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Silurian graptolite biostratigraphy in the Wojcieszków 1 borehole and its significance for the stratigraphic correlation on the Lublin Slope of the East European Platform, Poland

Teresa PODHALAŃSKA[1, *]

[1] Polish Geological Institute – National Research Institute, Rakowiecka 4, 00-975 Warszawa, Poland; ORCID: 0000-0002-9732-4620

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On a deep shelf of the marginal part of the East European Platform in Poland the flat-lying Silurian succession is represented by the siliciclastic sedimentary rocks with graptolites. In the Wojcieszków 1 borehole some of the Silurian graptolite biozones have been documented assigned to Llandovery, Wenlock, Ludlow and Pridoli, including most of its stages. The stratigraphic gap in the base of the Silurian spans the lower part of the Rhuddanian. The Jantar Formation is dated by *Atavograptus atavus*-*Coronograptus cyphus* interval indicating upper Rhuddanian age. The age of the Pasłęk Formation is defined as the Aeronian and Telychian, based on the graptolite biozones from *Demirastrites triangulatus* to *Cyrtograptus insectus*. The next major gaps in the biostratigraphic record are found in the Telychian. These gaps are related to the environmental changes during the sedimentation of the Pasłęk Formation. The biochronostratigraphy of the Pelplin Formation is based on the assemblage of the ?latest Llandovery, Wenlock and Ludlow graptolites. All Homerian and three Gorstian biozones have been documented in the profile, along with the so-called “Cucullograptus Band”. The deposition of coarse-grained siliciclastics of the Kociewie Formation begins in the *Lobograptus scanicus* Chron of the latest Gorstian. The interval with *Bohemograptus* documents the lower Ludfordian part of the Kociewie Formation. The Silurian ends with the Puck Formation of the Pridoli series. The distribution of the graptolite biozones and the chronostratigraphic succession of lithostratigraphic units correspond closely to the developmental pattern of the Baltic Basin in the marginal East European Platform.

Key words: Silurian, stratigraphy, graptolites, Wojcieszków 1 borehole, East European Platform, Poland.

INTRODUCTION

The great interest in prospecting for unconventional hydrocarbon deposits in Poland gave rise to drilling new boreholes by Polish and foreign exploration companies after 2010. Ordovician and Silurian mudstones of the marginal zone of the East European Platform (EEP), including black shale horizons of the Middle Ordovician, Llandovery and Wenlock, have become the subject of intense multidisciplinary research, aimed at evaluating their potential for hydrocarbon generation (e.g., Poprawa, 2006, 2020; Więcław et al., 2010; Golonka and Bębenek, 2017; Podhalańska et al., 2020).

The boreholes drilled in Poland after 2010 provided many new palaeontological data, allowing refinement and verification of the lower Paleozoic stratigraphy and regional correlations (Podhalańska et al., 2010, 2020; Podhalańska, 2017, 2019, 2025; Porębski and Podhalańska, 2017, 2019). One of them is Wojcieszków 1 exploratory borehole, drilled in 2013, located NW of Lublin.

The paper presents the Silurian stratigraphy based on graptolite fauna from drill core samples mainly of the Llandovery and Wenlock black mudstones. The preliminary results of the research were presented as an effort of the project entitled *Blue Gas – Polski Gaz Łupkowy* and *Rozpoznanie stref perspektywicznych występowania niekonwencjonalnych złóż węglowodorów w Polsce* (e.g., Podhalańska, 2017, 2019; Porębski and Podhalańska, 2017, 2019, Podhalańska et al., 2020, 2023). The Wojcieszków 1 borehole, with thick Silurian deposits and a high core yield, may be used as one of the benchmarks for the Silurian litho- and biostratigraphy in the marginal (rim) zone of the Lublin slope of the EEP. The lithostratigraphy is based on the lithostratigraphic classification developed for the Silurian deposits by Modliński et al. (2006) and Podhalańska et al. (2010), and updated by Porębski and Podhalańska (2017, 2019), Trela and Podhalańska (2026). The biostratigraphy is based on the regional graptolite biozones established by Teller (1969), Tomczyk (1990), Urbanek and Teller (1997), Kozłowska-Dawidziuk (1999), Porębska et al. (2004) and Podhalańska (2019), compatible with the standard

* E-mail: teresa.podhalanska@pgi.gov.pl

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biozonal scheme after Melchin et al. (2020). The aim of the present study is the biostratigraphic documentation of the Silurian sedimentary rocks, mainly graptolite-rich black mudstones to supplement, verify and confirm the universality of the biostratigraphic record for the Silurian interval of the Lublin part of the EEP and thus to enable a precise stratigraphic correlation of rock complexes on a regional scale.

GEOLOGICAL SETTING

The Silurian sedimentary rocks currently found in eastern Poland are part of the sedimentary cover of the EEP. This area represented a pericratonic marine Baltic sedimentary basin developed in early Paleozoic times on the Precambrian crystalline basement of the Baltica palaeocontinent at middle and low latitudes of the Southern Hemisphere (Golonka et al., 2017) in the temperate and warm climatic zone. The Ordovician and Silurian deposits of the Baltic Basin that stretched along the south-western rim of the EEP in Poland, southern Sweden, the Baltic States, Belarus and Ukraine are represented by various facies belts and by a wide spectrum of environments, ranging from the shelf edge and deep basin in the west, through neritic environments, to littoral ones in the east (e.g., Jaanusson, 1976; Nestor and Einasto, 1997; Jaworowski, 2000; Lazauskiene et al., 2003; Modliński, 2010; Radkovets, 2015; Fig.1).

Lower Paleozoic sedimentary rocks are preserved in structural lows i.e. Baltic and Podlasie Depressions (Syneclises) and in the area of the Lublin slope of the EEP (Fig. 1). The basin formation and the deposition of Lower Paleozoic sedimentary rocks are associated with the Neoproterozoic break-up of the Rodinia/Pannotia continent (Poprawa et al., 1999; Jaworowski, 2002; Poprawa and Pacześna, 2002). The Ordovician-Silurian succession of the EEP is interpreted as recording the transition from a passive margin into a Caledonian foredeep, induced by the collision of East Avalonia with Baltica (Poprawa, 2019; Poprawa et al., 1999; Poprawa and Pacześna, 2002). The early Paleozoic deposition was controlled by both tectonic and eustatic factors (e.g., Jaworowski, 1971, 2000, 2002; Kozłowski, 2003; Modliński and Podhalańska, 2010; Kozłowski et al., 2014). Flexural bending of the Baltica crust, induced by the overthrusting of the Caledonian orogen, resulted in an increase in the subsidence rate in the basin, reaching its peak in the Ludlow and Pridoli. The development of the basin in the marginal zone of Baltica was conditioned by a zonal pattern of lithofacies, with an increasing proportion of clastic deposits towards the west, and carbonates towards the east (e.g., Jaworowski, 1971, 2000; Tomczykowa and Tomczyk, 1979; Tomczykowa, 1988; Tomczyk, 1990; Paškevičius, 1997; Modliński, 2010; Modliński and Podhalańska, 2010; Porębski et al., 2013). It is considered that the Caledonian accretionary prism, which formed along the Baltica-Avalonia collision zone, was the source area of clastic material, while the proximal zone and shallows in the basin are considered to supply carbonate material (Poprawa et al., 1999; Jaworowski, 2000; Porębski et al., 2013; Kozłowski et al., 2014; Mazur et al., 2018).

An important feature of the Silurian succession in this area is erosion in its upper and lower parts. In the eastern and south-eastern areas of the Lublin and Podlasie regions, a significant part of the Llandovery section is missing or totally absent. In the north-westernmost part of the area, the stratigraphic gap at the base of the Llandovery spans, at most, one biostratigraphic zone or it is not there at all. The gap gradually increases to the east of the area (Podhalańska, 2019) just as in the Baltic Syneclise (Modliński et al., 2006). The Wenlock (Sheinwoodian and Homerian) and lower Ludlow (Gorstian) deposits are the most stable stratigraphic horizons in terms of biostratigraphy and thickness.

The Wojcieszków 1 borehole is located in eastern Poland in the distal (rim) part of the Lublin slope of the EEP (Figs. 1 and 2). The drilling reached a depth of 3094 m within Cambrian deposits. The Silurian sedimentary rocks (1056 m thick) are covered by Carboniferous with a large stratigraphic gap.

The boundary between the Ordovician marls and the Silurian shales on the base of the geophysical data is established at the depth of 3031 m. The upper boundary of the Silurian System is at 1975 m at an erosional contact with the Carboniferous. The Ordovician and Silurian rocks lie horizontally or dip at a slight angle of no more than a few degrees.

The Wojcieszków 1 borehole provides important new information on the Silurian formations and fauna due to the high core recovery especially in the lower part of the section. The nearby Siedliska IG 1 borehole, which was drilled in 1970, with the Silurian thickness of 1058.2 m (1481.9–2540 m), is characterized by a smaller core recovery and more incomplete coring (Podhalańska, 2018; Fig. 2).

