VOLUMINA JURASSICA, 2019, XVII: 49–80
DOI: 10.7306/VJ.17.4

Ammonite stratigraphy and organic matter of the Pałuki Fm. (Upper Kimmeridgian–Lower Tithonian) from the central-eastern part of the Łódź Synclinorium (Central Poland)

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Key words: ammonites, Upper Kimmeridgian, Lower Tithonian, organic matter distribution and maturity, hydrocarbon generation.

Abstract: The ammonite biostratigraphy as well as the organic matter content, its type and maturity of the Pałuki Formation, belonging to the fine, siliciclastic Kimmeridge Clay type facies, were investigated in five deep boreholes from the central-eastern part of the Łódź Synclinorium in Central Poland. The studied deposits are assigned to the Eudoxus and Autissiodorensis zones of the Upper Kimmeridgian as well as the Klimovi, Sokolovi, Pseudoscythica and Puschi (=Tenuicostata) zones of the Lower Tithonian ("Lower Volgian"). The Pałuki Formation shows in its lower and middle parts average TOC concentrations of *ca.* 2.5 wt.% and prominent, restricted increases in organic matter content, which are found in the mid-Eudoxus Zone, the lowermost part of the Autisiodorensis Zone, and at the Sokolovi–Pseudoscythica zone boundary. These stratigraphical intervals correlate well with rich in organic matter levels present in the Kimmeridge Clay Formation of NW Europe. The periodic expansions of Submediterranean and Subboreal-Boreal ammonites corresponded mostly to the transgressive phases, often correlated with a higher content of organic matter. The development of special morphologies of ammonites, such as the small-sized, nectopelagic forms of *Nannocardioceras* in the Late Kimmeridgian, has also been related to the deposition of shales rich in organic matter during the transgression maxima.

The organic matter present in the Pałuki Formation mostly consists of Type II kerogen and is immature or early mature with respect to hydrocarbon generation, which is in agreement with previously published data. Evaluation of the new and published geochemical, lithological and structural data from the Pałuki Formation in the central-eastern part of the Łódź Synclinorium shows that these deposits could not have been a considerable source of crude oil or gas.

INTRODUCTION

The Upper Kimmeridgian–Lower Tithonian Pałuki Formation (also known as the Shale-Marly-Siltstone Formation or VI) which occurs in north-central Poland is rich in organic matter and belongs to the so-called Kimmeridge Clay-type facies. It is underlain by the Lower Kimmeridgian–lowermost Upper Kimmeridgian Limestone-Marly-Coquina Formation (V) and overlain by the uppermost Lower Tithonian–Lower Berriasian Kcynia (Limestone-Evaporitic or VII) Formation (Dembowska, 1979). There are presently no outcrops of the Pałuki Formation in the study area and it is solely known from drill cores. Although the deposits of the Pałuki Formation are interesting from a sedimentological point of view and constitute potential source-rocks for hydrocarbons (*cf*. Bachleda-Curuś *et al.*, 1992; Więcław, 2016)

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they are poorly constrained biostratigraphically and lithostratigraphically, except in a limited area of the Tomaszów Syncline (Kutek, Zeiss, 1997). This hampers the correlation of geochemical results between drill cores, and the determination of the distribution of organic matter and lithology of this facies in the Łódź Synclinorium as well as its comparison to other siliciclastic fine-grained Kimmeridgian–Lower Tithonian deposits of Poland and NW and NE Europe.

The present study aims at documentation of the standard biostratigraphical subdivisions of the Pałuki Formation from the central-eastern (Poddębice–Uniejów) area of the Łódź Synclinorium, including the Ponętów-Wartkowice anticline structure, adjacent Koło and Wrząca troughs and the Uniejów elevation. It is based on the ammonite faunas from five drill cores (Uniejów IGH 1, Koło IG 3, Koło IG 4, Poddębice IG 1, Poddębice PIG 2; Fig. 1). The observed temporal variations in the ammonite assemblages are interpreted as faunistic migrations caused by palaeoceanographical and palaeoenvironmental changes in the mid-Polish basin as elsewhere in Europe. The distribution, type and thermal maturity of organic matter from the Pałuki Formation are studied based on new and published geochemical data. An attempt has also been made to correlate organic matter rich intervals in the Pałuki Formation with those from NW and NE Europe. Since the drill cores investigated are derived from one of the deepest parts of the Łódź Synclinorium, which has been suggested as a prospective area for Jurassic hydrocarbons (*cf.* Bachleda-Curuś *et al.*, 1992; Więcław, 2016) the presented data are also used in a discussion on the source-rock potential of the Upper Kimmeridgian–Lower Tithonian strata of this part of the Polish Lowland.

METHODS

The lithological sections of the Pałuki Formation from the Uniejów IGH 1 borehole (after Jaskowiak-Schoeneichowa *et al.*, 1991) have been visually inspected and their descriptions have been modified (Appendix: Table 1). Ammonites preserved in the collection of the Geological Museum of the Polish Geological Institute – National Research Institute in Warsaw and newly sampled specimens from the drill cores were determined taxonomically and photographed. The new, biostratigraphically important ammonites have been housed and catalogued in the collection of the Geological Museum of the Polish Geological Institute – National Research Institute in Warsaw. The studied specimens include the following collection numbers: Muz. PIG.1228.II (Koło IG 3); 1229.II (Koło IG 4); 1821.II (Poddębice IG 1); 1822.II (Poddębice PIG 2); 1823.II (Uniejów IGH 1). Samples for organic matter analyses were collected from drill cores. The samples were gently washed, dried at room temperature and ground. 50–110 mg weighted portions of homogenized samples were analysed using a Rock-Eval 6 Turbo device manufactured by Vinci Technology, according to the IFP Basic Method for source rocks (*cf.* Behar *et al.*, 2001), at the Polish Geological Institute – National Research Institute in Warsaw (for results see Appendix: Table 2).

LITHOLOGY AND LITHOSTRATIGRAPHY OF THE CORES

The major portion of the Pałuki (Shale-Marly-Siltstone or VI) Formation in the Poddębice–Uniejów region of the central-eastern part of the Łódź Synclinorium consists of monotonous claystone–mudstone–marly strata (Dembowska, 1979). Its lower boundary is easily determinable based both on the cores of the drilled wells and on geophysical data. The Pałuki Formation is underlain by the light grey limestones of the Limestone-Marly-Coquina (V) Formation, which often contain bivalve detritus with *Nanogyra* shells (Dembowska, 1990a–d; Gaździcka, 2012a, b). In practice, some problems may arise because of marly mudstone intercalations in the upper part of the Limestone-Marly-Coquina (V) Formation *e.g.* in the Uniejów IGH 1 section (Appendix: Table 1) or the presence of marly facies in the upper part of this Formation in the Poddębice PIG 2 borehole, which is located in the more distal part of the sedimentary basin. The lower and middle parts of the Pałuki Formation assigned to the Upper Kimmeridgian–lowermost Tithonian are more argillaceous and distinctly less calcareous than its upper part (Fig. 2). Starting at about 60–80 m in the section of the Pałuki Formation the strata pass more or less gradually into marls and marly limestones. An exception may be the Koło IG 3 borehole. However, this borehole was only partially cored, and the interpretation of its lithological succession is mostly based on drilling mud logging and geophysical data. The calcareous nature of the upper part of the Pałuki Formation hampers, in some cases, the determination of its upper boundary. In the present study, the boundary between the Pałuki and Kcynia (Limestone-Evaporitic or VII) formations is set at the transition between marly or marly limestone facies and pure limestone or limestone-dolomitic beds (Appendix: Table 1; Fig. 2). The marly and marly limestones beds of the uppermost part of the Pałuki Formation are often dark grey and differ from the lighter colored limestones of the Kcynia Formation (Table 1; Dembowska, 1990b, c). An exception is the Poddębice PIG 2 borehole located in the deeper part of the basin. Nevertheless, a transition to more calcareous Kcynia Formation is also noticeable in this borehole. The accepted interpretation of the lithological succession is in line with the study of Kutek and

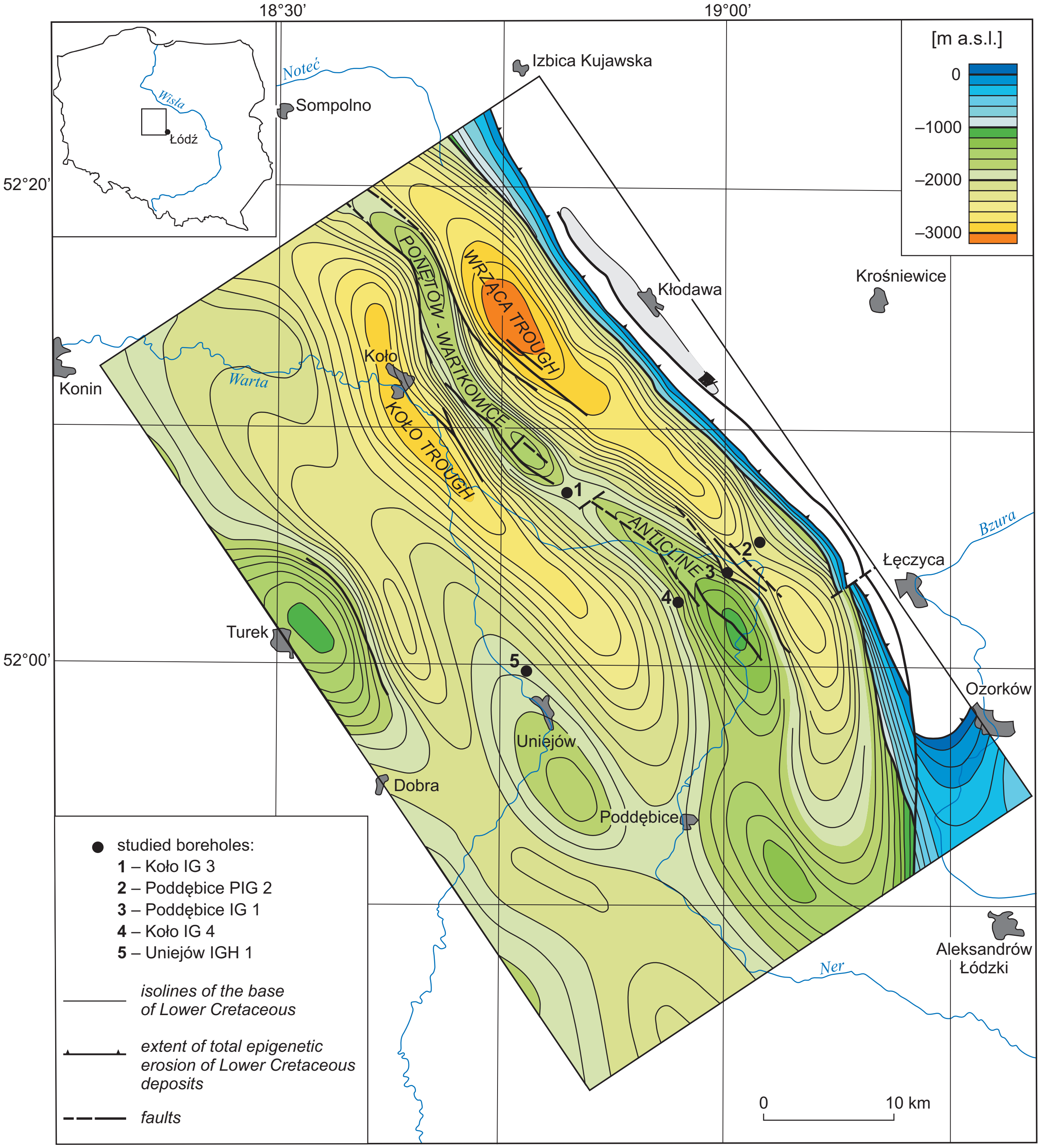


Fig. 1. Structural map of the top of the Kcynia Formation (Lower–Middle Berriasian boundary) in central-eastern part of the Łódź Synclinorium and location of the boreholes studied (after Leszczyński, 2002)

Zeiss (1997), who observed high calcium carbonate content and the presence of marly limestones in the uppermost part of the Pałuki Formation belonging to the Puschi (Tenuicostata) and Scythicus zones of the "Lower-Middle Volgian" (Lower Tithonian) in the Tomaszów Syncline in the SE part of the Łódź Synclinorium. It is also in agreement with the present findings of Pseudoscythica–Scythicus zone ammonites in the uppermost, marly limestone parts of the studied Koło IG 4 and Poddębice IG 1 borehole sections (see Ammonite biostratigraphy and correlations section). The accepted definition of the upper boundary of the Pałuki Formation and the ammonite data have placed its position towards the top of the section in the two mentioned boreholes (see Fig. 2). The Pałuki Formation has a total thickness of 100–107.9 m in the Uniejów IGH 1, Koło IG 3, Koło IG 4, Poddębice IG 1 boreholes and 125.5 m in the Poddębice PIG 2 borehole. The greater thickness of the Pałuki Formation in the Poddębice PIG 2 borehole may be related to the location of this area in a foredeep basin (Wrząca trough) of the Kłodawa Salt Diapir, which was characterized by a higher subsidence rate during the Jurassic (*cf*. Krzywiec, 2004; Krzywiec *et al*., 2015a, b; Cyz *et al*., 2016).

AMMONITE BIOSTRATIGRAPHY AND CORRELATIONS

Upper Kimmeridgian. The calcareous claystones and mudstones with intercalations of *Nanogyra* shells of the Limestone-Marly-Coquina Formation which directly underlie the deposits of the Pałuki Formation did not yield ammonites in the cores studied. These deposits previously cropped out at Stobnica (north western margin of the Holy Cross Mts) in the south-eastern limb of the Łódź Synclinorium where they yielded the Upper Kimmeridgian ammonites described by Kutek (1961) and subsequently discussed and partly re-interpreted by Ziegler (1962), Kutek (1962) and Kutek and Zeiss (1997). This assemblage of ammonites, consisting of numerous representatives of *Aulacostephanus*, including *A. eudoxus* (d'Orbigny), *A. pinguis* Durand, and *A. pseudomutabilis* (de Loriol), is indicative of the Eudoxus Zone. It can be well compared with the lower part of the Eudoxus Zone which yields common aulacostephanid ammonites (*e.g.* Callomon, Cope, 1971; Birkelund *et al.*, 1983). A single ammonite referred to as *Aulacostephanus* cf. *pseudomutabilis anglicus* (Steuer) has been found also at the base of the Pałuki Formation in the core Uniejów IGH 1 at 2204.6 m (Pl. 1: 1). This suggests continuation of the ammonite faunal assemblage discussed, corresponding to the lower part of the Eudoxus Zone, in the basal part of the Pałuki Formation in the area of study (Fig. 2).

A younger assemblage of ammonites consisting of numerous specimens of Aspidoceratidae occurs in the Pałuki Fm., in core Uniejów IGH 1 between 2184.4 and 2177.0 m. It consists of *Aspidoceras* sp. at 2184.4 m (Pl. 1: 3), *Sutneria* aff. *eumela* (d'Orbigny) at 2180.3 m (Pl. 1: 5a, b), *Aspidoceras* cf. *quercynum* Hantzpergue at 2178.4 m (Pl. 1: 4), *Sutneria* sp. at 2178.0 m, and *Aspidoceras* sp. at 2177 m; this assemblage yields also rare aulacostephanids such as *Aulacostephanus eudoxus eudoxus* (d'Orbigny) at 2178.6 m (Pl. 1: 2). An isolated occurrence of a single large-sized (about 80 mm in diameter) and heavy-ornamented cardioceratid *Hoplocardioceras elegans* (Spath) was also found in older deposits of the Pałuki Fm., at 2191.5 m (Pl. 1: 6) in core Uniejów IGH 1. The uppermost part of the stratigraphical interval in core Uniejów IGH 1 between 2178 and 2177 m yielded additionally small-sized (about 20–40 mm in diameters) cardioceratids referred to as *Hoplocardioceras elegans* (Spath) (Pl. 1: 7). Similar small-sized specimens (but also fragments of whorls of larger size) of *H. elegans* along with specimens *Aspidoceras* and *Sutneria* were found in the Pałuki Fm. between 2184.2 and 2179,7 m in core Koło IG 3, as well as between 2402.5 and 2400.1 m in core Poddębice IG 1 (Pl. 1: 8–10).

