLER & SANDBERG (1990), KLAPPER & FOSTER (1993), KLAPPER (1997), ZIEGLER & *al*. (2000), GOUWY & BULTYNCK (2000), OVNATANOVA & KONONOVA (2001) and BULTYNCK (2003)

features typical of *P. brevilaminus*. It is characterised by a narrow, flat and asymmetrical platform, and a high and massive-looking carina, instead of a symmetrical and wider platform with upturned margins along its entire length, and a carina that is neither very massive nor high, as seen, e.g. on the figured specimens of *P. brevilaminus* from the Famennian of the Unisław 2 borehole in the same paper (MATYJA 1993, pl. 24, fig. 11). Moreover, none of the remaining taxa listed for the depth interval 2798-2531 m by MATYJA (1993) makes its first appearance in the Lower *rhenana* Zone.

ZIEGLER & *al.*'s (2000, pl. 7, figs. 13 and 14) identification of *P. aequalis* also raises several doubts. In both figured forms the platform is too flat (this feature is particularly well seen in their fig. 14), the adcarinal troughs are rather shallow (particularly in the anterior part), and the anterior part of the platform of the left-curved specimen (op. cit., fig. 13) does not show the constriction that is so characteristic of left-curved specimens of *P. aequalis* as figured by KLAPPER & LANE (1985, figs 7, 9, 12). At the same time, the carina is too short and probably does not reach the platform termination, although the photographs are not very clear in that respect. The blade of the specimen figured in their fig. 13 is too long, whereas the anterior platform of their other specimen (fig. 14) does not end steeply as in the typical forms of KLAPPER & LANE (1985, figs 7-14). In contrast, it extends beyond a geniculation point. Moreover, this part of the platform lacks ornamentation. It may thus be concluded that the specimens of *P. aequalis* figured by ZIEGLER & *al*. (2000) do not show several diagnostic features of the species and therefore should not be used for establishing its total stratigraphic range.

The highest well-documented appearance of *P. aequalis* was noted near the base of the MN 11 Zone (KLAPPER & LANE 1985; KLAPPER 1997), corresponding to the *jamieae* Zone of the standard zonation (KLAPPER & BECKER 1999). Consequently the latter zone was here taken as the upper limit of the stratigraphic range of the species in question (Text-fig. 4).

Age of cycle VIa

In the Giełczew PIG 5 borehole, the base of Cycle VIa runs between the samples from 1863.0-1863.2 m and 1775.0 m depth (Text-fig. 2). The lower sample (Table 1) yielded *Polygnathus* aff. *P. seraphimae* (Pl. 1, Fig. 7), giving rather poor age resolution. Lower down in the section, the sample from 1925.6 m depth yielded *P. seraphimae* OVNATANOVA & KONONOVA, 1996 (Pl. 1, Figs 1, 5; Table 1), a species known to appear first in the upper part of the Lower *hassi* Zone (Text-fig. 4), and *P. pseudoxylus* KONONOVA, ALEKSEEV, BARSKOV & REIMERS, 1996 (Pl. 1, Fig. 4), which ranges from the *transitans* Zone to the *jamieae* Zone (see Text-fig. 4). The sample from 1775.0 m depth yielded *P. aequalis* (Pl. 1, Fig. 10) and *P. pseudoxylus* (Pl. 1, Fig. 11), both having their last occurrences in the *jamieae* Zone.The upper time limit for the age of the base of Cycle VI is therefore constrained to the latter zone.

In the Korczmin IG 1 borehole, the lower boundary of the undivided Cycle VI runs between the samples from 2367.8 m and 2162.0 m depth. The lower sample yielded a rich conodont assemblage (Table 2) dominated by *P. seraphimae* (Pl. 1, Figs 2, 3). Lower in the section, in the sample from 2375.3 m depth we found rare *Icriodus prealternatus* SANDBERG, ZIEGLER & DREESEN, 1992 (Pl. 1, Fig. 6), known to appear first in the Upper *hassi* Zone (Text-fig. 4). Therefore, the Upper *hassi* Zone sets the lower age limit for this sample and also for the sample from 2367.8 m depth. The assemblage from 2375.3 m depth is dominated by *P. aequalis* (Pl. 1, Figs 14, 15) which constrains the upper age limit to the *jamieae* Zone (Text-fig. 4). Representatives of this species were also identified in the sample from 2162.0 m depth (Pl. 1, Fig. 12).

In the Stężyca 1 borehole, the sample located just below the base of Cycle VIa (3132.4 m depth; Text-fig. 2) yielded three juvenile forms of *Polygnathus politus* OVNATANOVA, 1969 (Pl. 2, Fig. 2). A similar form was also found in the sample from 3146.9 m depth (Pl. 2, Fig. 5), and adult specimens of this species were encountered in the samples from 3203.9 m depth (Pl. 2, Fig. 4) and 3119.3 m depth (Pl. 2, Fig. 1). The total stratigraphic range of *P. politus* (Text-fig. 4), from the Upper *hassi* to *linguiformis* zones, thus represents the wide age interval for the base of Cycle VIa base in the Stężyca 1 section.