The Silurian in the Wojcieszków 1 borehole is represented by the Llandovery, Wenlock, Ludlow and Přidoli, including most of its stages assigned to the Jantar, Pasłęk, Pelplin, Kociewie and Puck formations, and to the Reda Member. The dominant Silurian lithologies are fine-grained clastics: mudstones, claystones and siltstones, calcareous at some intervals, as well as intercalations of rocks of pyroclastic origin. Graptolites are most common in the black fine-grained shales. In grey, light grey and green mudstones and calcareous interbeds, they are much less frequent, and the association of orthoconic cephalopods, molluscs and brachiopods appears.

MATERIAL AND METHODS

The palaeontological and stratigraphic analyses of fine-grained deposits with graptolites in the Wojcieszków 1 borehole have made it possible to identify several stratigraphic units and to determine the age of the deposits. Graptolites are the key organisms for the biostratigraphy of the Silurian system. They are the primary group of fossils employed in the orthostratigraphic division of mudstone-claystone sequences due to their significantly higher evolutionary rate and greater degree of resolution compared to other faunal groups.

Graptolites primarily occur in dark grey and almost black mudstones and claystones, which often exhibit high fissility. They are found to be much less frequent or absent in grey, fine-grained siliciclastic rocks. The state of preservation of graptolite fossils in drill core varies from good and complete to very poor and fragmentary with virtually no possibility of taxonomic identification. While most graptolites are compressed, three-dimensional individuals also occur. Some are filled with rock material containing pyrite. The graptolites have been the basis for the identification of the biozones and for the establishment of chronostratigraphic units. The occurrence of individual taxa was analysed in the samples stored in the drill core facility; the depths at which the samples were taken are given in Table 1.

Representative index and characteristic graptolites were selected for photography and presentation in Figures 3–6. Observations of the macrofossils were made using a stereoscopic microscope, and the photographic documentation was created

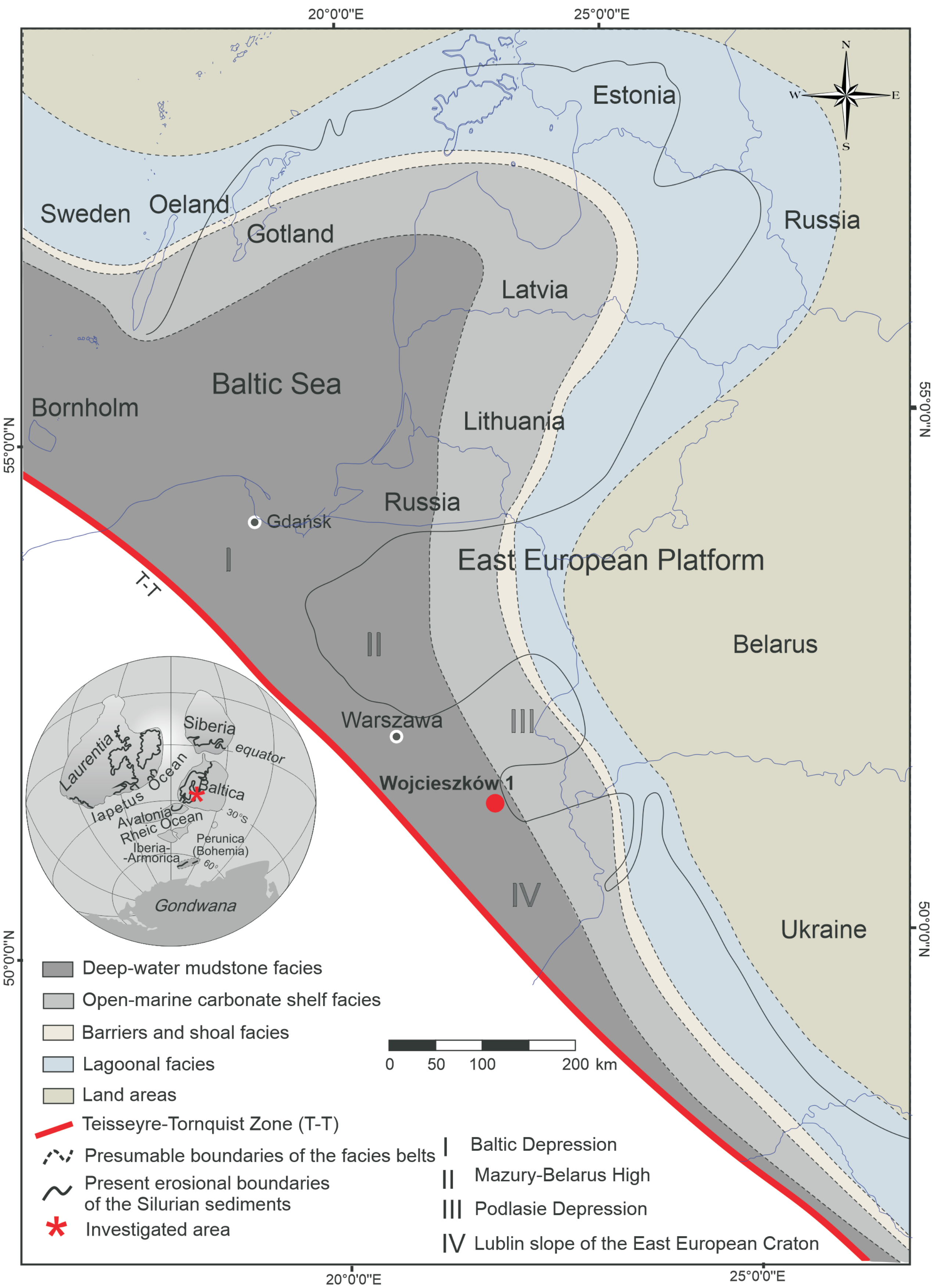

Fig. 1. Location map of the Wojcieszków 1 borehole against the major regional tectonic units and schematic distribution of the lithofacies along the western edge of the East European Platform in the Silurian (on the base of Teller, 1997; Kozłowski, 2003; Modliński, 2010; modified)

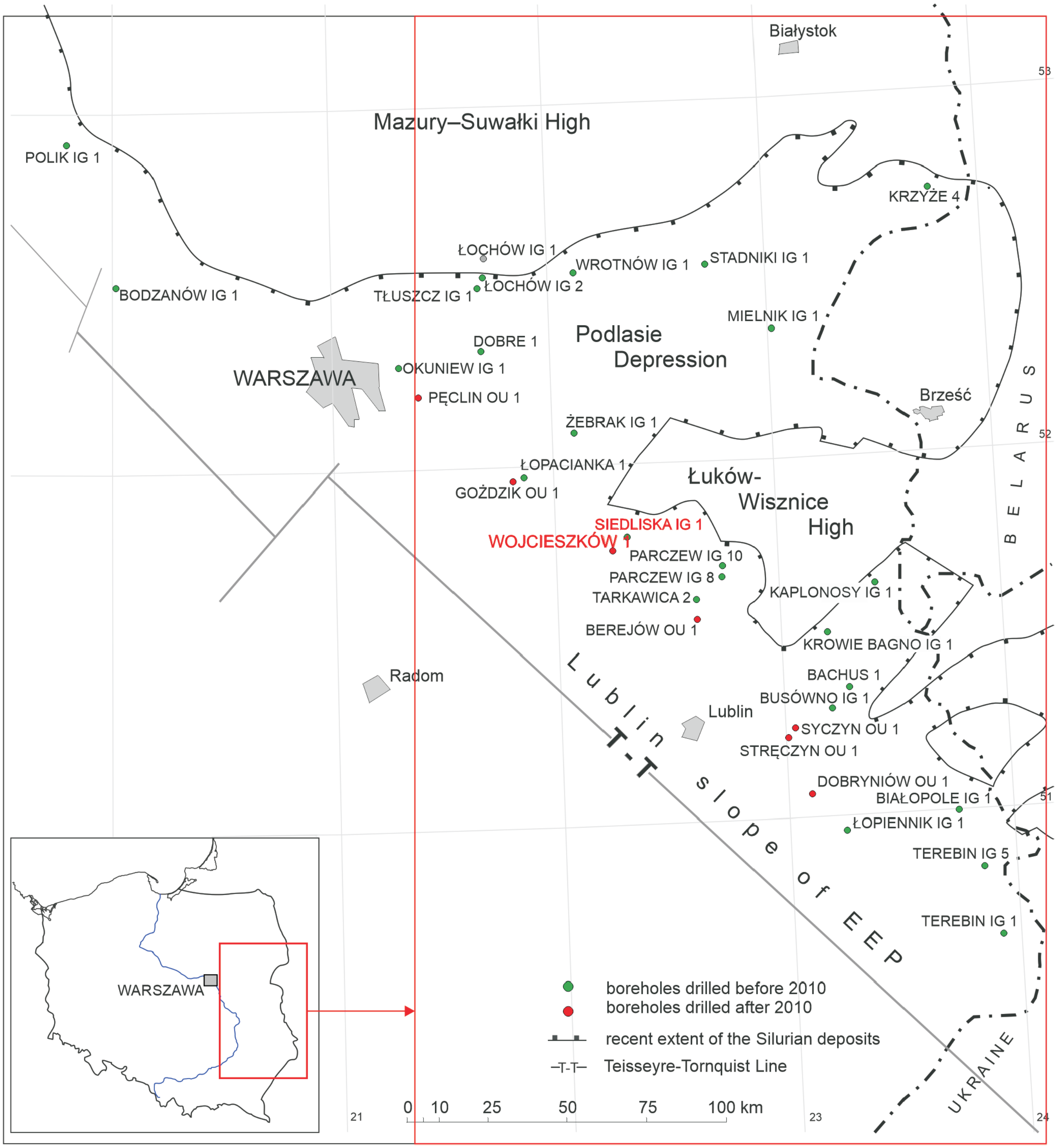

Fig. 2. Location sketch-map of the selected boreholes in the Podlasie Depression and the Lublin slope of the East European Platform (after Podhalańska, 2017; modified)