The deposits of the Eudoxus Zone from the cores studied, attain at least 14.5 m in thickness when considering the vertical range of the discussed ammonites (but ranging possibly even up to about 25 meters when placing their base directly above the occurrence of *Aulacostephanus* in the basal part of the Pałuki Fm. in core Uniejów IGH 1). Those strictly corresponding deposits in the south-eastern part of the Łódź Synclinorium, occurring directly above the deposits of the Limestone-Marly Coquina Formation, have yielded some aspidoceratid and oppeliid ammonites along with specimens of *H. elegans*, and attained an even larger thickness (35–50 meters). They were originally placed in the Eudoxus Zone and partly in the Eudoxus-Autissiodorensis uncertainty interval by Kutek and Zeiss (1997, fig. 3B, C), but there is no doubt, that all of them belong to the Eudoxus Zone. Such a stratigraphical interpretation of the deposits results from occurrence of *Aulacostephanus eudoxus* in the middle part of the interval in question in the Uniejów IGH 1, but also from the common occurrence of *Hoplocardioceras elegans* ammonites, indicative of the Boreal Elegans Zone which partly correlates with the Subboreal Eudoxus Zone except its lower part (*e.g.* Birkelund, Callomon, 1985; Wierzbowski, 1989; Wierzbowski, Smelror, 1993).

The detailed stratigraphical subdivision of the deposits which yield the specimens discussed needs some additional comments. The common occurrence of Aspidoceratidae (especially the *Aspidoceras-Sutneria* assemblage) along with other Submediterranean ammonites is encountered in a middle part of the Eudoxus Zone recognized as the Caletanum Subzone, as well as in the directly overlying deposits, representing some upper parts of the Eudoxus Zone (Contejeani Subzone) in sections of the so called "biome franco-germanique", including areas of the Aquitaine and Paris basins as well as northern Germany (Hantzpergue, 1989; Hantzpergue *et al.*, 1997; Schweigert, 1999). Of marked stratigraphical

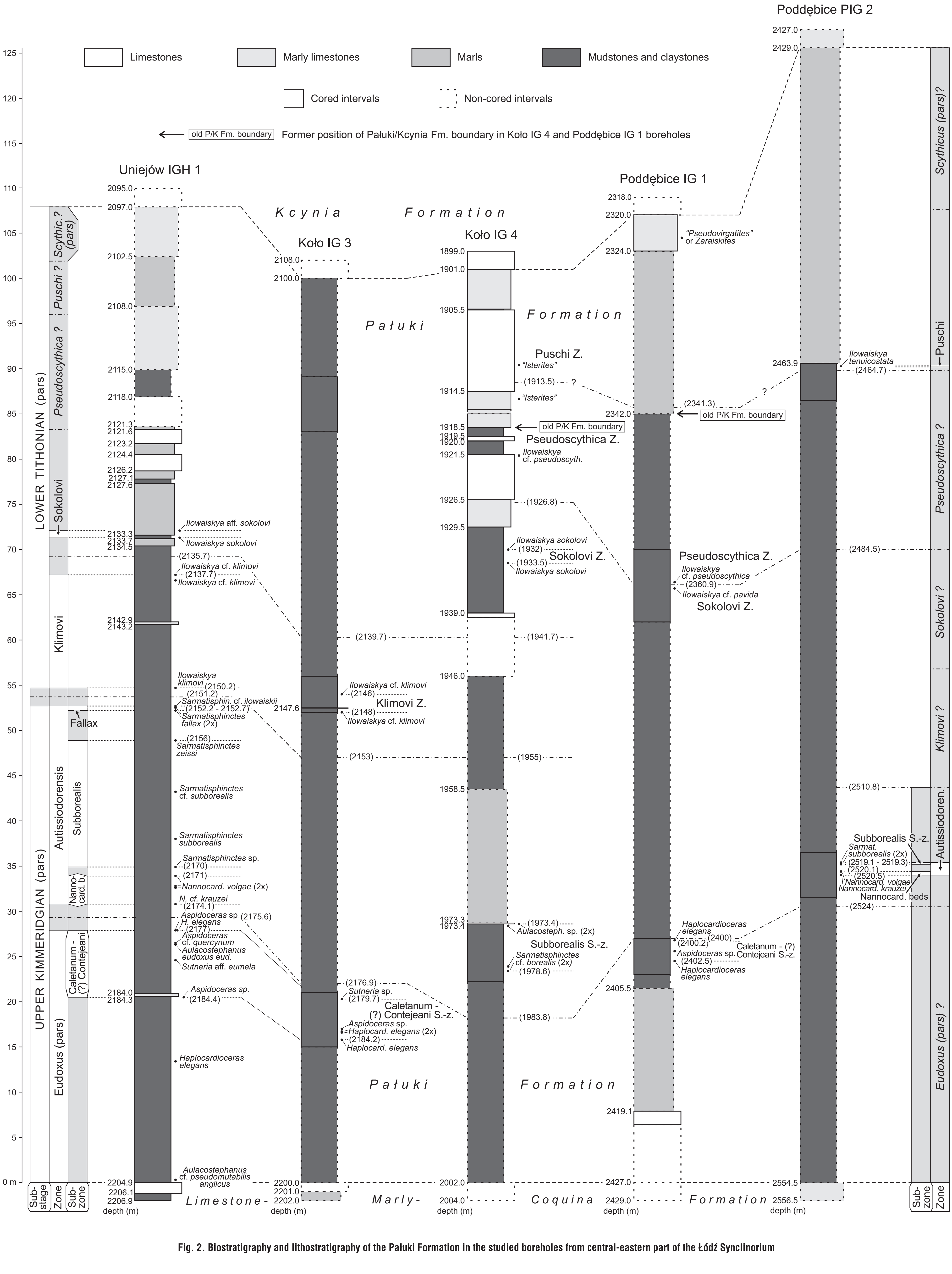


Fig. 2. Biostratigraphy and lithostratigraphy of the Pałuki Formation in the studied boreholes from central-eastern part of the Łódź Synclinorium

importance is the occurrence of *Aspidoceras* close to *A. quercynum* Hantzpergue in the upper part of the succession studied in borehole Uniejów IGH 1. This species is known to occur in the upper part of the Caletanum Subzone, and the lower part of the Contejeani Subzone (Hantzpergue, 1989, 1995). A similar distribution of aspidoceratids in the Eudoxus Zone is observed also in the Subboreal areas (Geyssant, 1994; see also Callomon, Cope, 1971). Thus the whole discussed interval corresponds to the middle and some upper part of the Eudoxus Zone – the Caletanum Subzone, and possibly a lower part of the Contejeani Subzone (Fig. 2).

The recognized stratigraphical interval of occurrence of *Hoplocardioceras elegans* in the Eudoxus Zone in the cores studied can be subdivided into two parts: a lower, rather thick interval, attaining up to several meters in thickness where the specimens of *H. elegans* occur rarely (from 2191.5 to 2178.0 m in core Uniejów IGH 1), and an upper interval, rather thin, possibly a few meters in thickness only – where these ammonites, generally smaller in size, are encountered commonly (recognized in cores: 2178.0–2177.0 m in Uniejów IGH 1; 2184.2–2183.0 m in Koło IG 3, and 2402.5–2400.1 m in Poddębice IG 1). The younger deposits of the Pałuki Formation in the cores studied yield other small cardioceratids referred to the genus *Nannocardioceras.* They are represented by *N.* cf. *krausei* (Salfeld) found at 2174.1 m (Pl. 2: 1), and *Nannocardioceras volgae* (Pavlov) at 2172.3, 2172.1 and 2171.0 m in core Uniejów IGH 1 (Pl. 2: 2–4). Similar ammonites were encountered in the cored interval of the Poddębice PIG 2 section between 2520.5 and 2520.1 m. These deposits are distinguished herein as the *Nannocardioceras* beds (Fig. 2).

It should be remembered that the Upper Kimmeridgian deposits in central and northern Poland which yielded cardioceratid ammonites were distinguished in the past (Dembowska, 1965; see also Malinowska, 1976, 2001) as the *Amoeboceras* beds (or zone) with *Hoplocardioceras* and *Nannocardioceras* (as interpreted herein) occurring commonly, *Aulacostephanus* occurring rarely, and *Glochiceras*, *Taramelliceras*, *Aspidoceras*, *Sutneria* encountered only in their lower part. According to this definition – the beds with common small-sized *H. elegans* found in the cores studied – which yield also Submediterranean ammonites should be correlated with a lower part of the *Amoeboceras* beds, whereas the younger deposits with common *Nannocardioceras* and generally poor in Submediterranean ammonites should belong to their upper part. Malinowska (2001) correlated originally all the *Amoeboceras* beds with the Eudoxus Zone, but there is no doubt that their upper part belongs already to the lowermost part of the Autissiodorensis Zone (see Kutek, Zeiss, 1997; Rogov, 2010).

The *Nannocardioceras krausei* species has been described also from core sections in the south-eastern part of the Łódź Synclinorium "near the base of the strata ascribed to the Autissiodorensis Zone", whereas *N. volgae* is encountered in large profusion in a narrow stratigraphical interval called the Volgae Bed, corresponding already to the lower part of the Autissiodorensis Zone (Kutek, Zeiss, 1997, p. 126). Ammonites of the genus *Nannocardioceras* represented by two closely related but possibly different species *N. anglicum* (Salfeld) and *N. krausei* (Salfeld) were described from the Warlingham Borehole in southern England (Callomon, Cope, 1971) from deposits of the upper Eudoxus Zone and lower Autissiodorensis Zone. According to Cox and Gallois (1981, p. 19) the highest representative of the *Nannocardioceras* in Dorset, southern England, is "a distinctive form with fine-rectiradiate ribbing assigned to *N.* aff. *anglicum*", and this form corresponds already to *N. volgae* (see Rogov, 2010, and earlier references given therein). More recently Rogov (2010) has shown, that in the Gorodishchi section (Middle Volga area, Russia) specimens similar to the species *N. anglicum* occur in the uppermost part of the Eudoxus Zone, whereas *N. krausei* occurs in the lowermost part of the Autissiodorensis Zone. The younger assemblage composed of *N. volgae* represents there the well-defined *volgae* horizon in the lower part of the Autissiodorensis Zone, corresponding to a lower part of the Subborealis Subzone (Rogov, 2010). These data indicate that the interval with the ammonites *Nannocardioceras krausei* and *N. volgae* from Uniejów IGH 1 between 2174.1 and 2171.0 m (and its cored fragment in Poddębice PIG 2 between 2520.5 and 2520.1 m) should correspond already to the lowermost part of the Autissiodorensis Zone, and thus the boundary with the underlying Eudoxus Zone should be placed directly below this interval (Fig. 2). This suggests that the thickness of the uppermost part of the Eudoxus Zone, although not faunistically recognized in the cores studied, does not exceed a few meters.

Younger deposits from the Uniejów IGH 1 core yielded an assemblage of ammonites composed mostly of representatives of the genus *Sarmatisphinctes.* An older assemblage of these ammonites appears at 2170 m (*Sarmatisphinctes* sp.), and then it occurs between 2166.9 and 2161.8 m (*S. subborealis* – cf. *subborealis* (Kutek et Zeiss) (Pl. 2: 6, 7), continuing up to 2156 m (*S. zeissi* Rogov) (Pl. 2: 8). Additionally some ammonites of the genus *Aulacostephanus* are reported from 2170 m (Pl. 2: 5), but they are generally poorly preserved being unsuitable for specific identification. Similar ammonites occur also in other cores studied: in Koło IG 4, *Sarmatisphintes* cf. *subborealis* (Kutek et Zeiss) at 1978.6 and 1978.1 m, and *Aulacostephanus* sp. at 1973.6 and 1973.4 m; and in Poddębice PIG 2, *S. subborealis* at 2519.3–2519.1 m (Pl. 2: 9), directly above the last ammonites of the genus *Nannocardioceras.*

The genus *Sarmatisphinctes* Kutek et Zeiss, 1997 was originally established for ammonites grouped around *Sarmatisphinctes fallax* Ilovaisky, 1941 (described and illustrated in: Ilovaisky and Florensky, 1941, p. 45, pl. 2: 5; 3: 6–8), the species showing highly irregularly developed virgataxioceratoid ribbing. This form evolved according to Kutek and Zeiss (1997) from Mediterranean/Submediterranean *Discosphinctoides* through the species newly established by them – *Discosphinctoides subborealis.* This latter form according to Scherzinger and Mitta (2006) and Rogov (2010) should be interpreted, however, already as an early representative of the genus *Sarmatisphinctes.* Such an assumption is based on a tendency to develop the irregular mode of furcation of ribs which is observed in some specimens of this species. All these species were derived possibly from still earlier forms of *Discosphinctoides*. A few specimens possibly belonging to that genus have been reported from the Eudoxus Zone in cores in the south-eastern part of the Łódź Synclinorium (Kutek, Zeiss, 1997, pl. 1: 7, 8).

The lower part of the Autissiodorensis Zone characterized by the common occurrence of an early representative of *Sarmatisphinctes* was distinguished by Zeiss (2003) as the Subborealis Subzone. It was emended by Rogov (2010) who distinguished the *S. zeissi* horizon it its upper part, marked by the occurrence of the species *Sarmatisphinctes zeissi* Rogov. This species includes forms similar to the earlier *S. subborealis* but showing more commonly occurring triplicate ribs. The total range of early representatives of *Sarmatisphinctes* in the Middle Volga area of Russia (Rogov, 2010) includes both older horizons with *Nannocardioceras* such as *N. krausei* and *N. volgae*, and younger ones where the ammonites *Sarmatisphinctes* prevail – and these units altogether define the Subborealis Subzone. According to this interpretation the total thickness of the Subborealis Subzone in core Uniejów IGH 1 attains about 18–20 meters, and is similar to that of coeval deposits from south-eastern part of the Łódź Synclinorium (*cf.* Kutek, Zeiss, 1997). It should be remembered that the basal part of the Subborealis Subzone of the Autissiodorensis Zone occurs both in the Uniejów IGH 1 core and the Poddębice PIG 2 core in a similar stratigraphical position about 30–35 meters above the top of the Limestone-Marly-Coquina Formation, which means that the underlying deposits of the Eudoxus Zone (except its lower part) are of nearly all the same thicknesses. A similar situation occurs possibly in core Poddębice IG 1. On the other hand, the interval between the top of the Limestone-Marly-Coquina Formation, and the first occurrence of *Sarmatisphinctes* in core Koło IG 4 is smaller, attaining about 20 meters. This is also possibly the case in core Koło IG 3 where the assemblage of ammonites composed of small *Hoplocardioceras elegans* together with *Aspidoceras* and *Sutneria* occurs about 10 meters lower in the succession when compared with the coeval level in the cores Uniejów IGH 1 and Poddębice IG 1 (Fig. 2). These observations suggest some synsedimentary reduction of thickness of the Upper Kimmeridgian deposits in cores Koło IG 3 and Koło IG 4 when compared with other cores, possibly related with salt-movements in the substrate in the active tectonic zone (Dadlez, Franczyk, 1976; *cf*. Dembowska, 1990d).

