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GRAPTOLITE BIOSTRATIGRAPHY AND DATING OF THE ORDOVICIAN–SILURIAN SHALE SUCCESSION OF THE SW SLOPE OF THE EAST EUROPEAN CRATON

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Abstract: This paper deals with the graptolite biostratigraphy and age determination of the Ordovician and Silurian lithological successions of the Baltic, Podlasie and Lublin basins that existed during the early Palaeozoic on the SW slope of the East European Craton. The biostratigraphic research described was conducted on core material coming from old boreholes and cores from several new wells. Graptolite zones were identified and the chronostratigraphic succession was constrained, with the depths to the stratigraphic units, especially those considered prospective for petroleum, being determined in the individual borehole sections. Old local stratigraphic schemes of the Silurian used for many years in the Polish geological literature are correlated with the standard schemes. The most complete succession of graptolite zones, both in the Ordovician and the Silurian, is observed in the Baltic region. The number of stratigraphic gaps increases towards the east and southeast of the regions. The stratigraphic range of the Sasino Shale Formation decreases in this direction; in the Podlasie and Lublin regions, it comprises only the Katian Stage. The stratigraphic range of the Jantar Formation in the western part of the area spans not only the Rhuddanian but also part or the whole of the Aeronian. In the Podlasie and especially the Lublin regions, sedimentation of the Jantar Formation began in the latest Rhuddanian–Aeronian. A large stratigraphic gap, spanning part or the whole of the Llandovery and increasing eastwards, was documented in the Podlasie-Lublin region. The biostratigraphic research allowed a more precise constraint on the temporal and spatial extent of erosion of Pridoli deposits and the beginning of coarse-grained, siliciclastic sedimentation (Kociewie Formation) in the Baltic Basin.

Key words: Biostratigraphy, Ordovician, Silurian, graptolites, East European Craton**.**

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INTRODUCTION

In connection with research to identify formations prospective for unconventional hydrocarbon deposits, various studies have been carried out, notably stratigraphic investigations. The verification and refinement of the Ordovician and Silurian graptolite biostratigraphy in selected representative boreholes along the southwest margin of the East European Craton were crucial to establishing the chronostratigraphy. Chronostratigraphic units have been distinguished and the positions of lithostratigraphic boundaries amended, which in turn allowed dating of the individual formations and members, especially those considered prospective. These data are the basis for regional lithostratigraphic correlations, including sweet-spot correlations, dating of depositional sequences and their boundaries, and determination of the depositional history in the basin and the amount of post-depositional erosion.

The Lower Palaeozoic deposits, which occur in Pomerania and in the Podlasie and Lublin areas as well as in the basement of the Płock-Warsaw Trough, represent part of an extensive sedimentary cover that was deposited in the pericratonic Baltic Basin, developed on the Precambrian basement of the Baltica palaeocontinent. At that time, it was in medium and low, southern latitudes and in temperate and warm, climatic zones with a cold episode in the latest Ordovician. The Baltic Basin was a vast, epicratonic sea, surrounded by flat shores with slow carbonate and fine, clastic sedimentation, with large amounts of bioclasts and belt-like facies distribution. The accumulation of black shales took place in the distal part of the Baltic Basin on the outer shelf and slope in anoxic conditions.

Ordovician and Silurian shale successions of the marginal zone of the East European Craton, including black shale (mudstone and claystone) horizons of the Middle and Upper Ordovician, Llandovery and Wenlock, are the most important for the occurrence of unconventional hydrocarbon deposits in Poland.

The boreholes analysed were drilled mainly in the 1970s and differ greatly in terms of the length of cored intervals, core yield at individual depth intervals, core condition and completeness, as well as the state of preservation of graptolites and other fossils. The new boreholes drilled recently by exploration companies provided considerable amounts of palaeontological data, allowing the verification and refinement of the Ordovician and Silurian stratigraphy of the East European Craton.

The fossils found on bedding planes were examined. Those from the Ordovician and Silurian sections are usually flattened, though in some intervals they are preserved in semi-relief or rarely three-dimensionally; in such cases, they are filled mostly with pyrite. Owing to changes in taxonomy and graptolite systematics, some taxa were subject to amendment and updating of taxonomic names as well as the correction of stratigraphic ranges.

Verification of the stratigraphy of Silurian sections in Poland started a few years ago and was dictated by the need to determine the boundaries and ranges of some series and stages, as well as the boundaries of the system. The chronostratigraphic standard of the Silurian was developed by the International Subcommission on Silurian Stratigraphic Classification (ISSC) in the early 1980s. Regional stratigraphic schemes from the sections of classic natural exposures of the areas of Wales and England and central Bohemia have been accepted as the standard subdivision. The boundaries of the System and the stratigraphic ranges of the individual series have been ratified by the International Commission on Stratigraphy (ICS); the ratification procedures were carried out successively in 1980 for the Wenlock and Ludlow and in 1984 for the Llandovery and Pridoli (Cocks, 1985; Holland, 1985; Holland and Bassett, 1989).

The Ordovician and Silurian graptolite-based biostratigraphy was established by studying core material, stored in the core archives of the PIG-PIB (Polish Geological Institute-National Research Institute). Biostratigraphic studies were also carried out on a number of newly drilled boreholes, made available by PGNiG (Polish Oil and Gas Company) and Orlen Upstream. This contribution is a modified version of a paper by Podhalańska (2017), published in Polish.

ORDOVICIAN AND SILURIAN CHRONOSTRATIGRAPHY

Graptolites and their significance to the stratigraphy of Ordovician and Silurian shale successions

Graptolites belong to the most numerous, most diverse and usually the only group of fossils occurring in Ordovician and Silurian shale successions. They are commonly found in dark claystones and mudstones. Graptolites are the basis for the stratigraphy of the Ordovician and Silurian systems and they are the most important fossils for chronostratigraphic subdivision in particular borehole sections. The biostratigraphic classification based on this group of fossils is the best tool of stratigraphic correlation. Identifying the stratigraphic ranges of graptolites enables precise stratigraphic correlation of prospective rock successions on a regional scale.

Graptolites are accompanied by other groups of fossils: inarticulate brachiopods, nautiloids, tentaculites, bivalves and microfossils (acritarchs and Chitinozoa), but none of these groups can replace graptolites in dating and correlating the Lower Palaeozoic mudstone-claystone succession.

The state of preservation of the graptolites and their frequency and diversity in shales can indicate the type of sedimentary environment and the level of early diagenesis, including the redox conditions prevailing at the bottom of the sedimentary basin, and can enable the identification of aerobic and anaerobic intervals. These features are crucial for understanding the processes of accumulation and alteration of organic matter leading to the formation of hydrocarbons in the rocks investigated. The lack of fossils of benthic organisms and the concomitant abundance of graptolites indicate the prevalence of anoxic conditions in the bottom waters. Accordingly, graptolites can be considered one of the tools useful in the assessment of the source-rock potential of shales for hydrocarbons (Podhalańska, 2013).

Chronostratigraphic schemes of the Ordovician and Silurian

As a result of changes in the global chronostratigraphic standards, made by the International Commission on Stratigraphy and the International Union of Geological Sciences, e.g., lower and upper system boundaries and base of the Ludlow Series, it has become necessary to adapt regional stratigraphic subdivisions, or those previously used, to new global schemes in order to improve correlation.

The reasons for the need to verify and update the stratigraphy of these systems in Poland were: (1) changes to both the boundaries of variously ranked stratigraphic units and the ranges of nominative and index taxa, (2) the availability of new biostratigraphic data, and, in the case of the Silurian, (3) the need to apply the changes of the boundaries and ranges of some series and stages of the Silurian System to the Polish sections. The verification process continues as new sections are examined and the Silurian sedimentary basins of Poland are analysed (e.g., Szymański and Modliński, 2003; Modliński *et al*., 2006; Podhalańska *et al*., 2010, 2016).

Stratigraphic scheme of the Ordovician

According to the current scheme, the Ordovician is subdivided into three series: Lower, Middle and Upper. These are subdivided further into global stages. Seven global stages have been established: Tremadocian, Floian, Dapingian, Darriwilian, Sandbian, Katian and Hirnantian. The boundaries of most of these are defined by graptolite zones (Cooper *et al*., 2012). The graptolite zones established in the platform area of Poland are correlative with the standard ones. In some cases, they are identified on the basis of other nominative and index taxa (Tab. 1). The ratification of the new chronostratigraphic scheme for the Ordovician does not exclude the use of the former British-based series:

Table 1

Chronostratigraphic subdivision and the standard and regional graptolite zones in the Ordovician.

SERIES	STAGE	BRITISH SERIES	Graptolite zones (Cooper *et al.*, 2012)	East European Craton graptolite zones (in Poland)
UPPER	HIRNANTIAN	ASHGILL	*Normalograptus persculptus*	*Normalograptus persculptus*
			N. extraordinarius	Not distinguished in carbonate facies
	KATIAN		*Dicellograptus anceps*	
			Dic. complanatus	
		CARADOC	*Pleurograptus linearis*	*Climacograptus styloideus*
			Dicranograptus clingani	*Dicranograptus clingani*
	SANDBIAN		*Diplograptus multidens*	*Diplograptus multidens*
			Nemagraptus gracilis	*Nemagraptus gracilis*
MIDDLE	DARRIWILIAN	LLANVIRN	*Hustedograptus teretiusculus*	*Hustedograptus teretiusculus*
			Didymograptus murchisoni	*Didymograptus murchisoni*
			Didymograptus artus	Not distinguished in carbonate facies
		ARENIG	*Expansograptus hirundo*	
	DAPINGIAN		*Isograptus gibberulus*	
LOWER	FLOIAN		*Exp. simulans* *Corymbograptus varicosus* *Tetragraptus phyllograptoides*	*Phyllograptus elongatus* *Phyllograptus densus* *Didymograptus balticus* *Tetragraptus phyllograptoides*
	TREMADOCIAN	TREMADOC	*Hunnegraptus copiosus – Araneograptus murrayi*	Not distinguished
			Adelograptus tenellus	
			Rhabdinopora flabelliformis	*Rhabdinopora flabelliformis*

Tremadocian, Arenigian, Llanvirnian, Caradocian and Ashgillian (Cooper *et al.*, 2012).

Stratigraphic scheme of the Silurian

As the formal standard graptolite scale, the Generalized Graptolite Zonation scheme of Koren *et al*. (1996) with modifications by Melchin *et al*. (2012) is currently used. Biostratigraphic schemes of the Silurian developed for the successions in the platform area of Poland (Teller, 1969; Urbanek and Teller, 1997), modified by Porębska *et al*. (2004) and Podhalańska *et al*. (2010) and recently updated, are close to the standard stratigraphic schemes (Tab. 2).

The stratigraphy of the majority of Silurian sections in Poland was based on the stratigraphic scheme of Tomczykowa (1988) and Tomczyk (1990). This scheme was used for all borehole sections, analysed at the Polish Geological Institute in the second half of the 20th century, and for most oil compa-

Table 2

Chronostratigraphic subdivision and the standard and regional graptolite zones in the Silurian.

SERIES	STAGE	Graptolite zones (Melchin *et al*., 2012)	Graptolite biozones (EEC) (Teller, 1969; Urbanek and Teller, 1997; Porębska *et al*., 2004), changed
PRIDOLI		*Monograptus transgrediens*	*Monograptus transgrediens*
		M. bouceki	*M. perneri*
			M. bouceki
		Neocolonograptus lochkovensis *N. branikensis*	*M. samsonowiczi*
			M. chelmensis
			Neocolonograptus lochkovensis
		N. ultimus	*N. ultimus*
		N. parultimus	*N. parultimus*
LUDLOW	LUDFORDIAN	*Formosograptus formosus*	*M. spineus*
			Monograptus protospineus
			M. acer
			Pseudomonocl. latilobus /M. balticus
		Neocucullograptus kozlowskii	*Neocucullograptus kozlowskii*
		Polonograptus podoliensis	*Neoc. inexpectatus*
			Neolobograptus auriculatus
		Bohemograptus	*Bohemograptus cornutus*
			B. praecornutus
		Saetograptus leintwardinensis	*Saetograptus leintwardinensis*
	GORSTIAN	*Lobograptus scanicus*	*Cucullograptus hemiaversus*
			Lobograptus invertus
			L. scanicus
		Neodiversograptus nilssoni	*L. progenitor*
			Neodiversograptus nilssoni
WENLOCK	HOMERIAN	*Colonograptus ludensis*	*Colonograptus ludensis*
		C. deubeli	*C. deubeli*
		C. praedeubeli	*C. praedeubeli*
		Gothograptus nassa	*Gothograptus nassa*
		Pristiograptus parvus	*Pristiograptus parvus*
		Cyrtograptus lundgreni	*Cyrtograptus lundgreni*
	SHEINWOODIAN	*C. perneri*	*C. perneri*
		C. rigidus	*C. rigidus*
		Monograptus belophorus	*Monograptus belophorus (= M. flexilis)*
		M. riccartonensis	*M. antennularius*
			M. riccartonensis
		Cyrtograptus murchisoni	*Cyrtograptus murchisoni*
		C. centrifugus	*C. centrifugus*
LLANDOVERY	TELYCHIAN	*C. insectus*	*Cyrtograptus lapworthi*
		C. lapworthi	
		Oktavites spiralis	*Oktavites spiralis*
		Monoclimacis crenulata– *Monocl. griestoniensis*	*Monoclimacis crenulata–* *Monocl. griestoniensis*
		Monograptus crispus	*Monograptus crispus*
		Spirograptus turriculatus	*Spirograptus turriculatus*
		Spirograptus guerichi	
	AERONIAN	*Stimulograptus sedgwickii*	*Stimulograptus sedgwickii*
		Lituigraptus convolutus	*Lituigraptus convolutus*
		Monograptus argenteus	*Monograptus gregarius*: *Monograptus argenteus*
		Demirastrites pectinatus– *Demirastrites triangulatus*	*Diplograptus magnus* *Demirastrites triangulatus*
	RHUDDANIAN	*Coronograptus cyphus*	*Coronograptus cyphus*
		Cystograptus vesiculosus	*Cystograptus vesiculosus*
		Parakidograptus acuminatus	*Parakidograptus acuminatus*
		Akidograptus ascensus	*Akidograptus ascensus*

ny boreholes. The scheme was thoroughly reviewed by Szymański and Modliński (2003) and Podhalańska *et al*. (2010). For some sections, the scheme of Teller (1969), Urbanek and Teller (1997) and Porębska *et al*. (2004) was used.