Red rectangle – investigated area

Table 1

Graptolite distribution in Wojcieszków 1 section

Sample	Depth	Formation	Graptolites	Age	Image
1	3029.0	Jantar	Fragments of normalograptids, *Normalograptus angustus* (Perner), *Normalograptus* cf. *medius* (Törnquist)	Llandovery, Rhuddanian	Fig. 3A
2	3028.0–3027.0		*Neodiplograptus diminutus* (Elles et Wood), *Normalograptus angustus* Perner, *Normalograptus* cf. *normalis* (Lapworth)	Llandovery, Rhuddanian, *pre-cyphus* interval	Fig. 3B
3	3027.0		*N.* cf. *normalis* (Lapworth), ?*Rhaphidograptus toernquisti* (Elles et Wood), *Glyptograptus* sp.	Llandovery, Rhuddanian, ?*atavus-cyphus* biozone	Fig. 3C, D, E
4	3025.1		*Neodiplograptus* sp., ?*Glyptograptus* sp.	Rhuddanian, ?*atavus-cyphus* biozone	Fig. 3F
5	3023.1	Pasłęk	*Clinoclimacograptus retroversus* Bulman and Rickards	Llandovery, Aeronian, *triangulatus* Biozone	Fig. 3G
6	3021.2–3021.1		*Demirastrites triangulatus* (Harkness), ?*Dimorphograptus* sp. (?*Orthograptus* sp.), *Neodiplograptus* sp. (incomplete specimens), numerous siculae	Aeronian, *triangulatus* Biozone	Fig. 3H, I
7	3018.2		*Campograptus lobiferus* (M'Coy), *Demirastrites decipiens* (Törnquist), *Monograptus limatulus* Törnquist	Aeronian *convolutus* Biozone	Fig. 3J
8	3016.2–3015.9		*Monoclimacis* sp., *Monograptus* sp.	Aeronian	
9	3015.5		*Torquigraptus* sp., *Torquigraptus tullbergi* (Bouček)	Llandovery, Telychian	Fig. 4A
10	3004.3		*Oktavites spiralis* (Geinitz), *Monoclimacis linnarssoni* (Tullberg), *Monoclimacis vomerina* (Nicholson)	Llandovery, upper Telychian, *spiralis* Biozone	Fig. 4B, C, D
11	3003.4		*Monograptus priodon* (Bronn), cyrtograptids	Llandovery, Telychian, *spiralis*, ?*lapworthi* biozones	Fig. 4E
12	3002.5		*M. priodon*, proximal part of cyrtograptids	Llandovery, Telychian	
13	3001.8		*Monoclimacis vomerina* (Nicholson), retiolitids, cyrtograptids	Llandovery, Telychian	Fig. 4F
14	2998.3	Pelplin	*Retiolites geinitzianus* Barrande (proximal part), ?*Mcl. linnarssoni* (Tullberg)	Llandovery, Telychian, *lapworthi – insectus* biozones	Fig. 4G, I
15	2995.3		*Mediograptus kodymi* Bouček), *Cyrtograptus ?insectus* Bouček., *M. priodon*, *Retiolites geinitzianus*, *Monograptus pseudocultellus* Bouček	Llandovery, Telychian, *insectus* Biozone	Fig. 4H, J
16	2990.3		*Pristiograptus* sp., *Mediograptus vittatus* (Štorch), *Monograptus priodon/flemingi* group, *Monoclimacis ?vomerina* (Nicholson), *Retiolites geinitzianus*	Wenlock Sheinwoodian *insectus – centrifugus* biozones	
17	2985.0		*Mediograptus* sp. (?*Mediograptus kolihai* (Bouček), *Retiolites geinitzianus*	Wenlock, Sheinwoodian *insectus – centrifugus* biozones	Fig. 5A
18	2976.5		*Monograptus flexilis* Elles, *Pristiograptus dubius* (Suess)	Wenlock, Sheinwoodian, *Monograptus flexilis* Biozone	
19	2974.3		*Monograptus flexilis* Elles	Wenlock, Sheinwoodian, *flexilis* Biozone	Fig. 5B
20	2972.2		*Cyrtograptus* cf. *linnarsoni* Lapworth *Monograptus flemingi* (Salter), *Pristiograptus dubius* (Suess)	Wenlock, Sheinwoodian	
21	2969.2		*Mediograptus flexuosus* (Tullberg), *Pristiograptus dubius* (Suess)	Wenlock, Sheinwoodian	Fig. 5C
22	2958.2		*Cyrtograptus* cf. *perneri* Bouček, numerous siculae	Wenlok, Sheinwoodian, ?*Cyrtograptus perneri* biozone	Fig. 5D
23	2936.5–2936.0		*Cyrtograptus lundgreni* Tullberg, *Pristiograptus dubius*, *Monograptus flemingii* (Salter)	Wenlock, Homerian, *Cyrtograptus lundgreni* Biozone	Fig. 5E
24	2935.5		*Testograptus testis* (Barrande)	Homerian, *lundgreni* Biozone	Fig. 5I
25	2933.4		*Cyrtograptus lundgreni, Testograptus testis, Pristiograptus dubius, Cardiola* sp.	*lundgreni* Biozone	Fig. 5G
26	2932.2		*Cyrtograptus* sp., *Monograptus flemingii*	*lundgreni* Biozone	

Tabl. 1 cont.

27	2931.0		*Pristiograptus dubius* s.l., immature specimen	Homerian	Fig. 5H
28	2932.0–2923.0		*Pristiograptus dubius, Gothograptus nassa* (Holm)	*Homerian, Gothograptus nassa* Biozone	Fig. 5F, J
29	2925.7		*Pristiograptus dubius*	Homerian	Fig. 5F
30	2923.9		*Gothograptus nassa*	Homerian, *nassa* Biozone	Fig. 5J
31	2918.4		*Colonograptus praedeubeli* (Jaeger), *Pristiograptus dubius*	Homerian, *Colonograptus praedeubeli* Biozone	Fig. 6A
32	2917.4–2914.4		*Colonograptus ?ludensis* (Murchison), *Pristiograptus dubius* s.l.	Homerian, *Colonograptus ludensis* Biozone	
33	2914.4		*Colonograptus ludensis* (Murchison)	Homerian, *ludensis* Biozone	Fig. 6D
34	2913.0		*Lobograptus progenitor* Urbanek	Ludlow, Gorstian, *Lobograptus progenitor* Biozone	Fig. 6B
35	2910.0		*Saetograptus chimaera* (Barrande), *Bohemograptus bohemicus*	Gorstian	Fig. 6C
36	2907.2		?*Lobograptus progenitor* Urbanek, *Colonograptus colonus* (Barrande), *Pristiograptus dubius*	Gorstian, "Cucullograptus Band" (?*progenitor* biozone)	
37	2902.0		*Lobograptus scanicus* (Tullberg), *Pristiograptus* ex. gr. *dubius*	Gorstian, "Cucullograptus Band", *scanicus* biozone	
38	2898.1		*Pristiograptus dubius*, unidentified specimens of ?*Lobograptus*, ?*Cucullograptus*	Gorstian	
39	2894.1		?*Cucullograptus* sp. (*Cucullograptus* cf. *hemiaversus* Urbanek)	Gorstian ?*Cucullograptus hemiaversus* biozone	Fig. 6E
40	2885,0		?*Lobograptus* cf. *scanicus* (Tullberg), *Saetograptus* sp., Bohemograptus sp.	Gorstian	
41	2880.1		*Saetograptus* sp., *Bohemograptus* sp., *B. bohemicus* (Barrande)	Gorstian "Cucullograptus Band"	
42	2877.3		*Lobograptus* cf. *scanicus* (Tullberg)	Gorstian,? *L. scanicus* Biozone	
43	2872.4		*Bohemograptus* sp., *Saetograptus* sp., *Pristiograptus dubius*	Ludlow, Ludfordian	
44	2763.6		*Pseudomonoclimacis* sp., *Bohemograptus bohemicus* (Barrande)	Ludfordian	
45	2679.5		*Pseudomonoclimacis* sp.	Ludfordian	
46	2588.3		*Bohemograptus tenuis* (Bouček), *Pseudomonoclimacis dalejensis* (Bouček)	Ludfordian,	
47	2586.8	Kociewie	*Bohemograptus tenuis*, *Pristiograptus dubius* s.l.	Ludfordian, *Bohemograptus tenuis* Biozone	Fig. 6F
48	2581.4		*Egregiograptus* sp. (*Egregiograptus ?rhinellae* Koren' et Suyarkova)	Ludfordian, *tenuis* Biozone	Fig. 6G
49	2550.7		*Linograptus* sp. (?*Linograptus posthumus* (Richter), *Monograptus* sp.	Ludfordian	
50	2028.0		Nautiloids	Pridoli	

using a *Hand USB Microscope Camera* and a *Canon Power Shot A700* digital camera. The research methodology was determined by the requirements of the owner of the geological data. One of the requirements was a limitation on the disintegration of the provided drill core fragments thus the boundaries of the biozones, as well as boundaries of the chronostratigraphic units determined on their basis, are often approximate. Drill cores from the Wojcieszków 1 borehole are stored currently at the PGNiG S.A. Central Drill Core Storage Facility, Chmielnik.

