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Inoceramid stratigraphy and depositional architecture of the Campanian and Maastrichtian of the Miechów Synclinorium (southern Poland)

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ABSTRACT:

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Dynamic evolution of the Campanian and Maastrichtian (Upper Cretaceous) of the Miechów Synclinorium is presented. Through chronostratigraphic analysis, the geometry of the Campanian and Maastrichtian of the area is interpreted, while microfacies analysis allowed determination of some of the paleoenvironmental parameters (rate of sedimentation, bottom condition and terrigenous input). The chronostratigraphy is based on inoceramid biostratigraphy. Nine inoceramid zones are recognized: *Sphenoceramus patootensiformis, Sphaeroceramus sarumensis-Cataceramus dariensis* and *'Inoceramus' azerbaydjanensis-'Inoceramus' vorhelmensis*, *'Inoceramus' tenuilineatus*, *Sphaeroceramus pertenuiformis, 'Inoceramus' inkermanensis* and *'Inoceramus' costaecus-'Inoceramus' redbirdensis* (Campanian); *Endocostea typica* and *Trochoceramus radiosus* (Maastrichtian). Five unconformities (isochronous in the study area) represented by horizons of slower sedimentation rate, were recognized. They correlate with eustatic sea-level changes, well recorded in European successions (Jarvis *et al.* 2002, 2006; Niebuhr *et al.* 2011). Unconformity horizons allow six alloformations to be distinguished. The thickness of particular chronostratigraphic units within the Campanian and Lower Maastrichtian increases progressively toward the axis of the Danish-Polish Trough, which indicates that the inversion of the trough could not have started before the Late Maastrichtian.

Key words: Upper Cretaceous; Miechów Synclinorium; Inoceramid bivalves; Biostratigraphy; Inversion of the Danish-Polish Trough.

INTRODUCTION

During the Late Cretaceous, the area of the present Miechów Synclinorium was a marginal part of the Polish-Danish Trough (Text-fig. 1). The area is critical for the interpretation of the evolution of extra-Carpathian Poland and first of all for deciphering the final stages (Campanian and Maastrichtian) of the inversion history of the Danish-Polish Trough (Marcinowski 1974; Walaszczyk 1992; Kutek 1996; Krzywiec 2006). This is because of its marginal position, which made the area sensitive to both regional (Subhercynian tectonics movements) and global events (eustatic changes). These events affected the sedimentary history of the area and are well recorded in available geological successions. Progress in the field was hindered so far by relatively

Text-fig. 1. Tectonic-sketch map of Poland (without the Cenozoic cover) (after Pożaryski 1974; modified after Żelaźniewicz 2008 and Żelaźniewicz *et al.* 2011)

rough chronostratigraphic recognition of the Campanian and Maastrichtian of the synclinorium, which is critical in the proper interpretation of the basin evolution. The existing studies are either too general (older publications, e.g., Sujkowski 1926, 1934; Paszewski 1927; Kowalski 1948), or are limited geographically (e.g. Rutkowski 1965; Łyczewska 1965). However, as demonstrated in some recent publications (Jagt *et al.* 2004; Machalski *et al.* 2004; Walaszczyk *et al.* 2008) the Campanian and Maastrichtian of the Miechów Synclinorium contain most of the stratigraphically important fossil groups that can serve for constructing a refined chronostratigraphy of the upper Upper Cretaceous of the area.

This paper presents the Campanian and Maastrichtian inoceramid-based chronostratigraphic framework of the Miechów Synclinorium, based on which the depositional architecture and sedimentary history of the area is discussed.