Lower boundary of the Silurian System. The boundary corresponds to the base of the *Akidograptus ascensus* Zone, defined by the first occurrence of the species *Akidograptus ascensus* and *Parakidograptus praematurus* (Melchin *et al*., 2012). In the stratigraphic schemes established in Poland by H. Tomczyk, the lower boundary of the Silurian was placed at the base of either the *Normalograptus persculptus* Zone or the *Akidograptus ascensus* Zone (Tomczykowa, 1988; Tomczyk, 1990). Szymański and Modliński (2003), criticising the Silurian schemes of Tomczykowa and Tomczyk (Tomczykowa, 1988; Tomczyk, 1990), defined the lower boundary of the Silurian at the base of the *Parakidograptus acuminatus* Zone.

Upper boundary of the Silurian System. This boundary is defined by the first occurrence of the species *Monograptus uniformis uniformis* and *Monograptus uniformis angustidens*. In the stratigraphic scheme of Tomczyk (1990) and Tomczykowa (1988), the Silurian-Devonian boundary was drawn at the top of the *angustidens* Zone, which significantly changed the Pridoli range. According to the current scheme, the upper boundary of the Silurian is defined by the top of the *Monograptus transgrediens* Zone (Tab. 2).

Wenlock-Ludlow boundary. The Wenlock-Ludlow boundary (corresponding to the Homerian-Gorstian boundary) is defined by the *Neodiversograptus nilssoni* Zone with its index species and *Saetograptus varians*. In all sections examined stratigraphically by Tomczykowa and Tomczyk (Tomczykowa, 1988; Tomczyk, 1990), the Wenlock-Ludlow boundary was drawn at the base of the *Gothograptus nassa* Zone, i.e., lower in the section, in an interval of an anomaly visible on the GR log, related to an increase in carbonate content. Such a position of the Wenlock-Ludlow boundary and its correlation with an excursion of the GR curve resulted in ambiguous stratigraphic interpretations. In consequence, the base of the Ludlow, defined by the International Stratigraphic Commission on the Silurian has been "raised" in the Polish historical sections by several metres increasing thereby the Wenlock thickness in relation to that determined previously (Szymański and Modliński, 2003). The depth ranges of the Wenlock and Ludlow, with the Ludlow boundary at the base of the *Neodiversograptus nilssoni* Zone, are given in the Central Geological Database (date of access 2019) for most sections e.g., for Lębork IG 1 profile, in papers by Podhalańska (2013, 2015), Podhalańska *et al*. (2016), and in the sections described in this article.

CHRONOSTRATIGRAPHY AND GRAPTOLITE-BASED DATING OF THE LITHOSTRATIGRAPHIC UNITS IN THE BALTIC AREA

The ranges of graptolite zones in the Ordovician of Poland are correlative with the standard zones, although different nominative species for these zones are used in some cases (Tabs 1, 2). The ongoing biostratigraphic studies have supported the applicability of the Silurian graptolite zone-based subdivision in the western part of the East European Craton with only minor modifications, e.g., some zones in the Ludfordian (from *Monograptus ac*er to *Monograptus spineus*) in the Urbanek and Teller (1997) scheme cannot be easily identified. These zones are equivalent to the broader zone of *Formosograptus formosus*, excluding its lowermost part (Tab. 2).

The Ordovician and Silurian are present in all historical boreholes, mostly with partial coring, drilled in the Baltic area, and in new boreholes drilled by exploration companies. The review and analysis of core material in the boreholes from the Baltic Depression have allowed selection of the most representative sections (Fig. 1) with the most nearly complete Ordovician and Silurian graptolite successions.

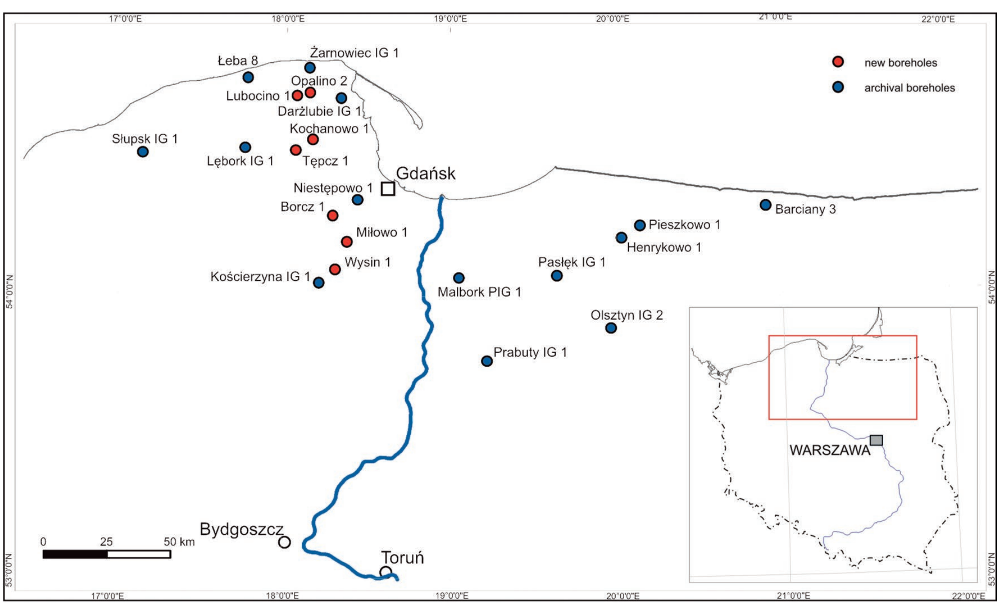


Fig. 1. Location sketch-map of selected boreholes in the Baltic Depression.

The Ordovician

Graptolite biostratigraphy of the Ordovician

Over most areas, a stratigraphic gap spans the Tremadocian (and locally the Floian of the Lower Ordovician) and the Cambrian is overlain by Ordovician limestones, marls and mudstones, up to 80 m in thickness. In the Kościerzyna IG 1 borehole, the thickness of this succession is 31 m, in the Gdańsk IG 1 borehole it is 50 m, in the Darżlubie IG 1 borehole it is 70 m, and in the central part of the Baltic Depression, in the Prabuty IG 1 borehole it is 56.6 m and increases towards the depocentre in the central part of the present-day Baltic Sea. The percentage of clastic material in the strata increases towards the southwest (Modliński, 2010; Modliński and Podhalańska, 2010).

Abundant and diverse graptolites have allowed the distinction of several graptolite zones in the Ordovician. These zones document the presence of the Floian, Dapingian, Darriwilian, Sandbian and Katian. Among the most nearly complete Ordovician sections in this part of the basin is the newly drilled Borcz 1 borehole (Tab. 3), in which the graptolite zones documenting the Floian through Katian have been found, as well as the Miłowo 1, Kochanowo 1 and Żarnowiec IG 1 boreholes (Tab. 4). Below, there is the fragmentary Furongian in these sections, represented by a thin layer of black bituminous clays

Table 3

Ordovician and Silurian graptolite zones and chronostratigraphy in the Borcz 1 borehole (driller's depths are given in figures), interpreted in non-cored intervals.

Series	Stage	Graptolite zones	Top from (m)	Base to (m)	Lithostratigraphy
Pridoli					
Ludlow	Ludfordian				Kociewie Fm
	Gorstian		?	3454.0	
		Lobograptus progenitor-Neodiversograptus nilssoni	3405.0	3454.0	Pelplin Fm
Wenlock			3454.0	?3537.3	
	Homerian	*Colonograptus ludensis-Colonograptus praedeubeli*	3454.0	3502.0	
		Gothograptus nassa	3502.0	3507.0	
		Pristiograptus dubius-Monograptus flemingi	3507.0	3512.1	
		Cyrtograptus lundgreni with *Testograptus testis*	3512.1	?3537.3	
	Sheinwoodian		?3537.3	3633.0	
		Cyrtograptus perneri-Cyrtograptus rigidus	?3537.3	3594.0	
		Monograptus flexilis	3594.0	3615.0	
		Monograptus riccartonensis	3615.0	3624.0	
		Cyrtograptus murchisoni-Cyrtograptus centrifugus	3624.0	3633.0	
Llandovery	Telychian	?*Cyrtograptus lapworthi* *Octavites spiralis, Monoclimacis crenulata*	3633.0	?3658.0	Pasłęk Fm
	Aeronian	*Stimulograptus sedgwickii. Lituigraptus convolutus Demirastrites triangulatus*	?3658.0	3682.4	
	Rhuddanian	*Coronograptus cyphus - ?Akidograptus ascensus*	3682.4	3690.3	Jantar Fm
Upper Ordovician	Hirnantian–Katian (Ashgillian)	Marls and limestones without graptolites	3690.3	3697.3	Prabuty Fm
	Katian–Sandbian–Darriwilian	*Climacograptus styloideus. Dicranograptus clingani. Diplograptus multidens. Nemagraptus gracilis. Hustedograptus teretiusculus*	3697.3	3712.70	Sasino Fm
	Dapingian	Limestones	3712.7	3722.5	Kopalino Fm
	Floian	*Phyllograptus elongatus – Tetragraptus phyllograptoides*	3722.5	3725.0	Słuchowo Fm

Table 4

Ordovician and Silurian graptolite zones and chronostratigraphy in the Żarnowiec IG 1 borehole.

System	Series	Stage	Graptolite zones	Top from (m)	Base to (m)	Lithostratigraphy
Silurian	Pridoli		Lack of graptolites	829.2	1315.0	Puck Fm
	Ludlow	Ludfordian	*Monograptus balticus–Formosograptus formosus*	1315.0	1851.5	
				1851.5	2045.0	Kociewie Fm
			Bohemograptus cornutus–Neocucullograptus kozlowskii	?2045.0	2145.0	
			?	2145.0	2201.4	
			Bohemograptus praecornutus	2201.4	2209.0	Pelplin Fm
				2209.0	2240.0	
			?*Bohemograptus praecornutus*	2240.0	2247.0	
		Ludfordian–Gorstian	?*Lobograptus scanicus*–?*Saetograptus leintwardinensis*	2247.0	2325.0	
		Gorstian	*Lobograptus scanicus*	2325.0	2331.8	
			?*Lobograptus progenitor* *Lobograptus scanicus*	2331.5	2400.4	
			Lobograptus progenitor	2400.4	2403.0	
			?*Neodiversograptus nilssoni*	2403.0	2408.4	
			Neodiversograptus nilssoni	2408.0	2414.4	
			?	2414.4	2420.0	
	Wenlock	Homerian	?*Colonograptus deubeli, Colonograptus praedeubeli, Colonograptus ludensi*s	?2420.0	?2450.0	
			Gothograptus nassa	2450.0	2455.0	
			Cyrtograptus lundgreni (with *T. testis*)	2455.0	2462.0	
			Cyrtograptus lundgreni (with *T. testis*)	2462.0	2491.0	
			Cyrtograptus lundgreni (Cyrtograptus lundgreni with *Testograptus testis)*	?2491.0	2508.0	
		Sheinwoodian	Cyrtograptus rigidus–Cyrtograptus perneri	2508.0	2543.0	
			Monograptus antennularius–M. flexilis	2543.0	2558.0	
			Monograptus riccartonensis	?2558.0	2569.0	
			Cyrtograptus murchisoni	2569.0	2582.0	
	Llandovery	Telychian	?*Cyrtograptus lapworthi*	2582.0	2584.0	Pasłęk Fm
			Oktavites spiralis	2584.0	2591.0	
			Monoclimacis griestoniensis–Monoclimacis crenulata	2591.0	2618.0	
			Monograptus crispus	2618.0	2627.0	
			Spirograptus turriculatus	2627.0	2632.0	
		Aeronian	*Stimulograptus sedgwickii*	2632.0	2637.5	
			Lituigraptus convolutus	2637.5	2638.0	
			Demirastrites triangulatus	2638.0	2640.0	Jantar Fm
		Rhuddanian	?*Akidograptus ascensus–C. cyphus*	2640.0	2645.0	
Ordovician	Upper Ashgillian	Hirnantian	Lack of graptolites	2645.0	2655.3	Prabuty Fm
	Caradocian	Katian	*Normalograptus styloideus*	2655.3	2659.9	Sasino Fm
			Dicranograptus clingani	2659.9	2669.0	
		Sandbian	*Diplograptus multidens*	2669.0	2683.5	
			Nemagraptus gracilis	2683.5	2687.5	
	Llanvirnian	Darriwi–llian	*Hustedograptus teretiusculus*	2687.5	2689.2	

of the Piaśnica Formation. The Tremadocian, like the uppermost Cambrian, is limited to a narrow area of the Baltic Sea; most of these deposits were affected by pre-Arenigian erosion (Modliński, 1973, 1982).

Towards the east of the area and thus towards the proximal parts of the Baltic Basin, the Ordovician deposits are represented by limestones or marls with a smaller proportion of shales with graptolites (Modliński, 2010; Modliński and Podhalańska, 2010). They contain numerous stratigraphic gaps and their biostratigraphic succession becomes less nearly complete. In the Prabuty IG 1 borehole (Tab. 5), located in the borderland of the western and eastern parts of the Baltic Depression, the presence of the Sandbian and lower Katian (Caradocian) is demonstrated by graptolites of the *gracilis* to *styloideus* zones, but in the boreholes, located to the east of the area, the graptolitic facies is replaced in the Caradocian by carbonates containing a benthic fauna.

Dating of the Ordovician lithostratigraphic units

In the study area, the Ordovician is represented by the Słuchowo Formation, Kopalino Formation, Sasino Formation and Prabuty Formation (Modliński and Szymański, 1997). Locally, in the northern part of the Baltic area below the Słuchowo Formation, a very thin bituminous shale of the upper Furongian–lowermost Tremadocian Piaśnica Formation is documented. The updated lithostratigraphic correlation chart of the Ordovician and Silurian succession between the Baltic, Podlasie and Lublin region is presented by Porębski and Podhalańska (2019) in Figure 2.

One of the goals of the research was the biostratigraphic dating of lithostratigraphic formations and members using graptolites. The results for selected representative sections in the Baltic area are presented in Figures 3, 4 and Table 5.

The oldest Ordovician graptolite-dated deposits in the western part of the Baltic Depression are black bituminous shales of the Słuchowo Formation. This usually includes four graptolite zones, from the bottom: *Tetragraptus phyllograptoides*, *Didymograptus balticus*, *Phyllograptus densus* and *Phyllograptus angustifolius elongatus*. They correspond fully to the ranges of the standard graptolite zones from *Tetragraptus phyllograptoides* to *Expansograptus simulans*, proving the Floian (early Arenigian) age of the deposits (Tab. 1). The presence of these zones was shown in all historical boreholes and in the new ones: Lubocino 1, Kochanowo 1, Wysin 1 and Miłowo 1 (Podhalańska, 2017). The base of the formation is dated by the lower boundary of the *phyllograptoides* or *balticus* zones and the top by the upper boundary of the *angustifolius elongatus* Zone (the standard *simulans* Zone). Thus, the Słuchowo Formation spans here the Floian and probably the lowermost Dapingian (Arenigian).

