Graptolites – stratigraphic tool in the exploration of zones prospective for the occurrence of unconventional hydrocarbon deposits

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A b s t r a c t. In connection with the exploration of zones prospective for the occurrence of unconventional hydrocarbon deposits, numerous studies of source rocks have been conducted in Poland. Stratigraphic examinations are among the basic elements. The main group of fossils occurring in shale successions, being a potential source of hydrocarbons, is graptolites. This paper describes the assemblages of graptolites from Ordovician and Silurian deposits and shows their importance for the stratigraphy of shale complexes. Due to their abundance and rapid evolution, graptolites are an excellent tool for biostratigraphic dating, regional correlations and biozonation of rock successions in terms of the high-resolution sequence stratigraphy. The paper presents the significance of taphonomic research of graptolites to identify zones of increased accumulation of hydrocarbons in rocks. It has been found that graptolites are an equally important instrument, in addition to elevated TOC values or increased gamma ray radiation on well logs, that allows identification of potential source rocks for hydrocarbons, including shale gas.

Keywords: *graptolites, black shale, stratigraphy, Ordovician, Silurian, East European Craton*

The great interest in prospecting for unconventional hydrocarbons deposits both in Poland and all over the world have caused that stratigraphic research, from biostratigraphy to high-resolution sequence stratigraphy, become an important field of the activities of scientific and industrial institutions. The purpose of this paper is to review some issues related to the Ordovician and Silurian stratigraphy and the role of graptolites as a significant tool in the dating, correlation and exploration of the zones prospective for the occurrence of unconventional hydrocarbon deposits in shale successions.

The areas with the greatest potential for prospecting and production of gas in fine-grained detrital rocks, so called shale gas, are connected with the occurrence of the Ordovician and Silurian deposits on the western slope of the East European Craton (EEC), in a zone that stretches out in the form of a diagonal belt from the Middle Pomerania, through Podlasie Region, to the Lublin Region. The Sandbian to lower Katian (the Upper Ordovician) as well as the Llandovery and Wenlock sediments (Silurian) are considered to be the most prospective for the occurrence and production of shale gas. Lately, due to the exploration of the unconventional hydrocarbon deposits, paleontological and stratigraphical studies on the Ordovician and Silurian rocks both in the archive boreholes and in the newly drilled wells, in the Baltic-Podlasie Depression and in the Lublin region have been carried out.

The history of the stratigraphic studies of the Ordovician and Silurian in Poland dates back the early 20th century (Samsonowicz, 1916; Czarnocki, 1919). The aforementioned authors, and then Tomczyk (i.a. 1962, 1968, 1990) as well as Tomczykowa (i.a. 1964), and other scientists dealing with the early Paleozoic issues, created the first stratigraphic schemes for the Ordovician and Silurian deposits in Poland. The studies published by Teller (1964, 1969, 1986), Urbanek (e.g. 1958, 1966), Urbanek and Teller (1997) and numerous articles by Modliński (i.a. 1973, 1982), Modliński et al. (2006), Podhalańska (1980, 2009), Podhalańska and Modliński (2006) have provided a lot of new stratigraphic data and correlation schemes which are currently being used to explore perspective zones for the extraction of unconventional hydrocarbon resources in the Ordovician and Silurian deposits in Poland – both onshore and offshore.

GEOLOGICAL CHARACTERISTICS OF THE ORDOVICIAN AND SILURIAN DEPOSITS AS POTENTIAL SOURCES OF HYDROCARBONS

The Ordovician and Silurian deposits which now occur in Pomerania, the Podlasie Region and the Lublin Region represent the remainder of a much larger sedimentary rock cover that was deposited in the Baltic Basin which was in early Paleozoic a pericratonic sea basin developed on a crystalline Precambrian basement of the Baltica paleocontinent. The Ordovician and Silurian rocks of the East European Craton have been found in the profiles of several dozen boreholes. The boreholes: Lębork IG-1 and Kościerzyna IG-1 and profiles from the Łeba Elevation are the reference sections for the western part of the region. Here, of a special interest is the profile of the Lębork IG-1 borehole where the Silurian rocks, found in the interval 1027.8–3273 m were almost entirely cored and now they are the subject of thorough stratigraphical, sedimentological and geochemical analyses.

In the Ordovician and Silurian, the Baltic Basin stretched out alongside the south-western rims of the East European Craton at low southern latitudes. In Ordovician, it was characterized by a low, almost flat relief, a slight south-western inclination as well as by a little subsidence, which is proved by a small thickness of the deposits, from several dozen to 100 meters maximally. The Ordovician and Silurian deposits of the Baltic Basin are developed in varied facies belts and represent a wide spectrum of environments from the edge of the shelf in the west part, through neritic environments, to littoral ones in the east (Jaanusson, 1976; Nestor & Einasto, 1997; Jaworowski, 2000; Modliński et al., 2006) (Fig. 1). The Ordovician sedimentation started with terrigenous deposits, while the