The upper part of the Autissiodorensis Zone corresponds to the Fallax Subzone. It is defined by the occurrence of ammonites of the genus *Sarmatisphinctes* showing highly irregular virgataxioceratid ornamentation on the outer whorls (Ilovaisky, Florensky, 1941; Kutek, Zeiss, 1997). Although the specimens of *S. fallax* as interpreted by Kutek and Zeiss (1997, p. 147) show a "wide spectrum of intraspecific variability at each level", the species "permits to separate out a narrow interval of high correlation value, at the top of the Autissiodorensis Zone". The form *Sarmatisphinctes ilowaiskii* as distinguished by Rogov (2010) includes morphotypes characterized by a rarity of virgatotome ribs, and the prevalence of biplicate and triplicate ribs, defining the upper part of the Fallax Subzone, directly below the Lower Tithonian Klimovi Zone. The deposits of the Fallax Subzone were recognized in core Uniejów IGH 1 at 2152.7 (*S. fallax* – Pl. 3: 1), at 2152.4 (*S.* cf. *fallax* – Pl. 3: 2), and at 2152.2 m (*S.* cf. *ilowaiskii* – Pl. 3: 3). These ammonites occur between the last find of *Sarmatisphinctes* (*S. zeissi*) at 2156.0 m indicative of the upper part of the Subborealis Subzone of the Autissiodorensis Zone, and the first occurrence of *Ilowaiskya klimovi* (Ilovaisky) at 2150.2 m indicative already of the Klimovi Zone of the lowermost Tithonian. These data indicate that: (1) the total thickness of the Fallax Subzone of the uppermost Kimmeridgian is very small, and it does not range above a few meters in thickness in core Uniejów IGH 1, and the situation is similar in the south-eastern part of the Łódź Synclinorium where it attains about 3 meters in thickness only, as shown by Kutek and Zeiss (1997): (2) that the boundary between the Kimmeridgian and Tithonian can be placed in core Uniejów IGH 1 in a narrow interval between 2152.2 and 2150.2 m (Fig. 2).

Lower Tithonian. The Lower Tithonian deposits in the cores studied are characterized by the occurrence of ammonites of the genus *Ilowaiskya* strictly comparable with the Russian representatives of the "Lower Volgian" succession (see Rogov, 2017 and earlier papers cited therein). They are recognized as corresponding to the successive ammonite zones: the Klimovi Zone, the Sokolovi Zone, the Pseudoscythica Zone according to Ilovaisky and Florensky (1941) and Mikhailov (1964), as well as the following Puschi Zone or the Tenuicostata Zone according to Kutek and Zeiss (1974, 1988, 1994, 1997). All these zones together with the younger Scythicus Zone of the lowermost "Middle Volgian" correspond to the Lower Tithonian in the twofold division of this stage (Matyja, Wierzbowski, 2016; Pszczółkowski, 2016; Wierzbowski *et al*., 2017; and earlier papers cited therein).

The Klimovi Zone is defined by the occurrence of *Ilowaiskya klimovi* (Ilovaisky) characterized by dominant biplicate ribbing on the inner whorls, followed by bi- and triplicate ribbing at larger diameters. The species occurs between 2150.2 (*I. klimovi* – Pl. 3: 4) and 2138.3 to 2137.7 m (*I.* cf. *klimovi* – Pl. 3: 5, 6) in core Uniejów IGH 1. It was recognized also in core Koło IG 3 between 2148.0 and 2146.0 m (*I.* cf. *klimovi*). These findings are generally in a similar stratigraphical position in the cores, beginning from about 52–55 meters above the top of the Limestone-Marly-Coquina Formation, but the approximate total thickness of the Klimovi Zone can be calculated in the Uniejów IGH 1 core only where it attains about 15 meters (Fig. 2). It is generally comparable with that given in south-eastern part of the Łódź Synclinorium (Kutek, Zeiss, 1997).

The younger Sokolovi Zone is recognized also in the cores studied. The occurrence of *Ilowaiskya sokolovi* (Ilovaisky) interpreted according to Mikhailov (1964) was recognized in core Uniejów IGH 1 at 2133.6 (Pl. 4: 1), and at 2132.75 m (Pl. 4: 2), although the latter specimen differs from typical forms of the species in its having more involute coiling of the inner whorls. The same species was recognized in core Koło IG 4 between 1933.5 and 1932.0 m. Another form from the same zone referred to as *Ilowaiskya* cf. *pavida* (Ilovaisky) has been found in core Poddębice IG 1 at 2361.3 m (Pl. 4: 3). This species is characteristic of the upper part of the Sokolovi Zone (Kutek, Zeiss, 1997; Rogov, 2010). These data make possible the correlation between the particular core sections, and suggest similar thicknesses for the deposits of the zone, which may be approximated to about 10–15 meters when taking into account also the occurrence of ammonites of the still younger Pseudoscythica Zone in both Koło IG 4 and Poddębice IG 1 cores (Fig. 2). It is comparable to that of the Sokolovi Zone in the south-eastern part of the Łódź Synclinorium (Kutek, Zeiss, 1997).

Ammonites of the Pseudoscythica Zone referred to as *Ilowaiskya* cf. *pseudoscythica* (Ilovaisky) are recognized in core Koło IG 4 at 1921.6 m (Pl. 4: 4), and in core Poddębice IG 1 at 2360.6 m. Both of them show a characteristic dischizotomous subdivision of the ribs which takes place rather high on the whorl side – very similar to the specimens of this species illustrated by Mikhailov (1964, pl. 2: 1, 2). These specimens represent a rather more coarsely ribbed variant of *I. pseudoscythica* which "seems to be restricted to some relatively low levels in the Pseudoscythica Zone" (Kutek, Zeiss, 1997, p. 165). Some of these specimens from core Koło IG 4 have been referred in the past (Dembowska, 1990c, d) erroneously to the genus *Zaraiskites.*

The youngest ammonites in the core sections are indicative of the Puschi Zone (=Tenuicostata Zone). The Tenuicostata Zone (*e.g*. Kutek, Zeiss, 1997) is based on the occurrence of *Ilowaiskya tenuicostata* (Mikhailov), and a specimen referred to that species has been recognized in core Poddębice PIG 2 at 2464.2 m (*I. tenuicostata* – Pl. 4: 5). According to Rogov (2017) the Puschi Zone as originally distinguished in central Poland by Kutek and Zeiss (1974) on the basis of the ammonite "*Pseudovirgatites*" has priority over the Tenuicostata Zone. Moreover, the species *I. tenuicostata* occurs only in the lower part of this zone, whereas the more heavily ornamented ammonites of the genus "*Pseudovirgatites*" sensu Kutek and Zeiss (1974) occur throughout the zone and are the phylogenetic forerunner of later *Zaraiskites.* A fragment of such a heavily ornamented whorl with mostly biplicate ribbing has been found at 2322.5 m in core Poddębice IG 1. Because of fragmentary preservation it may be referred either to the genus "*Pseudovirgatites*" or even to *Zaraiskites*. It should be remembered that the name "*Pseudovirgatites*" as used for ammonites grouped around such species as "*P.*" *puschi* Kutek et Zeiss and "*P.*" *passendorferi* Kutek et Zeiss and its allies is inappropriate, because it is a homeomorph of the much younger Late Tithonian genus name *Pseudovirgatites* (Rogov, 2017).

The data indicate the occurrence of the lower part of the Puschi (=Tenuicostata) Zone in the section Poddębice PIG 2 at 2464.2 m, and an interval corresponding either to an upper part of the Puschi (=Tenuicostata) Zone or some lower part of the Scythicus Zone in the section Poddębice IG 1 at 2322.5 m, but they do not offer any possibility of detailed recognition of the zone boundaries (Fig. 2). They indicate, however, that the deposits between 2320–2324 m in core Poddębice IG 1 cannot be compared with the characteristic "brachiopod layer" (as suggested by Dembowska, 1990d), because this layer was originally distinguished by Dembowska (1973, 1979) in central Poland in a much younger part of the succession with ammonites of the genus *Zaraiskites*. Moreover, there is no direct palaeontological criterion enabling the distinction of the stratigraphical interval corresponding to the Puschi (=Tenuicostata) Zone in the other cores studied. The only ammonites found at 1911.6 m and 1915.3 m in core Koło IG 4 are very fragmentarily preserved and difficult to interpret. It should be remembered, however, that their ornamentation is very heavy and irregular which suggests some relation with "*Isterites*" sensu Kutek and Zeiss (1974) and/or "*Danubisphinctes*" as interpreted by Rogov (2017), known from the upper part of the Pseudoscythica Zone and of the Puschi Zone of central Poland (Kutek, Zeiss, 1974).

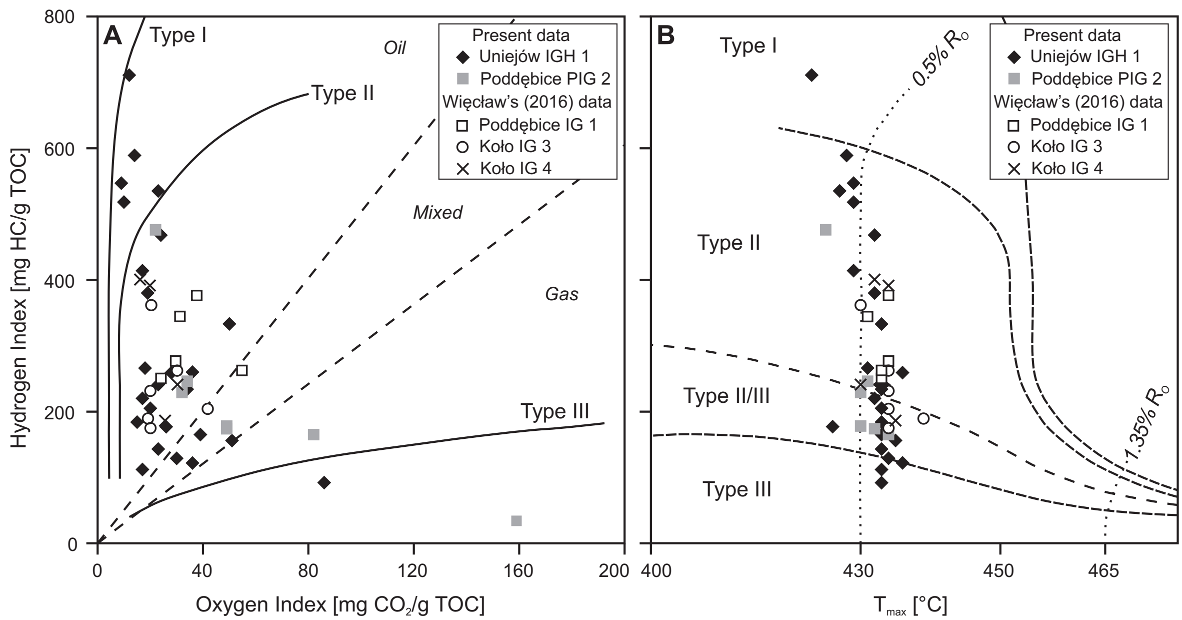


Fig. 3. Hydrogen index versus (A) oxygen index and (B) T_{max} values diagrams used for the identification of genetic types of kerogen

ORGANIC MATTER

Conducted Rock Eval analyses of samples from the Uniejów IGH 1 and Poddębice PIG 2 boreholes have revealed Total Organic Carbon (TOC) concentrations between 0.3 and 9.2 wt.% (mean 2.7 wt.%) in the Pałuki Formation (Appendix: Table 2). The published TOC concentrations from the Pałuki Formation of the Koło IG 3, Koło IG 4, Poddębice IG 1, and Poddębice PIG 2 boreholes range from 0.2 to 4.7 wt.% (*cf.* Rzepkowska, 1990; Klimuszko, 2012; Więcław, 2016). Our findings and Więcław's (2016) data show the predominance of Type II kerogen with an admixture of Type III (Fig. 3). Four samples characterized by high TOC concentrations (3.4 to 9.6 wt.%) from the Uniejów IGH 1 borehole show, however, elevated hydrogen indexes (518 to 711 mg HC/g TOC) and low oxygen indexes (9 to 14 mg CO_2/g TOC), which places them close to the pathway of Type I kerogen (Fig. 3). The effects of mineral matrix and possible oxidation processes on hydrogen and oxygen indexes are noticeable for samples with TOC concentrations below 1.5 wt.%. High values of correlation co-efficients between TOC and both hydrogen and oxygen index values are also observed (Fig. 4). The present Rock Eval data from the Uniejów IGH 1 and Poddębice PIG 2 boreholes are similar to those of Więcław (2016) derived from the Pałuki Formation in the Poddębice IG 1, Koło IG 3, and Koło IG 4 boreholes (Figs 3, 4). All the present and Więcław's (2016) Rock Eval data show low T_{max} (423 to 439°C) and low productivity index values (0.03 to 0.12; Fig. 5).

Temporal variations of TOC contents and hydrogen index values, based on published and new data as well as the biostratigraphy of the studied sections, are depicted on Fig. 6. Average TOC concentrations amount to 2.5 wt.% in the lower and middle parts of the Pałuki Formation (middle Eudoxus–lower Pseudoscythica zones) except for some intervals enriched in organic carbon (up to 9.2 wt.%; Fig. 6). The general TOC concentration likely falls to *ca.* 1 wt.% in the upper part of the Pałuki Formation (in the upper Pseudoscythica–Scythicus zone interval; Fig. 6). Apart from a single data point increase in TOC content in the mid-Eudoxus Zone (to 9.2 wt.%), distinct increases occur in the lowermost part of the Autissiodorensis Zone (to 6.8 wt.%) and at the Sokolovi–Pseudoscythica zone boundary (to 6.9 wt.%). Increases in TOC concentrations are mostly correlated with elevated values of the hydrogen index (390–710 mg HC/g TOC), albeit high values of the hydrogen index (330–590 mg HC/g TOC) are also observed in the lowermost part of the Pałuki Formation belonging to the Eudoxus Zone and the Klimovi Zone (Fig. 6). Possible spatial differentiation of TOC and HI of samples between various boreholes cannot be determined because of the scatter of data points and the scarcity of samples in some stratigraphical intervals.