Above the Słuchowo Formation is the Kopalino Formation, represented by marly limestones with abundant bioclasts and minor organodetritic limestones. A trilobite and conodont assemblage identified in these deposits shows the presence of the Dapingian (upper Arenigian) and the lower part of the Darriwilian (Llanvirnian).

The Late Ordovician transgression, advancing from the west, and the sedimentation of graptolitic facies (Sasino Formation) with numerous graptolites (Fig. 5) started at the earliest during the Darriwilian (Llanvirnian) in the *Hustedograptus teretiusculus* Zone in the Wysin 1 (Fig. 3) and Lubocino 1 boreholes (Fig. 4) and even in the *Didymograptus murchisoni* Zone in the Kościerzyna IG 1 borehole (Modliński and Szymański, 1997). Sedimentation of the “graptolitic shale” facies continued throughout the Caradocian (Sandbian and early Katian). The following zones and their ranges have been documented: *N. gracilis*, *D. multidens* (= *D. foliaceus*), *D. clingani* and *Climacograptus (Normalograptus) styloideus* (a regional equivalent to the standard Zone of *Pleurograptus linearis*). The Darriwilian and Sandbian (Llanvirnian and lower Caradocian) are commonly represented by condensed sections. The onset of the Late Ordovician transgression is manifested by a sedimentary discontinuity surface with iron ooids and phosphatisation. The condensation characteristic of the bottom part of the Sasino Formation and the mass appearance of graptolites are manifestations of marine inundation and mark a parasequence boundary in the sedimentary record in the Ordovician Baltic Basin (Podhalańska, 1980, 2009).

The *Climacograptus styloideus* Zone is the uppermost Ordovician graptolite zone in most boreholes drilled on the East European Craton of Poland, dating the top of the Sasino Formation in this area. The upper Hirnantian *Glyptograptus persculptus* Zone can be distinguished at the top of the Ordovician, above the Prabuty Formation, in only some boreholes of the Łeba Elevation and there is sedimentary continuity into the Silurian deposits in some of them (Podhalańska, 2009). In the Ashgillian Prabuty Formation**,** graptolites are absent. The stratigraphy of the upper Katian and Hirnantian (Ashgillian) is based on the benthic faunas of trilobites and brachiopods.

The Silurian

In most boreholes in the western part of the East European Craton, there is a continuous Silurian section documented by graptolite zones. The Silurian commonly overlies disconformably the Upper Ordovician Prabuty Formation (Hirnantian); the Ordovician/Silurian transition is conformable only locally. The Silurian is overlain by Permian (Rotliegend or Zechstein) deposits. An erosional gap above the Silurian spans the Devonian and Carboniferous and in many areas also part of the Pridoli. The Silurian/Gedinnian (Devonian) contact is found only sporadically in the Baltic Sea. The thickness of the Silurian succession in the individual boreholes varies from several metres in the east of Poland, up to 860.0 m in the Prabuty IG 1 borehole, 2244.4 m in the Lębork IG 1 borehole, and 3340.0 m in the Słupsk IG 1 borehole.

Graptolite biostratigraphy of the Silurian

Graptolites allowed the documentation of all series and stages of the Silurian: Llandovery (comprising the Rhuddanian, Aeronian and Telychian), Wenlock (comprising the Sheinwoodian and Homerian), Ludlow (Gorstian and Ludfordian) and part of the Pridoli, as well as their basin-wide correlation (Fig. 6).

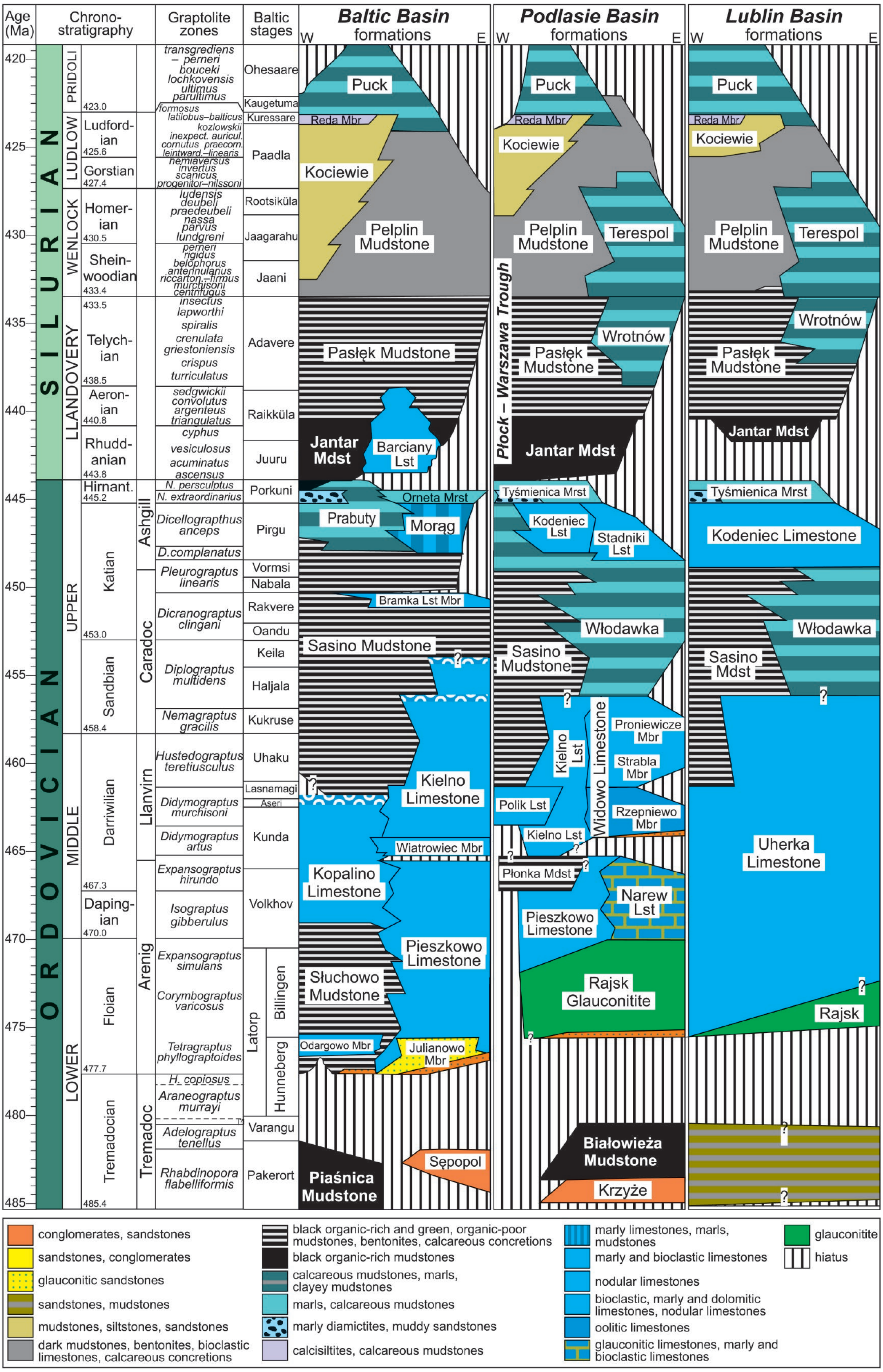


Fig. 2. Lithostratigraphic subdivision of the Ordovician and Silurian succession in the East European Craton (from Porębski and Podhalańska, 2019; data sources are listed in the text); Ordovician–Silurian chronostratigraphy, graptolite zonation and correlation of the Ordovician and Silurian standard stages to the Baltic regional stages after Cooper *et al*. (2012) and Melchin *et al*. (2012). The standard graptolite zonation is modified to include the local zones of Urbanek and Teller (1997) and Porębska *et al*. (2004). Hinant. – Hirnantian, Lst. – limestone; Mdst – mudstone; Mbr – Member.

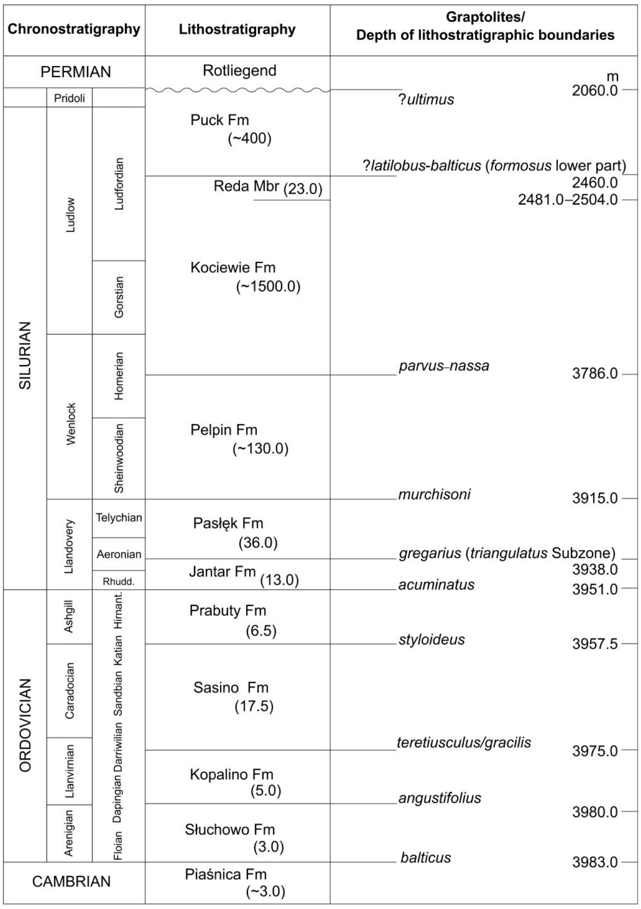


Fig. 3. Dating and depths of boundaries of the Ordovician and Silurian lithostratigraphic units in the Wysin 1 borehole. Thickness (m) in brackets. Hirnant. – Hirnantian, Rhudd. – Rhuddanian

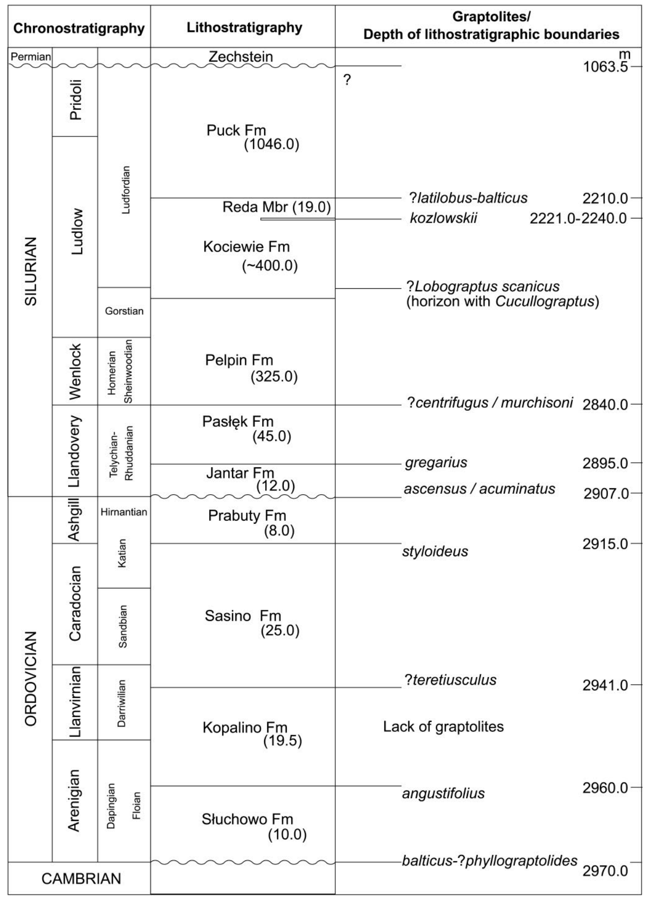


Fig. 4. Dating and depths of boundaries of the Ordovician and Silurian lithostratigraphic units in the Lubocino 1 borehole. Thickness (m) in brackets.

The lowermost graptolite zone in the Silurian of northern Poland is the *Akidograptus ascensus* Zone or the *Parakidograptus acuminatus* Zone. These zones, dating the lowermost Llandovery, Rhuddanian deposits, were found in most sections of the western part of the Baltic Basin. In this area, the marine transgression, which occurred after a period of eustatic relative drop in sea level in the early Hirnantian, started even as early as during the *Normalograptus persculptus* Chron of the late Hirnantian (Tomczyk, 1990; Podhalańska, 2009). In the western part of the Baltic area, the Silurian graptolite record is continuous, except for in the Pridoli deposits, the upper part of which is dated by ostracods, owing to facies changes (e.g., Tomczykowa, 1988). Biostratigraphical studies of the Upper Silurian allowed the determination of the temporal and spatial range of the erosion that affected the Pridoli deposits. An area of minimal erosion was situated in the central part of the Łeba Elevation, and the erosional gap increases towards the east and south from the Żarnowiec IG 1, Darżlubie IG 1 and Lubocino 1 boreholes (Fig. 7). Examples of sections with almost complete biostratigraphic documentation for the Silurian are Lębork IG 1 (Podhalańska, 2015), Żarnowiec IG 1 (Tab. 4), Żarnowiec IG 1a and Kościerzyna IG 1, as well as the new boreholes Opalino 2, Kochanowo 1, Borcz 1 (Tab. 3), Wysin 1 (Fig. 3) and some others. The detailed zonation of the Silurian deposits and the determination of the boundaries of the Silurian series and stages in the individual sections, based on the zones identified, enabled their chronostratigraphic correlation (Fig. 6).

Dating of the Silurian lithostratigraphic units

The following lithostratigraphic units have been distinguished in the Silurian in the western part of the Baltic area: the Jantar Formation, Pasłęk Formation, Pelplin Formation, Kociewie Formation, Reda Member and Puck Formation. Their boundaries are dated by graptolite zones (Figs 3–4 and Tab. 5).

The Jantar Formation**,** previously ranked as the Jantar bituminous shale member, comprises the lower part of the Pasłęk Formation (Modliński *et al*., 2006) and is the lowermost lithological unit of the Llandovery. It spans at least the Rhuddanian, documented by the zones from *Akidograptus ascensus* to *Coronograptus cyphus*. In the western part of the basin in the Lębork IG 1 borehole, the *Glyptograptus persculptus* Zone has been determined (Tomczyk, 1990). In some boreholes, e.g., Kościerzyna IG 1, Darżlubie IG 1, Wysin 1, Lubocino 1, Kochanowo 1 and Opalino 2, the unit ranges upwards to the Aeronian *gregarius* Zone (Figs 3, 4, 8). Intercalations of clay shales, enriched in organic matter, occur also in the eastern part of the basin within the upper Llandovery shallow-water deposits.