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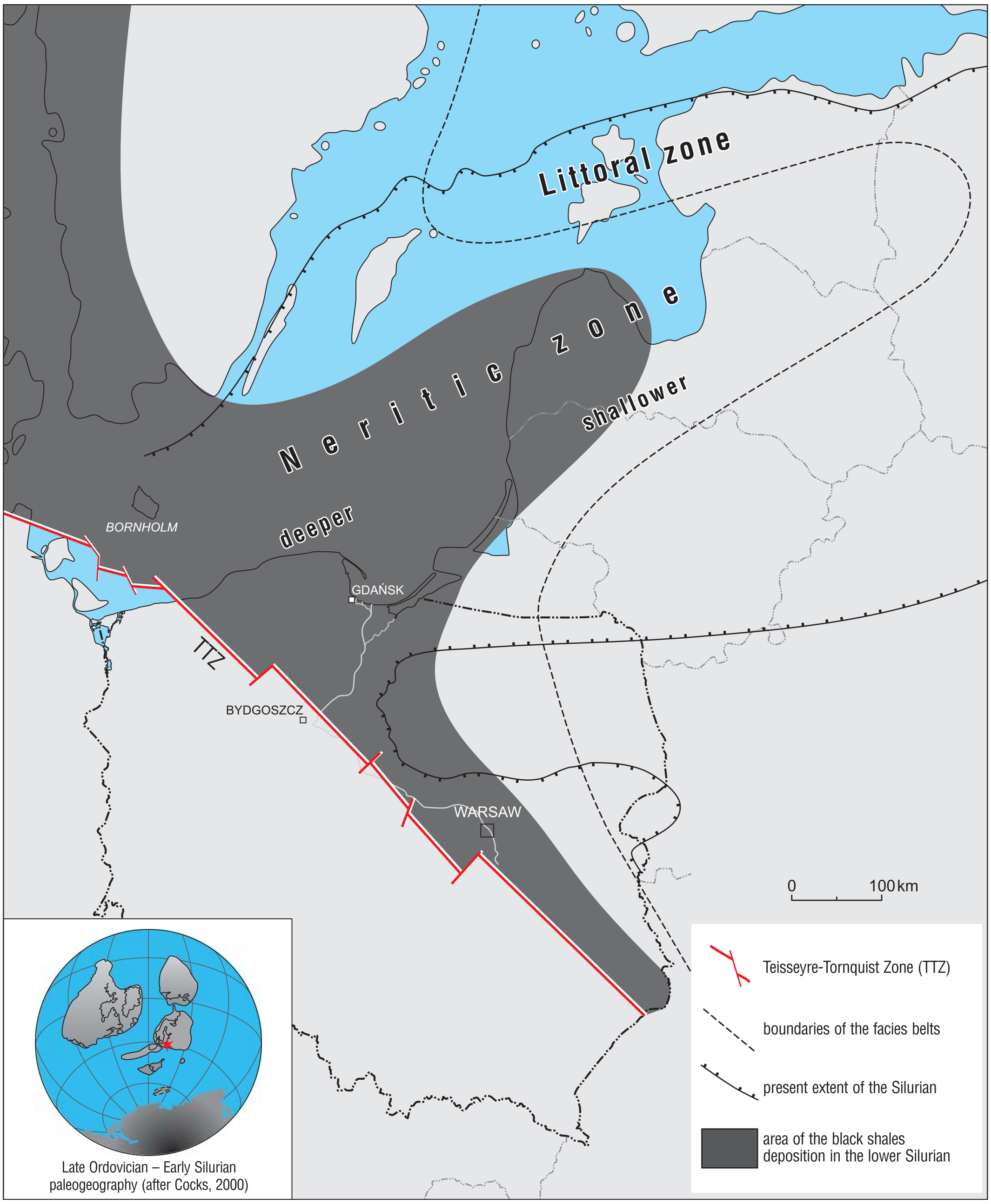

Fig. 1. Distribution of the black shales facies in the Baltic Basin in the lower Silurian. The boundaries of the facies belts after Jaanusson, 1976; Verniers et al., 2008; simplified

upper part of the profile is mainly built of carbonate rocks. Among them, an important correlation level is formed by the Upper Ordovician dark fine-grained siliciclastic sediments, enriched with organic substances that were built in so called Scanian zone of the Baltic Basin which is equivalent to the distal part of the Baltica shelf turning into the slope zone. To the west, the Proterozoic and lower Paleozoic deposits of the Baltic Basin come into contact, along the faults of the Teisseyre-Tornquist Tectonic Zone (TTZ), with the tectonically deformed deposits of the Trans-European Suture Zone (TESZ) and the Paleozoic Platform (Dadlez, 2000). The sedimentation of the Silurian deposits, with the arrangement of the facial zones similar to that of Ordovician, was the result of the process of flexural bending of the western rim of the East European Craton which was caused by the collision of Avalonia and Baltica, and began most probably in late Ordovician (Lazauskiene, 2003; Poprawa, 2006). The early stage of flexural subsidence corresponding to the Llandovery did not cause any significant increase in the deposit thickness, but it is marked by a condensed facies of black bituminous shale with abundant graptolites. Their deposition was also the result of an early Llandovery transgression, conditioned by the climate (Podhalańska, 2009) which was favourable to the development of anaerobic conditions in shelf environments ("hot shales", see Lüning et al., 2000). These factors, in the Polish part of the Baltica's shelf, are marked by the shale of the Jantar Member (Modliński et al., 2006), characterized by the highest content of TOC in the whole Silurian. The accelerated rate of terrigenous material accumulation together with a significant accommodation volume caused by flexural bending of the rim of the East European Craton

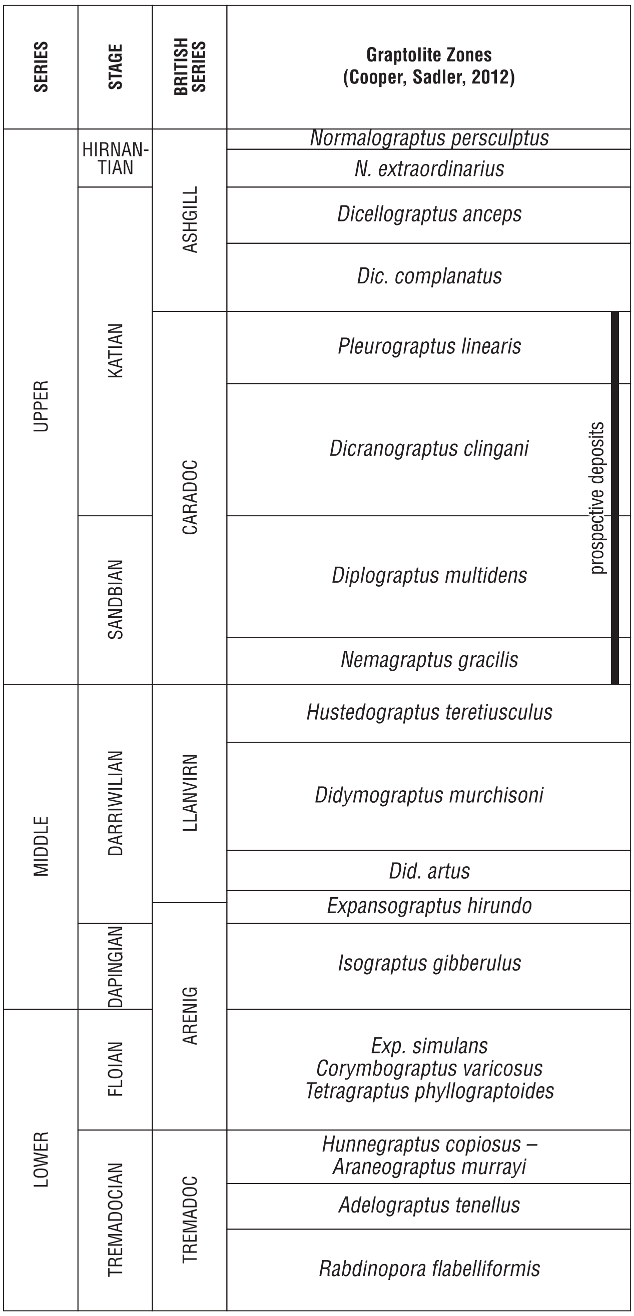

Fig. 2. Ordovician chronostratigraphic chart and graptolite zonal scheme (Cooper & Sadler, 2012)

resulted in a deposition of Ludlow and Pridoli thick sedimentary succession of a thickness exceeding 1000 m (Modliński, 2010).