RESULTS

The Silurian in the Wojcieszków 1 borehole disconformably overlies the Ordovician carbonate-marly deposits of the Tyśmienica Formation – mostly Hirnantian, and is represented by a succession of siliciclastic deposits with a variable carbonate content. Its top surface is covered disconformably by Carboniferous siliciclastic deposits. An important feature of the Silurian succession is erosion in its lower and upper parts.

The distribution of the characteristic and index graptolites as well as the age of the Silurian rock samples and their lithostratigraphical affiliation are presented in Table 1.

The selected graptolite specimens are illustrated in Figures 3–6. The lithostratigraphic divisions, dominant lithologies within the core as well as the biochronostratigraphical interpretation are showed in Figure 7.

JANTAR MUDSTONE FORMATION

A distinct lithological change from marly deposits of the Upper Ordovician (Hirnantian) Tyśmienica Formation to mud shales of the Jantar Formation occurs at a depth of 3031 m ac-

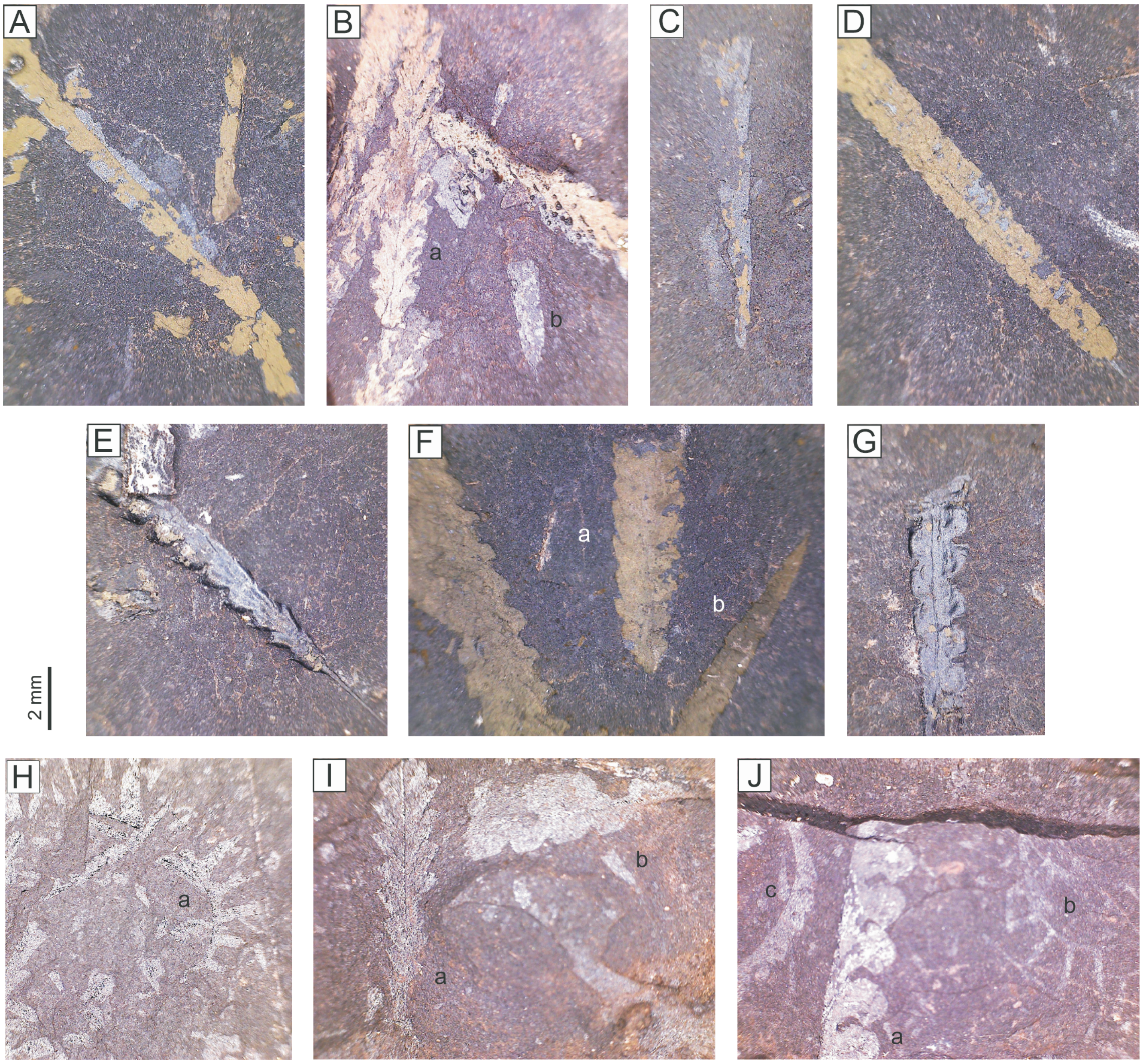

Fig. 3. Some of the Silurian graptolites identificated in the Wojcieszków 1 borehole, graptolites of the Jantar and Pasłęk Formation

A – *Normalograptus angustus* (Perner), depth 3029.0 m; **B** – a. *Neodiplograptus diminutus* Elles et Wood, b. *Normalograptus angustus* (Perner), juvenile stadium, depth 3028.0 m; **C** – *Rhaphidograptus toernquisti* (Elles et Wood), depth 3027.0 m; **D** – *Normalograptus* cf. *normalis* (Lapworth), depth 3027.7 m; **E** – *Glyptograptus* sp., depth 3027.0 m; **F** – a. *Neodiplograptus* sp., b. ?*Glyptograptus* sp., depth 3025.1 m; **G** – *Clinoclimacograptus retroversus* Bulman and Rickards, depth 3023.1 m; **H** – a. *Demirastrites triangulatus* (Harkness), depth 3021.2 m; **I** – a. ?*Dimorphograptus* sp. (?*Orthograptus* sp.), b. *Diplograptus* sp., depth 3021.2 m; **J** – a. *Campograptus lobiferus* (M'Coy), b. *Demirastrites decipiens* (Törnquist), c. *Monograptus limatulus* Törnquist, depth 3018.2 m

cording to geophysical data. The earliest determinable graptolites were recognized in the black mudstones of the Jantar Mudstone Formation at a depth of 3029 m. Jantar Formation consists of pyrite-rich, bituminous argillaceous mudstones often laminated and non-bioturbated. The lowest graptolites are represented by normalograptids and neodiplograptids. They were recognized at a depth of 3029 m in sample 1 (Table 1). In samples 1–4 at a depth from 3029 m to 3025.1 m (Table 1 and Fig. 3A–F) the following species have been determined: *Normalograptus angustus* (Perner), *Neodiplograptus diminutus* (Elles et Wood), *Rhaphidograptus toernquisti* (Elles et Wood), *Normalograptus* cf. *normalis* (Lapworth*)*,), *Neodiplograptus* sp., and *Glyptograptus* sp.). The age of the Jantar Formation in the Wojcieszków 1 borehole is defined as the Early Llandovery – Rhuddanian.