Table 5

Ordovician and Silurian graptolite zones and chronostratigraphy in the Prabuty IG 1 borehole.

System	Series/British series	Stage	Graptolite zones	Top from (m)	Base to (m)	Lithostratigraphy
Permian					2499.0	
Silurian	Ludlow	Ludfordian	?*Linograptus* sp., *Pristiograptus* sp.	2499.0	2530.0	Kociewie Fm
			?	2530.0	2590.0	
			?	2590.0	2605.0	
			Neocucullograptus kozlowskii	2605.0	2609.0	
			Fauna *Bohemograptus* sp.	2609.0	2821.0	
			Bohemograptus sp. *Bohemograptus praecornutus*	?2821.0	2830.5	
			Bohemograptus sp. ?*Bohemograptus cornutus*– ?*B. praecornutus*	2830.5	2932.0	
			Cucullograptus aversus	2932.0	2941.5	
			?	2941.5	3040.0	
			Saetograptus leintwardinensis	3040.0	3055.0	Pelplin Fm
		Gorstian	*Cucullograptus hemiaversus*	3055.0	3063.0	
			?*Lobograptus scanicus*	3063.0	3127.0	
			Lobograptus scanicus	3127.0	3153.0	
			?*Lobograptus scanicus*– ?*Neodiversograptus nilssoni*	3153.0	3189.0	
			Neodiversograptus nilssoni	3189.0	?3206.0	
	Wenlock	Homerian	*Colonograptus ludensis*	3206.0	3232.0	
			Gothograptus nassa	3232.0	3235.0	
			Testograptus testis	3235.0	3258.0	
			Testograptus testis, *Cyrtograptus lundgreni*	3238.0	3275.0	
		Shein–woodian	*Cyrtograptus* ? *perneri*, *C. rigidus*	3275.0	3305.2	
			Monograptus flexilis– *M. antennularius*	3305.2	3320.1	
			Monograptus riccartonensis	3320.1	?3324.0	
			Cyrtograptus murchisoni	3324.0	3334.0	Pasłęk Fm
	Llandovery	Telychian	?*Cyrtograptus lapworthi*	3334.0	3335.5	
			Oktavites spiralis	3335.5	3338.0	
			Monoclimacis crenulata	3338.0	3340.3	
			Green mudstones without graptolites	3340.0	3345.0	
			Monoclimacis griestonensis– *Monograptus crispus*	3345.0	3347.0	
			Spirograptus turriculatus	3347.0	3348.0	
		Aeronian	*Stimulograptus sedgwickii*– *D. triangulatus*	3348.0	3348.6	?Jantar Fm
		Rhuddanian	Limestones without graptolites	3348.6	3356.5	Barciany Fm
Ordovician	Upper/Ashgillian	Hirnantian– Upper Katian	Marls without graptolites	3356.5	3367.9	Prabuty Fm
	Caradocian	Lower Katian	*Climacograptus styloideus*	3367.9	3371.0	Sasino Fm
			Dicranograptus clingani	3371.0	3373.5	
		Sandbian	*Diplograptus multidens*	3373.5	3382.4	
		Sandbian	*Nemagraptus gracilis*	3382.4	3383.8	

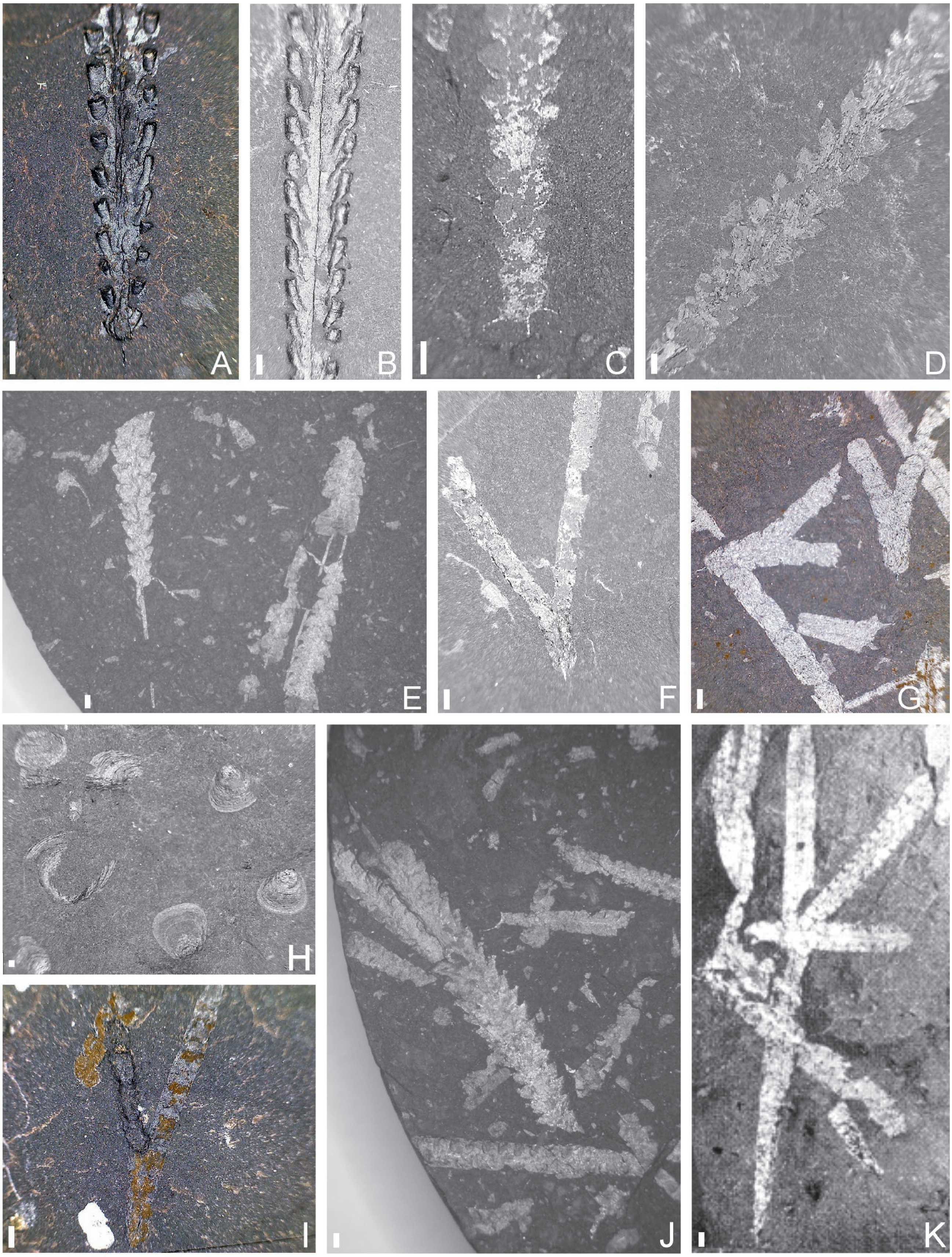


Fig. 5. Index and characteristic graptolites of the Sasino Formation (Ordovician). **A, B.** *Archiclimacograptus* sp. (pers. comm. D. Goldman); A – proximal part, B – distal part, Berejów OU 1, 2557.0 m. **C.** *Diplograptus compactus*, proximal part; Goździk OU 1, 4156.2 m. **D.** *Diplograptus compactus*; Goździk OU 1, 4159.6 m. **E.** *Orthograptus calcaratus*; Kochanowo 1, 3219.4 m. **F.** *Dicranograptus clingani*; Stoczek OU 1, 3085.54 m. **G.** *Dicranograptus clingani*; Goździk OU 1, 4173.0 m. **H.** Brachiopoda *Obolus* sp.; Goździk OU 1, 4173.9 m. **I.** *Dicranograptus clingani*; Berejów OU 1, 2560.2 m. **J.** *Orthograptus calcaratus* and *Climacograptus* cf. *spiniferus*; Kochanowo 1, 3219.4 m. **K.** *Climacograptus styloideus*; Dębki 2, 2597.7 m. Scale bars 1 mm.

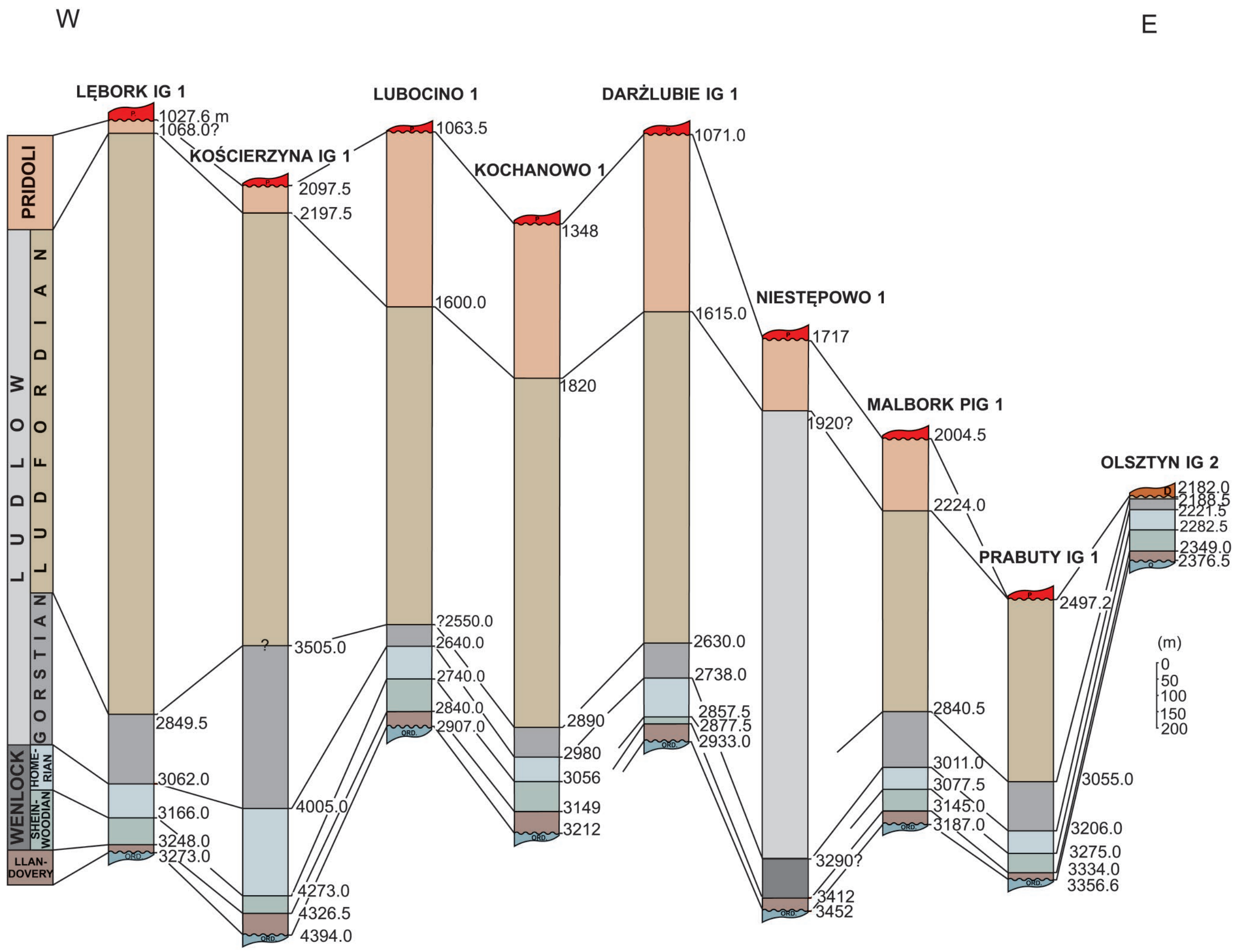


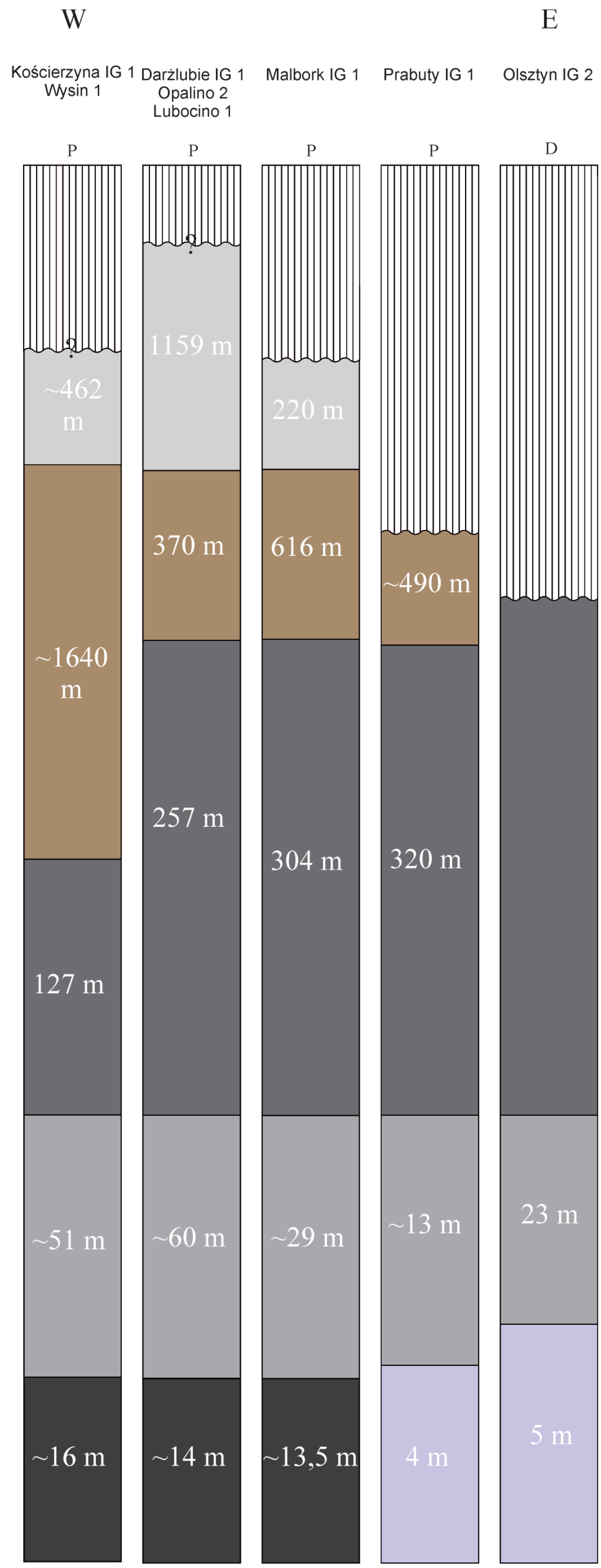
Fig. 6. Chronostratigraphic correlation of Silurian sections in the Baltic Depression (after Podhalańska *et al*., 2010; supplemented).