The Silurian in the western part of the Baltic Basin is characterised by continuity of sedimentation and is represented by a complex of siliciclastic deposits of a significant thickness which is more than 3000 m in the Słupsk IG-1 borehole (Jaworowski, 2000; Szymański & Modliński, 2003). In the profile, mudrocks are predominant: siliciclastic rocks of various fractions, mostly mudstones s.s., and less frequently claystones and siltstones. Non-terrigenous rocks are in a smaller proportion being limited to thin interbeds of pyroclastic deposits (bentonites, tuffites) and carbonate rocks: marlstones and marly limestones. The Silurian claystone-mudstone-siltstone deposits which occur in the western part of the Baltic Depression were investigated by Jaworowski (2000), who described them as exoflish deposited in a foreland basin formed at the margin of the East European Craton.

ASSEMBLAGES OF GRAPTOLITES AND THEIR SIGNIFICANCE FOR THE STRATIGRAPHY AND EXPLORATION OF PROSPECTIVE DEPOSITS

The basic group of fossils to be found in the Ordovician and Silurian dark claystones and mudstones is that of graptolites – colonial plankton organisms that make a perfect stratigraphic and correlation tool since they are in abundance in deep-sea deposits. They are frequently accompanied by inarticulate brachiopods, acritarchs, Chitinozoa, though none of these fossil groups plays such an important role for the stratigraphy and correlation of the deposits in question as the graptolites do. Therefore, they constitute the main group of fossils which is used in the orthostratigraphic division of the Ordovician and Silurian mudstone-claystone successions, apart from carbonate deposits, which are mostly dated with the use of conodonts. Graptolites significantly surpass other groups of fauna in terms of stratigraphic value and degree of resolution. Many reference profiles and stratotype points (GSSP) for newly-determined stages of the Ordovician, the Ordovician/Silurian and the Silurian/Devonian boundaries were based on the range of graptolite taxa. Graptolites abound in the rocks which are considered to be prospective for the exploration and exploitation of unconventional hydrocarbon deposits in Poland and the biostratigraphic classification based on this fossil group is the most usefull tool for stratigraphic correlation. Thanks to graptolites it is possible "to date" stratigraphic sequences and their boundaries as well as the rich in organic matter anoxic levels which are the source of hydrocarbons in the rock. By tracking the range of particular species, the points of the first appearance datum one can precisely carry out a stratigraphic correlation of the prospective complexes on a regional scale.

Assemblage of graptolites from the Sasino Formation of Upper Ordovician

The Upper Ordovician deposits are one of the important rock complexes recognized as prospective for exploration and exploitation of natural gas from the early Paleozoic unconventional deposits in Poland. Their development in the most complete form, related to a distal zone of the early Paleozoic Baltic Basin, can be observed along the current south-western slope of the East European Craton. In the Łeba Elevation, as well as in the western part of the Baltic Depression, they make up the Sasino Formation (Modliński & Szymański, 1997). The belt of claystone-mudstone facies of a smaller stratigraphic extension and smaller thickness stretches out further to the south-east direction in the area of the Podlasie Region and the Lublin Region.

The rocks of the Sasino Formation, which are known from many boreholes in the northern Poland, are developed in the form of mudstones and claystones of dark gray and black colour, bituminous, seldom greenish, locally marly, in parts strongly bioturbated, having the thickness of up to

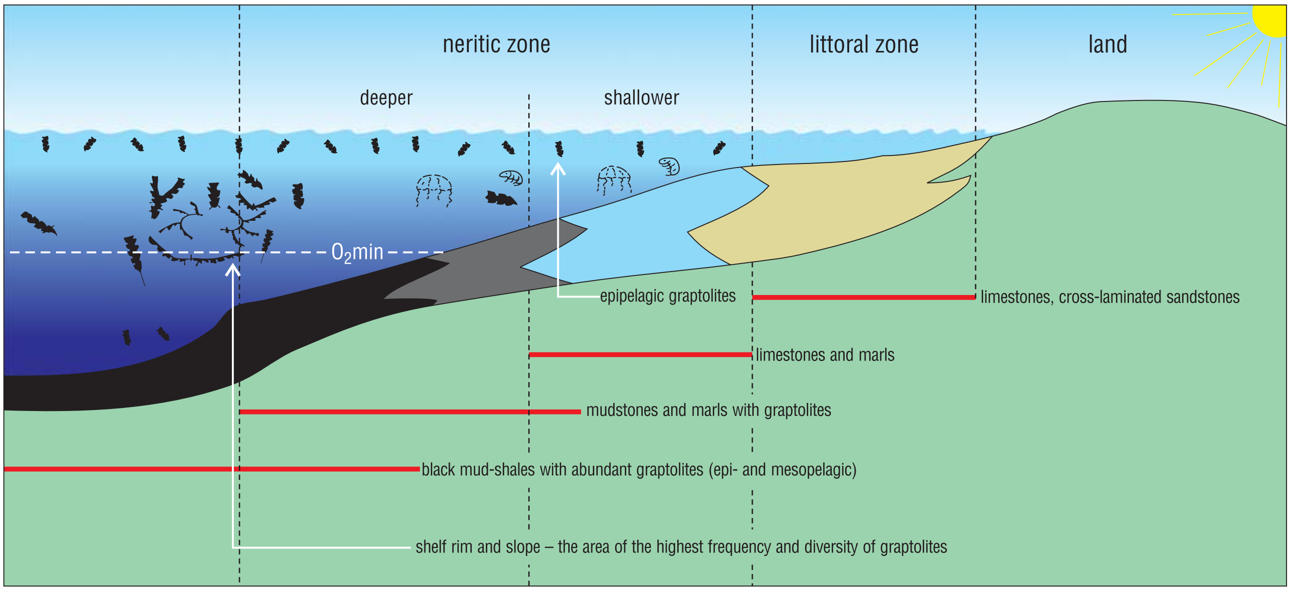

Fig. 3. Schematic distribution of the lithofacies and graptolite biofacies in the sedimentary basin. The graptolite biofacies – Finney & Berry, 1999; Cooper et al., 2007; modified and complemented

a few tens of meters, with interbeds of tuffites and bentonites (Podhalańska, 1980; Modliński & Szymański, 1997). According to the updated chronostratigraphic division of Ordovician (Webby et al., 2004), these deposits correspond to the uppermost part of the Darriwillian Stage, Sandbian and the lower part of the Katian Stage of the Upper Ordovician, and under the British regional division they relate to the uppermost Llanvirn and Caradoc (Fig. 2). The lower boundary of the Sasino Formation constitutes the surface of a marine transgression, highlighted by a sedimentary discontinuity and the presence of phosphate ooids (Podhalańska, 1980, 2009).