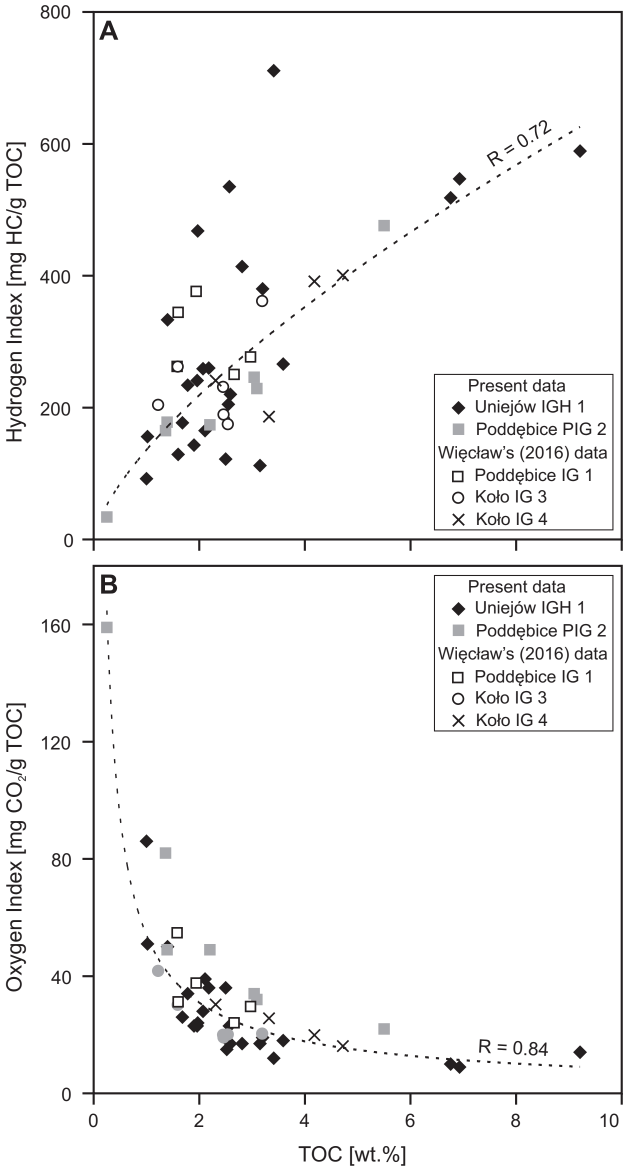


Fig. 4. TOC versus (A) hydrogen index and (B) oxygen index diagrams. A strong (R = 0.72, p <0.01) and very strong, power function, correlation (R = 0.84, p <0.05) observed between the TOC and, respectively, HI and OI values reveal mineral matrix and oxygenation effects

DISCUSSION

SOURCE, TYPE, THERMAL MATURITY AND DISTRIBUTION OF ORGANIC MATTER

Several models explaining the accumulation of widespread organic-rich Upper Jurassic strata in the Subboreal basins of Europe have been proposed. The "stratified basin model" of Tyson *et al*. (1979) predicts a stable pycnocline as a source of anoxic conditions on the sea bottom. In the models of irregular bottom topography ("the puddle model") of Hallam and Bradshaw (1979) and Wignall and Hallam (1991) deep-water anoxic conditions are postulated to have occurred in areas of high subsidence rate and limited water advection. Oschmann (1988, 1991) suggests in turn the presence of temporal upwelling or thermal stratification of the water column during a hot season. According to Miller (1990) changes in water density contributed to the appearance of a superficial "Boreal current" which flowed southward into the NW European basins on top of warm, saline bottom water. Other authors emphasize the role of phytoplankton blooms for the deposition of Upper Jurassic blackshales (Kessels *et al*., 2003; Shchepetova *et al*., 2011). It should be also noted that the deposition of Upper Jurassic organic-rich facies is often considered as facilitated by a high-sea level as "transgressions commonly generate silled basins which are favourable for preservation of the organic matter…" (Herbin *et al*., 1995, p. 192, 193). Although the role of marine transgressions in the deposition of Upper Jurassic organic matter-rich facies in deeper, restricted areas of sedimentary basins is highlighted in many studies (*e.g.* Wignall, Hallam, 1991; Smelror *et al*., 2001; Kessels *et al*., 2003; Shchepetova *et al*., 2011) one should remember that they must have had a regional impact only and did not break the partial isolation of the Subboreal basins. This is substantiated by the occurrence of local ammonite faunas in the Upper Kimmeridgian–Lower Tithonian of northern Europe and a recent clumped isotope study from the Russian Platform which documents restriction and slight freshening of the Middle Russian Sea (Volga Basin) during the sedimentation of Kimmeridgian organic-rich strata (Wierzbowski *et al*., 2018). Diminished water circulation and salinity stratification of the water column might have been key factors responsible for the occurrence of bottom water anoxia in epeiric Subboreal basins including north-central Poland.

Measured TOC concentrations (0.2 to 9.2 wt.%) in the Pałuki Formation from the central-eastern part of the Łódź Synclinorium are comparable to those of the Kimmeridge Clay facies of NW Europe (*cf.* Gallois, 1979; Cooper *et al*., 1995; Morgans-Bell *et al*., 2001), however, particularly organic-rich samples with TOC concentrations above 10 wt.% have not been found in Central Poland (Appendix: Table 2).

Present Rock Eval data from the Uniejów IGH 1 and Poddębice PIG 2 boreholes are in line with the study of Więcław (2016), which shows the predominance of the oil-prone, marine Type II kerogen in the Upper Kimmeridgian part of the Pałuki Formation in Central Poland. A bias of oxygen and hydrogen indexes of some samples characterized by low TOC concentrations to the pathway of Type III kerogen is partly an effect of mineral matrix and secondary oxygenation processes (*cf.* Espitalié *et al*., 1980, 1984; Pe-

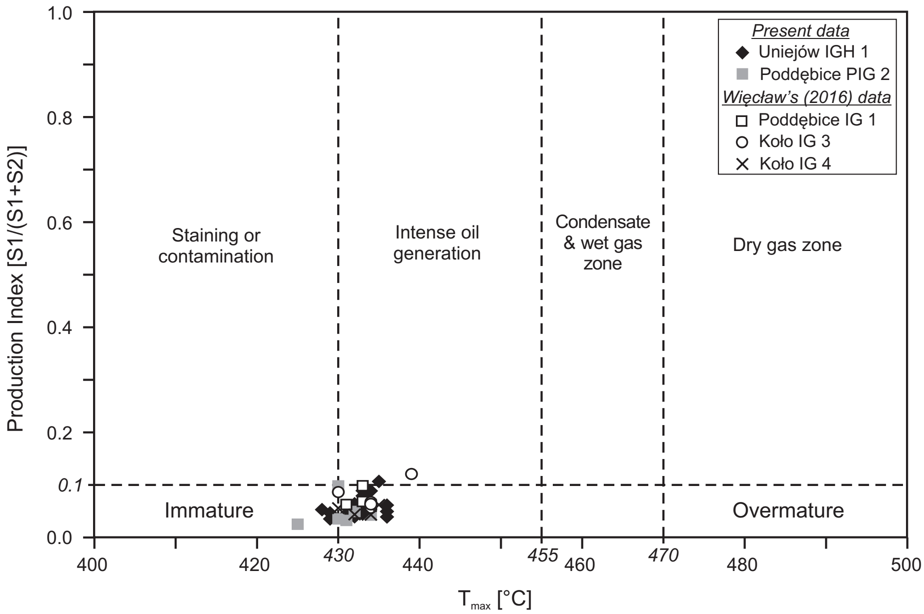


Fig. 5. T_{max} values versus production index. Low values of both parameters show weak thermal maturity of the Pałuki Formation deposits in the studied boreholes from central-eastern part of the Łódź Synclinorium

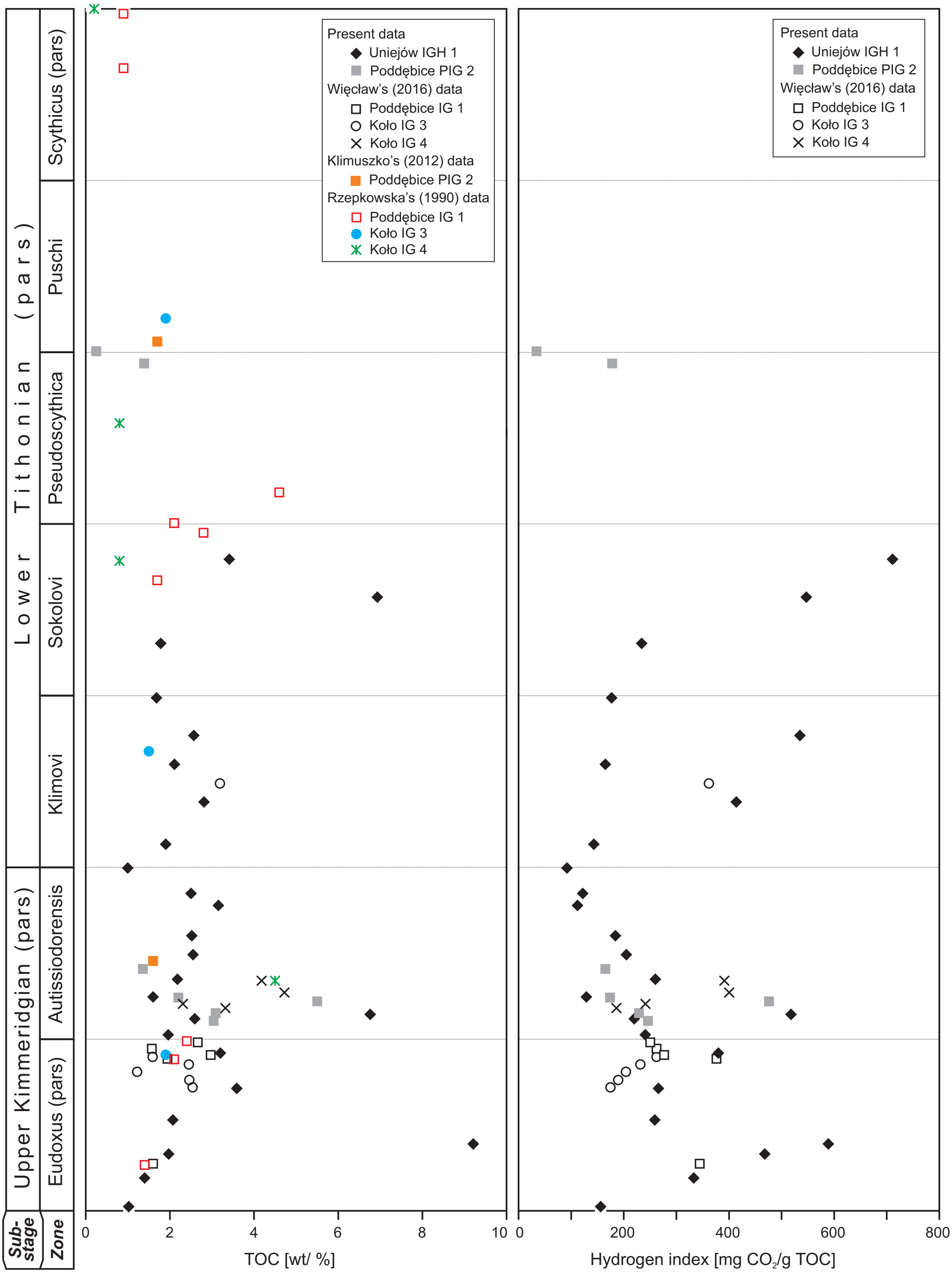
ters, 1986; Dembicki, 1992; Więcław, 2016). Very high hydrogen and low oxygen indexes of some samples with high TOC content (3.4 to 9.6 wt.%) from the Uniejów IGH 1 borehole may indicate the presence of highly reactive Type IIS kerogen, as the studied strata were deposited in the marine depositional environment and should not contain chemically similar Type I kerogen of lacustrine or brackish origin. Additional biomarker and atomic ratio studies are necessary to verify these results. It is worth noting that the presence of Type IIS kerogen is documented from the Kimmeridge Clay and inferred as an admixture in the Upper Kimmeridgian strata of Central Poland (*cf*. Gallois, 1979; Cooper *et al*., 1995; Więcław, 2016). The Polish samples from the Szczecin-Łódź-Miechów Synclinorium studied by Więcław (2016) had, however, a maximal TOC content of 4.7 wt.% (and 6.6 wt.% in the Mid-Polish Anticlinorium) and mostly comprised other kerogen types. This may be due to the investigation of partially cored sections, which did not include the most organically rich intervals.

Więcław (2016) has documented the fair to excellent theoretical petroleum potential of the Pałuki Formation in central Poland. Low T_{max} (*ca.* 430°C) and production index values (usually below 0.1) in both the present and Więcław's (2016) datasets from the Łódź Synclinorium show, however, low thermal maturity and initial hydrocarbon generation in the studied rocks (Fig. 5). The Rock Eval data are in agreement with published results of vitrinite reflectance analyses showing low R_o values (mostly between 0.5 and 0.6%) of the Pałuki Formation in the Łódź Synclinorium (Grotek, 2012a; Więcław, 2016). Although higher values of R_o of *ca.* 1.0% were reported for the Upper Jurassic deposits in the Przybyłów 1 borehole by Burzewski *et al.* (1990) these results have not be substantiated by the recent study of Więcław (2016), who documented the R_o value of *ca.* 0.8% and T_{max} of *ca.* 430°C for the Pałuki Formation from this borehole. Higher and scattered R_o values from the Przybyłów 1 borehole may be a result of suppression or misidentification of vitrinite particles (*cf*. Dembicki, 2017).

It is often postulated that the Pałuki Formation could be a commercial source of hydrocarbons, especially in the deepest, central-eastern part of the Łódź Synclinorium, where thermogenic processes are predicted to be more advanced (*cf.* Burzewski *et al*., 1990; Nowicki *et al*., 1990; Bachleda-Curuś *et al*., 1992; Krzywiec *et al*., 2014, 2015a, b; Cyz *et al*., 2016; Socha, Makos, 2016; Więcław, 2016). Nevertheless, a structural map of the top of the Kcynia Formation in the study area (Fig. 1) and the vitrinite reflectance trend obtained for the Poddębice PIG 2 borehole (Grotek, 2012a) suggest that deposits of the Pałuki Formation may reach maximally *ca.* 0.7% R_o in depressions which occur between elevated salt structures, *e.g.* in the Koło and Wrząca troughs at depths of 3000–3200 m. This value of thermal

→

Fig. 6. Distribution of TOC and hydrogen index in the Pałuki Formation from the studied boreholes in central-eastern part of the Łódź Synclinorium. The vertical scale of the diagram is based on the assumption of equal duration of ammonite zones of the Upper Kimmeridgian–Lower Tithonian


Present data
Uniejów IGH 1
Poddębice PIG 2
Więcław's (2016) data
Poddębice IG 1
Koło IG 3
Koło IG 4
Klimuszko's (2012) data
Poddębice PIG 2
Rzepkowska's (1990) data
Poddębice IG 1
Koło IG 3
Koło IG 4
Sub-stage
Zone
Upper Kimmeridgian (pars)
Lower Tithonian (pars)
Eudoxus (pars)
Autissiodorensis
Klimovi
Sokolovi
Pseudoscythica
Puschi
Scythicus (pars)
TOC [wt/ %]
Hydrogen index [mg CO_2/g TOC]

maturity is still located in the early oil window (*cf.* Dembicki, 2009). Taking into account the low permeability (*cf.* Szewczyk, 2012) and significant thickness of the deposits of the Pałuki Formation, their thermal maturity seems to be insufficient to allow (i) either the expulsion and migration of large amounts of hydrocarbons into the overlying rocks, which is possible at peak of the oil window (at R_o between 0.8 and 1.0% for Type II kerogen), (ii) or the formation of a working shale gas play (possible at R_o between 1.2 and 2.5%; *cf*. Dembicki, 2017).

The high thermal maturity of the Pałuki Formation in the deep troughs of the Łódź Synclinorium postulated by some authors (*cf.* Burzewski *et al.*, 1990; Socha, Makos, 2016), seems to be a result of misidentification of vitrinite particles (see discussion above) or the transposition of the higher R_o values of other Jurassic–Triassic sediments occurring at depths of 1500–2800 m in the Kujavian segment of the Mid-Polish Anticlinorium (*cf.* Grotek, 2008; 2012b). It is worth noting that the two to four times higher thermal conductivity of salt compared to other sedimentary rocks may produce positive temperature anomalies (Magri *et al*., 2008; Zhuo *et al*., 2015). This should result in higher temperatures and maturity of the Upper Jurassic rocks from the sedimentary cover of salt diapirs in the Łódź Synclinorium, which is also partly revealed in geological sections with geoisotherms (see Górecki *et al.*, 2006). It should, however, be born in mind that the Upper Jurassic rocks forming the sedimentary cover of salt domes from central-eastern part of the Łódź Synclinorium occur at a much shallower depth than those from intervening troughs (Fig. 1) and could also have not reached the advance phases of hydrocarbon generation.