The Pasłęk Formation encompasses almost all or the upper part of the Aeronian in the study area, ranging from the *Coronograptus gregarius* Zone or even the *L. convolutus* Zone to the base of the *Cyrtograptus centrifugus* (or *C. murchisoni*) Zone of the Telychian. However, owing to numerous graptolite-barren carbonate interbeds, it has not been possible to document all the graptolite zones in the Llandovery. The *Oktavites spiralis* Zone, the upper boundary of which was thought to correspond to the top of the Llandovery (Teller, 1969), represents the upper Telychian graptolite zone. It is found in all sections of the study area. The uppermost zone distinguished in some Llandovery sections of the Baltic part of the basin is the *Cyrtograptus lapworthi* Zone, which is also a graptolite zone in the standard Llandovery scheme (Melchin *et al*., 2012). It has been identified, e.g., in the Borcz 1 (Tab. 3), Żarnowiec IG 1 (Tab. 4) and Prabuty IG 1 (Tab. 5) boreholes, and may correspond to the *Stomatograptus grandis* Zone (or part of it), determined by Tomczyk (1990) as the uppermost graptolite zone of the Llandovery. The Jantar and Pasłęk formations contain an abundant and diverse graptolite assemblage (Fig. 9).

The Pelplin Formation is widespread across the entire Polish part of the Baltic Depression. Its lower boundary corresponds to the base of the Wenlock and is defined by the *Cyrtograptus centrifugus* or *Cyrtograptus murchisoni* zones. The upper boundary (and thus the lower boundary of the Kociewie Formation) is diachronous and placed within various zones of the Wenlock or Ludlow. The stratigraphic range and the upper boundary of the formation change from west to east. For instance, in the Kościerzyna IG 1 borehole and near the Wysin 1 borehole (Fig. 3), its stratigraphic range terminates in the Homerian *Gothograptus nassa* Zone; in the Lubocino 1 borehole, in the Gorstian *Lobograptus scanicus* Zone (Fig. 4); and in the Darżlubie IG 1 and Opalino 2 boreholes, in the ?*Saetograptus leintwardinensis* Zone, corresponding to the lower boundary of the Ludfordian (Fig. 7). The Pelplin Formation contains a diverse graptolite assemblage (Fig. 10).

Kociewie Formation contains thin interlayers and laminae of coarser-grained clastics with an admixture of carbonate material. These rocks commonly are represented by heterolithic mudstones and siltstones. On the slope of the East European Craton, this facies appeared earliest in its western part: in the Llandovery in the Słupsk IG 1 borehole (Jaworowski, 2000, 2007) and in the Homerian *Gothograptus nassa* Zone in the Kościerzyna IG 1 borehole. Towards the NE, the Kociewie Formation appeared latest in the stratigraphic record and its lower boundary

SERIES	STAGE	Graptolite biozones (Melchin *et al.*, 2012)	Graptolite biozones (EEC) (Teller, 1969; Urbanek and Teller, 1997, Porębska *et al.*, 2004) changed
PRIDOLI		*Monograptus transgrediens*	*Monograptus transgrediens*
		Monograptus bouceki	*Monograptus perneri*
			Monograptus bouceki
		Neocolonograptus lochkovensis	*Monograptus samsonowiczi*
			Monograptus chelmensis
		Neocolonograptus branikensis	*Neocolonograptus lochkovensis*
		Neocolonograptus ultimus	*Neocolonograptus ultimus*
		Neocolonograptus parultimus	*Neocolonograptus parultimus*
LUDLOW	LUDFORDIAN	*Formosograptus formosus*	*Monograptus spineus*
			Monograptus protospineus
			Monograptus acer
			Pseudom. latilobus /M. balticus
		Neocucullograptus kozlowskii	*Neocucullograptus kozlowskii*
		Polonograptus podoliensis	*Neocucullograptus inexpectatus*
			Neolobograptus auriculatus
		Bohemograptus	*Bohemograptus cornutus*
			Bohemograptus praecornutus
		Saetograptus leintwardinensis	*Saetograptus leintwardinensis*
	GORSTIAN	*Lobograptus scanicus*	*Cucullograptus hemiaversus*
			Lobograptus invertus
			Lobograptus scanicus
		Neodiversograptus nilssoni	*Lobograptus progenitor*
			Neodiversograptus nilssoni
WENLOCK	HOMERIAN	*Colonograptus ludensis*	*Colonograptus ludensis*
		Colonograptus deubeli	*Colonograptus deubeli*
		Colonograptus praedeubeli	*Colonograptus praedeubeli*
		Gothograptus nassa	*Gothograptus nassa*
		Pristiograptus parvus	*Pristiograptus parvus*
		Cyrtograptus lundgreni	*Cyrtograptus lundgreni*
	SHEINWOODIAN	*Cyrtograptus perneri*	*Cyrtograptus perneri*
		Cyrtograptus rigidus	*Cyrtograptus rigidus*
		Monograptus belophorus	*Monogr. belophorus (= M. flexilis)*
		Monograptus riccartonensis	*Monograptus antennularius*
			Monograptus riccartonensis
		Cyrtograptus murchisoni	*Cyrtograptus murchisoni*
		Cyrtograptus centrifugus	*?Cyrtograptus centrifugus*
LLANDOVERY	TELYCHIAN	*Cyrtograptus insectus*	*Cyrtograptus lapworthi*
		Cyrtograptus lapworthi	
		Oktavites spiralis	*Oktavites spiralis*
		Monoclimacis crenulata–Monoclimacis griestoniensis	*Monoclimacis crenulata–Monocl. griestoniensis*
		Monograptus crispus	*Monograptus crispus*
		Spirograptus turriculatus	*Spirograptus turriculatus*
		Spirograptus guerichi	
	AERONIAN	*Stimulograptus sedgwickii*	*Stimulograptus sedgwickii*
		Lituigraptus convolutus	*Lituigraptus convolutus*
		Monograptus argenteus	*Monograptus gregarius*: *Monograptus argenteus*
		Demirastrites pectinatus–Demirastrites triangulatus	*Diplograptus magnus* *Demirastrites triangulatus*
	RHUDDANIAN	*Coronograptus cyphus*	*Coronograptus cyphus*
		Orthograptus vesiculosus	*Orthograptus vesiculosus*
		Parakidograptus acuminatus	*Parakidograptus acuminatus*
		Akidograptus ascensus	*Akidograptus ascensus*



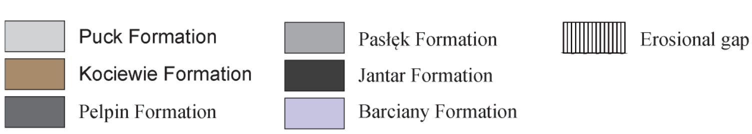


Fig. 7. Dating of boundaries of the Silurian lithostratigraphic units and the ranges of erosion of Pridoli deposits along the Kościerzyna IG 1- Olsztyn IG 2 line. The numbers denote thicknesses in metres; in the Darżlubie IG 1, Opalino 2 and Lubocino 1 composite log, the thicknesses refer to the Darżlubie IG 1 borehole.

corresponds to the Gorstian-Ludfordian boundary or it lies within the Ludfordian.

The top part of the Kociewie Formation is marked presently by the Reda Member, with a thickness ranging from a few to more than 20 m (Porębski and Podhalańska, 2019). This is a widespread facies horizon in the Ludfordian, which is probably a record of global environmental changes (e.g., Kozłowski, 2015) within the stratigraphic interval of *kozlowskii-latilobus-balticus*.

In the eastern part of the Baltic Depression, there is a clear predominance of carbonate and marly facies and the graptolite evidence in the Silurian is increasingly fragmentary. In the uplifted areas of Barciany, Kętrzyn and Morąg, the lower Llandovery is represented by the Barciany Limestone Formation, devoid of graptolites.

CHRONOSTRATIGRAPHY AND DATING OF THE LITHOSTRATIGRAPHIC UNITS IN THE PODLASIE-LUBLIN REGION AND IN THE BASEMENT OF THE PŁOCK-WARSAW TROUGH

In the Early Palaeozoic, these areas were at a similar palaeogeographic position with respect to the Baltic part of the basin, namely they were in the marginal, subsiding part of the East European Craton. Owing to such a location, the regions show similarity in both the lithology and stratigraphy of the Lower Palaeozoic successions. Like the Baltic area, the Podlasie-Lublin region and the area currently located in the basement of the Płock-Warsaw Trough were also part of the same basin in Early Palaeozoic times. These areas extended along the southwestern slope of the Baltica palaeocontinent. The development of the basin on the edge of Baltica constrained the zonal lithofacies pattern, with an increasing proportion of clastic deposits towards the west and of carbonates towards the east (e.g., Modliński, 2010; Modliński and Podhalańska, 2010; Porębski *et al*., 2013). Being a single sedimentary basin in the Palaeozoic, the Podlasie area (Podlasie Depression) is currently separated from the Baltic Depression by the Mazury-Suwałki Elevation and from the Lublin region by the Łuków-Wisznica Elevation, where no Lower Palaeozoic deposits have been found (Fig. 11). Like the Baltic area, the Podlasie-Lublin area also has been explored extensively by means of boreholes. There are several historical deep boreholes, e.g., Polik IG 1 and Bodzanów IG 1, and a few new ones drilled by exploration companies, which reached the basement of the Płock-Warsaw Trough. The most representative boreholes, selected from among the ones analysed, are shown in Figure 11.

The Ordovician

In the Podlasie Depression and on the Lublin slope of the East European Craton, the Ordovician succession disconformably overlies Series 3 deposits (middle Cambrian). During the Middle–Late Ordovician, the sediment deposition rate was not high. The thickness of the Ordovician varies from 25 m in the central area of the Podlasie Depression in the Tłuszcz IG 1 borehole to more than 80 m in

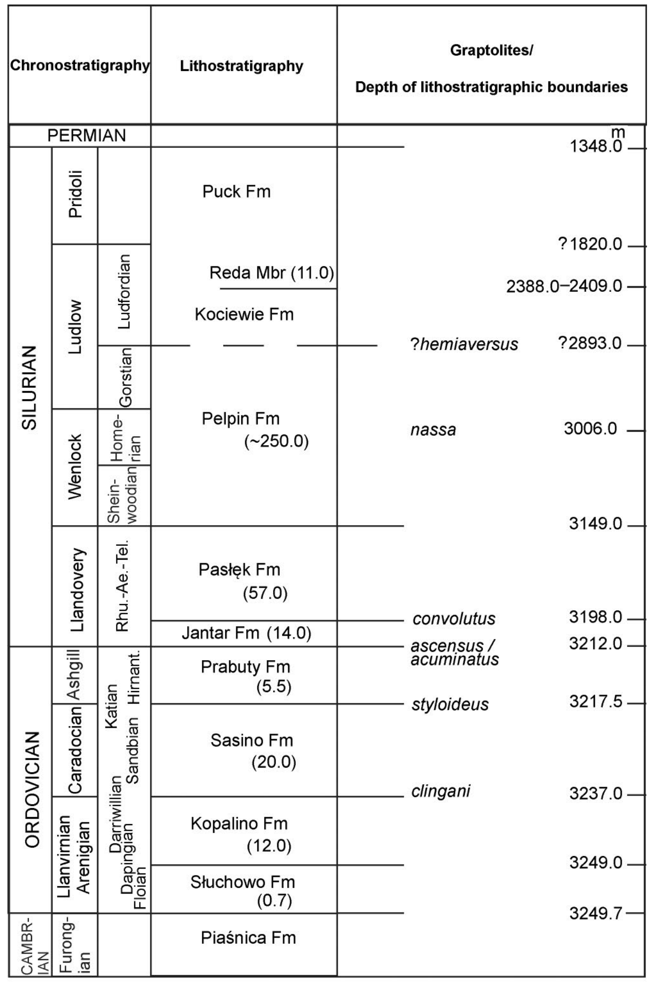


Fig. 8. Dating and depths of boundaries of the Ordovician and Silurian lithostratigraphic units in the Kochanowo 1 borehole. Ae. – Aeronian; Hirnant. – Hirnantian; Rhu. – Rhuddanian; Tel. – Telychian. Thickness (m) in brackets.

the west of the Lublin region. The Polik IG 1 is one of the few boreholes that penetrated the Ordovician deposits in the basement of the Płock-Warsaw Trough. The thickness of the Ordovician is 67 m in this borehole.