In the macrofauna assemblage which occurs in the black shale of the Sasino Formation, plankton forms are predominant, mainly graptolites, whereas benthos plays a secondary part. Fine-grained clastic deposits with graptolite fossils are to be found in upper Darriwilian, and this can be observed in the Kościerzyna IG-1borehole at the earliest where a presence of *Didymograptus murchisoni* Biozone was documented (Modliński, 1982). In the other profiles, claystones with graptolites are predominant starting from the *Hustedograptus teretiusculus* Biozone (Podhalańska, 1980) that outlines the top of Darriwilian (or Llanwirn according to the Great Britain series). A change in the sedimentation record and condensation connected with the base of the Sasino Formation and mass appearance of diverse graptolite fauna are the sign of a marine transgression which determines the parasequence boundary in the Ordovician rock record of the Baltic Basin (Podhalańska, 1980, 2009).

The claystone succession of Sandbian and lower Katian (an equivalent of the British Caradoc) is rather monotonous in terms of lithology and distinguished by the presence of numerous graptolites of every zone of this stratigraphic interval from *Nemagraptus gracilis* to *Climacograptus styloideus* zones (Modliński, 1973; Podhalańska, 1980). The *styloideus* Zone represents a regional equivalent of the *Pleurograptus linearis* Zone. A numerous assemblage of Chitinozoa (Podhalańska, 1979) and acritarchs (Szczepanik, 2000) accompanies the graptolites, in the lower part in particular.

In accordance with the ecological model of the distribution of graptolites in the sea, the "bloom" of graptolite plankton was mainly due to the fertile areas of the rim of the continental shelf and their largest amount falls for the periods of transgression and a high relative sea level (Finney & Berry, 1999). Upwelling zones of a high primary productivity – responsible for the bloom of fito- and thus zooplankton constitute the main area of graptolite development as they are characteristic of an increased supply of nutrients which are released in the process of organic matter decomposition in an oxygen minimum zone (Piper & Calvert, 2009). Trophic conditions and oxygen content are the two factors that determine presence of graptolite fauna and diversity of graptolite biofacies (Cooper et al., 2007). It is assumed that epipelagic graptolites lived in the near-the-top zone of the sea, irrespective of bathymetry and distance from the sea-shore whereas mesopelagic graptolites occupied ecological niches located in a water column mainly above the slopes and rims of continental shelves (Fig. 3). Graptolite remains are to be found in a variety of rocks, mostly on the surfaces of black shales, although they also occur of the fracture surfaces of light limestones and marlstones.

In Sandbian and Katian, during the sedimentation of the black shales of the Sasino Formation, the relative sea level was the highest ever in the whole geological history of the Earth (Nielsen, 2004). At that time, there happened a blossom and modification of the graptolite assemblage which was manifested by the appearance of new families and genera. In the Łeba Elevation and in the margin zone of the East European Craton, the abundant and taxonomically diverse assemblage of graptolites is dominated by the Dicranograptidae and Nemagraptidae families. Also new diplograptids turn up. The *Dicellograptus* genus is to be found until the end of the Ordovician, together with diplograptids: *Normalograptus* i *Paraorthograptus* (Podhalańska, 1980).

SERIES	STAGE	Graptolite biozones (Melchin et al., 2012)		Graptolite biozones (EEC) (Urbanek & Teller, 1997, modified; Modliński et al., 2006, modified)
PRIDOLI		*Monograptus transgrediens*		*M. transgrediens*
		M. bouceki		*M. perneri*
				M. bouceki
		Neocolonograptus lochkovensis *N. branikensis*		*M. samsonowiczi*
				M. chelmensis
				N. lochkovensis
		N. ultimus		*N. ultimus*
		N. parultimus		*N. parultimus*
LUDLOW	LUDFORDIAN	*Formosograptus formosus*		*M. spineus*
				M. protospineus
				M. acer
				Pseudomonocl. latilobus
		Neocucullograptus kozlowskii		*Neoc. kozlowskii*
		Polonograptus podoliensis		*Neoc. inexpectatus*
				Neolob. auriculatus
		Bohemograptus		*B. cornutus*
			?	*B. praecornutus*
		Saetograptus leintwardinensis		*S. leintwardinensis*
	GORSTIAN	*Lobograptus scanicus*		*Cucullo. hemiaversus*
				L. invertus
				L. scanicus
		Neodiversograptus nilssoni		*L. progenitor*
				Neodiver. nilssoni
WENLOCK	HOMERIAN	*Colonograptus ludensis*		*C. ludensis*
		C. deubeli		*C. deubeli*
		C. praedeubeli		*C. praedeubeli*
		Gothograptus nassa		*G. nassa*
		Pristiograptus parvus		*P. parvus*
		Cyrtograptus lundgreni		*C. lundgreni*
	SHEINWOODIAN	*C. perneri*		*C. perneri*
		C. rigidus		*C. rigidus*
		Monograptus belophorus		*M. belophorus (= M. flexilis)*
		M. riccartonensis		*M. antennularius*
				M. riccartonensis
		Cyrtograptus murchisoni	prospective deposits	*C. murchisoni*
		C. centrifugus		*C. centrifugus*
LLANDOVERY	TELYCHIAN	*C. insectus*		?
		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		↕
		Monograptus argenteus		
		Demirastrites pectinatus–Demirastrites triangulatus		*Demirastrites triangulatus*
	RHUDDANIAN	*Coronograptus cyphus*		*Coronograptus cyphus*
		Orthograptus vesiculosus		*Orthograptus vesiculosus*
		Parakidograptus acuminatus		*Parakidograptus acuminatus*
		Akidograptus ascensus		*Akidograptus ascensus*

Fig. 4. Silurian chronostratigraphic chart and graptolite zones. Wenlock, Ludlow, Pridoli zones in East European Craton – after Urbanek & Teller (1997), Llandovery – after Modliński et al. (2006), modified

The taxonomic composition of the Ordovician graptolite assemblages occurring in the deposits formed in the margin zone of the East European Craton in Poland shows a striking similarity with the graptolite assemblages which are to be found in other areas of the former Baltic Basin: in Scania and Bornholm (Bjerreskov, 1975), and also with the assemblages known from other areas in Europe and in the world (Goldman et al., 2013; Ross & Berry, 1963; Zalasiewicz et al., 2009). Therefore, the genera and species of graptolites which occur in profiles in Poland not only explicitly determine the stratigraphic position of the rock complexes which represent potential source of hydrocarbons in Poland, but also form a basis for regional and global correlations.