No samples were studied from below the base of Cycle VIa in the Tarkawica 2 borehole (Table 3). The age of the samples from 1487.2 m and 1483.6 m depth, located ca. 50 m above the cycle base, corresponds to the interval spanning ?Lower-Upper *hassi* to *jamieae* zones, based on the total ranges of *P. seraphimae* (Pl. 1, Fig. 9), *P. politus* (Pl. 1, Fig. 6), and *P. aequalis* (Pl. 1, Fig. 13) (cf. Text-fig. 4).

Dating of the top of Cycle VIa was possible in the Giełczew PIG 5 and Tarkawica 2 boreholes. In the Giełczew PIG 5 borehole, the boundary runs between the samples from 1574.2-1574.4 m and 1508.5 m depth. The lower sample (Table 1) yielded only one stratigraphically important species, *P. krestovnikovi* OVNATANOVA, 1969, represented by a single poorly preserved left-curved specimen (Pl. 2, Fig. 14). The earliest representatives of this species appear in the Lower *rhenana* Zone (Text-fig. 4). Four metres below, in the sample from 1578.4 m depth, we found a single, very well preserved right-curved specimen of *P. krestovnikovi* (Pl. 2, Fig. 13) and a single *Icriodus alternatus alternatus* BRANSON & MEHL, 1934 (Pl. 2, Fig. 9). The latter taxon first appears in the upper part of the Lower *rhenana* Zone (MN 12 Zone) which would thus represent the lower age limit of the 1574.2-1574.4 m depth level. The upper limit is defined by the last occurrence of *P. krestovnikovi* in the *linguiformis* Zone (Text-fig. 4). The sample from 1506.6-1506.4 m depth yielded left-curved specimen of *P. krestovnikovi* (Pl. 2, Fig. 12) and a form identified as *Palmatolepis* cf. *bogartensis* (Pl. 2, Fig. 10). Representatives of both taxa have their last occurrences in the *linguiformis* Zone.

In the Tarkawica 2 borehole, the sample from 1255.2 m depth is located ca. 20 metres above the top of Cycle VIa. The age of the relatively abundant and diverse assemblage (Table 3) may be attributed to the interval between the upper part of the Lower *rhenana* Zone and the lower part of the Upper *rhenana* Zone (MN 12 to lower MN 13 zones), based on the total range of *Palmatolepis hassi sensu* KLAPPER & FOSTER (1993) (Pl. 2, Fig. 11).

Biostratigraphic conclusions

In summary, it may be concluded that the onset of Cycle VIa (and undivided cycle VI) deposition is constrained to the upper part of the Upper *hassi* Zone and the *jamieae* Zone. The upper boundary of Cycle VIa falls between the upper part of the Lower *rhenana* Zone and the lower part of the Upper *rhenana* Zone.

THE EUSTATIC VERSUS TECTONIC CONTROLS OF CYCLE VI – A DISCUSSION

Tectonic subsidence analysis of the Lublin Basin (NARKIEWICZ & *al.* 1998a) revealed that the onset of the Late Devonian was marked by a distinct increase in subsidence rates, following the period of standstill or even small relative uplift during the Middle Devonian. The pulse of subsidence may be detected over the entire basin area except for its north-western termination. At the same time, however, the following strong Famennian subsidence continued only in the central parts of the basin (area around the city of Lublin – Text-fig. 1B). However, the stratigraphic resolution of the backstripping data was generalized to a stage level and therefore the results did not display possible subsidence changes in shorter time-slices. Setting more precise stratigraphic constraints on the subsidence history is now possible using the sedimentological and conodont data available. This will be discussed below in the context of possible controls on the Frasnian depositional cyclicity.

Evidence from basin architecture

The lowermost Frasnian T-R cycles IVb and V are similar to the Middle Devonian T-R cycles in their widespread occurrence and relatively uniform thickness development throughout the entire Lublin Basin. In particular, Cycle V shows the widest distribution of all the Middle-Upper Devonian T-R cycles. Its thickness varies between 140 metres in the south-east (Korczmin IG 1 borehole) and 80 metres in the north-west (Izdebno IG 1 borehole), whereas the lateral facies variability is insignificant. In contrast, Cycle VIa displays more pronounced thickness and facies gradients, with a depocentre developed in the central basin segment. The approximate extent of this depocentre corresponds to the distribution of sulphate facies in Fig. 1B. It is characterised by an occurrence of the thick calcareous-evaporitic facies which followed without any apparent interruption after the peritidal evaporitic deposition of the earlier regressive phase of Cycle V. The transgressive lower part of Cycle VIa is here marked by the presence of calcareous intercalations with progressively more open-marine fauna. In corresponding basin-margin settings, a distinct erosional discontinuity is followed by peritidal cycles devoid of sulphates, grading upwards into more open marine carbonate platform strata.