PASŁĘK MUDSTONE FORMATION

The characteristic feature of the Pasłęk Formation (depth 3024–3003 m, thickness 21 m); is a "zebra-like" colour banding due to the alternation of dark grey and grey-green, usually bioturbated mudstone laminae (Porębski and Podhalańska,

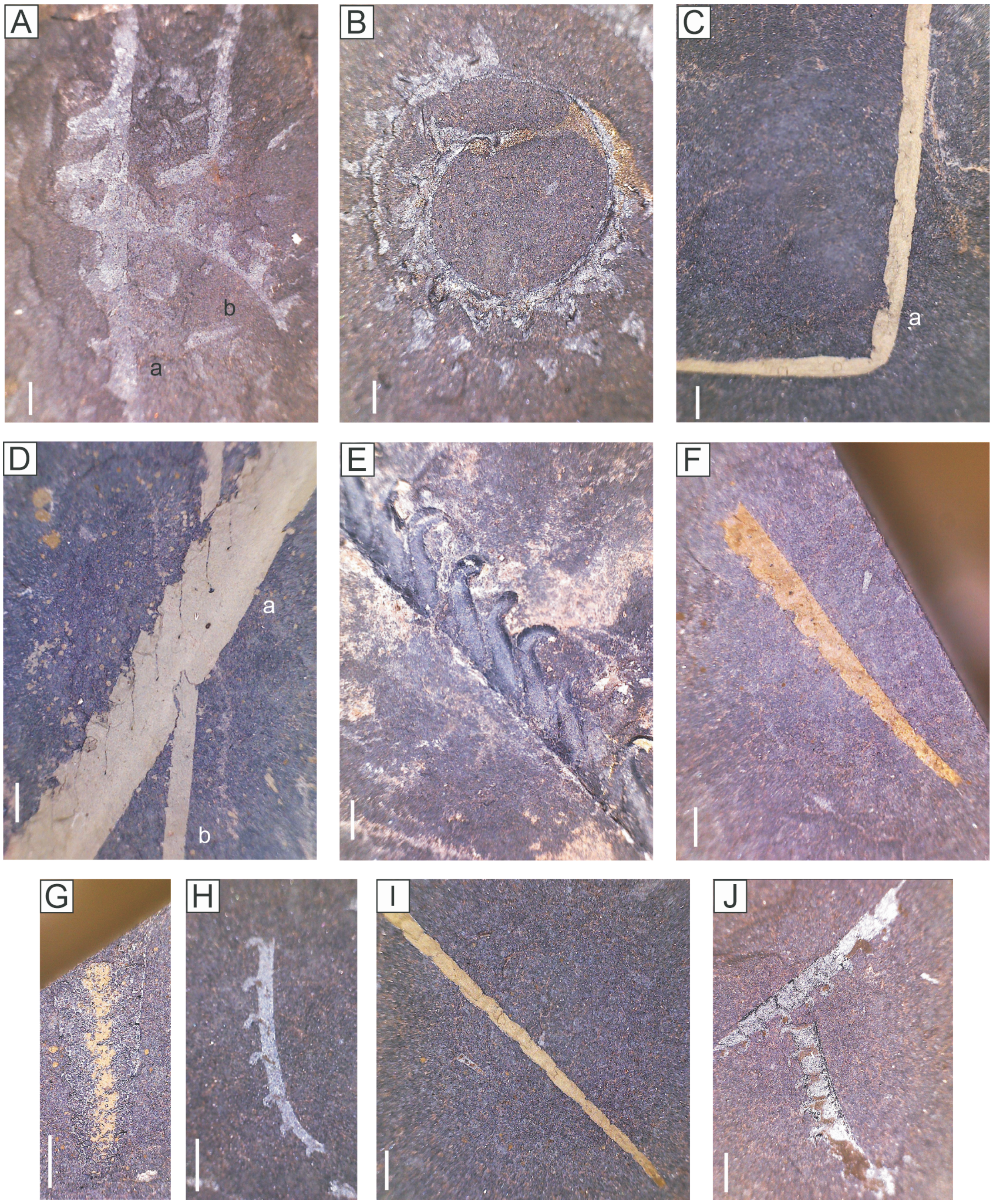

Fig. 4. Graptolites of the Pasłęk and Pelplin Formations

A – a, b. *Torquigraptus* sp. [?*Torquigraptus tullbergi* (Bouček)], incomplete specimen, depth 3015.5 m; **B** – *Oktavites spiralis* (Geinitz), depth 3004.3 m; **C** – *Monoclimacis linnarsoni* (Tullberg), depth 3004.3 m; **D** – a. *Monoclimacis vomerina* (Nicholson), b. *Monoclimacis* cf. *linnarsoni* (Tullberg), depth 3004.3 m; **E** – *Monograptus priodon* (Bronn), depth 3003.4 m; **F** – *Monoclimacis vomerina* (Nicholson), depth 3001.8 m; **G** – *Retiolites geinitzianus* Suess (proximal part), depth 2998.3 m; **H** – *Mediograptus kodym*i (Bouček), depth 2995.3 m; **I** – *Monoclimacis ?linnarsoni* (Tullberg), depth 2998.3 m; **J** – *Monograptus pseudocultellus* Bouček, depth 2995.3 m; scale bars are 2 mm

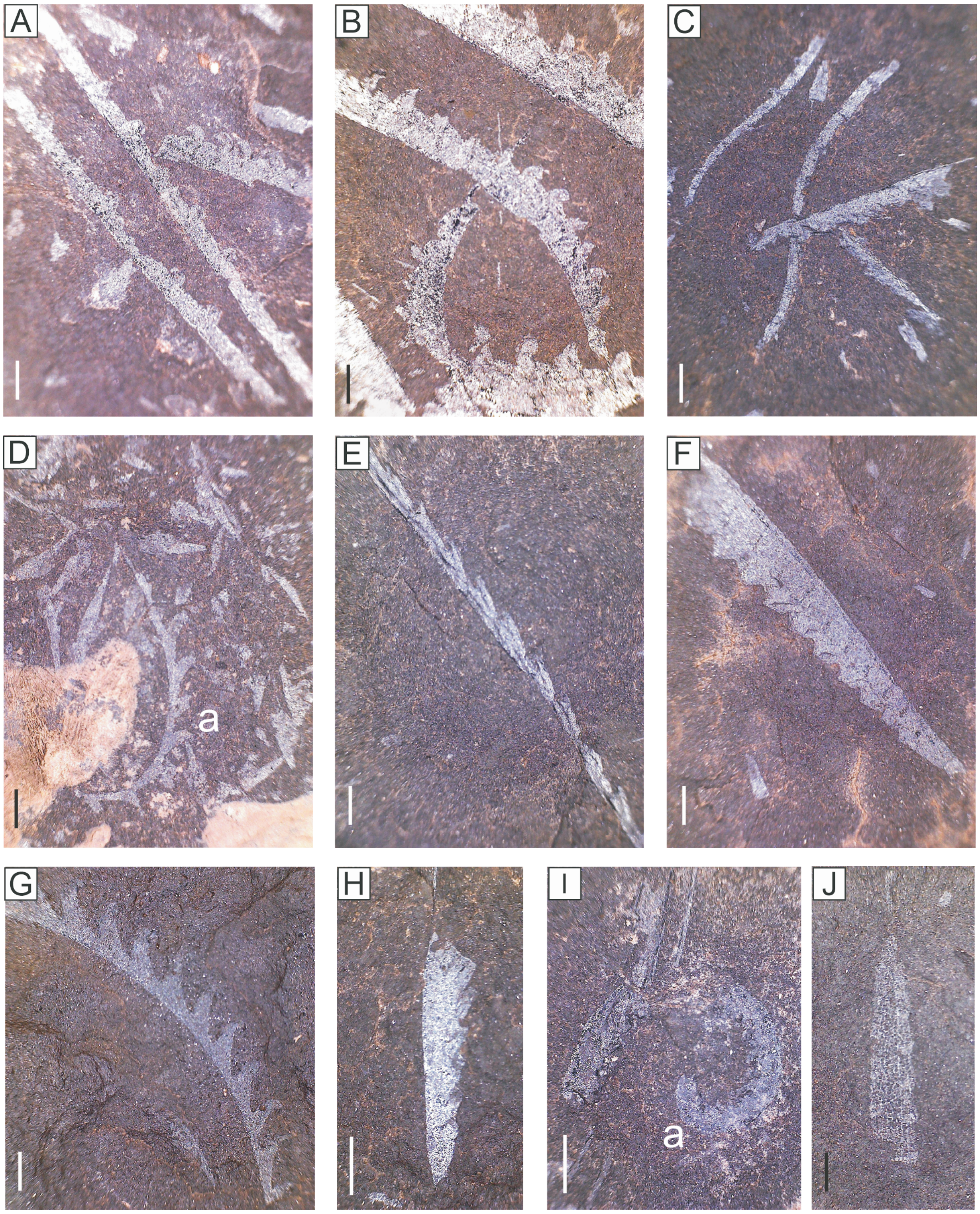

Fig. 5. Graptolites of the Pelplin Formation

A – *Mediograptus* sp., depth 2985 m; **B** – *Monograptus flexilis* Elles, depth 2974.3 m; **C** – *Mediograptus flexuosus* (Tullberg), depth 2969.2 m; **D** – fragments of *Cyrtograptus* cladium: a – proximal part of *Cyrtograptus* cf. *perneri* Bouček, and numerous siculae, depth. 2958.2 m; **E** – *Cyrtograptus lundgreni* Tullberg, incomplete thecal cladium, depth 2936.5 m; **F** – *Pristiograptus dubius* (Suess), depth 2925.7 m; **G** – *Cyrtograptus lundgreni* Tullberg, proximal portion, depth 2933.4 m; **H** – *Pristiograptus dubius* s.l., immature specimen, depth 2931.0 m; **I** – *Testograptus testis* (Barrande), depth 2935.5 m; **J** – *Gothograptus nassa* (Holm), depth 2923.9 m; scale bars 2 mm