Another important question is the concentration of organic matter in the lithostratigraphical section of the Pałuki Formation. Earlier studies failed to solve this problem because of local sampling intervals and the lack of the biostratigraphical data which might have allowed correlation of different boreholes. The compilation of published and new data shows a general TOC concentration of *ca.* 2.5 wt.% in the lower and middle parts of the Pałuki Formation with narrow intervals enriched in organic carbon (up to 9.2 wt.%). A fall of TOC concentrations (to *ca.* 1 wt.%) is observed in the upper, more calcareous, part of the Pałuki Formation (Figs 2, 6). This documents short- and long-term variations in the organic matter content of the Pałuki Formation in the stratigraphical profile, which is similar to the characteristic of the Kimmeridge Clay Formation (*cf.* Gallois, 1979; Morgans-Bell *et al*., 2001). It is worth noting that small scale rhythms, mostly 1 to 2 m thick, are observed in the Kimmeridge Clay. They consist, in the upper part of the Lower Kimmeridge and the Upper Kimmeridge Clay, of packages of oil shales, dark grey mudstones and grey calcareous mudstones showing marked differences in TOC content (Gallois, 1979). Although such rhythms are difficult to recognized in drill cores, their occurrence may explain high amplitude variations of organic matter content of the sections studied.

The detailed correlation of a single data point increase in TOC content from the middle part of the Eudoxus Zones with a similar increase from southern England (*cf.* Birkelund *et al.*, 1983, fig. 2) is not certain. High TOC values are also reported there from unit KC29 and the lowermost part of unit KC30 corresponding to the upper middle part of the Eudoxus Zone (Morgans-Bell *et al.*, 2001, fig. 4). Distinct increases in TOC content from the lowermost part of the Autisiodorensis Zone and from the Sokolovi–Pseudoscythica zone boundary of the Łódź Synclinorium clearly correspond to the exceptionally organic-rich deposits of England, which are assigned to the uppermost Eudoxus–lowermost Autissiodorensis Zone, and the Wheatleyensis–Hudlestoni boundary interval (*cf.* Gallois, 1979; Birkelund *et al*., 1983; Morgans-Bell *et al*., 2001; see also discussions in the next section). This points to a strict similarity in environmental conditions and water circulation between the mid-Polish and the NW European basin during the latest Kimmeridgian–Early Tithonian.

As more stable anoxic conditions are generally inferred for the deeper parts of sedimentary basins of the Kimmeridge Clay type facies characterized by a high subsidence rate (*cf.* Hallam, Bradshaw, 1979; Wignall, Hallam, 1991; Smelror *et al*., 2001; Kessels *et al*., 2003; Shchepetova *et al*., 2011) the spatial differentiation of organic matter content in the Pałuki Formation from Central Poland may also be expected. Krzywiec (2004), Krzywiec *et al*. (2015a, b), and Cyz *et al*. (2016) have shown that the growth of salt structures in the Łódź Synclinorium, starting from the Early Triassic, resulted in thinning of their sedimentary cover and shallower facies development. The salt tectonics is simultaneously responsible the occurrence of deeper Jurassic facies and their larger thickness in the intervening synclines (Krzywiec *et al.*, 2015a, b; Cyz *et al*., 2016). The rise of the salt structures at the boundary of the Łódź Synclinorium and the Kujavian segment of the Mid-Polish Anticlinorium during the Late Jurassic is also documented by a growth of Oxfordian microbial-sponge bioherms (Matyja, Wierzbowski, 1985). In addition, this lithological pattern is substantiated by the thickening of the Pałuki Formation to 125 m in the Poddębice PIG 2 borehole located at the edge of a foredeep basin (Wrząca trough) of the Kłodawa Salt Diapir (Gaździcka, 2012a; Fig. 2). Although the present data do not reveal visible changes in organic matter content between coeval parts of borehole sections (Fig. 6) some increase in TOC concentrations may be inferred for the deepest parts of the Łódź Synclinorium, which were characterized by a higher subsidence rate during the Jurassic (Fig. 1). Unfortunately, this hypothesis cannot be empirically verified as there are no available drill cores from Jurassic deposits from those deep troughs (*e.g*. Koło and Wrząca troughs) located in the study area.

CHANGES IN AMMONITE ASSEMBLAGES AND BIOSTRATIGRAPHIC CORRELATIONS OF THE ORGANIC MATTER RICH DEPOSITS

Palaeobiogeographical and stratigraphical setting. The occurrence of deposits rich in organic matter in the Upper Jurassic succession in areas of the north-west European shelf (northern France, and southern and eastern England) as well as of central Russia is well recognized and well-defined in terms of ammonite stratigraphy (see *e.g*. Gallois, 1979; Geyssant *et al.*, 1993; Herbin, Geyssant, 1993; Herbin *et al.*, 1995; Hantzpergue *et al.*, 1998; Morgans-Bell *et al.*, 2001; Zakharov *et al.*, 2017). This enables the precise recognition of the intervals enriched in organic matter and their correlation with those from the territory of Poland. Additional comments on ammonite phylogeny and palaeobiogeography during the Late Kimmeridgian–Early Tithonian may be used as a palaeobiological approach to changes in the environment and sedimentation responsible for the accumulation of the organic-rich deposits.

The relative sea-level changes were marked by changes in ammonite assemblages. The periodic expansions of Submediterranean and Subboreal ammonites corresponded mostly to the transgressive phases and the maximum sea-level rises on the Western European shelf. The spread of Subboreal (and Boreal) ammonites occurred mostly during the deepening events, whereas ammonites of Submediterranean origin commonly produced thereafter local endemic lineages (Hantzpergue, 1995). Moreover, during the rise of sea-level and with the higher distribution of the organic matter ammonites with evolute, serpenticone shells (mostly Subboreal in nature) dominated, whereas in the episodes of a smaller palaeodepth – ammonites with globulous morphology directly originating from Submediterranean forms appeared (Geyssant *et al.*, 1993; Geyssant, 1994). The study of the ammonite assemblages in term of ammonite composition and morphology in the cores studied, and their comparison with those in the different successions of northern European areas, gives thus the basis for definition of the main transgressive impulses marked by a higher content of organic matter in the Upper Kimmeridgian and Lower Tithonian.

The overall transgression during the latest Early Kimmeridgian resulted in the appearance of belts of similar facies on the whole northern Tethyan shelf, and brought here the new ammonite faunas. Towards the south, the siliciclastic and lumachelle deposits of the Kimmeridge Clay-type facies are replaced laterally by the marls and limestones of the “facies virgulien” with oyster *Nanogyra virgula*. The ammonites of Subboreal affinity of the family Aulacostephanidae with the genus *Rasenioides*, and its descendant the genus *Aulacostephanoides*, dominated everywhere in the north, whereas the new Tethyan representatives of the family Ataxioceratidae with such genera as *Crussoliceras* and *Garnierisphinctes* occurred mostly in the south. These two areas corresponded during the Late Kimmeridgian to the Subboreal Province, and the Submediterranean Province, respectively, and were subdivided by an intermediate biogeographical area of latitudinal continuation in the middle of the northern Tethyan shelf. Detailed analysis showed that its faunas were composed both of Subboreal and Submediterranean (Tethyan) ammonites along with some endemic forms. The faunas originally distinguished as typical of the “biome franco-germanique” (French-German Biome) occurred in the intermediate area called the Western Europe Swell (see Hantzpergue, 1989, 1995; Enay *et al*., 2014). This characteristic palaeobiogeographic unit continued intermittently, however, farther east to central Poland (Kutek, Zeiss, 1997), and even more eastward to the central part of European Russia (Rogov *et al*., 2017).

The Upper Kimmeridgian ammonite succession from the epicratonic area of Poland shows thus several features in common with both Submediterranean and Subboreal (and even Boreal) areas, but it reveals also the specific features which enable recognition of some of the ammonite zones and subzones of the intermediate areas corresponding to the “biome franco-germanique” according to Hantzpergue (1989). The Upper Kimmeridgian succession begins with deposits of the Limestone-Marly-Coquina Formation in the SW margin of the Holy Cross Mts in central Poland and the coeval deposits of the lower part of the Pałuki Formation in the Kujawy area of northern Poland. These deposits yielded some ammonites from the Divisum Zone of the topmost part of the Lower Kimmeridgian to the Mutabilis Zone of the lower part of the Upper Kimmeridgian. These latter include both Mutabilis Subzone forms and Lallierianum Subzone forms with the *Orthaspidoceras schilleri* horizon at the top, the youngest horizon of the Mutabilis Zone (Matyja, Wierzbowski, 2000a; Matyja *et al.*, 2006). It should be remembered, however, that the ammonite succession in the Mutabilis Zone has not been recognized in sufficient detail in Poland to enable a precise correlation to be made between the distribution of the organic matter and the biostratigraphy.

Organic matter rich shale has been recorded outside Poland, in central Russia in Tatarstan and in eastern England (Yorkshire) in the lower part of the Upper Kimmeridgian (see Hantzpergue *et al.*, 1998). The detailed ammonite stratigraphy in central Russia (Rogov *et al*., 2017; Zakharov *et al*., 2017) suggests that the deposits rich in organic matter occur near the top of the Mutabilis Subzone in beds which yield Subboreal (*Aulacostephanoides*) and Boreal (small unidentifiable cardioceratids), as well as Submediterranean aspidoceratid ammonites, which correlates well with the location of the maximum sea-level rise as interpreted by Hantzpergue (1989, 1995). The main levels with organic matter-rich shales occur, however, higher in the succession, especially in the uppermost Kimmeridgian, and in the Lower Tithonian.

Upper Kimmeridgian – middle Eudoxus Zone. The Upper Kimmeridgian deposits of the Eudoxus Zone, the oldest of the stratigraphical intervals being the main subject of the study, represent the beginning of the new transgressive pulse in Poland (Kutek, 1994; Wierzbowski, 2019), and everywhere (*e.g.* Enay *et al.*, 2014, and older papers cited therein). The sudden appearance of the new Subboreal ammonite fauna with the genus *Aulacostephanus* at the base of the Eudoxus Zone gives "the impression of an abrupt faunal transgression" – this is observed not only in southern England (Birkelund *et al.*, 1983), but also commonly in the northern part of the Tethyan shelf. The aspidoceratids along with representatives of the *Aspidoceras caletanum* group, and their microconchs of the genus *Sutneria*, migrated commonly into the Subboreal Province of England from the late Mutabilis Chron and during the later Kimmeridgian, being especially common in the middle of the Eudoxus Chron (Callomon, Cope, 1971; Geyssant, 1994). In central Poland, the lower part of the Eudoxus Zone seems to be dominated by ammonites of the genus *Aulacostephanus*, indicating stronger Subboreal influences, but the overlying beds yield numerous Submediterranean ammonites, showing stronger Submediterranean influences. These beds may be correlated with the Caletanum Subzone, representing the middle part of the Eudoxus Zone of the "biome franco-germanique" (Hantzpergue, 1989).

In the Eudoxus Zone begins the Late Kimmeridgian–Lower Tithonian interval where organic-rich mudstones are especially widely distributed in the Subboreal-Boreal areas of the northern Tethyan shelf (*e.g.* Herbin *et al.*, 1995; see also Wignall, 1994 and papers cited therein). In Dorset, southern England, the middle part of the Eudoxus Zone includes a narrow organic-rich interval in chronostratigraphical unit KC 29 (Gallois, 2016) which includes Subboreal (*Aulacostephanus*) and Submediterranean (*Aspidoceras*, *Sutneria*) ammonites with less common Boreal cardioceratids. The ammonite fauna indicates a correlation with the Caletanum Subzone (Birkelund *et al.*, 1983, tab. 1). These deposits are considered as formed during the deepening phase (Hantzpergue, 1989, 1995). The overlying KC 30 unit contains Submediterranean *Crussoliceras* that has been correlated with Hantzpergue's (1989) E6 (=XXVI) marker bed and referred already to the Contejeani Subzone of the upper Eudoxus Zone (Birkelund *et al.*, 1983).

In the Polish cores studied a single data point increase in organic matter content (to 9.2 wt.%) is observed in the middle part of the Eudoxus Zone of the Uniejów IGH 1 core at 2193.5 m.

Upper Kimmeridgian – uppermost Eudoxus to lowermost Autissiodorensis Zone and the problem of the *Nannocardioceras* faunas. A marked change in the ammonite faunas took place in the succession studied from Poland in the Eudoxus Zone, and it is shown by occurrence of the Boreal ammonites *Hoplocardioceras elegans* Spath. Although the first appearance of this ammonite is noted already in the middle part of the Eudoxus Zone, it becomes especially common in the higher part of this zone. The common occurrence of the *H. elegans* assemblage in the Eudoxus Zone suggests stronger Boreal influences. It should be remembered, however, that ammonites of Submediterranean affinity are commonly encountered also in this part of the succession in central Poland (Malinowska, 2001).

The problem of the boundary between the Eudoxus Zone and the Autissiodorensis Zone is strictly related in the succession studied in Poland with occurrence of a very characteristic faunal assemblages composed of numerous small-sized cardioceratids attributed to the genus *Nannocardioceras* which generally follow here the assemblage of *Hoplocardioceras elegans.* The cardioceratid ammonites are not known, however, from the succession representing the "biome franco-germanique" of western Europe, where the highest assemblage of the Eudoxus Zone, well above that of the Caletanum Subzone, is characterized by occurrence of *Aulacostephanus* such as *A. contejeani* (Thurmann) and *A. yo* (d'Orbigny) indicative of the Contejeani Subzone (Hantzpergue, 1989). The recently recognized occurrence of *Aulacostephanus yo* in the Subboreal succession of southern England (Gallois *et al.*, 2015), very close to the beds with numerous *Nannocardioceras*, indicates the top of the Eudoxus Zone, and makes correlation possible with the typical succession of the "biome franco-germanique". On the other hand, the new fauna of *Aulacostephanus* composed of *A. volgensis* and *A. autissiodorensis* groups indicative of the Autissiodorensis Zone, appears fairly sharply and it occurs together with some *Nannocardioceras* in southern England, central Poland and central Russia (Callomon, Cope, 1971; Kutek, Zeiss, 1997; Rogov, 2010).

The stratigraphical succession of *Nannocardioceras* ammonites at the boundary between the Eudoxus Zone and the Autissiodorensis Zone has been discussed recently by Rogov (2010) who described the Upper Kimmeridgian deposits that crop out in the banks of the middle part of the River Volga in central Russia. He recognized forms similar to *N. anglicum* (Salfeld) in the topmost part of the Eudoxus Zone, followed by *N. krausei* (Salfeld) and *N. volgae* (Salfeld) (see also Scherzinger and Mitta, 2006) in the lowermost part of the Autissiodorensis Zone. In southern and eastern England *N. anglicum* and *N. krausei* occur together in the *Nannocardioceras* – rich beds adjacent to the Eudoxus and Autissiodorensis zonal boundary, with the highest recorded *N. krausei* in the lower Autissiodorensis Zone (Callomon, Cope, 1971). The well-defined Volgae Marker Bed with abundant *N. volgae* occurs in the lower part of the Autissiodorensis Zone in southern England above the youngest *N. krausei* (Gallois, 2017, and earlier papers cited therein). The common occurrence of *N. krausei* below *N. volgae* is recognized also in the lower part of the Autissiodorensis Zone in south-eastern part, and in central part of the Łódź Synclinorium (Kutek, Zeiss, 1994; and data presented herein). These observations indicate that the general succession of the cardioceratid ammonites at the boundary of the Eudoxus and Autissiodorensis zones shows strong similarities over a large area including central Russia, central Poland, southern and eastern England of the northern Tethyan shelf.