The basin architecture of Cycle VIa outlined above may be interpreted in terms of a development of a distinct depocentre within a semi-restricted shallow-marine basin. The subtidal anhydrite deposition was associated with periods when the basin was more restricted. On the other hand, intermittent better communication with the open sea and a more vigorous circulation enabled deposition of calcareous strata, in part with an open marine fauna. Basin margins were exposed to erosion and weathering, leading to dissolution of the sulphates of the regressive Cycle V interval and development of solution-collapse breccias. At the same time, continuous sedimentation in the depocentre protected the underlying Cycle V sulphates from dissolution.

The above interpretation implies that the basin architecture was governed by a differential (localised) tectonic subsidence in the central basin segment. The subsidence pulse interrupted a relatively uniform subsidence and/or eustatic stepwise transgression controlling the laterally uniform development of the mid-Devonian to early Frasnian T-R cycles. It is significant that the resulting mid Frasnian depocentre was later reactivated over approximately the same area during the Famennian. The latter subsidence pulse was stronger in terms of total magnitude, resulting in the deposition of up to 2000 metres of the Bychawa and Firlej marly deeper-shelf strata (ŻELICHOWSKI & KOZŁOWSKI 1983).

Implications of biostratigraphic-chronostratigraphic correlation

An independent approach to interpretation of controls on the T-R cycles is based on time constraints obtained from biostratigraphic data, which in turn enable comparisons with recognized temporal pattern of eustatic events. Such comparisons reveal that the age interval including the onset of Cycle VI (Upper *hassi* – *jamieae* zones) does not correspond to any eustatic transgression as interpreted by JOHNSON & *al.* (1985), JOHNSON & SANDBERG (1988) and SANDBERG & *al.* (2002). The IIc and IId (*semichatovae*) transgressions of those authors are recorded in the upper part of the *transitans* Zone and in the Lower *rhenana* Zone, respectively.

Nevertheless, the Rhinestreet black shales interval from New York State, USA, which was previously regarded as representing the onset of the IId cycle, is now placed within a broad interval comprising MN zones 6 to 11, i.e. Upper *punctata* to *jamieae* zones (HOUSE & *al.* 2000; HOUSE 2002). HOUSE (2002) argued that the interval in fact comprises four independent transgressive levels in the New York succession. The faunal control, however, is weak and it is not yet possible to place each of the successive levels in the chronostratigraphic framework (HOUSE 2002). Moreover, the data from other regions do not readily fit the New York pattern. In Western Australia, the rapid transgressive event correlated by BECKER & *al.* (1993) with the onset of the Rhinestreet Event is dated as goniatite Zone G, equivalent to MN zones 7 and ?8. The sea-level highstand corresponds to zones H-I (=MN 9 to 11), whereas the ensuing rapid regression-transgression couple is ascribed to the boundary between the MN 11 and 12 zones. On the other hand, sea-level changes interpreted for the Timan area of Russia by HOUSE & *al.* (2000) include a slow gradual transgression encompassing the MN zones from 7 to 8-9. This is followed by a strong regression (early MN 10) and transgression (late MN 10), continuing to the end of MN Zone 11.

Based on the currently available data, it appears probable that the onset of the Rhinestreet black shale deposition may in fact correspond to an eustatic event close to the boundary between MN zones 6 and 7 (i.e. *punctata-hassi*) (see also PISARZOWSKA & *al.* 2006).

On the other hand, further subdivision of this interval into discrete transgressive pulses and their correlation with possible counterparts worldwide is still open to question. In particular, there is so far no evidence supporting the existence of an eustatic transgressive pulse near the boundary between the *hassi* and *jamieaea* zones. We may therefore conclude that there is no proven eustatic transgression correlatable with the initial transgression of Cycle VIa. This negative evidence, coupled with the basin architecture data reported above, favours the tectonic nature of the onset of our VIa T-R cycle.

Cycle VIa is equivalent to two to three conodont zones, in contrast to the early Frasnian IVb-V cycles (four to five zones) and comparable to late Frasnian cycles VIb-d (two to three zones). Taking into account the thicknesses of particular cycles (see above), this further corroborates the increased rates of subsidence corresponding to Cycle VIa, particularly when contrasted with the rates of deposition during cycles IVb-V. This conclusion remains true if we take into account the duration of particular cycles based on the recent time calibration of the Devonian conodont zonation by KAUFMANN (2006). The respective durations based on the scale cited are: ca. 3 Ma (cycles IVb-V), ca. 3 Ma (VIa) and ca. 2 Ma (VIb-d).