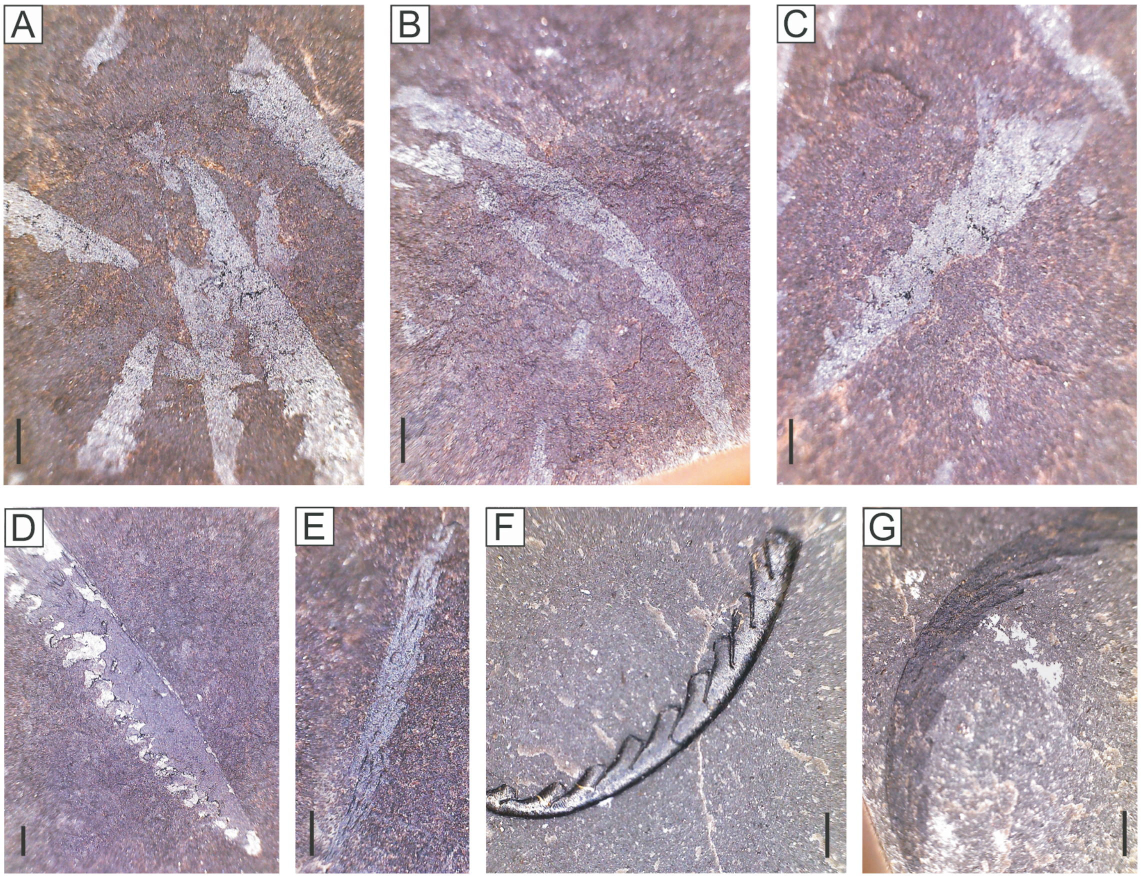

Fig. 6. Graptolites of the Pelplin and Kociewie formations

A – *Colonograptus praedeubeli* (Jaeger), depth 2918.4 m; **B** – *Lobograptus progenitor* Urbanek, depth 2913.0 m; **C** – *Saetograptus chimaera* (Barrande), depth 2910.5 m; **D** – *Colonograptus ludensis* (Murchison), depth 2914.4 m; **E** – *Cucullograptus* cf. *hemiaversus* Urbanek, fragment of a distal part, depth 2894.1 m; **F** – *Bohemograptus tenuis* (Bouček), depth 2586.8 m; **G** – *Egregiograptus* sp. (*Egregiograptus* ?*rhinellae* Koren' et Suyarkova), depth 2581.4 m; scale bars 2 mm

2017). Both mudstone facies tend to be non-calcareous with only rare lenses or laminae of quartz silt and shell detritus. The top of the formation is gradational and its upper boundary is defined at the uppermost green bioturbated mudstone laminae. In black layers the frequency of the graptolites is high while in grey and green laminae is low or the graptolites are absent. The samples 5–13 (Table 1) contain numerous and usually well preserved graptolites. Besides the graptolite detritus the lowest sample of the Pasłęk Formation from the core depth of the 3023.1 m contains *Clinoclimacograptus retroversus* Bulman (Fig. 3G), *Neodiplograptus* sp. , *Orthograptus* sp. (?*Dimorphograptus* sp.; Fig. 3I) and slightly higher (3021.2 m) *Demirastrites triangulatus* (Harkness) (Fig. 3H), an index fossil of the *triangulatus* Biozone. In sample 7 (3018.2 m), well-preserved fauna contains *Demirastrites decipiens* (Törnquist), *Campograptus lobiferus* (M'Coy) and *Monograptus limatulus* Törnquist (Fig. 3J). suggesting the *Lituigraptus convolutus* Biozone of Aeronian. *Monoclimacis* sp., *Monograptus* sp. and *Torquigraptus* sp. (?*Torquigraptus tullbergi* (Bouček) (Fig. 4A) are the only identifiable graptolites from 3016.2 to 3015.5 m from near the Aeronian-Telychian boundary.

A major gap in the graptolite record is observed between 3015.5 m (sample 9) and 3004.3 m (sample 10) in the upper part of the Pasłęk Formation. The graptolitic samples at 3004.3–3001.8 m (samples 10–13) bear again a diverse assemblage indicative of the *Oktavites spiralis* Biozone (Table 1) with *O. spiralis* (Geinitz), *Monoclimacis linnarsoni* (Tullberg), *M. vomerina* (Nicholson), *Monograptus priodon* (Bronn) (Fig. 4B–F) as well as fragments of retiolitids and cyrtograptids.

The age of the Pasłęk Formation in the investigated borehole is defined as the Aeronian and Telychian, based on the graptolite biozones *Demirastrites triangulatus* – *Oktavites spiralis.*

PELPLIN MUDSTONE FORMATION

The dominant lithology of the Pelplin Formation comprises dark grey, massive or laminated, argillaceous mudstones with diagenetic carbonate concretions, thin bentonite laminae and thin lags of shelly detritus. The thickness of the Pelplin Formation is 128 m. The graptolites of the Pelplin Formation in Wojcieszków 1 core are numerous and taxonomically diverse. The earliest of them were recognized in the sample no 14 (2998.3 m; Table1).

The graptolite assemblage of the lower part of the Pelplin Formation is dominated by retiolitids (*Retiolites geinitzianus* Barrande) (Fig. 4G), mediograptids (*Mediograptus kodymi* (Bouček) (Fig. 4H), *Mediograptus* sp. (Fig. 5A) as well as monograptids (*M. psedocultellus* Bouček) (Fig. 4J), pristiograptids, *Pristiograptus dubius* (Suess) (Fig. 5F) and cyrtograptids preserved as the incomplete thecal cladia (Fig. 5D, E). In samples 23–33 (Table 1) the sequence of biozones with the index graptolites *Cyrtograptus lundgreni*, *Testograptus testis*, *Gothograptus nassa*, *Colonograptus praedeubeli* and *Col. ludensis* was documented (Figs. 5F–J and 6A, D). The age of just described part of Pelplin Formation is defined as the uppermost Telychian – Homerian (Fig.7).

In samples 34–42 (depth 2913–2877.3; Table 1) the graptolite assemblage is characterized by the occurrence of genus *Saetograptus* (*Saetograptus chimaera* (Barrande) (Fig. 6C), *Pristiograptus dubius* and *Colonograptus colonus* (Barrande) and the first appearance of the representative of the cucullograptid lineage (*Lobograptus progenitor* Urbanek, sample 34, Fig. 6B).

The Ludlow (Gorstian) part of the Pelplin Formation is described here as a "Cucullograptid Band" firstly distinguished in Mielnik IG 1 bore core by Urbanek (1966) for the interval with Gorstian cucullograptids and lobograptids. In Wojcieszków 1 borehole the "Cucullograptus Band" is 35.7 m thick and comprises graptolites with apertural lobes. The graptolites are flattened, uncompleted, poorly preserved and hardly visible on the rock surface. Only some of them was able to distinguished: *Lobograptus progenitor* (Fig. 6B), *Cucullograptus ?hemiaversus* Urbanek (Fig. 6E). The stratigraphical position of the "Cucullograptus Band" *sensu* Urbanek and Teller (1997) responds the Gorstian *scanicus* Biozone.