Also other representatives of macrozooplankton appear in the Ordovician clayey facies deposits and among them soft-shelled inarticulate brachiopods of the genera *Lingulella*, *Paterula* i *Hisingerella*, with the most characteristic cosmopolitan forms: *Paterula bohemica* Barrande and *Paterula portlocki* Geinitz (Podhalańska, 1980). Graptolites are usually accompanied by this fauna in a typical black shale facies indicating a similar behavioural and trophic structure within the pelagic biotic assemblage.

Silurian graptolites

The Silurian shale successions of the margin zone of the East European Craton are of the greatest importance for the occurrence of unconventional hydrocarbon deposits in Poland, and among them the Llandovery and Wenlock levels of black shales. With the abundant graptolite fauna, it was possible to precisely determine biostratigraphic zones in this seemingly lithologically monotonuos succession and outline the boundaries of chronostratigrapic units (Teller, 1969; Tomczyk, 1968, 1990; Urbanek & Teller, 1997; Szymański & Modliński, 2003; Modliński et al., 2006). The division of the Silurian System adopted in Poland relates to international agreements and is correlative with so called Generalized Graptolite Zonation – GGZ) (Koreń et al., 1996) and with the latest graptolite division accepted as a standard (Melchin et al., 2012) (Fig. 4).

Apart from being important in terms of stratigraphy and correlation (Fig. 5) , graptolites have proved to be an excellent tool for tracing biotic crises in a Silurian fossil record (Urbanek, 1993; Calner, 2008). Each of the events related to environmental disturbances involved an extinction of certain genera and species and appearance of new taxa in the phase of recovery and radiation. After the period of mass extinction in Hirnatian, due to global climate changes (Sheehan, 2001; Podhalańska, 2009), a recovery of graptolite assemblage took place in the earliest Silurian (Chen Xu et al., 2000). The radiation phase related to a marine transgression in Ordovician/Silurian took place in the *ascensus* Biozone of the earliest Llandovery. Then, some new taxa appeared which represented types of graptolite colony development not known before. Those new genera and species that turned up suddenly and spread fast all over the world (Williams, 1988; Fan & Chen Xu, 2007) were also found in profiles in Poland (Podhalańska, 2009). A lot of them, such as *Akidograptus ascensus* Davies, *Parakidograptus acuminatus* Nicholson, are used as nominative species of the lowest Silurian graptolite zones (Fig. 6A, B).

Fig. 5. Index graptolites for some Ordovician and Silurian biozones. **A** – *Dicranograptus clingani* (Carruthers) and *Diplacanthograptus caudatus* (Lapworth), *Dicranograptus clingani* Biozone; the first appearance of *Diplacanthograptus caudatus* (Lapworth) defines the lower boundary of the Katian Stage (Ordovician); coll. T. Podhalańska, photo by B. Ruszkiewicz. **B** – *Oktavites spiralis* (Geinitz), *Oktavites spiralis* Biozone, Llandovery, Telychian; coll. and photo by T. Podhalańska. **C** – *Monoclimacis crenulata* (Törnquist), preserved in full-relief, *Monoclimacis crenulata-M. griestoniensis* Biozone, Llandovery, Telychian; coll. T. Podhalańska, photo by B. Ruszkiewicz. **D** – *Monograptus riccartonensis* (Lapworth), *Monograptus riccartonensis* Biozone, Wenlock, Sheinwoodian; coll. and photo by T. Podhalańska

This enables it to determine the lower boundary of Silurian in each profile of a graptolite facies.

Evolution of the Silurian graptolites was disturbed by several crises. The lundgreni event, which was referred to by Jaeger (1991) as "a big crisis", took place at the top of *lundgreni* Zone (Wenlock) and constituted a turning point in the history of graptolites, i.e. a disappearance of species *Cyrtograptus* and *Monograptus* of the evolution line *priodon-flemingi*, *vomerina* and *exiguus* (e.g. Porębska et al., 2004) which are characteristic and index for Wenlock. In turn, after the global Kozlowskii event in Ludlow, specialized graptolites with ventrally curved rhabdosomes (Fig. 6H), of the genera *Neocucullograptus*, *Bohemograptus* and *Polonograptus* became extinct (Urbanek, 1993).

TAPHONOMY OF GRAPTOLITES

Graptolites which are on the surfaces of shale layers and also light limestones and marlstones (Fig. 6J, K) are characterized by a diverse state of preservation. It has an effect on their usefulness for determining the stratigraphy of rocks being explored on the one hand, and indicates the