REGIONAL COMPARISONS AND IMPLICATIONS

In the remaining area of the Polish Variscan foreland, the most convincing evidence of synsedimentary Late Devonian extensional tectonics has been reported from the Holy Cross Mts. (see summary in RACKI & NARKIEWICZ 2000; SZULCZEWSKI in NARKIEWICZ & *al*. 2006). There, the structural evidence for the tectonic-sedimentary phenomena is usually observed at the smaller scale provided by individual exposures; these structures have no apparent connection with a regional tectonic subsidence pulse. Moreover, the exact age of these structures, including e.g., the spectacular unconformity between the ?lower Frasnian and middle Famennian in the Ostrówka Quarry (SZULCZEWSKI & *al*. 1996), is mostly poorly constrained. In all probability, the extensional structures are heterochronous, related to the prolonged extensional stress regime during the Late Devonian and Early Carboniferous (LAMARCHE & *al*. 2003). It cannot be excluded, however, that they are partly coeval with the tectonic event that initiated Cycle VI in the Lublin Basin, as suggested by RACKI & NARKIEWICZ (2000).

The biostratigraphic data presented above allow a more precise correlation between the Lublin Basin and Pripyat Graben successions, the latter being a part of the larger Pripyat-Dniepr-Donets rift system (STEPHENSON & *al*. 2006). In the Pripyat Graben, the earliest phase of rifting processes, and associated magmatic activity, corresponds to or partly predates the transgressive Rechitsa Horizon (KONISHCHEV & *al*. 2001; OBUKHOVSKAYA & *al*. 2005; Text-fig. 5). This unit overlies the Semiluki Horizon with a regional disconformity and associated erosion and stratigraphic gap (KRUCHEK & *al*. 1996). The conodont assemblage found in the upper part of the Semiluki Horizon (Buinovichi Beds) includes i.a. *Polygnathus seraphimae* and *P. aspelundi* (OBUKHOVSKAYA & *al*. 2002, 2005), which constrains its age to the Upper *hassi* to *jamieae* zones (compare Text-fig. 4). The Rechitsa Horizon yielded a conodont assemblage containing *Polygnathus komi* KUZMIN & OVNATANOVA, 1989 (OBUKHOVSKAYA & *al*. 2002), the stratigraphic range of which is limited to the Lower to Upper *rhenana* zones, based on sections from the Russian part of the East European Platform (ZIEGLER & *al*. 2000; OVNATANOVA & KONONOVA 2001). The overlying Strelichev Beds show the first occurrence of *Palmatolepis semikhatovae* (in the upper part of the unit), in addition to *P. churkinii* and *Polygnathus unicornis* (OBUKHOVSKAYA & *al*. 2002, 2005). Based on the total ranges of the above-mentioned species, the Strelichev Beds may be referred to the Lower-Upper *rhenana* zones.

The Belarussian biostratigraphic data discussed above suggest that the age brackets of the Buinovichi Beds and overlying Rechitsa Horizon do not overlap, thus confirming the existence of a stratigraphic gap between them. This gap may comprise the upper part of the *jamieae* Zone and the lower part of the Lower *rhenana* Zone. On the other hand, the age of the Rechitsa Horizon as well as that of several other Upper Devonian units appears rather poorly constrained, given the lack of index conodont taxa due to unfavourable biofacies (see ALEKSEEV & *al*. 1996). The authors cited in fact correlate the Rechitsian regional stage with the Upper *hassi* to *jamieae* zones. Therefore, it cannot be excluded that, taking into account poor recognition of the key species, *P. komi*, the Rechitsa Horizon corresponds at least in part to the *jamieae* or even Upper *hassi* zones. This would imply a much narrower time-gap connected with the sub-Rechitsa disconformity. In either case, it may be concluded that, given the present resolution of the conodont data, the age of the base of Cycle VI in the Lublin Basin overlaps with the time interval equivalent to the erosional gap directly preceding the Pripyat Graben rifting. Therefore, based on current data, it is plausible that the onset of the VIa tectonic subsidence