KOCIEWIE MUDSTONE AND SILTSTONE FORMATION AND REDA MEMBER

The Kociewie Formation is characterized by siliciclastic and calcareous siltstone beds within clayey or silty mudstones and sandstones usually cemented with calcite or dolomite, and is dated by graptolites mainly of the genera *Lobograptus*, *Bohemograptus*, *Saetograptus*, and *Monograptus*. Its lower boundary established after the geophysical data at 2875 m corresponds to the top of the Pelplin Formation. Only 6 samples were the subject of research. The beginning of the Kociewie Formation in the Wojcieszków 1 borehole falls within the *Lobograptus scanicus* Biozone (sample 43). Poorly preserved fragments of *Pseudomonoclimacis* sp. and *Bohemograptus bohemicus* (Barrande) were identified at the depth of 2763.6 m and 2679.5 m (samples 44–45). *Bohemograptus tenuis* (Bouček), *Egregiograptus* sp. (*E.* cf. *rhinellae* Koren' et Suyarkova) (Fig. 6F, G) were found in a sample just below the Reda Member (Fig. 7) and *Linograptus* sp. (?*Linograptus posthumus* (Richter) has been found just above the Reda Member (sample 49). In the upper part of the Kociewie Formation, the Reda Member is confirmed at a depth of 2580–2560 m. This horizon, which spans the Ludfordian regional *kozlowskii* – *latilobus-balticus* interzone and reflects a global environmental perturbation (Kozlowski/Lau Event), is evident as a distinct anomaly on the GR in Wojcieszków 1 borehole as well as in many boreholes in the Baltic Syneclise and therefore it is usefull to correlation (e.g., Modliński et al., 2006; Kozłowski and Sobień, 2012; Porębski et al., 2013; Kozłowski, 2015, 2020; Porębski and Podhalańska, 2017, 2019).

PUCK FORMATION

No graptolites have been found in the uppermost sample representing the Puck Formation (sample no 50) from a depth of 2028.0 m; only a few nautiloids, brachiopod shells, and other unidentified organic detritus were present. The grey and greenish calcareous claystone/mudstone of the Puck Formation terminates the Silurian succession and spans part of the Pridoli and, in the central area of the Podlasie – Lublin region, the upper Ludfordian, e.g. in the Wojcieszków 1 and Siedliska IG 1, and many other boreholes (Podhalańska et al., 2010; Podhalańska, 2017, 2019). The upper boundary of the formation is erosional.

INTERPRETATION

The biostratigraphic research provided more details on the ranges of the lithostratigraphic formations in the Wojcieszków 1 borehole as well as the thickness of the Silurian series and stages (Fig. 7).

The lowest Silurian graptolites, mainly normalograptids and neodiplograptids (Table 1 and Fig. 7) were recognized at a depth from 3029 to 3025.1 m as the *atavus-cyphus* biozone therefore the Jantar Formation may be assigned to the upper Rhuddanian. The Aeronian and Telychian stages are documented by more diverse and numerous graptolites (Table 1 and Fig. 7). Between 3025.5 and 2990.3 m, the following biozones were distinguished *Demirastrites triangulatus*, *Lituigraptus convolutus* in the Aeronian (depth 3025.1–3015.5 m) and *Oktavites spiralis*, ?*Cyrtograptus insectus* in the Telychian (depth 3015.5–2990.3 m) dating the Pasłęk Formation as middle and upper Llandovery. The top of the Llandovery is established at 2990.3 m; thickness 38.7 m.

Both the Sheinwoodian and Homerian stages have been documented in the Wenlock at a depth from 2990.3 m to ~2913 m (thickness 77.3 m). In Sheinwoodian the following graptolite biozones have been documented: *Cyrtograptus centrifugus, Monograptus flexilis,* and an interval containing numerous albeit incomplete fragments of graptolites of the genus *Cyrtograptus*, most probably representing the *Cyrtograptus perneri* Biozone (Fig. 7).

The earliest occurrence of the *Cyrtograptus lundgreni* Biozone was found at a depth of 2936.0 m. The lower boundary of this biozone coincides with the lower boundary of the Homerian. It is dated by the graptolites of the following biozones: *Cyrtograptus lundgreni-Testograptus testis, Colonograptus praedeubeli* and *Colonograptus ludensis* (Fig. 7). Thus, a sequence of graptolite biozones in the Wojcieszków 1 is close to those in the Homerian documented in the Baltic region of Polish part of the EEP (Kozłowska-Dawidziuk, 1999; Porębska et al., 2004).

The age of the Pelplin Formation is based on the assemblage of Wenlock (?uppermost Llandovery) and Ludlow graptolites. Its lower boundary runs at the base of the ?*Cyrtograptus insectus* Biozone, while the upper boundary runs within the late Gorstian *Lobograptus scanicus* Biozone. The latest Telychian–Gorstian age of the Pelplin Formation is documented by the following biozones*: insectus, flexilis, ?perneri, lundgreni-testi*s, *nassa*, *praedeubeli*, *ludensis*, *progenito*r, *chimaer*a, *scanicus* (Fig. 7). In Pelplin Formation the graptolite succession is complete.

The lower boundary of the Ludlow is set at a depth of ~2913 m at the first appearance of linograptids (genera *Lobograptus* and *Neodiversograptus*). Based on the similarity to the Siedliska IG 1 borehole, the thickness of the Ludlow in the analysed borehole is several hundred (>500) metres. The upper boundary of the Ludlow is difficult to determine due to the lack of drill core. In stratigraphic terms, the youngest graptolites of the Ludlow, *Linograptus* sp. and *Monograptus* sp. have been found in a sample from a depth of 2550 m, i.e. several hundred metres from its lower boundary. Two stages have been documented in the Ludlow deposits: Gorstian and Ludfordian. The Gorstian is documented from a depth of ~2913 to 2877.3 m (35.7 m) by the presence of the following biozones: *Lobograptus progenitor*, *Saetograptus chimaera* and *Lobograptus scanicus* as well as

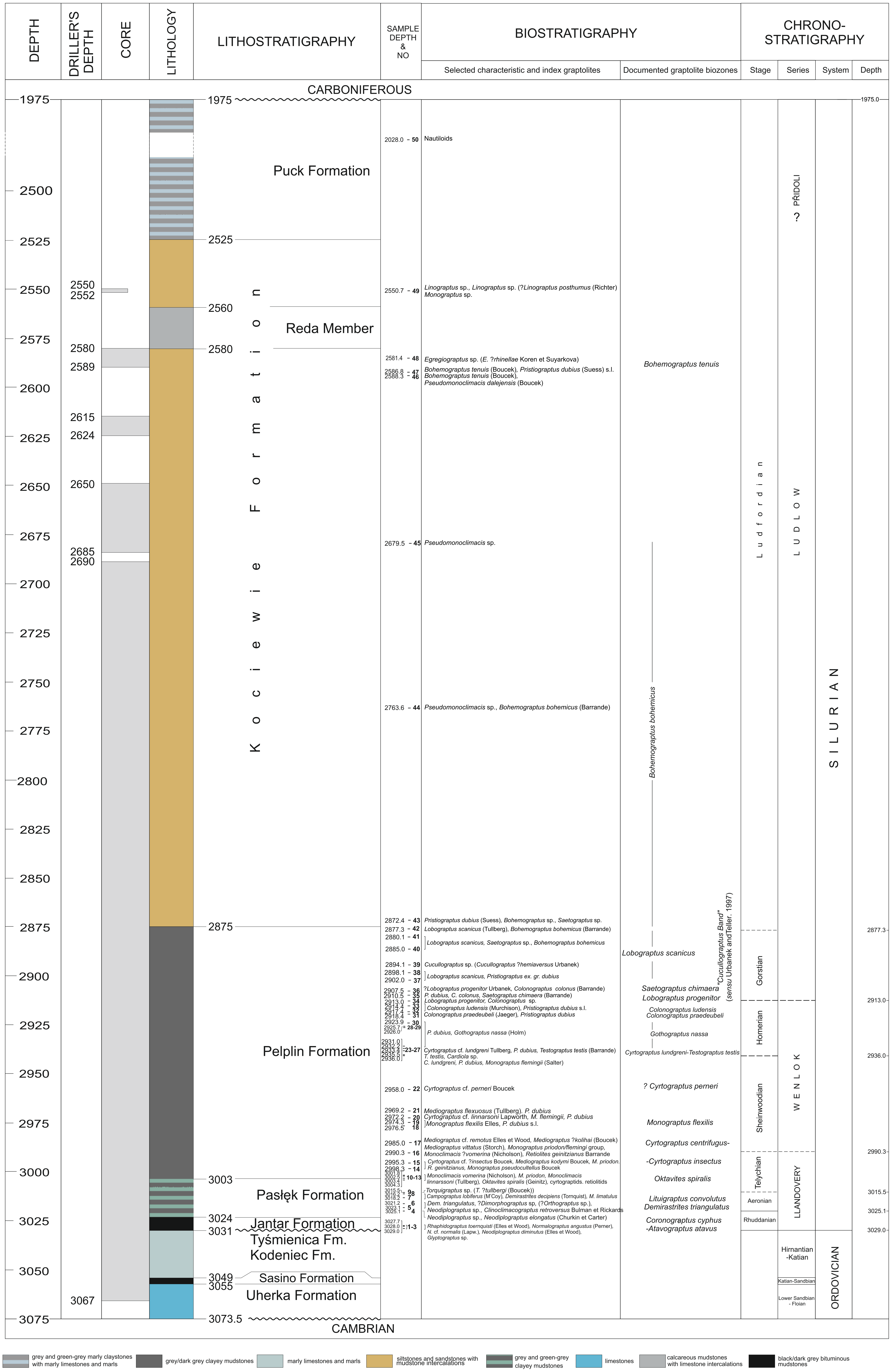

Fig. 7. Lithostratigraphy, characteristic and index graptolites, documented graptolite biozones and chronostratigraphy of the Silurian in the Wojcieszów 1 borehole

graptolites of the "Cucullograptus Band" (*sensu* Urbanek and Teller, 1997), dating the upper Gorstian and lowermost Ludfordian.