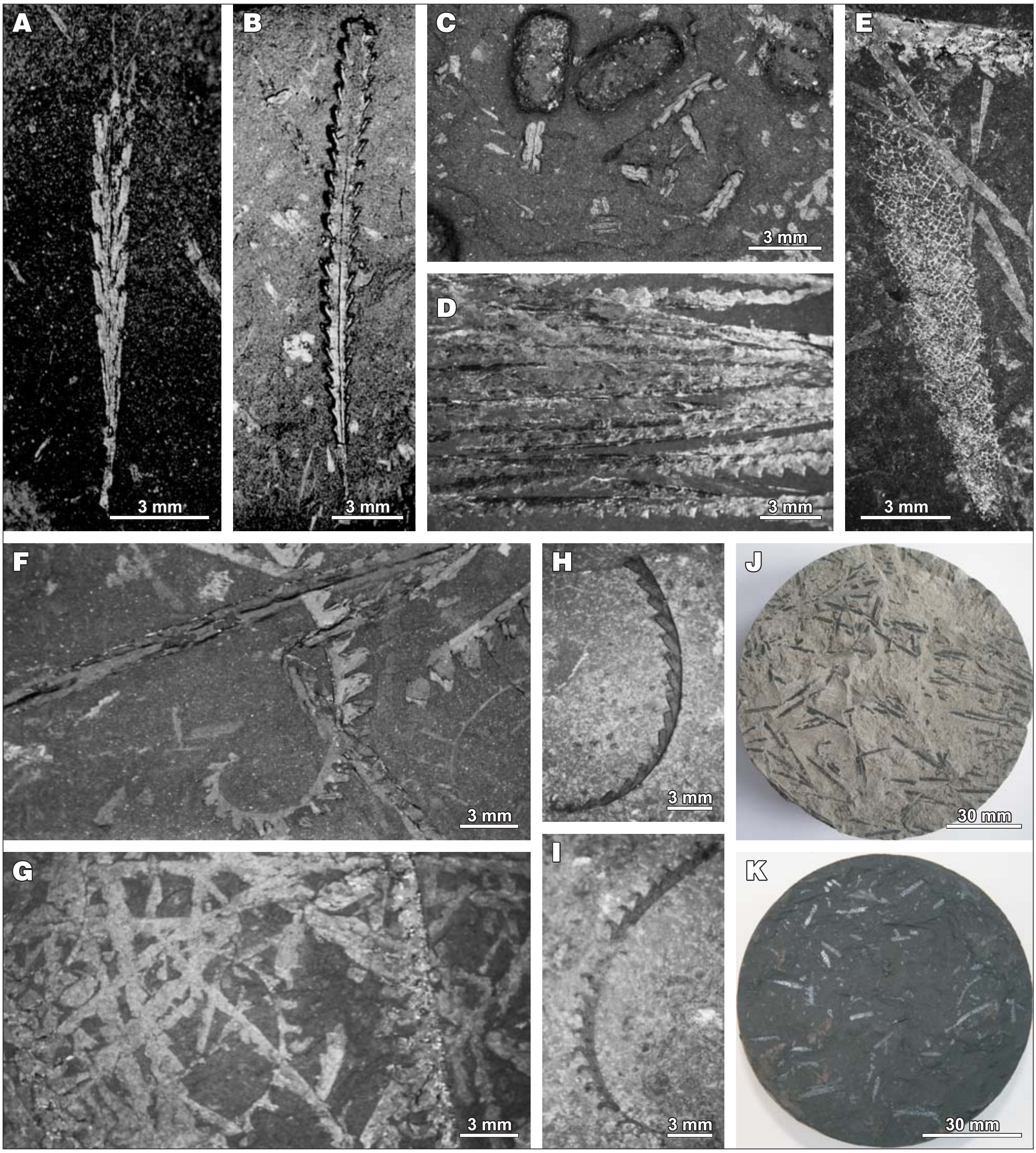

Fig. 6. Graptolites from the deep boreholes of the East European Craton. **A** – *Akidograptus ascensus* Davies, Łeba-8, depth 2658.7 m, *ascensus* Biozone, Llandovery. **B** – *Parakidograptus acuminatus* Nicholson, Kościerzyna IG-1, depth 4393 m, *acuminatus* Biozone, Llandovery. **C** – Graptolites preserved in half relief from the Ordovician/Silurian boundary interval and coprolites pyritized partly, Hel IG-1, depth 2971 m. **D** – Parallel distribution of the graptolites *Monograptus* sp., Kościerzyna IG-1, depth 4388 m, Llandovery. **E** – Flattened *Retiolites angustidens* Elles & Wood, deep borehole from the Łeba Elevation, lower Wenlock. **F** – *Demirastrites fimbriatus* Nicholson, Prabuty IG-1, depth 3348 m, Llandovery. **G** – Random distribution of the graptolite rabdosomes, all flattened, Kościerzyna IG-1, depth 4384 m, middle Llandovery. **H** – *Bohemograptus bohemicus bohemicus* Barrande, in half relief, Lębork IG -1, depth 2634.5 m, Ludlow. **I** – *Formosograptus formosus* Bouček, index species for *formosus* Biozone, Bytów IG-1, depth 1899 m, Ludfordian. **J** – Monotonous assemblage of the graptolites *Monograptus* in the light gray marl, Gołdap IG-1, depth 1142 m, Ludfordian. **K** – Typical graptolite preservation in black shales, Lębork IG-1, depth 3219 m, Wenlock. Photo by T. Podhalańska (A–I), J. Roszkowska-Remin (J–K)

sedimentation conditions and early diagenesis of the sediment on the other. Information on graptolite taphonomy can be used in practice for the exploration of zones enriched with organic matter and zones prospective for accumulation of hydrocarbons.

The Llandovery and Wenlock graptolite fauna in the western part of the Baltic Depression is abundant and taxonomically diverse similarly to that in the profiles in Latvia (Loydell i in., 2003; Loydell i in., 2010) and on the island of Saaremaa in Estonia (Loydell et al., 1998). However, the graptolites occurring in Ludlow and Pridoli show a relatively lower abundance, probably because of the dispersion of rhabdosomes in a large sediment mass.

Most of the graptolites explored in the Ordovician and Silurian profiles in the northern and south-eastern Poland is flattened (Fig. 5A, D; Fig. 6A, E). In some depth intervals there occur some forms preserved in a half or full relief (Fig. 5C; 6B, C). Three-dimentional rhabdosomes were originally filled with pyrite. Such forms were built when the empty parts of a graptolite colony were filled in with a sediment enriched in the sulphides which crystallized before the compaction, thus preventing rhabdosomes from being flattened. The process of crystallization caused that a periderm was removed and such a rhabdosome is now preserved in the form of an internal cast. Schieber (2003) claims that conditions for preferably localized crystallization of pyrite inside an empty graptolite skeleton might be possible in the environment of a slightly aerated bottom water. In anoxic and euxinic environments, pyrite occurs in a dispersed form or in the form of very small-size grains, including tiny framboids (Schieber, 2003; Zatoń et al., 2008).

Three-dimensional forms of graptolites filled up with pyrite (Fig. 5C; 6B, C) were unexpectedly found in the lower part of black shales of the Jantar Member of lower Llandovery in the boreholes Hel IG-1, Białogóra-1 and others in the Łeba Elevation (Podhalańska, 2009). Such a behavior of rhabdosomes was also found in other Ordovician and Silurian narrow stratigraphic intervals. If one assumes the Schieber's hypothesis (2003), their presence may prove that there were short dysoxic episodes in a sedimentary basin where anaerobic conditions were prevailing.

Within the Ordovician and Silurian shale successions in the East European Craton, the graptolite rhabdosomes are usually distributed in a random way on a surface layer (Fig. 5D; 6F, G, J, K). This proves that the dead remains were freely falling down the bottom without any current interference. However, the current activity, which was likely due to sea storm operations in the Baltic Basin occasionally accompanying the mudstone sedimentation process, is documented by the parallel arrangement of rhabdosomes on layer surfaces (Fig. 6D).

Fragments of graptolite colonies, and actually their periderm, might be employed to determine a thermal maturity level of a sediment (Riediger et al., 1989; Goodarzi, 1990). Reflectance of organic matter of a graptolite origin depends, as in case of vitrinite, on the lithology, weathering processes, tectonic, hydrothermal processes and the depth of burial (Goodarzi, 1990).

SUMMARY

Graptolites occur in various facies from shallow neritic to basin ones, and their largest abundance and taxonomic diversity is observed on the continental margin zones.

Owing to their extremely fast evolution, they make an excellent tool for biostratigraphy of the Ordovician-Silurian succession, also in terms of a high-resolution sequence stratigraphy. The mass appearance of diverse graptolite fauna is the sign of a marine transgression outlining the parasequence boundary in the rock record.