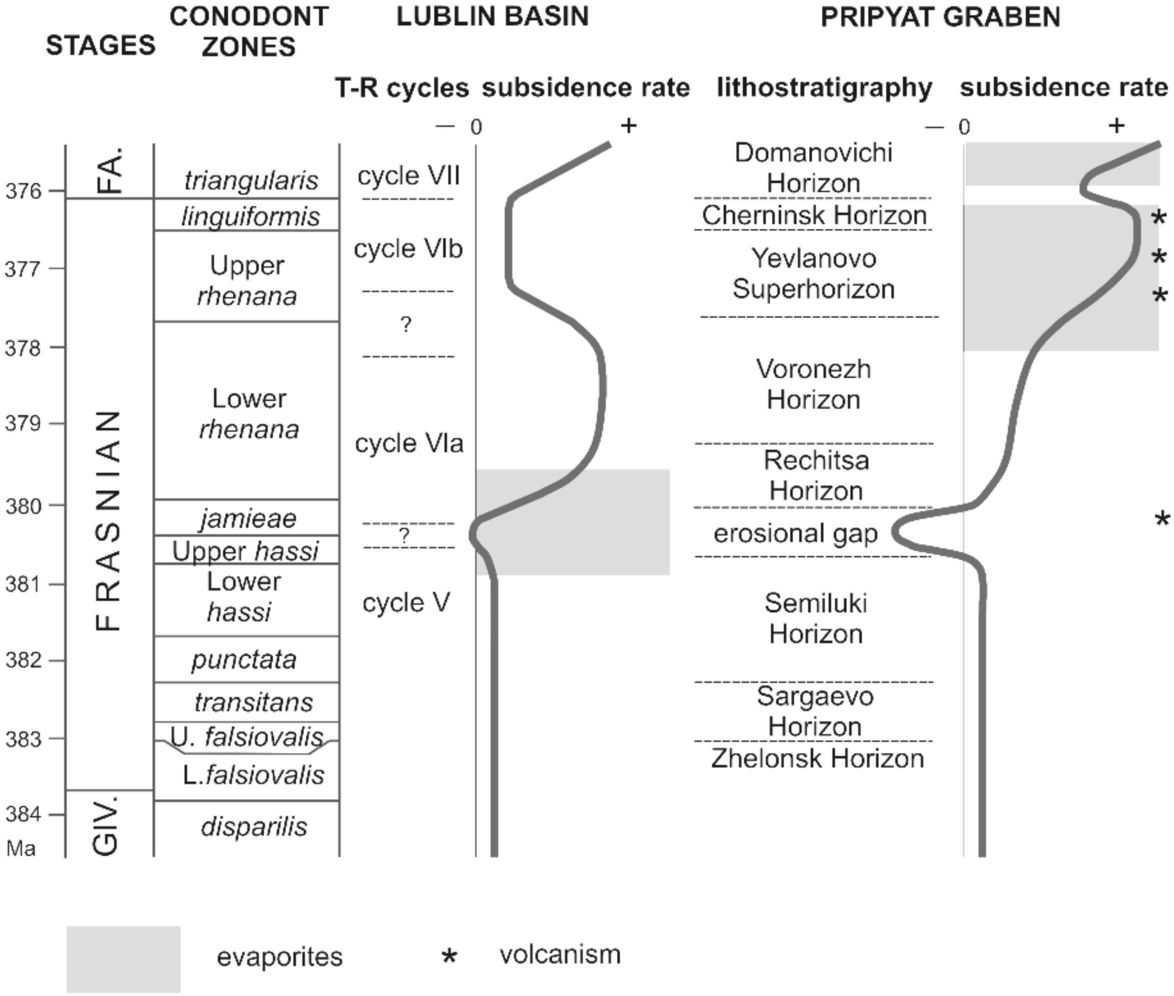

Fig. 5. Comparison of the Frasnian subsidence development in the Lublin Basin and Pripyat Graben. Subsidence rates are relative and not to scale. Conodont zonation after ZIEGLER & SANDBERG (1990); age calibration in Ma after KAUFMANN (2006). Stratigraphy of the Pripyat Graben area after OBUKHOVSKAYA & *al*. (2005)

and the initiation of the Pripyat rifting event correspond closely in age, being thus attributable to the common tectonic mechanism of regional extension. It must be stressed that, starting from the early Famennian, both areas were characterised by a strong renewed subsidence. In fact, the Late Devonian subsidence reached its peak during the Famennian, apparently in response to the strongest extension (KUSZNIR & *al*. 1996; NARKIEWICZ 2007).

There are, however, significant differences between the Lublin Basin and the Pripyat Graben (Text-fig. 5):

(1) Although the Late Devonian depocentre of the Lublin Basin is framed by regional fault zones (Text-fig. 1), it nevertheless does not represent a typical rift, neither in an overall depositional development nor in the crustal configuration. The latter features much better fit the concept of the “true” rift in the case of the Pripyat Graben (KUSZNIR & *al*. 1996; STEPHENSON & *al*. 2001).

(2) The magnitude of erosion in the Belarussian area implies regional uplift, whereas only the margins of the Lublin Basin were subjected to erosion and weathering.

(3) There is no evidence of Late Devonian magmatic processes in south-east Poland, in contrast to the Pripyat Graben, where volcanogenic material is found in the Rechitsa Horizon and tens of Rechitsa-age alkali ultrabasic diatremes were documented in the northern rift shoulder (WILSON & LYASHKEVICH 1996; KONISHCHEV & *al*. 2001). This contrast is even greater in the Famennian, with its voluminous volcanism associated with the main stage of the Pripyat Graben rifting.

(4) While in the Lublin Basin a relative subsidence-standstill is characteristic of the late Frasnian, in the

Pripyat Graben this interval was characterised by much increased subsidence rates, with the deposition of nearly 1 km of carbonates and evaporites and a considerable volcanogenic input (KONISHCHEV & *al*. 2001; OBUKHOVSKAYA & *al*. 2005). Therefore, the maximum tectonic subsidence appears diachronous, peaking in the middle Frasnian in the Lublin Basin and in the late Frasnian in the Pripyat Trough (Text-fig. 5). Nevertheless, it should be noted that the Frasnian–Famennian boundary interval is marked in the Pripyat Graben by the Intra-salt Beds, i.e. non-evaporitic sediments between the lower and upper salt-bearing strata representing decelerated subsidence (KONISHCHEV & *al*. 2001).