The spatial and chronostratigraphical relationships of the larger cardioceratid *Hoplocardioceras* and the smaller *Nannocardioceras* has been discussed by Wierzbowski and Rogov (2013, p. 1099) who recognized that the *Nannocardioceras* "is practically unknown in the high-latitude Arctic, being widely distributed in more southerly located areas like Britain, the Russian Platform, and central and northern Poland". According to these authors such a geographical distribution may suggest that the *Nannocardioceras* faunas represent a local offshoot from the main stock of *Hoplocardioceras*. This offshoot composed of "small-sized microconchs" developed mainly at the more peripheral areas having a special environmental conditions", and was replaced by the coeval normal-sized *Hoplocardioceras* towards the north in the Boreal Province.

This interpretation is strongly supported herein by new observations which suggest the continuous transition between the two groups of ammonites in the succession studied. The specimens of *Hoplocardioceras elegans* commonly occurring in the cores in the higher part of the Eudoxus Zone show generally fairly small-sizes for that species, from about 20–30 mm to about 40–50 mm in diameters. The fully grown specimens of the species from the typical Boreal areas like Spitsbergen are always much larger, usually about 40 to 90 mm in diameter (Wierzbowski, 1989). It should be mentioned that a single specimen found in the older part of the Eudoxus Zone Uniejów IGH 1 is also larger and attains about 80 mm in diameter. The common feature recognized both in Polish and Spitsbergen specimens of *H. elegans* is moreover the occurrence of some crowding of the ribs observed at different diameters evidently marking some differences in growth rate of the shell.

The stratigraphically older representatives of the genus *Nannocardioceras* show general similarity in their type of ornamentation to that of early stages of *H. elegans*, although the comparison is possible at small sizes of the shell (generally around 20 mm diameters for *Nannocardioceras*) [*cf.* ornamentation of small-sized *Nannocardioceras anglicum* (Salfeld) in: Callomon, Cope (1971, pl. 11: 5a, b) with that of *H. elegans* in: Birkelund, Callomon (1985, pl. 6: 4–6)]. On the other hand, some younger *Nannocardioceras* like *N. krausei* show ornamentation composed of simple or biplicate slightly flexuous ribs which thicken in the ventrolateral region, somewhat resembling ornamentation of the older *N. anglicum*, but it is replaced by dense faint ribbing and/or following less or more discernible striation on the last whorl. Still younger *N. volgae* shows the fine falcoid ribbing usually ranging to about 20 mm in diameter, becoming more fine or tending to be turned into striae at the end of the shell. This dense ribbing suggests the low rate of growth of the shell at its final stage. Some specimens from central Poland attributed to *N. volgae* are even larger, and what is especially interesting, show some ribs which "usually thicken in the ventrolateral region, displaying a tendency to form prorsiradiate clavi or less elongated tubercles" (Kutek, Zeiss, 1997, p. 136, pl. 12). Another form reported from Poland together with *N. volgae* is "*Amoeboceras*" *pristophorum* (Krause). It shows strongly developed ventrolateral tubercles and possibly "represent but an extreme variety" of *Nannocardioceras volgae* as interpreted by Kutek and Zeiss (1997, p. 138). It should be remembered that tubercles found in these extreme specimens referred to *N. volgae* are very similar to those of *Hoplocardioceras elegans*, although in the latter species they are usually recognized at larger diameters.

The *Nannocardioceras* ammonites were always considered as representing a separate dwarf-offshoot of the *Amoeboceras* lineage (Spath, 1935, p. 28). The data given suggest that they reveal in fact two-phase growth of their shells. The older stage of ornamentation is comparable to that of their possible forerunners – *H. elegans* with closing of its growth-range in phylogeny towards smaller diameters. In term of heterochrony it is a progenetic feature. The younger stage observed at a larger diameter is marked by a very slow growth rate of the shell which may be classified as dwarfism. Such changes of shell growth recognized in some invasive forms of *Amoeboceras* in the Upper Oxfordian of Poland were interpreted as relating to the special environmental conditions which could have influenced the development of ammonites (Matyja, Wierzbowski, 2000b).

A conspicuous interval of organic-rich rocks which has a large geographical distribution occurs in the uppermost Eudoxus (unit KC 33) and the lowermost Autissiodorensis Zone (lower part of unit KC 34) in southern England (Dorset). It contains common oil shales with numerous *Nannocardioceras* (Callomon, Cope, 1971; Cox, Gallois, 1981; Gallois, 2017; Gallois *et al.*, 2019). It has also been recorded at a single locality (Gorodishchi) in the Middle Volga area of central Russia (Zakharov *et al.*, 2017, and earlier papers cited therein). The same interval rich in organic matter is recognized in central and northern Poland as described herein (see also data on geographical distribution of these ammonites as given by Malinowska, 2001). In the cores studied it was recognized in Uniejów IGH 1 core at 2172.1 m, and in Poddębice PIG 2 core at about 2521.1 m where it directly corresponds to the *Nannocardioceras* beds, but a higher content of organic matter occurs also directly above, in the lowermost part of the Subborealis Subzone of the Autissiodorensis Zone, in Koło IG 4 at 1976–1974 m (see Rzepkowska, 1990; Więcław, 2016; Fig. 6). The interpretation of the small *Nannocardioceras* ammonites as the descendants of larger (“normal”) sized *Hoplocardioceras* which evolved in the special conditions of the Late Kimmeridgian open-marine basin has to take into account their numerous occurrence in shales rich in organic-matter. This may suggest that the development of *Nannocardioceras* took place during maxima of transgression in the surface waters, occurring generally as nectopelagic forms without any contact with the deeper zone of more or less anoxic bottom waters where the deposits rich in organic matter were preserved.

Upper Kimmeridgian – middle to upper parts of the Autissiodorensis Zone. A special group of ammonites appearing already in the Eudoxus Zone in central Poland are ataxioceratid ammonites closely related with the Tethyan genus *Discosphinctoides* (Kutek, Zeiss, 1997, p. 118; pl. 1: 6, 7). These ammonites evolved into *Sarmatisphinctes* during the Late Kimmeridgian in vast areas of the NE Subboreal areas of Europe from central and southern European Russia to central and northern Poland (Kutek, Zeiss, 1997; see also Rogov, 2010) where they are the dominant ammonite genus of all except the oldest part of the Autissiodorensis Zone. The parallel lineage in north-western European areas included mostly representatives of the genus *Subdichotomoceras* and other ammonites that were derived from the ataxioceratid group possibly related mostly to the genus *Crussoliceras* and its allies (Enay *et al*., 2014). The development of these ammonites marks the beginning of diversification of the ammonite faunas on the whole northern Tethyan shelf, similar to that which took part during the Early Kimmeridgian (*cf.* Wierzbowski *et al.*, 2016).

A smoothly evolving lineage of *Sarmatisphinctes* during the latest Kimmeridgian was described originally by Rogov (2010) from central European Russia. It is represented in the central Poland succession (see chapter on stratigraphy herein; see also Kutek, Zeiss, 1997) by several species including *S. subborealis* (Kutek et Zeiss), *S. zeissi* Rogov, *S. fallax* (Ilovaisky) and *S. ilowaiskii* Rogov. The general feature shown by the first three species of the lineage is the successive appearance of triplicate and later virgataxioceratoid ribs and a higher secondary/primary ribs ratio on the last whorl. This trend is reversed at the top of the Autissiodorensis Zone where the last representative of *Sarmatisphinctes – S. ilowaiskii* Rogov shows once more the dominance of triplicate and biplicate ribbing on the outer whorl, representing a transition to the first *Ilowaiskya* (*cf.* also Rogov, 2010, figs 4, 5). The evolution of the *Sarmatisphinctes* lineage thus shows marked changes in the rate of development, *i.e.* of heterochrony – initially with acceleration in the development of ornamentation, and later a slower rate of development of ornamentation. This interval is also relatively rich in organic matter on the Dorset coast albeit having total organic carbon contents less than those of the Eudoxus Zone (Gallois, 1979).

Lower Tithonian. The junction of the Kimmeridgian and Tithonian Stages is marked over much of NW and NE Europe by the disappearance of the Subboreal genus *Aulacostephanus* where it is replaced by genera that developed independently in separate basins, by *Pectinatites* and its descendants in the NW, and *Ilowaiskya* and its descendants in the NE. *Pectinatites* and *Ilowaiskya* gave rise to new Subboreal lineages during the later Tithonian and although the two lineages show special features in their evolution the stratigraphical correlation of particular members is difficult (see *e.g.* Callomon, Birkelund, 1982). The Submediterranean oppeliids in central Poland represented mostly by the genus *Neochetoceras* occur together with *Ilowaiskya* in the lower part of the Lower Tithonian (“Lower Volgian’) from the Klimovi Zone, but they are much more common in the overlying Sokolovi Zone, and completely disappear at the top of this zone (Kutek, Zeiss, 1997).

The stratigraphic distribution of the organic-rich facies is recognized in NW Europe in southern (Dorset) and eastern (Yorkshire) England and in northern France (Boulonnais area). Three organic-rich intervals have been recognized: (1) at the base of the Tithonian – in the Elegans Zone and the lower part of the Scitulus Zone, (2) in the upper part of the Wheatleyensis Zone and the basal part of the Hudlestoni Zone, and (3) in the upper part of the Hudlestoni Zone and the lowermost part of the Pectinatus Zone (Gallois, 1979), each of them marking transgressive impulses (Herbin, Geyssant, 1993; Herbin *et al*., 1995; Morgans-Bell *et al.*, 2001). Two closely spaced organic-rich intervals have been recorded in the successions in the Russian Platform: in the lower part of the Puschi Zone (=Tenuicostata Zone) and at the base of its upper part (Zakharov *et al.*, 2017). The correlation between the NW and NE European zonations (Callomon, Birkelund, 1982; *cf.* Rogov, Zakharov, 2009; Rogov, 2014; Wierzbowski *et al*., 2017) although “well assured” in the case of the Elegans Zone and the lower part of the Scitulus Zone, which correspond to the Russian and Polish Klimovi Zone, is “much less certain” in the case of younger levels. According to Rogov and Zakharov (2009), Rogov (2014), and Wierzbowski *et al*. (2017) the boundary between the English Wheatleyensis and Hudlestoni zones is in the youngest part of Russian (and Polish) Sokolovi Zone. That between the Hudlestoni and Pectinatus zones is in the upper part of the Pseudoscythica Zone. According to Hantzpergue *et al.* (1998, p. 30) the distribution of oil shale beds in the Kimmeridge Clay Formation, especially the Lower Tithonian examples "is completely different from those of the Volga Basin", because "these intervals were not associated with a relative change in water depth sufficient to allow dysoxic-anoxic conditions to be established".

The conditions, which possibly existed during the Early Tithonian in that part of central and northern Poland that was colonized by the *Ilowaiskya* and its descendants, seemed to be more suitable for preservation of organic matter. Levels with higher organic matter contents correlating possibly with the transgression maximum were recognized near the Sokolovi–Pseudoscythica zone boundary in core Poddębice IG 1 at 2357–2361 m (Rzepkowska, 1990) and in core Uniejów IGH 1 at 2124.5–2127.6 m. They correlate possibly with the *wheatleyensis* Band of Gallois (1979) comprising the Wheatleyensis–Hudlestoni zone boundary, which is the most organic rich level in England.

CONCLUSIONS

Precise biostratigraphical subdivision of the deposits of the Pałuki Formation in five boreholes (Uniejów IGH 1, Koło IG 3, Koło IG 4, Poddębice IG 1, Poddębice PIG 2) from the central-eastern part of the Łódź Synclinorium is presented based on new finds of ammonites and the revision of archive ammonite specimens. The studied strata comprise the Upper Kimmeridgian Eudoxus and Autissiodorensis zones and the Lower Tithonian Klimovi, Sokolovi, Pseudscythica and Puschi (=Tenuicostata) zones.

New and published geochemical data indicate low thermal maturity of the deposits and the predominance of oil-prone Type II kerogen. The biostratigraphical compilation of the data shows variations in the organic matter content within the profile of the Pałuki Formation. Average TOC concentrations amount to 2.5 wt.% in the lower and middle parts of the Pałuki Formation (middle Eudoxus–lower Pseudoscythica zones) and show narrow intervals enriched in organic carbon, *i. e*. a single increase in TOC content in the mid-Eudoxus Zones (to 9.2 wt.%), a distinct increase in the lowermost Autisiodorensis Zone (to 6.8 wt.%) and an increase at the Sokolovi–Pseudoscythica zone boundary (to 6.9 wt.%). The general TOC concentration decreases to ca. 1 wt.% in the upper part of the Pałuki Formation (the upper Pseudoscythica–Scythicus zones). Increases in TOC concentrations mostly correspond to elevated values of the hydrogen index and can be correlated with the most organic-rich intervals of the Kimmeridge Clay Formation of England. This indicates that similar environmental conditions prevailed during the latest Kimmeridgian–Early Tithonian in both the mid-Polish and the English basins. The changes in composition of the ammonite assemblages representing the different palaeobiogeographical provinces enable the recognition of the main transgressive impulses correlated with higher content of organic matter. The development of special morphologies of ammonites, including the occurrence of small-sized, nectopelagic forms of *Nannocardioceras* in the Late Kimmeridgian, is also related to the deposition of shales rich in organic matter during a transgression maximum.

Because of the scatter of data and scarcity of samples in some intervals the spatial differentiation of the organic matter content of the Pałuki Formation in the study area cannot presently be assessed. It is possible that the strata deposited in deeper areas of the sedimentary basin, characterized by a higher subsidence rate, contain more organic matter, but even there the relatively low thermal maturity of the deposits precludes the formation of large amounts of hydrocarbons. Additional investigations are needed to precisely document the distribution and high-amplitude variations in the organic matter content of the Pałuki Formation in the central-eastern part of the Łódź Synclinorium, the spatial variability of the composition of the deposits, and their relations to ancient sea-level and environmental changes.

Acknowledgements. This study was supported by the research grant no. 61.5101.1701.00.0 (supervisor – Anna Feldman-Olszewska) of the Polish Geological Institute – National Research Institute. Ammonites and stratigraphy were determined and elaborated by Andrzej Wierzbowski, whereas lithology and organic matter characteristics by Hubert Wierzbowski. The authors are grateful to Dariusz Więcław for kindly supplying the details of Rock Eval analyses from the Koło IG 3, Koło IG 4, and Poddębice IG 1 boreholes. Editorial referees – Ramues W. Gallois, Günter Schweigert and Dariusz Więcław are thanked for valuable comments and discussion.