Biostratigraphy of the Ordovician

The lowermost graptolite zones in the Ordovician borehole sections of the study areas are the Darriwilian *Hustedograptus teretiusculus* Zone, identified in the Bodzanów IG 1 borehole, and the Sandbian *Diplograptus multidens* Zone from the Polik IG 1 borehole, drilled into the basement of the Płock-Warsaw Trough. The upper graptolite zones, *Dicranograptus clingani* and *Climacograptus styloideus*, demonstrate the presence of the Katian (upper Caradocian). The complete Caradocian succession was documented only in the boreholes in the western part of the study area, e.g., Okuniew IG 1. The sections of the other boreholes, located slightly more to the east and southeast of the area, e.g., Siedliska IG 1 and Busówno IG 1, and of the new ones drilled by exploration companies (Stręczyn OU 1, Wojcieszków 1 and Berejów OU 1 and some others), comprise the upper zones of *Diplograptus multidens*

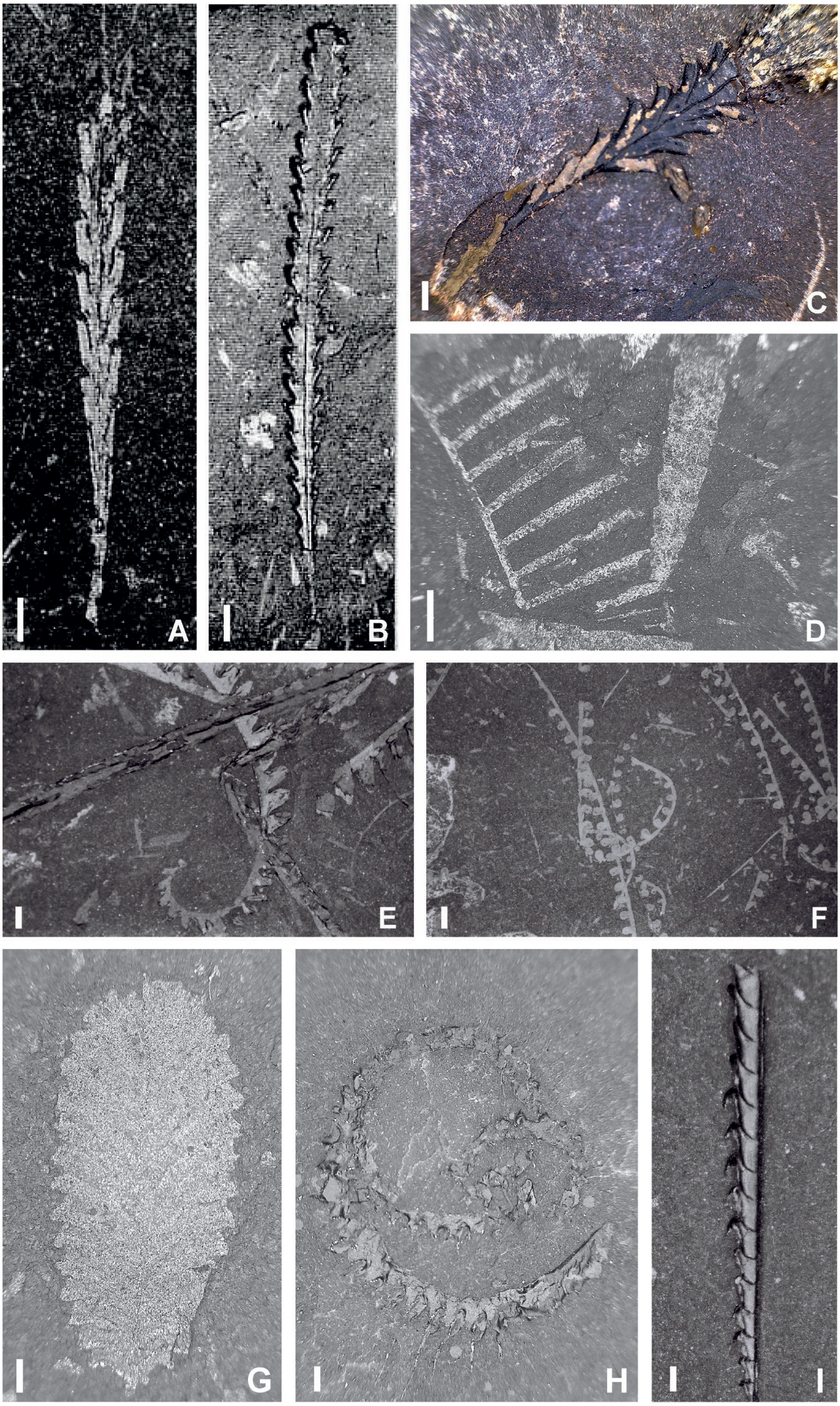


Fig. 9. Index and characteristic graptolites of the Jantar Formation and Pasłęk Formation (Silurian). **A**. *Akidograptus ascensus*; Łeba 8, 2658.7 m. **B.** *Parakidograptus acuminatus*; Kościerzyna IG 1, 4393.0 m (A, B from Podhalańska, 2009). **C.** *Dimorphograptus epilongissimus*; Opalino 2, 2882.0 m. **D.** *Rastrites longispinus*; Kościerzyna IG 1, 4383.0 m. **E.** *Demirastrites triangulatus fimbriatus*; Prabuty IG 1, 3348.0 m. **F.** *Streptograptus loydelli*; Lubocino 1, 2891.0 m. **G.** *Petalolithus minor*; Uścimów OU 1, 3334.0 m. **H.** *Spirograptus turriculatus*; Wysin 1, 3934.2 m. **I.** *Monograptus parapriodon*; Borcz 1, 3643.0 m. Scale bars 1 mm.

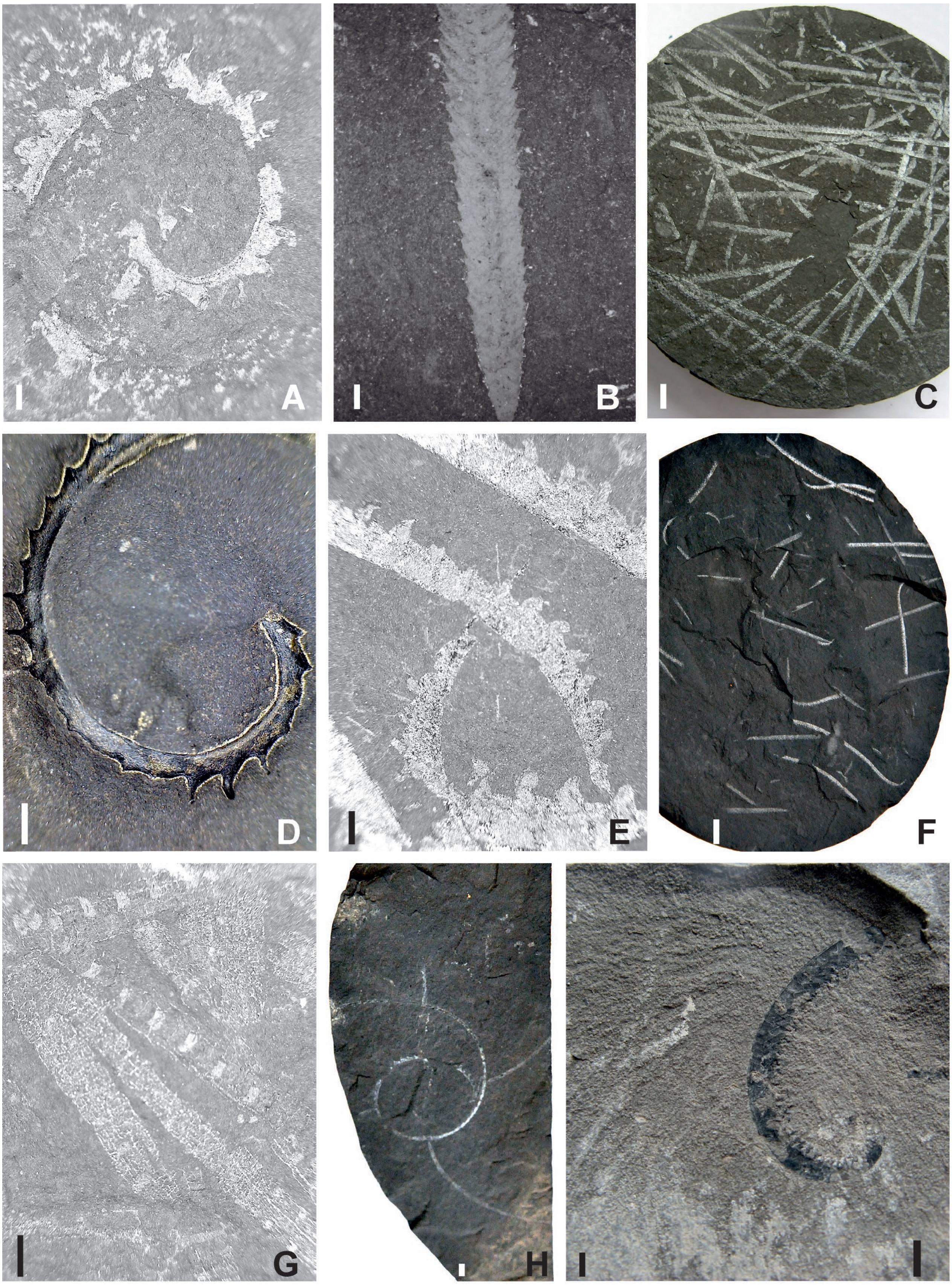


Fig. 10. Index and characteristic graptolites of the Pelplin Formation (Silurian). **A.** *Cyrtograptus* cf. *murchisoni*, proximal part; Syczyn OU 1, 2750.4 m. **B.** *Retiolites geinitzianus*; Opalino 2, 2817.0 m. **C.** *Monograptus riccartonensis;* Borcz 1, 3620.0 m. **D.** *Cyrtograptus* sp., proximal part; Opalino 2, 2819.1 m. **E.** *Monograptus flexilis*; Wojcieszków 1, 2974.3 m. **F.** *Mediograptus flexuosus*; Busówno IG 1, 2867.3 m. **G.** *Gothograptus nassa*; Kochanowo 1, 3003.3 m. **H.** *Cyrtograptus lundgreni*; Tłuszcz IG 1, 1870.5 m. **I.** *Testograptus testis*; Borcz 1, 3529.5 m. Scale bars 1 mm.

or *Dicranograptus clingani* to *Climacograptus styloideus* that indicate the presence of the Katian (upper Caradocian) with numerous graptolites (Fig. 5). The lower Caradocian is represented by carbonate facies. In the Ashgillian, as in the Baltic area, graptolites are absent. Towards the east of the area, the number and ranges of stratigraphic gaps increase in the Ordovician succession.

Dating of the Ordovician lithostratigraphic units

The Floian, Dapingian and Darriwilian (Arenigian and Llanvirnian) stages of the Ordovician succession are composed of limestones and marls, subdivided into a number of formations (overlying the lower Arenigian glauconitites), and the Sandbian and Katian (Caradocian) consist of organic-matter-enriched mudstones and claystones. In the basement of the Płock-Warsaw Trough and in the western part of the Podlasie region, they are represented by the Sasino Formation. In the Lublin region, there is an analogous succession of siliciclastic deposits, identified earlier by Modliński and Szymański (2008) as the Udal Claystone Formation. In the Łopiennik IG 1, Busówno IG 1 and Terebin IG 5 boreholes and in the newly drilled ones (e.g., Goździk OU 1, Berejów OU1 and Syczyn OU 1), the age of

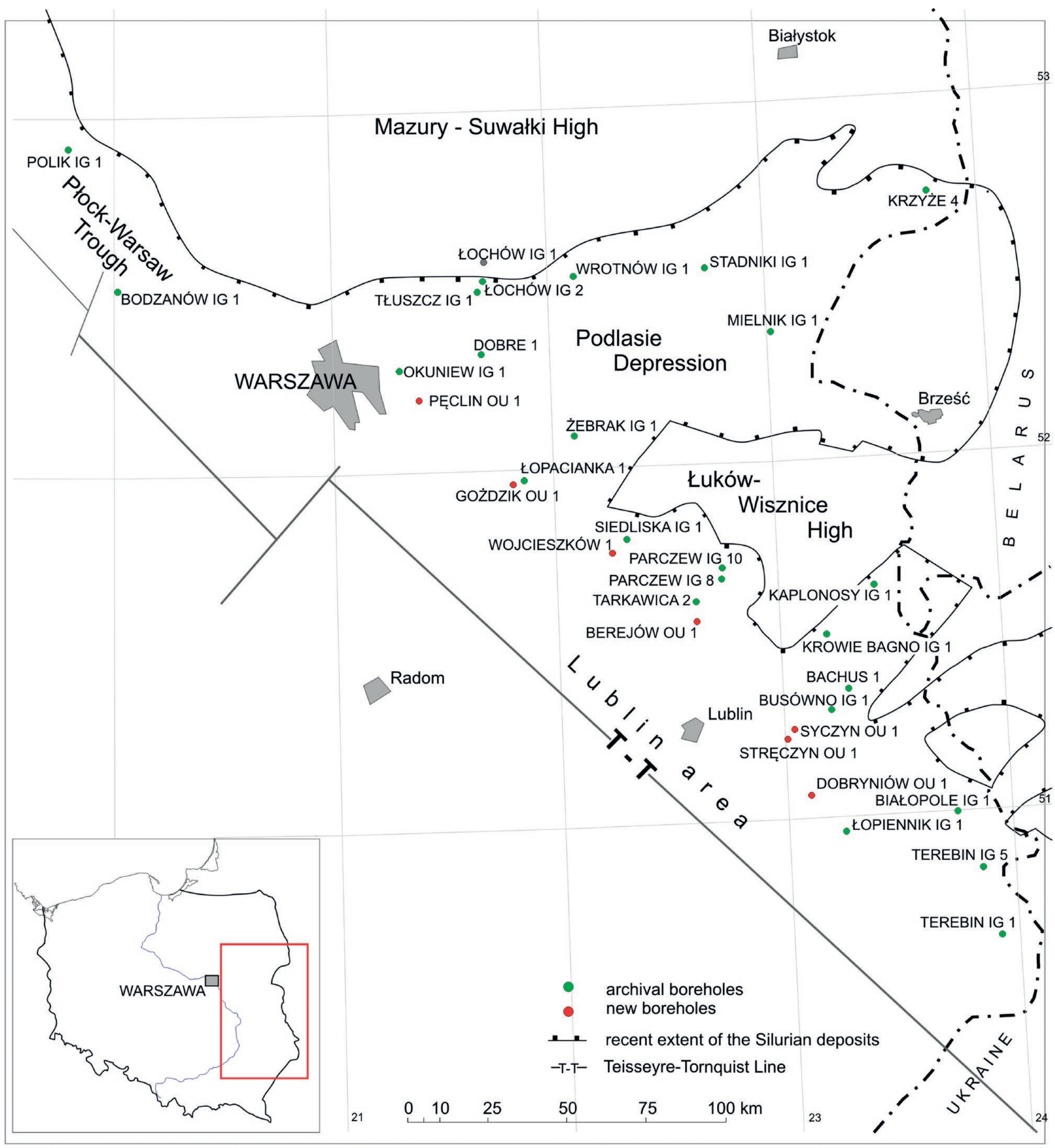


Fig. 11. Location sketch-map of selected boreholes in the Podlasie Depression, Płock-Warsaw Trough and Lublin region (after Podhalańska *et al*., 2010; modified).

these rocks is defined by the *Dicranograptus clingani* and *Climacograptus styloideus* zones. They show the Katian (late Caradocian) age of the sedimentation of these black graptolitic shales. In the Bodzanów IG 1 borehole, another, lower graptolite zone of the Ordovician has been documented: the *Nemagraptus gracilis* Zone. As in the Baltic area, the Late Ordovician marine transgression began earliest in the western part of the area and advanced gradually towards the east and southeast of the Podlasie-Lublin part of the East European Craton. The uppermost Ordovician, as in the Baltic area, is represented by marls and limestones of the Kodeniec and Tyśmienica formations.

The Silurian

The Silurian disconformably overlies the Ordovician carbonate-marly deposits – mostly Hirnantian, locally Katian or Sandbian (Caradocian). Its top surface is covered disconformably by Carboniferous siliciclastic deposits, Permian Rotliegend or Zechstein deposits, and Lower Triassic or Jurassic rocks. Sedimentary continuity of the Silurian marine facies into claystones of the Lower Devonian Sycyna Formation (lower Lochkovian) is observed only in the southwestern part of the Lublin region (Miłaczewski, 1981). The average thickness of the Silurian is smaller than in the Baltic region and ranges from several tens of metres in the east of the area to over 1,300 m in the Okuniew IG 1 and Łopiennik IG 1 boreholes located more to the west of the Podlasie-Lublin regions (Figs 12, 13). The Silurian succession in the Podlasie-Lublin region is represented by a succession of siliciclastic deposits with a variable carbonate content, increasing up the section and towards the east of the area.