The significant feature of the Lublin Basin, contrasting it with the Pripyat Graben (and other elements of the Pripyat-Dniepr-Donets rift system), is the apparent lack of any Late Devonian magmatic phenomena. It further implies the existence of a fundamental difference in the thermal state of the lithosphere before and during the onset of the mid-Frasnian tectonism. In the Pripyat area, an extensive mafic crustal underplating could have been responsible for regional uplift of the order of 300 metres and associated erosion during pre-Rechitsian times and later (KUSZNIR & *al*. 1996; WILSON & LYASHKEVICH 1996). At the onset of rifting, the mantle-derived volcanism was not directly related to the rift-bounding faults, while it became more focused by crustal discontinuities during the main syn-rift phase. The hotter lithosphere facilitated crustal stretching responsible for the late Frasnian and Famennian subsidence, while at the same time the lithosphere of the Lublin Basin was relatively colder and therefore less responsive to extensional stress. Also, thermal doming of the Pripyat crust may have given rise to differential tensional stresses which further contributed to lithospheric extension (ZIEGLER & CLOETINGH 2004). Overall, the lower thermal regime in the Lublin Basin lithosphere may at least partly explain the relatively smaller rates and magnitude of the Late Devonian tectonic subsidence interrupted by the late Frasnian standstill.

The close similarity in depositional and subsidence history of the Pripyat Graben and Lublin Basin implies that a common extensional stress pattern affecting the large south-eastern areas of the East European Platform was responsible for the initiation of both depocentres. In fact, the lack of magmatism in the Lublin Basin seems to indicate that intraplate stresses were the primary factors controlling the Late Devonian evolution of the East European Platform. The effects of the hypothetical mantle plume postulated by WILSON & LYASHKEVICH (1996) and KUSZNIR & *al*. (1996) may be conceived as facilitating and amplifying the rifting process by thermally weakening the lithosphere, leading to crustal doming in the area of the Pripyat-Dniepr-Donets rift system. Also, the magnitude and scenario of rifting was probably to a large extent controlled by lithospheric-scale magmatic phenomena. Nevertheless, the mid Frasnian onset of rifting, as well as its main phase in the Famennian, were a response to extensional stresses that were probably related to plate-boundary forces (see also NARKIEWICZ 2007, for a discussion of the broader continental context).

CONCLUSIONS

1. The age of the onset of the mid Frasnian transgressive-regressive Cycle VIa in the Lublin Basin falls into the interval between the upper part of the Upper *hassi* Zone and the *jamieae* Zone. The upper boundary of the cycle runs between the upper part of the Lower *rhenana* Zone and the lower part of the Upper *rhenana* Zone.

2. Both basin architecture and conodont biostratigraphic data support the tectonic nature of the mid Frasnian T-R cycle VIa, which represents a considerable short-term (two to three conodont zones) increase in subsidence and depositional rates in the central segment of the Lublin Basin.

3. Based on the present conodont data, it is plausible that the onset of the VIa tectonic subsidence and the Pripyat Graben rifting event correspond closely in age, being thus attributable to the common tectonic mechanism of regional extension in the south-eastern part of the East European Platform.

4. The lack of any Late Devonian magmatic activity in the Lublin Basin, and the synchronous development of this basin with the Pripyat Graben, favour the hypothesis that intraplate stresses induced by plate-boundary forces were the primary factors controlling subsidence in both depocentres during the mid Frasnian to Famennian. The hypothetical mantle plume invoked by several authors as a main, if not sole, subsidence-driving mechanism may have played a role in amplifying the effects of crustal stretching in the Pripyat-Dniepr-Donets rift system by thermal weakening of the lithosphere.

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PLATE 1

Selected conodonts from borehole samples

1-3, 5, 8-9 – *Polygnathus seraphimae* Ovnatanova & Kononova, 1996; 1 – Giełczew PIG 5, depth 1925.6 m; 2 – Korczmin IG 1, depth 2367.8 m, 2a – upper view; 2b – lateral view; 2c – lower view; 3 - Korczmin IG 1, depth 2367.8 m; 5 – Giełczew PIG 5, depth 1925.6 m; 5a – lateral view; 5b – lower view; 8 – Stężyca 1, depth 3200.1 m, 8a – upper view; 8b – lateral view; 9 – Tarkawica 2, depth 1487.2 m, 9a – upper view; 9b – lateral view.

4, 11 – *Polygnathus pseudoxylus* Kononova, Alekseev, Barskov & Reimers, 1996; 4 – Giełczew PIG 5, depth 1925.6 m; 11 – Giełczew PIG 5, depth 1775.0 m.

6 – *Icriodus prealternatus* Sandberg, Ziegler & Dreesen, 1992; Korczmin IG 1, depth 2375.3 m; 6a – upper view; 6b – lateral view.

7 – *Polygnathus* aff. *P. seraphimae*; Giełczew PIG 5, depth 1863.2-1863.0 m; 7a – upper view; 7b – lower view; note lack of the characteristic ornamentation typical of the species.