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PLATE 1

Fig. 1. *Aulacostephanus* cf. *pseudomutabilis anglicus* (Steuer); Uniejów IGH 1, depth 2204.6 m; Eudoxus Zone, lower part; specimen no. Muz.PIG.1823.II.01

Fig. 2. *Aulacostephanus eudoxus eudoxus* (d'Orbigny); Uniejów IGH 1, depth 2178.6 m; fully grown specimen with lappets; phragmocone/body chamber boundary in the missing part of the last whorl; Eudoxus Zone, Caletanum Subzone; specimen no. Muz.PIG.1823.II.03

Fig. 3. *Aspidoceras* sp; Uniejów IGH 1, depth 2184.4 m; Eudoxus Zone, Caletanum Subzone; specimen no. Muz.PIG.1823.II.21

Fig. 4. *Aspidoceras* cf. *quercynum* Hantzpergue; Uniejów IGH 1, depth 2178.4 m; phragmocone; Eudoxus Zone, Caletanum (or ? Contejeani) Subzone; specimen no. Muz.PIG.1823.II.04

Fig. 5a, b. *Sutneria* aff. *eumela* (d'Orbigny); Uniejów IGH 1, depth 2180.3 m; both sides of fully grown specimen with lappets, phragmocone/body chamber boundary is arrowed; Eudoxus Zone, Caletanum Subzone; specimen no. Muz.PIG.1823.II.24; ×1.5

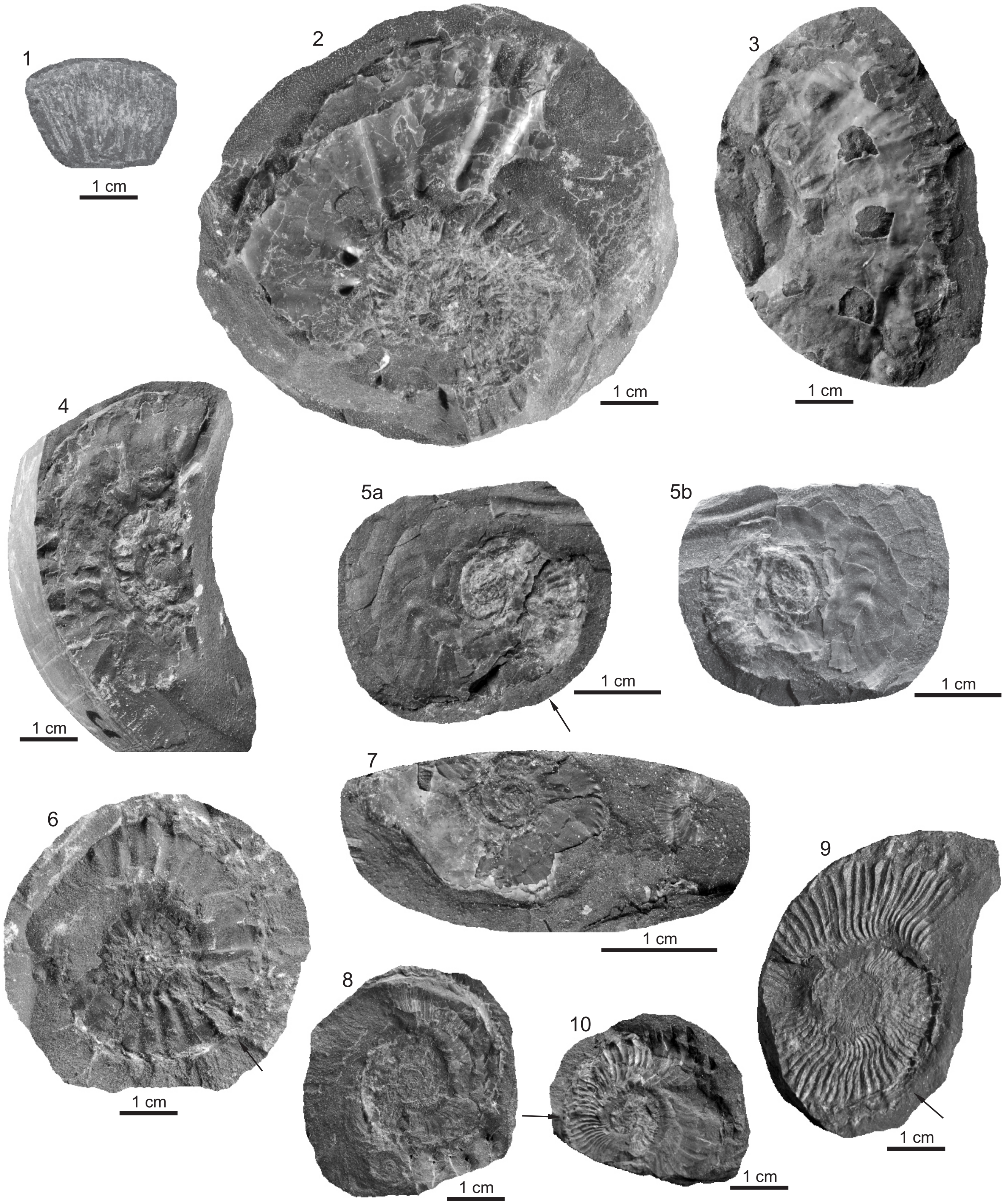
Fig. 6. *Hoplocardioceras elegans* (Spath); Uniejów IGH 1, depth 2191.5 m; heavily ornamented specimen similar to "*A. pseudoacanthophorum*" Spath (1935, pl. 5: 7, 8), phragmocone/body chamber boundary is arrowed; Eudoxus Zone, Caletanum Subzone; specimen no. Muz.PIG.1823.II.02

Fig. 7. *Hoplocardioceras elegans* (Spath) (left) – phragmocone and *Sutneria* sp. (right); Uniejów IGH 1, depth 2178.0 m; Eudoxus Zone, Caletanum Subzone (or ? Contejeani) Subzone; specimen no. Muz.PIG.1823.II.07; ×2

Fig. 8. *Hoplocardioceras elegans* (Spath); Poddębice IG 1, depth 2402.5 m; small fully grown specimen, phragmocone/body-chamber boundary is arrowed; Eudoxus Zone, Caletanum Subzone (or ? Contejeani); specimen no. Muz.PIG.1821.II.01

Fig. 9. *Hoplocardioceras elegans* (Spath); Poddębice IG 1, depth 2401.8 m; small fully grown specimen, phragmocone/body-chamber boundary is arrowed; Eudoxus Zone, Caletanum Subzone (or ? Contejeani); specimen no. Muz.PIG.1821.II.02

Fig. 10. *Hoplocardioceras elegans* (Spath); Poddębice IG 1, depth 2400.2 m; small fully grown specimen, phragmocone/body-chamber boundary is arrowed; Eudoxus Zone, Caletanum (or ? Contejeani) Subzone; specimen no. Muz.PIG.1821.II.03



Andrzej WIERZBOWSKI, Hubert WIERZBOWSKI – Ammonite stratigraphy and organic matter of the Pałuki Fm. (Upper Kimmeridgian–Lower Tithonian) from the central-eastern part of the Łódź Synclinorium (Central Poland)

PLATE 2

Fig. 1. *Nannocardioceras* cf. *krausei* (Salfeld); Uniejów IGH 1, depth 2174.1 m; ornamentation seen on phragmocone; *Nannocardioceras* beds, Autissiodorensis Zone; specimen no. Muz.PIG.1823.II.06; ×1.5

Fig. 2. *Nannocardioceras volgae* (Pavlov); Uniejów IGH 1, depth 2172.3 m; phragmocone, and a fragment of body-chamber preserved; *Nannocardioceras* beds, Autissiodorensis Zone, lowermost part; specimen no. Muz.PIG.1823.II.07; ×1.5

Fig. 3. *Nannocardioceras volgae* (Pavlov); Uniejów IGH 1, depth 2172.1 m; phragmocone and body chamber; *Nannocardioceras* beds, Autissiodorensis Zone, lowermost part; specimen no. Muz.PIG.1823.II.08; ×1.5

Fig. 4. *Nannocardioceras volgae* (Pavlov); Uniejów IGH 1, depth 2171.0 m; phragmocone and body chamber (half a whorl long); *Nannocardioceras* beds, Autissiodorensis Zone, lowermost part; specimen no. Muz.PIG.1823.II.09; ×1.5

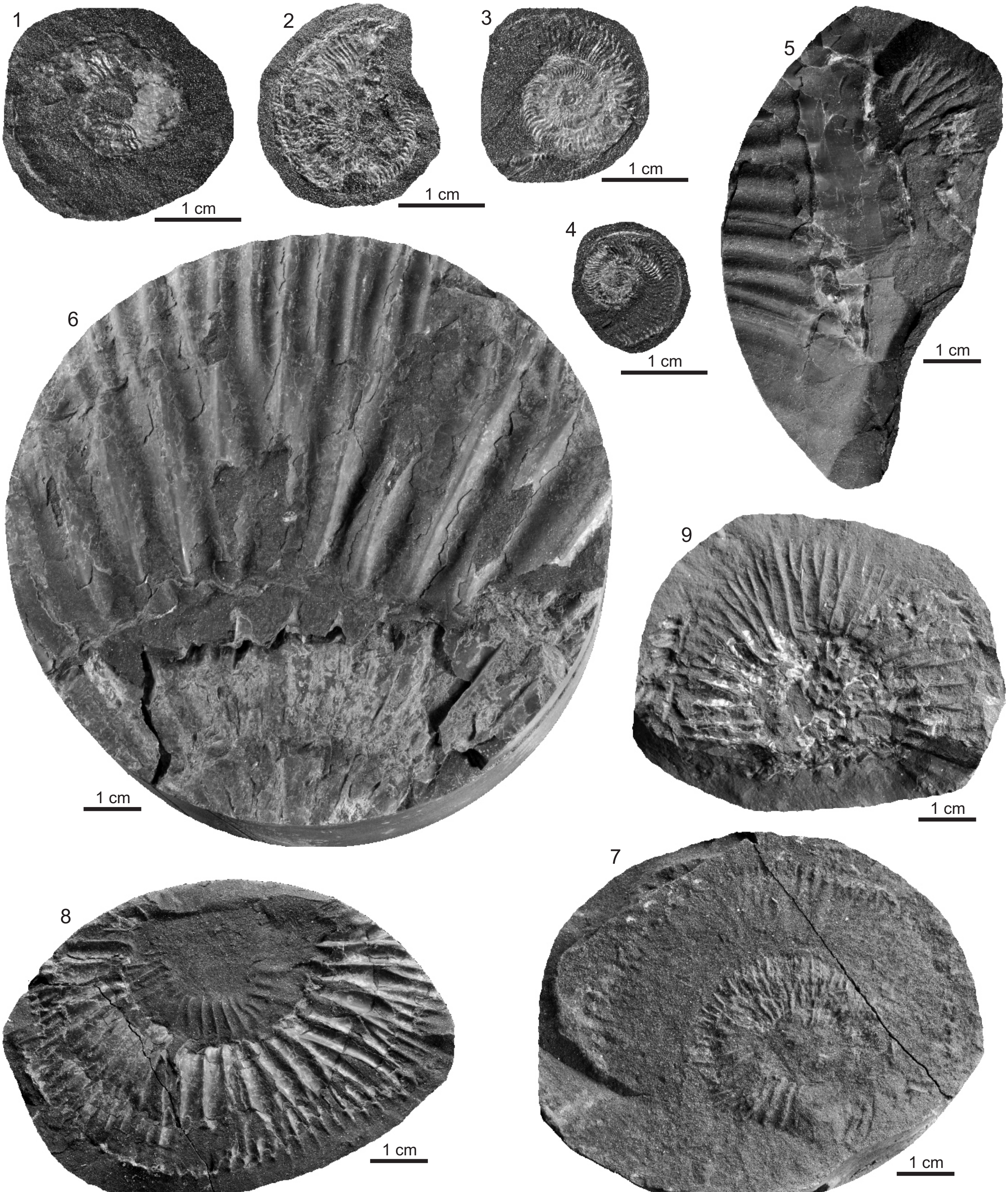
Fig. 5. *Aulacostephanus* sp. (left), and *Sarmatisphinctes* sp. (right); Uniejów IGH 1, depth 2170.0 m; Autissiodorensis Zone, Subborealis Subzone; specimen no. Muz.PIG.1823.II.10

Fig. 6. *Sarmatisphinctes subborealis* (Kutek et Zeiss); Uniejów IGH 1, depth 2166.9 m; inner whorls represent the phragmocone, a fragment of outer whorl – the body chamber; Autissiodorensis Zone, Subborealis Subzone; specimen no. Muz.PIG.1823.II.11

Fig. 7. *Sarmatisphinctes* cf. *subborealis* (Kutek et Zeiss); Uniejów IGH 1, depth 2161.8 m; Autissiodorensis Zone, Subborealis Subzone; specimen no. Muz.PIG.1823.II.12

Fig. 8. *Sarmatisphinctes zeissi* Rogov; Uniejów IGH 1; Uniejów IGH 1, depth 2156.0 m; Autissiodorensis Zone, Subborealis Subzone; specimen no. Muz.PIG.1823.II.13

Fig. 9. *Sarmatisphinctes subborealis* (Kutek et Zeiss); Poddębice PIG 2, depth 2519.1–2519.3 m; possibly only phragmocone; Autissiodorensis Zone, Subborealis Subzone; specimen no. Muz.PIG.1822.II.01



Andrzej WIERZBOWSKI, Hubert WIERZBOWSKI – Ammonite stratigraphy and organic matter of the Pałuki Fm. (Upper Kimmeridgian–Lower Tithonian) from the central-eastern part of the Łódź Synclinorium (Central Poland)

PLATE 3

Fig. 1. *Sarmatisphinctes fallax* (Ilovaisky); Uniejów IGH 1, depth 2152.7 m; Autissiodorensis Zone, Fallax Subzone; specimen no. Muz.PIG.1823.II.14

Fig. 2. *Sarmatisphinctes fallax* (Ilovaisky); Uniejów IGH 1, depth 2152.4 m; phragmocone/body-chamber boundary is arrowed; Autissiodorensis Zone, Fallax Subzone; specimen no. Muz.PIG.1823.II.15

Fig. 3. *Sarmatisphinctes* cf. *ilowaiskii* Rogov; Uniejów IGH 1, depth 2152.2 m; phragmocone; Autissiodorensis Zone, Fallax Subzone; specimen no. Muz.PIG.1823.II.22

Fig. 4. *Ilowaiskya klimovi* (Ilovaisky); Uniejów IGH 1, depth 2150.2 m; fragment of outer whorl represents the body-chamber; Klimovi Zone; specimen no. Muz.PIG.1823.II.16

Fig. 5. *Ilowaiskya* cf. *klimovi* (Ilovaisky); Uniejów IGH 1, depth 2138.3 m; Klimovi Zone; specimen no. Muz.PIG.1823.II.17

Fig. 6. *Ilowaiskya* cf. *klimovi* (Ilovaisky); Uniejów IGH 1, depth 2137.7 m; Klimovi Zone; specimen no. Muz.PIG.1823.II.18

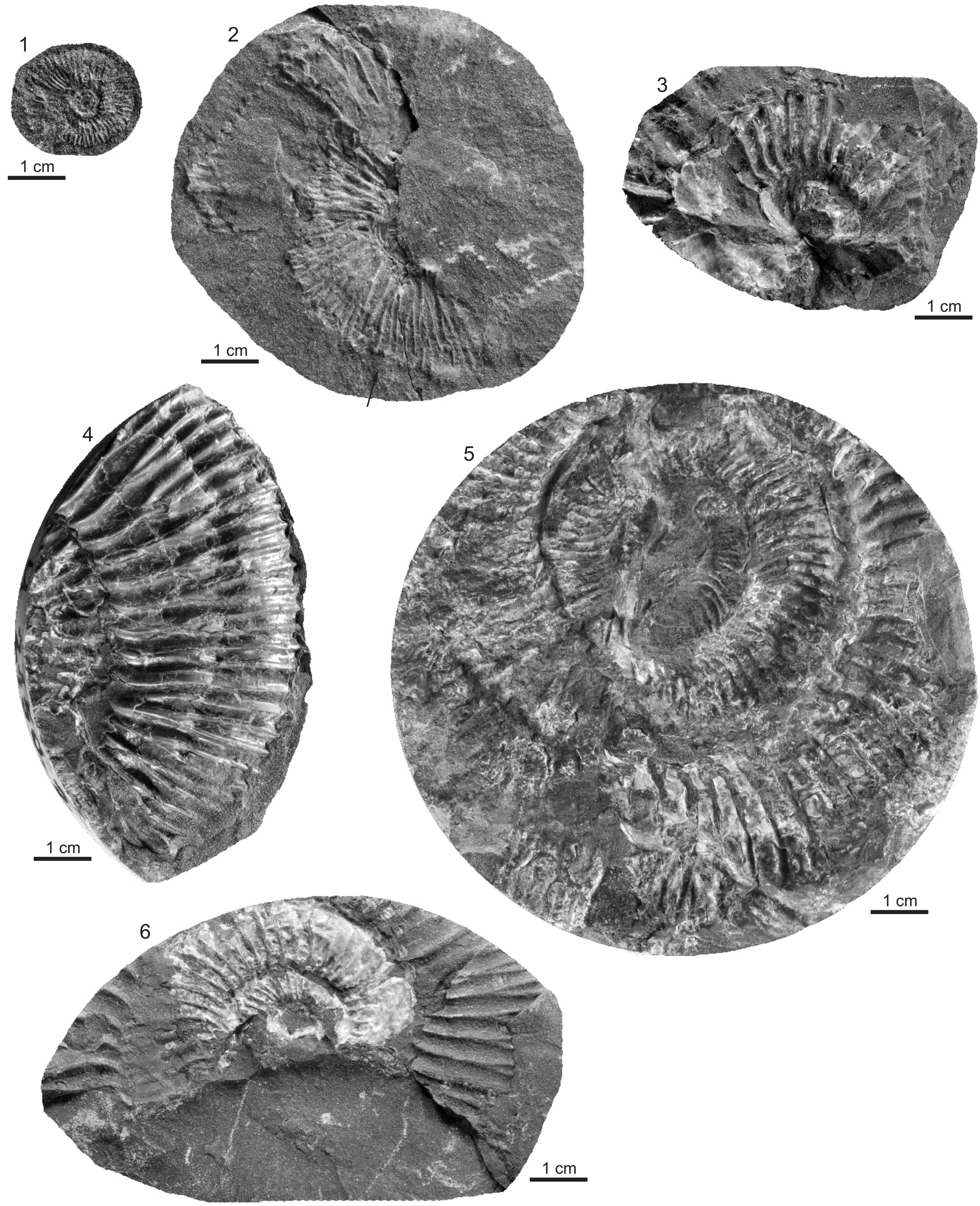


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PLATE 4

Fig. 1. *Ilowaiskya sokolovi* (Ilovaisky); Uniejów IGH 1, depth 2133.6 m; fragment of body-chamber; Sokolovi Zone; specimen no. Muz.PIG.1823.II.19