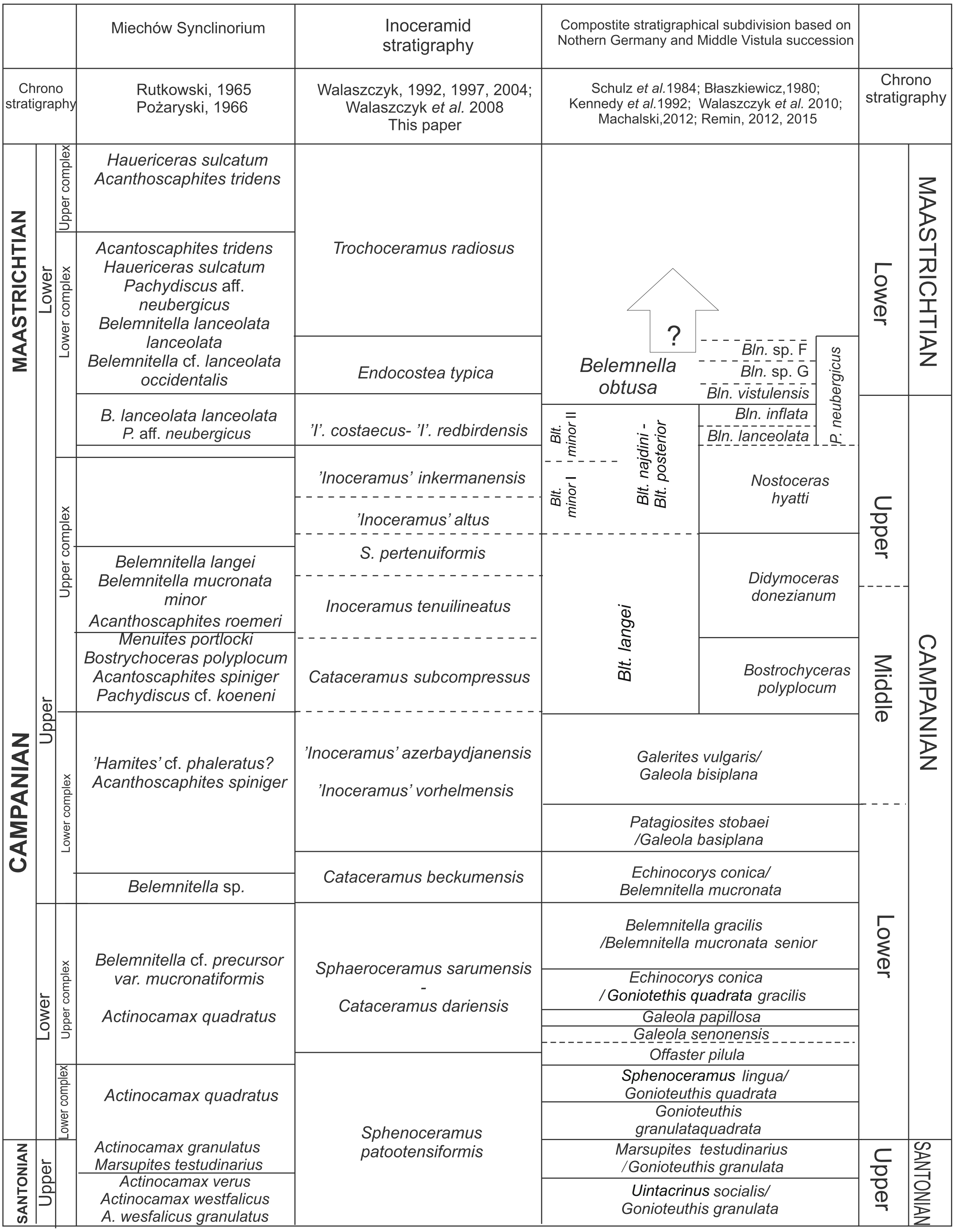
MATERIALS AND METHODS

Forty-one sections, mostly from the southern and central parts of the Miechów Synclinorium, were studied. Every section is documented with lithological and palaeontological samples. 220 specimens of inoceramid bivalves were collected and brought from the field. Three hundred and fifty thin sections were prepared in the AGH University of Science and Technology in Kraków and studied under the optical microscope at the Institute of Geological Sciences, Jagiellonian University in Kraków, and at the AGH University of Science and Technology in Kraków.

The palaeontological material is housed at the Institute of Geological Sciences of the Jagiellonian University in Kraków (collection No. UJ/220P/I). The bentonites were analysed by Jackson' s procedure (1969) at the Clay Minerals Laboratory of the Institute of Geological Sciences, Jagiellonian University in Kraków, and at the AGH University of Science and Technology in Kraków. Due to the lack of complete borehole cores, only the borehole cards hosted at the PIG-PIB were used.