The state of graptolite preservation may indicate redox potential on the bottom of a sedimentary basin and can be used for exploration of aerobic and anaerobic periods which are essential for organic matter and hydrocarbon accumulation. The fact of rhabdosomes random distribiution proves that the sedimentation conditions were quiet in the Baltic Basin; episodes of storm-generated currents, documented by the parallel distribution of graptolite remains, were observed sporadically.

Graptolites should be granted an equal status with the increased TOC indicators or increased values of gamma logs as a marker of zones enriched with organic matter. Without complicated and expensive analytical studies, graptolites are one of the instruments that enable exploring of potential source rocks for hydrocarbons, including shale gas.

REFERENCES

BJERRESKOV M. 1975 – Llandoverian and Wenlockian graptolites from Bornholm. Fossils and Strata, 8: 1–94.

CALNER M. 2008 – Silurian global events – at the tipping point of climate change. [In:] Elewa A.M.T. (ed.) Mass Extinction, Springer- -Verlag, Heidelberg: 21–58.

CHEN X., RONG J., MITCHELL C. D., HARPER D.A.T., JUNXUAN F., RENBIN Z., YUANDONG Z., LI RONG YU L. & WANG Y. 2000 – Late Ordovician to Earliest Silurian graptolite and brachiopod biozonation from the Yangtze region, South China, with a global correlation. Geol. Mag., 137: 623–650.

COOPER R.A. & SADLER P.M. 2012 – The Ordovician Period. [In:] Gradstein F.M., Ogg J.G., Schmitz M.D., Ogg G.M., The Geologic Time Scale 2012: 489–523.

CZARNOCKI J. 1919 – Stratygrafia i tektonika Gór Świętokrzyskich. Tow. Nauk. Warszawskie, Prace, 28.

DADLEZ R. 2000 – Pomeranian Caledonides (NW Poland), fifty years of controversies: a review and a new concept. Geol. Quart., 38: 169–190.

FAN J. & CHEN X. 2007 – Preliminary report on the Late Ordovician graptolite extinction in the Yangtze region. Palaeogeogr., Palaeoclimatol., Palaeoecol., 245: 82–94.

FINNEY S.C. & BERRY W.B.N. 1999 – Late Ordovician graptolite extinction: the record from continental margin sections in central Nevada, USA. Acta Univ. Carolinae, 43: 195–198.

GOLDMAN D., MITCHELL Ch.E., PODHALAŃSKA T., NÕLVAK J., MELCHIN M.J., SHEETS H.D. & FAN J. 2013 – Late Middle and Late Ordovician graptolite biostratigraphy – a reassessment from Polish and Baltoscandian drill core data. The IGCP 591 3rd Annual Meeting, 9–19 June 2013, Lund.

GOODARZI R.W. 1990 – Graptolite reflectance and thermal maturity of Lower Paleozoic Rocks. The AAPG /Datapages combined Publications Database, abstract.

JAANUSSON V. 1976 – Faunal dynamics in the Middle Ordovician (Viruan) of Balto-Scandia. [In:] The Ordovician System: Procceedings of a Palaeont. Ass. Symp. Birmingham, 1974: 301–326.

JAEGER H. 1991 – Neue Standard-Graptolithenfoge nach der "Grossen Krise" an der Wenlock/Ludlow Grenze (Silur). Neues Jahrbuch für Geologie und Paläontologie, 182: 303–354.

JAWOROWSKI K. 2000 – Facies analysis of the Silurian shale-siltstone succession in Pomerania (northern Poland). Geol. Quart., 44: 297–316.

KOREN T.N., LENZ A.C., LOYDELL D.K., MELCHIN M.J., ŠTORCH P. & TELLER L. 1996 – Generalized graptolite zonal sequence defining Silurian time intervals for global paleogeographic studies. Lethaia, 29 (1): 59–60.

LAZAUSKIENE L., SLIAUPA S., BRAZAUSKAS A. & MUSTEIKIS P. 2003 – Sequence stratigraphy of the Baltic Silurian succession: tectonic control on the foreland infill. Geological Society, London. Spec. Publ., 208: 95–115.

LOYDELL D.K., KALJO D. & MÄNNIK P. 1998 – Integrated biostratigraphy of the lower Silurian of the Ohesaare core, Saaremaa, Estonia. Geol. Mag., 135: 769–783.