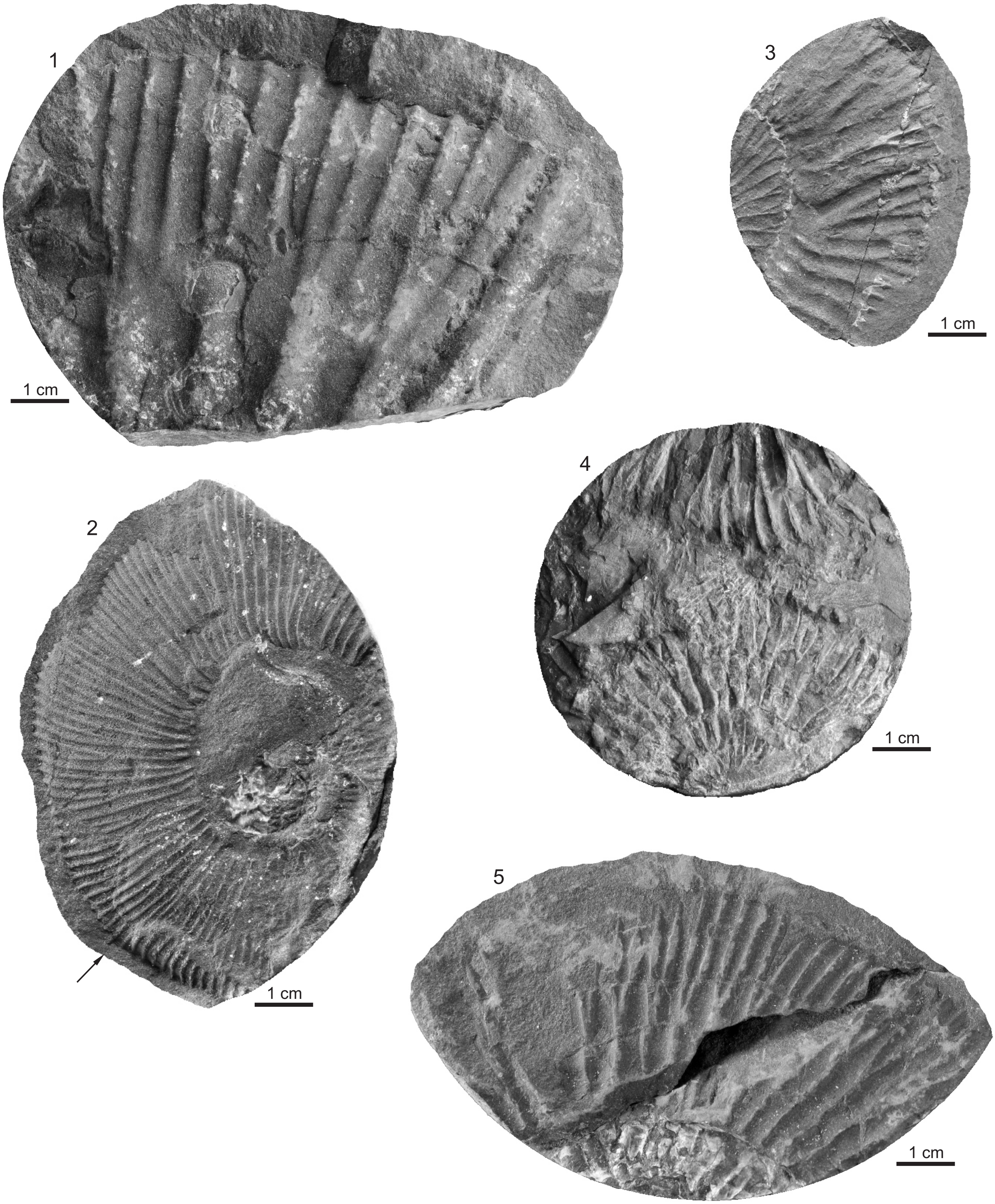
Fig. 2. *Ilowaiskya* aff. *sokolovi* (Ilovaisky); Uniejów IGH 1, depth 2132.75 m; phragmocone/body-chamber boundary is arrowed; Sokolovi Zone; specimen no. Muz.PIG.1823.II.20

Fig. 3. *Ilowaiskya* cf. *pavida* (Ilovaisky); Poddębice IG 1, depth 2361.3 m; Sokolovi Zone; specimen no. Muz.PIG.1821.II.12

Fig. 4. *Ilowaiskya* cf. *pseudoscythica* (Ilovaisky); Koło IG 4, depth 1921.6 m; Pseudoscythica Zone; specimen Muz.PIG.1929.II.3

Fig. 5. *Ilowaiskya tenuicostata* (Mikhailov); Poddębice PIG 2, depth 2464.2 m; Puschi =Tenuicostata Zone; specimen no. Muz.PIG.1822.II.04

All specimens in natural size unless specified otherwise



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(Upper Kimmeridgian–Lower Tithonian) from the central-eastern part
of the Łódź Synclinorium (Central Poland)

Appendix

Table 1

Lithology of the studied part of the Uniejów IGH 1 borehole (after Jaskowiak-Schoeneichowa *et al.*, 1991, modified)

Base [m]	Thickness [m]	Lithology	Fm	Data type	Remarks
2093.0	5.0	dolomitic limestone	VII	drill core	
2097.0	5.0	limestone	VII	geophysics	
2102.5	5.5	marly limestone	VI	geophysics	
2108.0	5.5	marls	VI	geophysics	
2115.0	7.0	marly limestone	VI	geophysics	
2118.0	3.0	claystone	VI	geophysics	
2121.3	3.3	grey limestone	VI	drill core	9.1 m core yield for 2118–2127.6 m
2121.6	0.3	dark grey marl	VI	drill core	
2123.2	1.6	grey limestone	VI	drill core	
2124.4	1.2	dark grey marl	VI	drill core	
2126.2	1.8	grey limestone	VI	drill core	
2127.1	0.9	dark grey marl	VI	drill core	
2127.6	0.5	dark grey claystone with muscovite	VI	drill core	
2133.3	5.7	dark grey marl	VI	drill core	
2133.7	0.4	dark grey, strongly calcareous claystone	VI	drill core	
2134.5	0.8	dark grey marl	VI	drill core	
2142.9	8.4	dark grey, strongly calcareous claystone (thick plates)	VI	drill core	
2143.2	0.3	grey marly limestone with calcite veins	VI	drill core	
2143.7	0.5	dark grey, strongly calcareous claystone (thick plates)	VI	drill core	
2144.8	1.1	dark grey, strongly calcareous claystone (thin plates)	VI	drill core	
2149.5	4.7	dark grey, strongly calcareous claystone (thick plates)	VI	drill core	
2157.5	7.8	dark grey claystone	VI	drill core	
2174.8	17.3	dark grey, strongly calcareous claystone (thick plates)	VI	drill core	
2184.0	9.2	dark grey marly claystone (thin plates)	VI	drill core	7.0 m core yield for 2174.8–2184.3 m
2184.3	0.3	grey marly limestone with bivalve debris	VI	drill core	
2202.1	17.8	dark grey marly claystone (thin plates)	VI	drill core	
2204.9	2.8	dark grey marly claystone	VI	drill core	
2206.1	1.2	oyster (*Exogyra*) coquina	V	drill core	
2210.3	4.2	dark grey marly claystone	V	drill core	
2211.3	1.0	oyster (*Exogyra*) coquina	V	drill core	
2211.9	0.6	dark grey marly limestone with marl intercalations	V	drill core	
2212.0	0.1	oyster (*Exogyra*) coquina	V	drill core	
2221.3	9.3	grey marly limestone with marl intercalations	V	drill core	7.0 m core yield for 2219.8–2228.6 m
2222.5	1.2	oyster (*Exogyra*) coquina	V	drill core	
2236.6	14.1	grey marly limestone with marl intercalations	V	drill core	
2237.4	0.8	grey marly limestone, with bivalve debris at the base	V	drill core	

V – Limestone-Marly-Coquina Formation, VI – Pałuki (Shale-Marly-Silstone) Formation, VII – Kcynia (Limestone-Evaporitic) Formation (after Dembowska, 1979).

Appendix

Table 2

Rock Eval data from the Uniejów IGH 1 and Poddębice PIG 2 boreholes

Borehole	Depth [m]	Zone	Position in zone	S1 [1]	S2 [1]	S3 [2]	T_{max} [°C]	HI [4]	OI [5]	PI [6]	TOC [wt.%]	RC [wt.%]	PC [wt.%]	MinC [wt.%]
Uniejów IGH 1	2124.5	Sokolovi	0.79	1.66	24.24	0.4	423	711	12	0.06	3.41	1.24	2.17	11.45
Uniejów IGH 1	2127.6	Sokolovi	0.57	1.67	37.94	0.64	429	547	9	0.04	6.93	3.61	3.32	1.55
Uniejów IGH 1	2131.4	Sokolovi	0.30	0.22	4.15	0.6	433	234	34	0.05	1.78	1.39	0.38	2.46
Uniejów IGH 1	2135.9	Klimovi	0.99	0.29	2.98	0.44	426	177	26	0.09	1.68	1.4	0.29	2.96
Uniejów IGH 1	2139.3	Klimovi	0.77	0.53	13.77	0.58	427	535	23	0.04	2.57	1.36	1.21	8.45
Uniejów IGH 1	2141.9	Klimovi	0.60	0.26	3.47	0.82	433	165	39	0.07	2.11	1.77	0.34	2.76
Uniejów IGH 1	2145.3	Klimovi	0.38	0.57	11.64	0.48	429	414	17	0.05	2.81	1.78	1.03	7.2
Uniejów IGH 1	2149.1	Klimovi	0.14	0.2	2.71	0.44	433	143	23	0.07	1.9	1.65	0.26	4.19
Uniejów IGH 1	2151.3	Autisiodorensis	1.00	0.09	0.92	0.86	433	92	86	0.09	1	0.89	0.11	1.43
Uniejów IGH 1	2154.9	Autisiodorensis	0.85	0.2	3.05	0.91	436	122	36	0.06	2.5	2.2	0.3	4.1
Uniejów IGH 1	2156.6	Autisiodorensis	0.78	0.26	3.54	0.53	433	112	17	0.07	3.15	2.81	0.33	3.32
Uniejów IGH 1	2160.9	Autisiodorensis	0.60	0.21	4.64	0.37	433	184	15	0.04	2.52	2.11	0.42	4.86
Uniejów IGH 1	2163.6	Autisiodorensis	0.49	0.31	5.23	0.52	433	205	20	0.06	2.55	2.07	0.48	4.57
Uniejów IGH 1	2167.1	Autisiodorensis	0.35	0.23	5.66	0.78	436	260	36	0.04	2.18	1.66	0.51	5.68
Uniejów IGH 1	2169.6	Autisiodorensis	0.25	0.2	2.06	0.47	434	129	30	0.09	1.6	1.4	0.2	6.32
Uniejów IGH 1	2172.1	Autisiodorensis	0.14	1.28	35.02	0.69	429	518	10	0.04	6.76	3.71	3.05	3.83
Uniejów IGH 1	2172.7	Autisiodorensis	0.12	0.27	5.71	0.45	432	220	17	0.05	2.59	2.08	0.51	4.61
Uniejów IGH 1	2175	Autisiodorensis	0.02	0.22	4.73	0.45	433	241	23	0.04	1.96	1.54	0.43	4.94
Uniejów IGH 1	2178	Eudoxus	0.92	0.5	12.15	0.59	432	380	19	0.04	3.2	2.13	1.07	4.48
Uniejów IGH 1	2184	Eudoxus	0.71	0.45	9.56	0.64	431	266	18	0.04	3.59	2.74	0.85	5.81
Uniejów IGH 1	2189.4	Eudoxus	0.53	0.28	5.37	0.58	436	259	28	0.05	2.07	1.58	0.49	5.32
Uniejów IGH 1	2193.5	Eudoxus	0.39	3.03	54.24	1.24	428	589	14	0.05	9.21	4.41	4.81	3.65
Uniejów IGH 1	2195.2	Eudoxus	0.33	0.63	9.2	0.46	432	468	24	0.06	1.97	1.13	0.83	8.93
Uniejów IGH 1	2199.3	Eudoxus	0.19	0.4	4.66	0.7	433	333	50	0.08	1.4	0.96	0.44	8.22
Uniejów IGH 1	2204.2	Eudoxus	0.02	0.19	1.59	0.52	435	156	51	0.11	1.02	0.86	0.16	6.98
Poddębice PIG 2	2464.6	Puschi	0.01	0.02	0.08	0.39	430	34	159	0.20	0.25	0.23	0.02	7.8
Poddębice PIG 2	2466	Pseudoscythica	0.93	0.27	2.48	0.68	430	178	49	0.10	1.39	1.14	0.25	1.53
Poddębice PIG 2	2518.6	Autisiodorensis	0.41	0.1	2.25	1.11	434	165	82	0.04	1.36	1.14	0.23	6
Poddębice PIG 2	2520.8	Autisiodorensis	0.24	0.2	3.83	1.09	432	174	49	0.05	2.2	1.83	0.37	5.74
Poddębice PIG 2	2521.1	Autisiodorensis	0.22	0.68	26.18	1.2	425	476	22	0.03	5.5	3.22	2.28	4.83
Poddębice PIG 2	2522	Autisiodorensis	0.15	0.26	7.08	0.98	430	229	32	0.04	3.09	2.45	0.64	4.21
Poddębice PIG 2	2522.6	Autisiodorensis	0.11	0.25	7.46	1.03	431	246	34	0.03	3.04	2.36	0.68	4.25

"Position in zone" – percentage position in the zone; [1] – [mgHC/gRock]; [2] – [mgCO_2/gRock]; [4] – [mgHC/gTOC]; [5] – [mgCO_2/gTOC]; [6] – [S1/S1+S2]