Biostratigraphy of the Silurian

All the Silurian series and stages have been identified in the Podlasie-Lublin region and in the basement of the Płock-Warsaw Trough. The most complete sections, as in the Baltic area, are known from the westernmost boreholes.

An important feature of the Silurian succession in this area is strong erosion in its upper and lower part. In the Podlasie area, erosion affected the top part of the Silurian succession. In many boreholes, such as Okuniew IG 1, Tłuszcz IG 1, Wrotnów IG 1 and Stadniki IG 1, the Pridoli and part of the Ludfordian are missing (Fig. 12). The greatest thickness of the Ludfordian, over 1,000 m, was found in the western part of the Podlasie Depression in the Okuniew IG 1 borehole (Fig. 12).

In the eastern and southeastern areas of the Lublin and Podlasie regions, a significant part of the Llandovery section is missing or totally absent. In the northwesternmost part of the area, in the Okuniew IG 1 and Pęclin OU 1 boreholes, the stratigraphic gap at the base of the Llandovery spans at the most one biostratigraphic zone. Towards the southeast, in the Goździk OU 1, Siedliska IG 1, Stręczyn OU 1, Berejów OU 1, Busówno IG 1 and Syczyn OU 1 boreholes, the gap gradually increases and in the Terebin IG 5 borehole the Llandovery is absent (Fig. 14). The Wenlock (Sheinwoodian and Homerian) and lower Ludlow (Gorstian) deposits are the most stable stratigraphic horizon in terms of biostratigraphy and thickness (Figs 12,13).

Dating of the Silurian lithostratigraphic units

The following lithostratigraphic units can be distinguished in the Silurian of the Podlasie-Lublin region: the Jantar Formation, Pasłęk Formation, Wrotnów Formation, Pelplin Formation, Terespol Formation, Kociewie Formation, Puck Formation and the Reda Member (Fig. 2). Most of them are dated by graptolites (Figs 15, 16). The Wrotnów and Terespol formations are the new lithostratigraphic units, established in the eastern part of the Podlasie-Lublin region (Podhalańska *et al*., 2010).

The base of the Jantar Formation or the Pasłęk Formation is diachronous. In the westernmost boreholes, such as Pęclin OU 1, Okuniew IG 1, Goździk OU 1 and Polik IG 1, the lower boundary of the very thin Jantar Formation is dated as Rhuddanian – the *acuminatus* Zone or *vesiculosus* Zone. Towards the southeast, the base of the Llandovery shale formation with a thin layer of the bituminous shales in the lowermost part is dated by the Aeronian zones (e.g., Siedliska IG 1 and Stręczyn OU 1) and Telychian (Berejów OU 1, Syczyn OU 1 and Dobryniów OU 1; Fig. 14). In the boreholes located yet farther east, this formation is replaced in the Telychian by the Wrotnów Marly Claystone Formation (Podhalańska *et al*., 2010).

The age of the Pelplin Formation is defined by an assemblage of Wenlock and Ludlow graptolites. The lower boundary runs at the base of the *Cyrtograptus murchisoni* Zone, while the upper boundary is clearly diachronous and placed within different biostratigraphic zones of the Ludlow. In the basement of the Płock-Warsaw Trough, in the Polik IG 1 borehole, its upper boundary corresponds to the Homerian *G. nassa* Zone (Fig. 15) and in the Podlasie and Lublin regions the upper boundary of the formation runs within different zones of the Ludlow.

The lower boundary of the Kociewie Formation corresponds to the top of the Pelplin Formation. In the Podlasie and Lublin regions, its age was defined as Ludlow (late Gorstian–Ludfordian) and its lower boundary runs within its different zones, e.g., within the *Lobograptus scanicus* Zone in the Wojcieszków 1 borehole (Fig. 16) and within the *Bohemograptus cornutus* Zone in the southeastern part of the area. Research conducted by the author has confirmed the presence of the Reda Member in a similar stratigraphic position as in the Baltic area. The Kociewie Formation is dated by graptolites mainly of the genera *Bohemograptus*, *Saetograptus*, *Lobograptus*, *Monograptus* and *Formosograptus* (Fig. 17).

The Puck Formation spans part of the Pridoli and, in the central area of the Podlasie Depression and the Lublin region, the upper Ludfordian, e.g., in Siedliska IG 1, Wojcieszków 1 and many other boreholes (Podhalańska *et al*., 2010). In the borehole sections of the Lublin region, e.g., Łopiennik IG 1 and Busówno IG 1, there is sedimentary continuity between the Puck Formation and the deposits of the overlying Devonian Sycyna Formation (Miłaczewski,

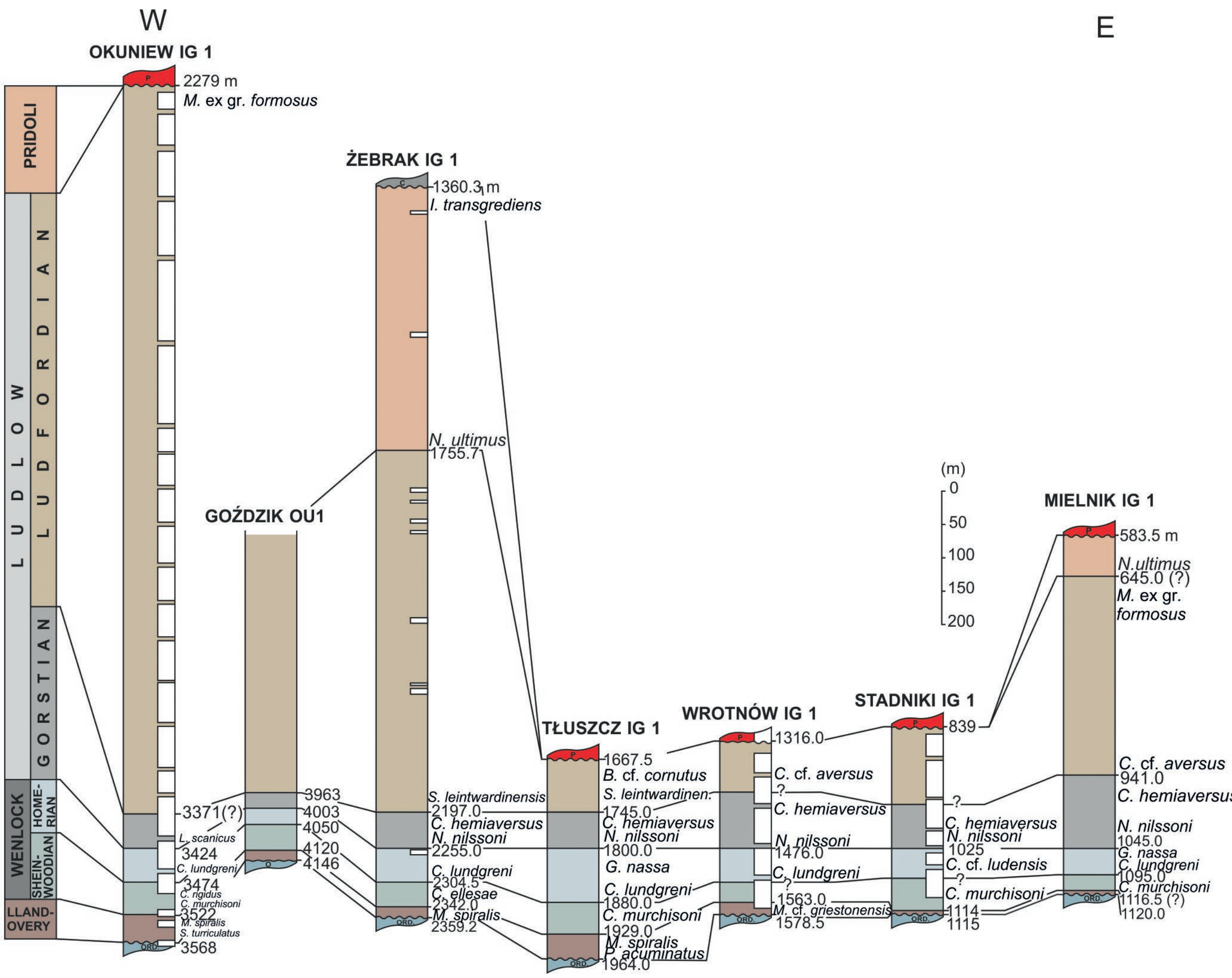


Fig. 12. Chronostratigraphic correlation of Silurian sections in the Podlasie area (after Podhalańska *et al*., 2010; supplemented).

2008). In other boreholes, the upper boundary of the formation is erosional. The erosion reached various zones of the Pridoli and Ludfordian.

CONCLUSIONS

Biostratigraphic studies of the Ordovician and Silurian were performed on selected historical and new boreholes, drilled by exploration companies in the western part of the East European Craton in the Baltic area, in the Podlasie and Lublin regions and in the basement of the Płock-Warsaw Trough.

The studies were based on graptolites that are the basis of the orthostratigraphy of these systems, owing to their abundance in shale facies and rapid evolution. A large accumulation of individuals in the rock indicates anoxic conditions at the sea bottom; these zones are the richest in undecayed organic matter, which is a potential source of hydrocarbons.

In the Ordovician and Silurian systems, biostratigraphic zones were identified, the chronostratigraphy was defined and verified, depths to the chronostratigraphic units in the individual borehole sections were determined, and more detailed ages of lithostratigraphic units were provided. It was particularly important to update the old local stratigraphic schemes of the Silurian, used for many years in Polish geological literature, and to adapt them to the standard schemes.

The succession of graptolite zones, closest to being complete, both in the Ordovician and the Silurian, is observed in the Baltic area. In the western part of the area, eight graptolite zones have been identified, corresponding to the Floian–lower Dapingian (Arenigian) and the upper Darriwilian–lower Katian (Llanvirnian–Caradocian) and represented by two Ordovician shale formations – the Słuchowo Formation and the Sasino Formation. In the basement of the Płock-Warsaw Trough, graptolites document the presence of the entire Caradocian, represented by the graptolitic shale facies. The number and range of stratigraphic gaps in the Ordovician succession increase towards the east and southeast. The stratigraphic range of the Caradocian shale formations decreases in this direction; in the Podlasie and Lublin regions, they comprise only the Katian (upper Caradocian).

The Silurian fine, clastic deposits contain taxonomically diverse and quantitatively variable graptolite assemblages. Graptolites evidenced the Llandovery (comprising the stages of Rhuddanian, Aeronian and Telychian), Wenlock (the stages of Sheinwoodian and Homerian), Ludlow (Gorstian

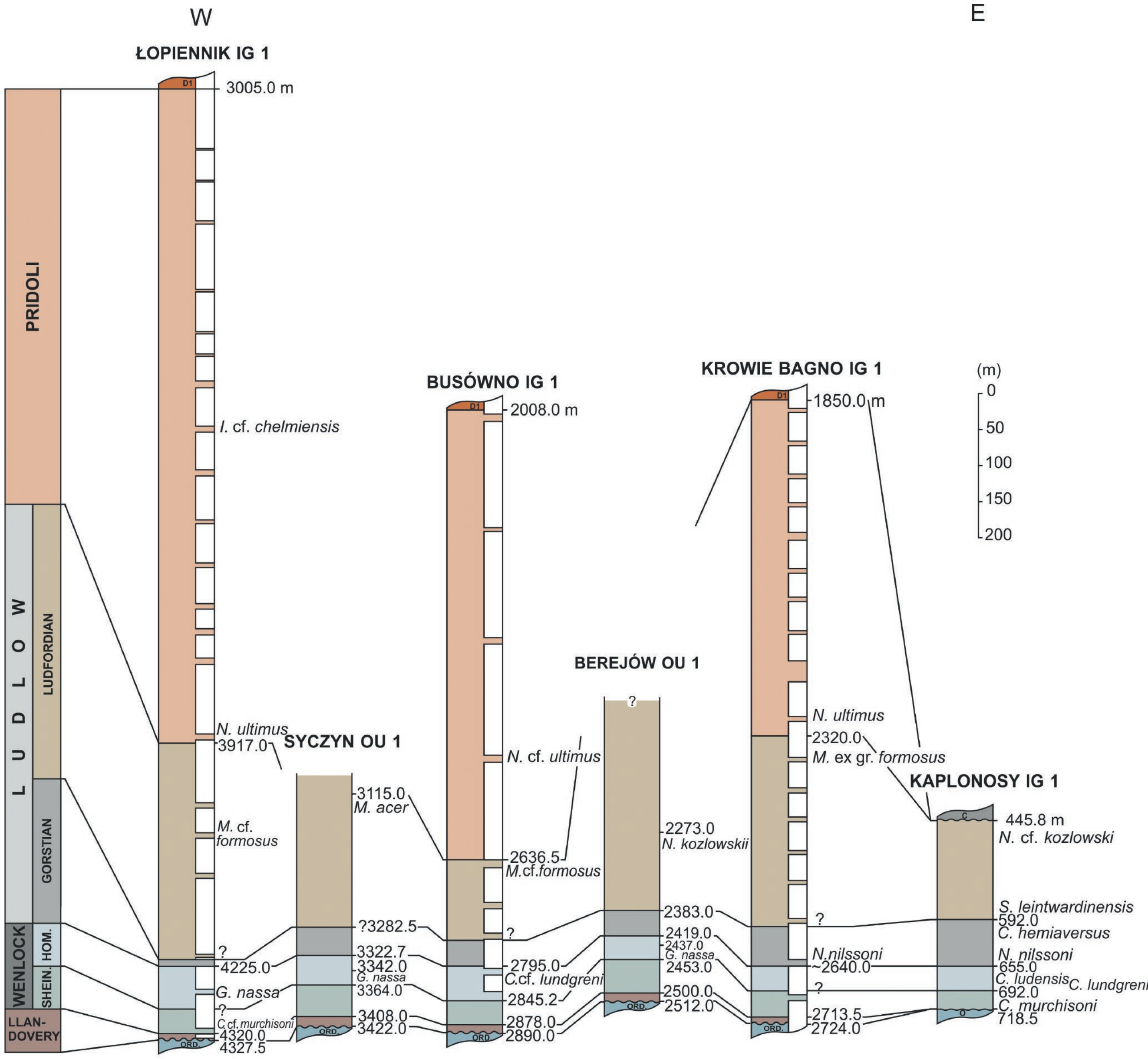


Fig. 13. Chronostratigraphic correlation of Silurian sections in the Lublin region (after Podhalańska *et al.*, 2010; supplemented). Hom. – Homerian; Shein. – Sheinwoodian.

and Ludfordian) and part of the Pridoli. The graptolite-dated Silurian sections closest to being complete are reported from the western, downdropped area of the craton, where no major stratigraphic gaps are found, except for the stratigraphic gap spanning various members of the Pridoli.