The Ludfordian age of the Kociewie Formation has been documented only partially in the uppermost cored interval (uppermost part of the section). Several tens of metres beneath the Reda Member of 2586.8 m, there are quite numerous individuals of bohemograptids as well as *Egregiograptus* sp. at a depth of 2581.4 m (Fig. 7).

Poorly preserved fragments of *Linograptus* sp. and *Monograptus* sp. were identified ~10 m above the upper boundary of the Reda Member.

No graptolites have been found in the uppermost sample from a depth of 2028.0 m. By comparing the thickness of the deposits and correlating them with other regional sections, e.g. the Siedliska IG 1 borehole, these deposits may be included in the Pridoli. The grey and greenish calcareous claystone/mudstone of the Puck Formation terminates the Silurian succession and spans part of the Pridoli and, in the central area of the Podlasie – Lublin region, the upper Ludfordian, e.g. in the Siedliska IG 1, Wojcieszków 1 and many other boreholes (Podhalańska et al., 2010; Podhalańska, 2017, 2019). The upper boundary of the formation is erosional.

DISCUSSION

The succession of the graptolite biozones, as well as the chronostratigraphic succession does not differ from the general pattern of the Baltic Basin development in the marginal zone of the East European Platform (e.g., Teller, 1969; Tomczyk, 1990; Urbanek and Teller, 1997; Podhalańska, 2019; Trela and Podhalańska, 2026). The most of graptolite species and their stratigraphical ranges are comparable with the graptolite data from Great Britain (Zalasiewicz, 2009); Barrandian area, Czech Republic (Štorch, 2023; Štorch et al., 2024) as well as East Baltic region (Paškevičius, 1997; Loydell et al., 2003; Radzevičius, 2013, Maletz et al., 2014).

The stratigraphic research based on graptolites provided more details on the temporal and spatial ranges of the lithostratigraphic formations and the number and range of stratigraphic gaps in the Silurian succession. The characteristic feature of the lower Silurian deposits at the EEP margin in Poland is diachronous appearance of black graptolitic shale formations from the north-west to the south-east.

In Podlasie-Lublin area a large stratigraphic gap spanning the part of the Llandovery and increasing eastwards. The base of Llandovery deposits, the base of Jantar Formation is diachronous and the early Silurian stratigraphic gap increases from the *acuminatus* to *atavus-cyphu*s biozones in Okuniew IG 1, Pęclin OU-1 , Siedliska IG 1 and Wojcieszków 1 boreholes respectively. Towards the SE basin edge, the gap between Ordovician and Silurian increases and in the Berejów OU- 1, Stręczyn OU- 1, Dobryniów OU- 1 boreholes (locality on Fig. 2) the black graptolitic facies begins in the latest Llandovery (Podhalańska, 2019: fig. 11).

The Lviv-Volyn Basin of western Ukraine was in the Early Paleozoic a continuation to the south-east of the Lublin part of the sedimentary basin in Poland. According to Rizun et al. (2007) the Llandovery is absent and the Silurian is represented by Wenlock, Ludlow and Pridoli deposits similarly as in Terebin IG 5 borehole situated in the SE part of the Lublin slope (Tomczyk and Podhalańska, 2014).

In Latvia the Lower Silurian succession comprises dark grey and black graptolite shales and dark grey and black clayey marls of the Aeronian and Telychian stages, which lie on top of carbonates of the lowermost Silurian (Rhuddanian). The base of the Dobele Formation, possibly an equivalent of the Jantar Formation in Aizpute-41 core, similarly to Wojcieszków 1 borehole lies within the Rhuddanian *cyphus* graptolite Biozone (Loydell et al., 2003). The Llandovery Jürmala Formation (Paškevićius, 1997) begins with the *triangulatus* Biozone (the base of Aeronian) similarly to the lowermost part of the Pasłęk Formation in Poland, the Dobele Formation (Aeronian), may be considered as an lithofacies equivalent of the Jantar Formation in the western part of the Baltic Basin in Poland.

Graptolites are very sparse in the lower part of the Ohesaare core (Saaremaa, Estonia) and indicate an age of latest Rhuddanian-Aeronian *Atavograptus atavus* Biozone as the beginning of the Silurian (Loydell et al., 1998).

The Silurian graptolite succession in the Wojcieszków 1 core is not complete in relation to the regional and global biozonal scheme (e.g., Urbanek and Teller, 1997; Urbanek et al., 2012; Porębska et al., 2004; Podhalańska, 2019; Melchin et al., 2020). The lack of continuity in the graptolite record is due to stratigraphic gaps, facies changes, the state of preservation of graptolites in the rock, as well as technological factors, e.g. limitations in sampling and drill core disintegration.

The significant gaps in the biostratigraphic documentation in the Wojcieszków 1 borehole refer to the Llandovery, particularly the Aeronian/LowerTelychian stages. Interbedded green and graptolitic dark grey mudstones of the Pasłęk Formation reflect the changeable oxic-anoxic conditions affecting the graptolite preservation in the rock. Similarly the basal Velise Formation, of the Estonian part of the Baltic shelf shows the environmental conditioning of the graptolite occurring in the rock. In Velise Formation of "relatively deep shelf" of the Saarema, Estonia, water depth had varied with local and eustatic changes in sea-level during the early Silurian. The unconformity is interpreted as resulting from regressions reflecting Aeronian and early Telychian eustatic falls in sea-level (Loydell, 1998).

In the Silurian, the migrating front of Caledonian collision determined shale deposition in the basin, and shale and siltstone in the upper part of the succession (e.g., Jaworowski, 2002; Modliński and Podhalańska, 2010; Porębski et al., 2013; Mazur et al., 2018). The beginning of the Kociewie Formation is characterized by the appearance of the siliciclastic and calcareous siltstone beds within clayey or silty mudstones and sandstones usually cemented with calcite or dolomite. In the Baltic sedimentary basin it is diachronous and getting younger platformwards (e.g., Jaworowski, 2000; Modliński et al., 2006; Mazur et al., 2018). In the Podlasie and Lublin region its age is defined as Ludlow (Gorstian–Ludfordian). The beginning of the Kociewie Formation in the Wojcieszków 1 borehole falls within the *Lobograptus scanicus* Biozone (Podhalańska, 2019) and within the *Bohemograptus cornutus* Zone in the south-eastern part of the area (Mazur et al., 2018).

CONCLUSION

The stratigraphic research based on graptolites provided more details on the temporal and spatial ranges of the lithostratigraphic formations and the number and range of stratigraphic gaps in the Silurian succession.

In the Wojcieszków 1 section, only part of the graptolite biozones have been documented. The lack of continuity in the graptolite record is due to stratigraphic gaps and facies changes but also due to "spotty" graptolite coverage, fragmentary preservation of the graptolite tubaria and limitations in sampling. Deposition of the Silurian sedimentary rocks begins with black graptolitic shales in the late Rhuddanian – *atavus-cyphus* interval. The largest gaps in the biostratigraphic documentation refer to the Llandovery, particularly the late Aeronian-Telychian Stage. The lack of graptolite documentation in some Aeronian and Telychian intervals results from facies changes in the Llandovery; these are related to variable environmental conditions during the sedimentation of the Pasłęk Formation. All the Homerian graptolite biozones analogous to those documented in the Baltic region of Poland's East European Platform (Kozłowska-Dawidziuk, 1999; Porębska et al., 2004) have been documented. Three Gorstian biozones, and the "Cucullograptus Band", which contains the *Cucullograptus* and *Lobograptus* genera, difficult to separate in the case of compressed graptolites, have been identified. Sedimentation of the coarser-grained siliciclastics of the Kociewie Formation began in the Late Gorstian. In the Late Ludfordian, *Bohemograptus* sp., graptolites with ventrally curved tubarium dominate. There are no biostratigraphic data for the uppermost Silurian due to the lack of coring in this part of the borehole section.

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