10, 12-15 – *Polygnathus aequalis* Klapper & Lane, 1985; 10 – Giełczew PIG 5, depth 1775.0 m; 12 – Korczmin IG 1, depth 2162,0 m, 12a – upper view; 12b – lateral view; 13 – Tarkawica 2, depth 1483.6 m; 14 – Korczmin IG 1, depth 2375.3 m; 15 – Korczmin IG 1, depth 2375.3 m.

Scale bar – 100 µm

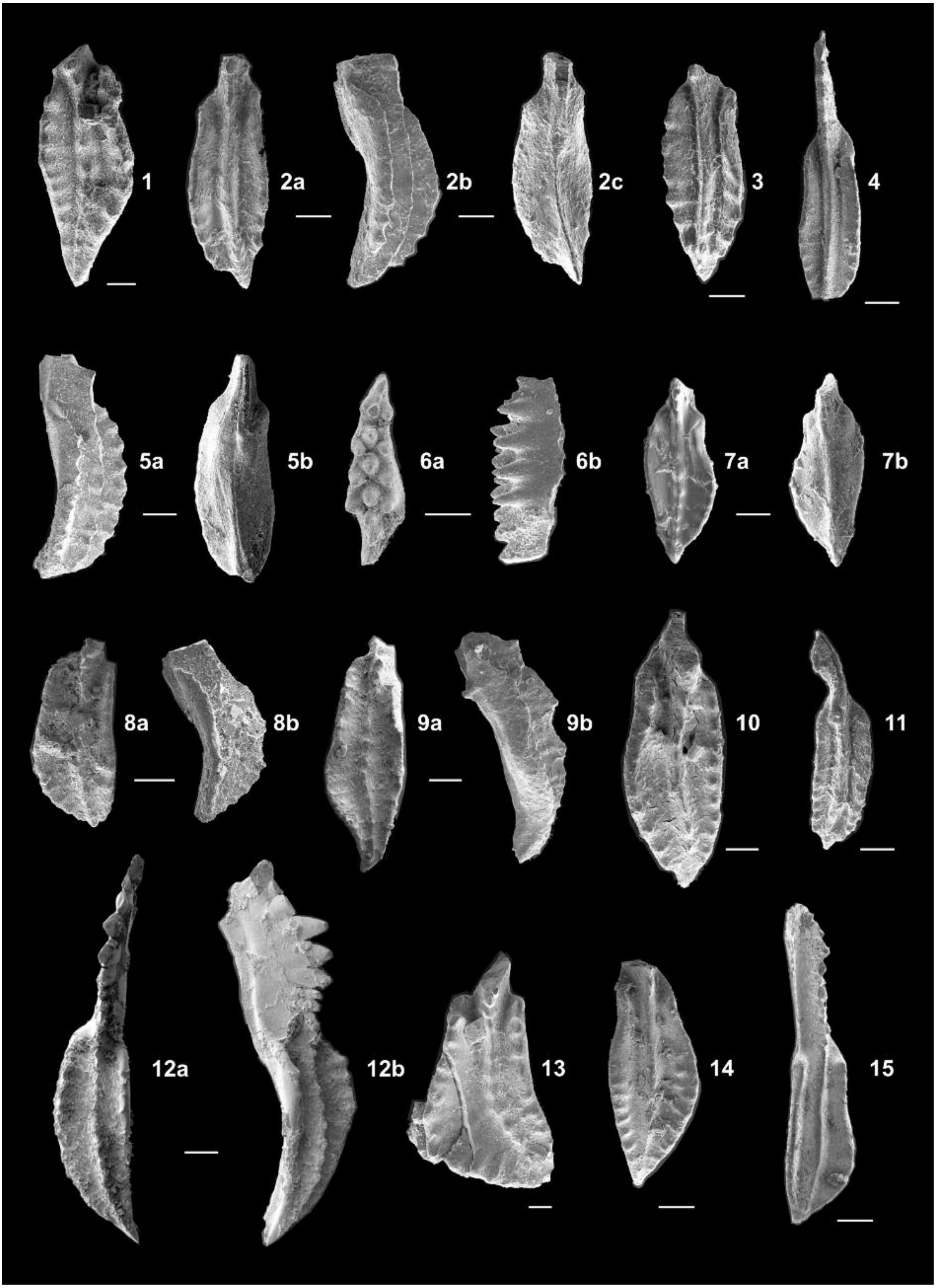
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PLATE 2

Selected conodonts from borehole samples

1-6 – *Polygnathus politus* OVNATANOVA, 1969; 1-2 – Stężyca 1, depth 3119.3 m; 1a – upper view; 1b – lower view; 2 – depth 3132.4 m, juvenile ontogenetic stage; 3 – Tarkawica 2, depth 1255.2 m, juvenile ontogenetic stage; 4-5 – Stężyca 1, depth 3203.9 m; 4a - upper view; 4b - lower view; 5 - depth 3146.9 m; 5a – lateral view; 5b – upper view; 6 – Tarkawica 2, depth 1483.6 m; 6a – upper view; 6b – lower view; 6c – lateral view;