LOYDELL D.K., MÄNNIK P. & NESTOR V. 2003 – Integrated biostratigraphy of the lower Silurian of the Aizpute-41 core, Latvia. Geol. Mag., 140: 205–229.
LOYDELL D.K., NESTOR V. & MÄNNIK P. 2010 – Integrated biostratigraphy of the lower Silurian of the Kolka-54 core, Latvia. Geol. Mag., 147: 253–280.
LÜNING S., CRAIG J., LOYDELL D.K., ŠTORCH P. & FITCHES B. 2000 – Lower Silurian hot shales in North Africa and Arabia: regional distribution and depositional model. Earth Sci. Rev., 49: 121–200.
MELCHIN M.J., SADLER P.M. & CRAMER B.D. 2012 – The Silurian Period. [In:] Gradstein F.M., Ogg J.G., Schmitz M.D., Ogg G.M., The Geologic Time Scale: 525–558.
MODLIŃSKI Z. 1973 – Stratygrafia i rozwój ordowiku w północno-wschodniej Polsce. Pr. Inst. Geol., 72: 1–74.
MODLIŃSKI Z. 1982 – Rozwój litofacjalny i paleotektoniczny ordowiku na obszarze platformy prekambryjskiej w Polsce. Pr. Państw. Inst. Geol., 102: 1–65.
MODLIŃSKI Z. 2010 (ed.) – Atlas paleogeologiczny podpermskiego paleozoiku kratonu wschodnioeuropejskiego w Polsce i na obszarach sąsiednich. Państwowy Instytut Geologiczny – PIB, Warszawa.
MODLIŃSKI Z. & SZYMAŃSKI B. 1997 – The Ordovician lithostratigraphy of the Peribaltic Depression (NE Poland). Geol. Quart., 41: 273–288.
MODLIŃSKI Z., SZYMAŃSKI B. & TELLER L. 2006 – Litostratygrafia syluru polskiej części obniżenia perybałtyckiego – część lądowa i morska (N Polska). Prz. Geol., 54: 787–796.
NESTOR H. & EINASTO R. 1997 – Ordovician and Silurian carbonate sedimentation basin. [In:] Raukas A., Teedumäe A. (eds.) Geology and Mineral Resources of Estonia. Estonian Academy, Tallinn: 192–204.
NIELSEN A.T. 2004 – Ordovician sea-level changes: a Baltoscandian perspective. [In:] Webby B.D., Paris F., Droser M.L., Percival I.G. (eds.) The great Ordovician biodiversification event: 84–93.
PIPER D.Z. & CALVERT S.E. 2009 – A marine biogeochemical perspective on black shale deposition. Earth Sci. Rev., 95: 63–96.
PODHALAŃSKA T. 1979 – The correlative significance of the Chitinozoa-bearing horizon in the Caradocian profiles of the Łeba region (NW Poland). Acta Geol. Pol., 29: 443–448.
PODHALAŃSKA T. 1980 – Stratigraphy and development of Middle and Upper Ordovician deposits in the Łeba Elevation (NW Poland). Acta Geol. Pol., 30: 327–390.
PODHALAŃSKA T. 2009 – Późnoordowickie zlodowacenie Gondwany – zapis zmian środowiskowych w sukcesji osadowej obniżenia bałtyckiego. Pr. Państw. Inst. Geol., 193.
PODHALAŃSKA T. & MODLIŃSKI Z. 2006 – Stratygrafia i rozwój facjalny osadów ordowiku i syluru strefy Koszalin–Chojnice, podobieństwa i różnice z obszarem południowo-zachodniej krawędzi kratonu wschodnioeuropejskiego i Rugii. [In:] Matyja H., Poprawa P. (eds.) Ewolucja facjalna, tektoniczna i termiczna pomorskiego segmentu szwu transeuropejskiego oraz obszarów przyległych. Pr. Państw. Inst. Geol., 186: 39–78.
POPRAWA P. 2006 – Rozwój kaledońskiej strefy kolizji wzdłuż zachodniej krawędzi Baltiki oraz jej relacje do basenu przedpola. [In:] Matyja H., Poprawa P. (eds.) Ewolucja facjalna, tektoniczna i termiczna pomorskiego segmentu szwu transeuropejskiego oraz obszarów przyległych. Pr. Państw. Inst. Geol., 186: 189–213.
PORĘBSKA E., KOZŁOWSKA-DAWIDZIUK A. & MASIAK M. 2004 – The lundgreni event in the Silurian of the East European Platform, Poland. Palaeogeogr., Palaeoclimatol., Palaeoecol., 213: 271–294.
RIEDIGER C., GOODARZI F. & MACQUEEN R.W. 1989 – Graptolites as indicator of regional maturity in Lower Paleozoic sediments, Selwyn Basin, Yukon and Northwest Territories, Canada. Can. Journ. Earth Sc., 26: 2003–2015.
ROSS R.J. Jr. & BERRY W.B.N. 1963 – Ordovician graptolites of the Basin Ranges in California, Nevada, Utah and Idaho. US Geol. Survey Bull., 1134: 1–177.
SAMSONOWICZ J. 1916 – Kambr i kambro-sylur Gór Świętokrzyskich. Spraw. Pos. Tow. Nauk. Warsz., 9. Warszawa
SCHIEBER J. 2003 – Simple gifts and buried treasures – implications of finding bioturbations and erosion surfaces in black shales. The Sedimentary Record., 1: 4–8.
SHEEHAN P.M. 2001 – The Late Ordovician mass extinction. Annual Rev. Earth and Planetary Sci., 29: 331–364.
SZCZEPANIK Z. 2000 – The Ordovician acritarchs of the Pomeranian Caledonides and their foreland – similarities and differences. Kwart. Geol. 44: 275–297.
SZYMAŃSKI B. & MODLIŃSKI Z. 2003 – Nowelizacja stratygrafii syluru w wybranych profilach wiertniczych obniżenia bałtyckiego (Polska północna). Biul. Państw. Inst. Geol., 405: 109–138.
TELLER L. 1964 – Graptolite fauna and stratigraphy of the Ludlovian deposits of the Chełm borehole, eastern Poland. Studia Geol. Pol., 13: 1–88.
TELLER L. 1969 – The Silurian biostratigraphy of Poland based on graptolites. Acta Geol. Pol., 19: 393–501.
TELLER L. 1986 – Morphology of selected Monograptidae from the Wenlock of NE Poland. Palaeontographica, 192.
TOMCZYK H. 1962 – Problem stratygrafii ordowiku i syluru w Polsce w świetle ostatnich badań. Pr. Inst. Geol., 35.
TOMCZYK H. 1968 – Sylur. [In:] Budowa geologiczna Polski. Stratygrafia, cz. 1, Prekambr i Paleozoik. Wydawnictwa Geologiczne, Warszawa.
TOMCZYK H. 1990 – Sylur. [In:] Budowa Geologiczna Polski. Atlas skamieniałości, cz. 1a. Paleozoik starszy. Wydawnictwa Geologiczne. Warszawa.
TOMCZYKOWA E. 1964 – Ordowik platformy wschodnioeuropejskiej na obszarze Polski. Kwart. Geol., 8: 491–504.
URBANEK A. 1958 – Monograptidae from erratic boulders of Poland. Palaeont. Pol., 9.
URBANEK A. 1966 – On the morphology and evolution of the Cucullograptina (Monograptidae, Graptolithina). Acta Palaeont. Pol., 4:1.
URBANEK A. 1993 – Biotic crises in the history of Upper Silurian graptoloids: a palaeobiological model. Historical Biology, 7: 29–50.
URBANEK A. & TELLER L. 1997 – Graptolites and stratigraphy of the Wenlock and Ludlow Series in the East European Platform. Palaeontologia Pol., 56: 23–58.
VERNIERS J. (koordynator), MALETZ J., KŘIŽ J., ŽIGAITE Z., PARIS F., SCHÖNLAUB H.P. & WRONA R. 2008 – Silurian. [In:] McCann T. (ed.) The Geology of Central Europe, v. 1: Precambrian and Palaeozoic: 249–302.
WEBBY B.D., COOPER A.R. & BERGSTRÖM S.M. 2004 – Stratigraphic framework and time slices. [In:] Webby B.D., Paris F., Drosser M.L., Persival I.G.(eds.) The Great Ordovician Biodiversification Event. Columbia Univ. Press, New York: 41–47.
WILLIAMS H. 1988 – Dob's Linn – The Ordovician-Silurian boundary stratotype. [In:] Cooks L.R.M., Rickards R.B. (eds.) A global analysis of the Ordovician-Silurian boundary. Bull. British Mus. Nat. Hist. (Geology), 43: 17–30.
ZALASIEWICZ J., TAYLOR L., RUSHTON A.W.A., LOYDELL D.K., RICKARDS R.B. & WILLIAMS M. 2009 – Graptolites in British Stratigraphy. Geol. Mag., 146: 785–850.
ZATOŃ M., RAKOCIŃSKI M. & MARYNOWSKI L. 2008 – Framboidy pirytowe jako wskaźniki paleośrodowiska. Prz. Geol., 56: 158–164.