Initially, the Silurian sedimentation of claystones and mudstones took place on an open shelf with a limited supply of clastic material and low oxygenation conditions at the bottom of the marine basin. In the early Llandovery, condensed and organic-matter-enriched deposits with abundant graptolite fauna accumulated. Later in the Llandovery and Wenlock, basin oxygenation was variable. The lack of graptolite evidence in some intervals results, for example, from facies changes. An example of this is the Pasłęk Formation, where environmental changes caused a lack of continuity in the Telychian graptolite record. The Pasłęk Formation with a relatively constant stratigraphic range in the Baltic area, the western part of the Podlasie-Lublin region and the Płock-Warsaw Trough, is replaced in the upper Llandovery of the Lublin region towards the SE by marls of the Wrotnów Formation.

The biostratigraphic research provided more details on the temporal and spatial ranges of the lithostratigraphic formations in particular borehole sections. The stratigraphic range of the Jantar Formation in the western part of the area is wider than previously thought and spans not only the Rhuddanian but also part or the whole of the Aeronian. The research results supported the synchronicity of the mid-Ludfordian geophysical positive anomaly (Reda Member) and the Lau (conodont)/Kozlowskii (graptolite) extinction event, which are a probable response to the climate changes and sea-level fluctuations.

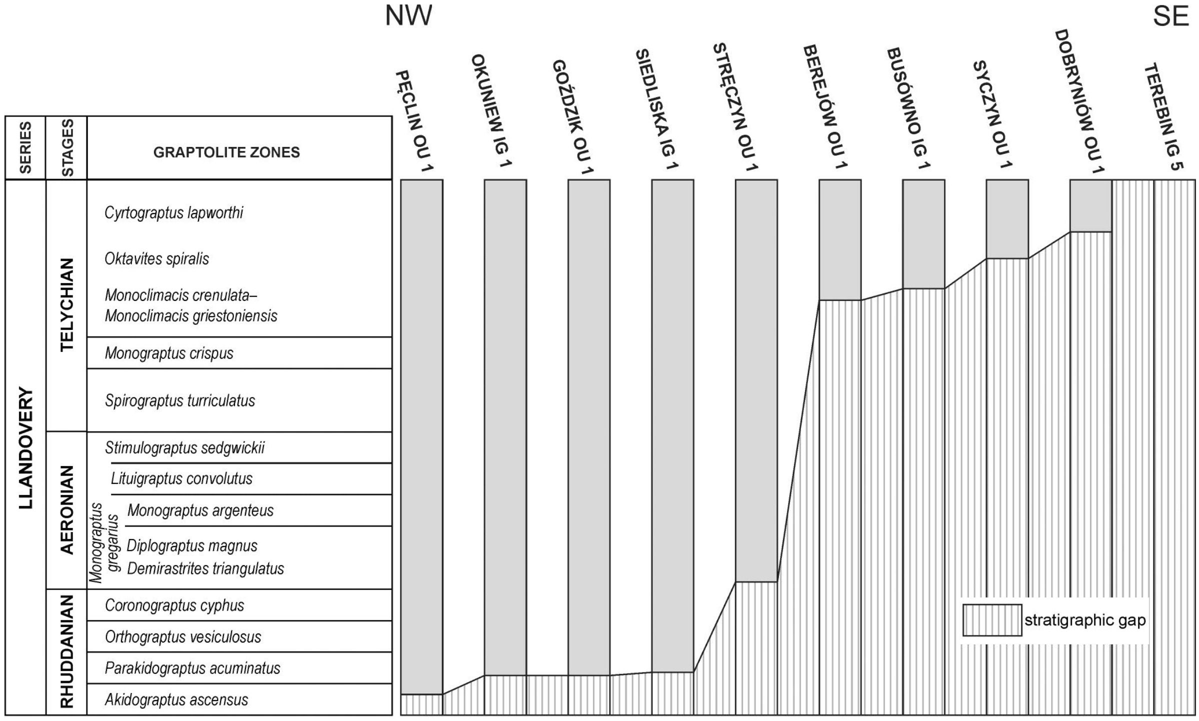


Fig. 14. The range of stratigraphic gap in the Llandovery in the Podlasie-Lublin area.

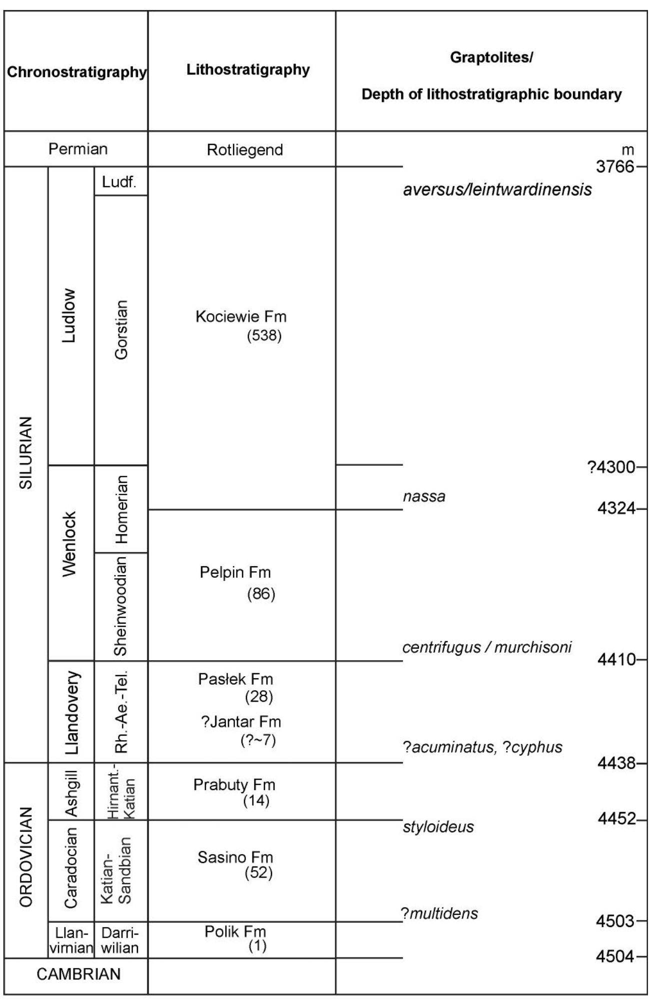


Fig. 15. Dating and depths of boundaries of the Ordovician and Silurian lithostratigraphic units in the Polik IG 1 borehole. Ae. – Aeronian; Hirnant. – Hirnantian; Ludf. – Ludfordian; Tel. – Telychian. Thickness (m) in brackets.

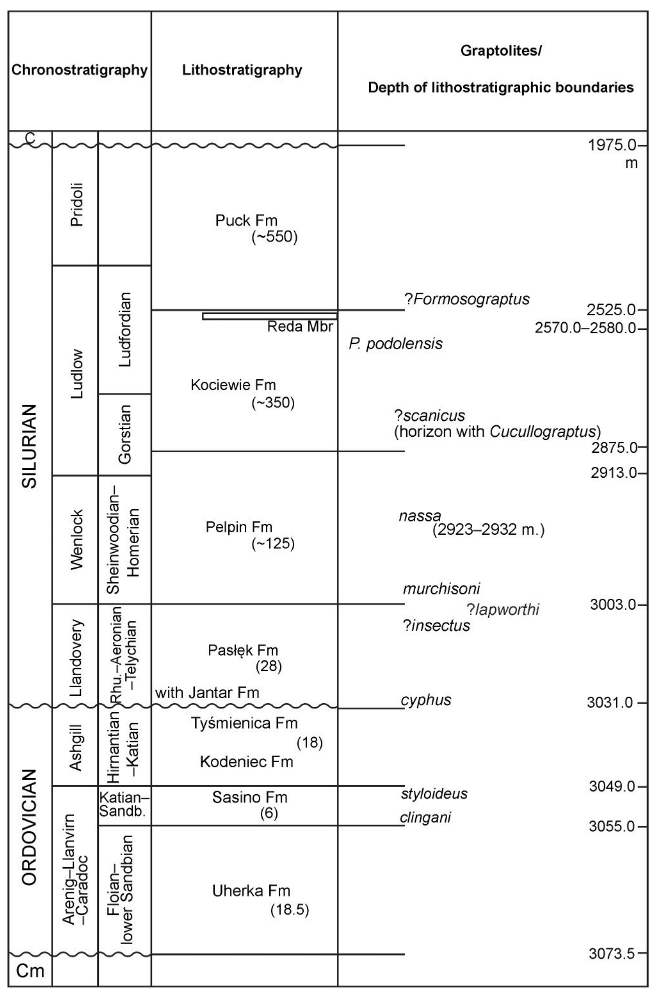


Fig. 16. Dating and depths of boundaries of the Ordovician and Silurian lithostratigraphic units in the Wojcieszków 1 borehole. Rhu. – Rhuddanian; Sandb. – Sandbian. Thickness (m) in brackets.

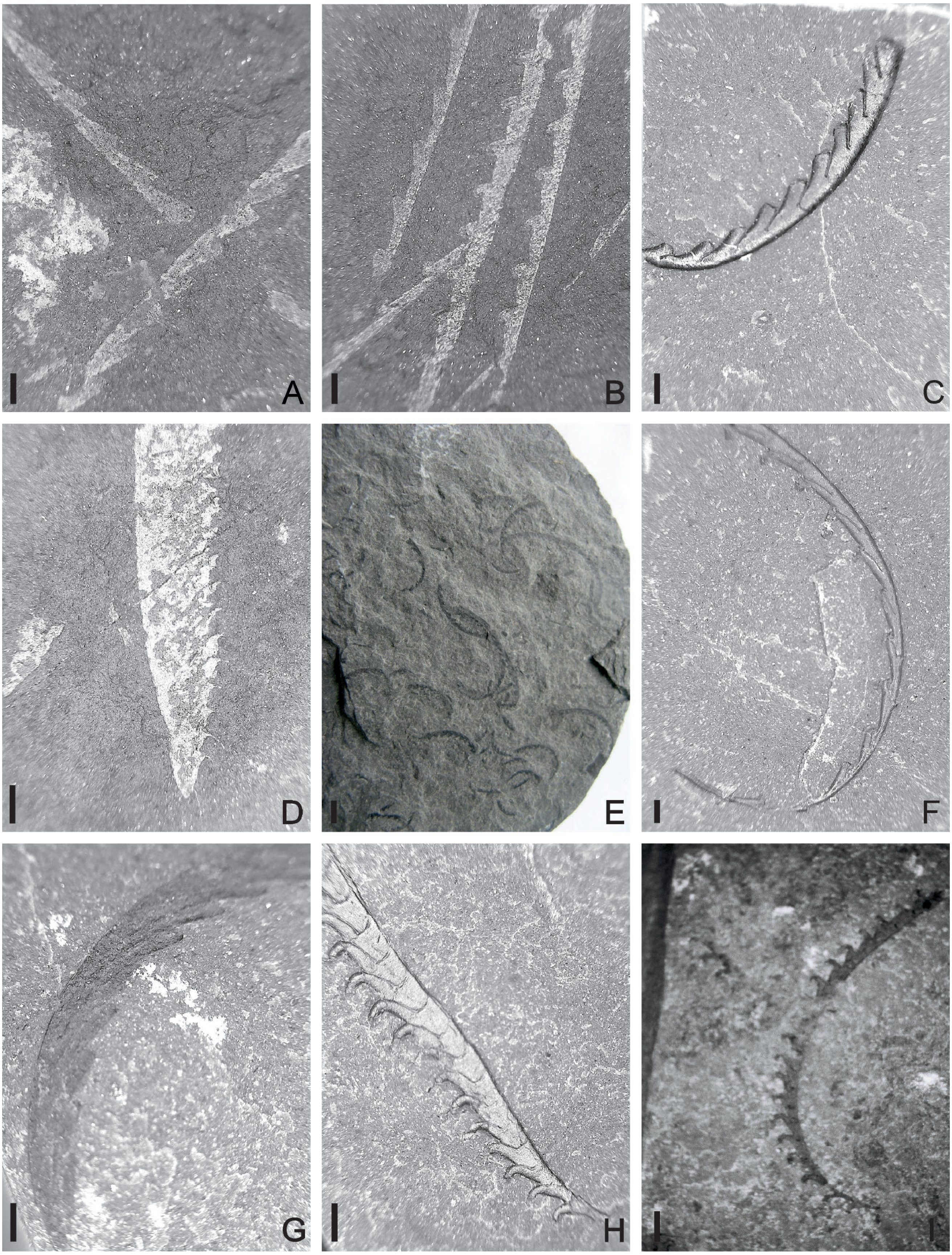


Fig. 17. Index and characteristic graptolites of the Kociewie Formation (Silurian). **A.** *Neodiversograptus nilssoni*, proximal part; Wysin 1, 3740.5 m. **B.** *Lobograptus scanicus*; Wysin 1, 3712.0 m. **C.** *Bohemograptus praecornutus*; Wojcieszków 1, 2586.8 m. **D.** *Saetograptus chimaera*; Uścimów OU 1, 3238.9 m. **E.** *Bohemograptus cornutus*; Borcz 1, 3740.0 m. **F.** *Neocucullograptus kozlowskii*; Wojcieszków 1, 2272. 9 m. **G.** *Polonograptus egregius*; Wojcieszków 1, 2581.4 m. **H.** *Slovinograptus balticus*; Syczyn OU 1, 3128.2 m. **I.** *Formosograptus formosus*; Bytów IG 1, 1899.0 m; from Podhalańska (2013). Scale bars 1 mm.

Sedimentation of coarser-grained siliciclastics of the Kociewie Formation began first in the Llandovery in the distal (currently western) part of the basin in the Słupsk area and next in the Homerian *G. nassa* Zone in the Kościerzyna and Wysin areas. In the basement of the Płock-Warsaw Trough, the coarser clastic material of the silt fraction began to appear in the Late Wenlock, as it did in the western part of the Baltic area. Towards the east and southeast of both these areas, the Silurian silt succession appears progressively later in various Ludfordian graptolite zones.

The biostratigraphic studies of the Upper Silurian allowed determination of the temporal and spatial extent of erosion of the Pridoli deposits. Minimal erosion is observed in the central part of the Łeba Elevation; it increases towards the east and south from the Żarnowiec IG 1, Darżlubie IG 1 and Lubocino 1 boreholes.

In the Podlasie-Lublin region, similar trends in the development of the Silurian basin are observed, except for a large stratigraphic gap spanning the Llandovery and increasing eastwards. The greatest thicknesses of the biostratigraphically demonstrated Pridoli are also reported from this area.

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