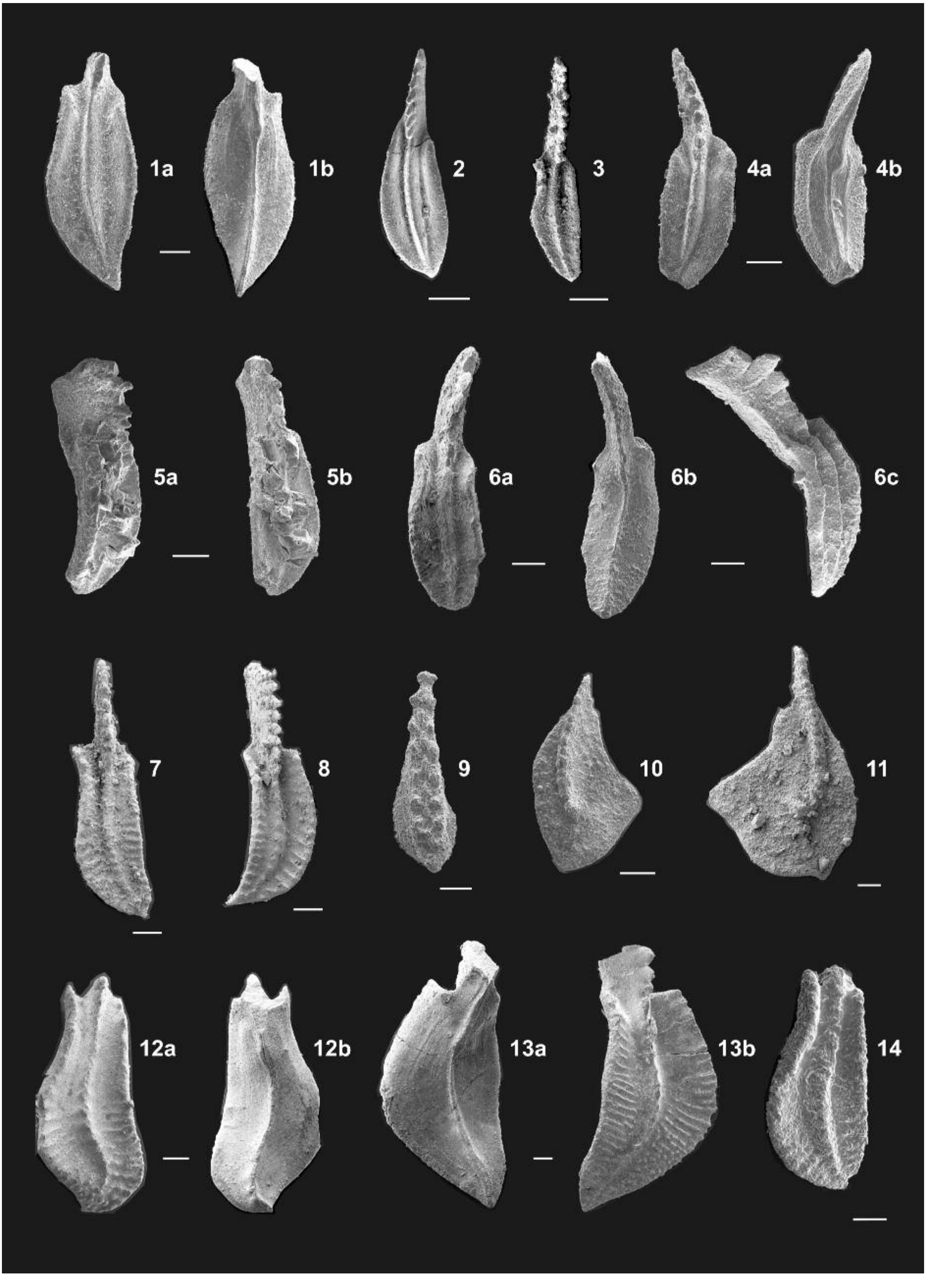
7-8, 12-14 – *Polygnathus krestovnikovi* OVNATANOVA, 1969; 7-8 – Tarkawica 1, depth 1255.2 m; 7 – left curved specimen; 8 – right curved specimen; 12-14 – Giełczew PIG 5; 12 – depth 1506.5 m; 12 a – upper view; 12b – lower view; 13 – depth 1578.4 m; 13a – lower view; 13b – upper view; 14 – depth 1574.4 -1574.2 m;

9 – *Icriodus alternatus alternatus* BRANSON & MEHL, 1934; Giełczew PIG 5, depth 1578.4 m;

10 – *Palmatolepis* cf. *P. bogartensis* (STAUFFER, 1938); Giełczew PIG 5, depth 1506.6-1506.4 m; juvenile ontogenetic stage;

11 – *Palmatolepis hassi sensu* KLAPPER & FOSTER,1993; Tarkawica 2, depth 1255.2 m.

Scale bar – 100 μm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