PREVIOUS STUDIES

Stolley (1897), using belemnites, subdivided the Upper Santonian, Campanian and Maastrichtian (his Senonian) into the lower part, with *Actinocamax westfalicus* and *Actinocamax granulatus*, and the upper, with *Actinocamax quadratus* and *Belemnitella mucronata*. Already in 1906 Smoleński recognised the lower unit with *Actinocamax quadratus* and the upper unit with *Belemnitella mucronata* from the Upper Cretaceous of Bonarka. In the NW part of the Miechów Synclinorium, Mazurek (1924, 1926, 1948) described beds with *A. granulatus*, *A. quadratus* and *B. mucronata*. Sujkowski (1926) distinguished zones with *Actinocamax verus* and *A. granulatus* and with *A. quadratus* and *B. mucronata* in the Wolbrom area. Kowalski (1948), Bukowy (1956), Senkowicz (1959), Rutkowski (1965), Pożaryski (1966) used a stratigraphical interpretation based on cephalopods and echinoids, proposed by Pożaryski (1938, 1948) and Kongiel (1962) (Text-fig. 2). The Santonian/Campanian boundary was defined with the last occurrence (LO) of the crinoid *Marsupites testudinarius* and the first occurrence (FO) of *Actinocamax quadratus,* and in the lower part, *Actinocamax quadratogranulatus* was documented (Pożaryski 1938). The Lower/Upper Campanian boundary was defined at the FO of *Belemnitella mucronata* (Kongiel 1962). The group of *B. langei,* composed of three species, *Belemnitella minor* and *Belemenitella najdini* and *Belemnitella langei* (Kongiel 1962), was significant in the Upper Campanian (Kongiel 1962). The *B. mucronata* Zone was divided using ammonites into the lower part, with *Acanthoscaphites spiniger,* middle part with *Hamites phaleratus*, and an upper part with *Bostrochyceras polyplocum*. The LO of the latter taxon defined the Campanian/Maastrichtian boundary (Pożaryski 1938). The Lower Maastrichtian was characterised by *Belemnitella lanceolata lanceolata* and



Text-fig. 2. Correlation of inoceramid zonation applied herein (after Walaszczyk 1997, 2004; Walaszczyk *et al.* 2008), with zonations based on ammonites, echinoids and belemnites for the Campanian and Lower Maastrichtian of Poland (Middle Vistula section; Błaszkiewicz 1980; Machalski 2012; Remin 2012, 2015) and Northern Germany (Schulz *et al.* 1984); and with faunal assemblages of Rutkowski (1965)

Belemnitella lanceolata occidentalis (Kongiel 1962). *Acantoscaphites tridens*, *Hoploscaphites constrictus vulgaris*, *Bostrychoceras schloenbachi* and *Pachydiscus* aff. *neubergicus* were considered the characteristic forms of the Lower Maastrichtian (Pożaryski 1948). A foraminiferal scheme for the Campanian and Maastrichtian was proposed by Gawor-Biedowa and Wytwicka (1960) and was used by Rutkowski (1965). Senkowicz (1959) proposed a more detailed local stratigraphic scheme within the zones of Campanian and Maastrichtian of the NW part of the Miechów Synclinorium (earlier described by Mazurek 1924, 1926, 1948), based on lithology and echinoids. Senkowicz (1959) and Rutkowski (1976) reported the occurrence of sandy organodetrital limestones which were regarded to be either of Maastrichtian or Late Campanian age and were discussed by Machalski *et al*. (2004) who dated them as Miocene. An ammonite-belemnite zonation proposed by Błaszkiewicz (1980), described from the Campanian and Maastrichtian of the Middle Vistula River, has never been used for the studied sequence. Recently, the inoceramid zonation of the Santonian and Campanian of the Miechów Synclinorium was published by Walaszczyk (1992), Jagt *et al.* (2004), Jurkowska *et al.* (2015), ammonite zonation by Machalski *et al.* (2004), and foraminiferal biostratigraphy by Dubicka (2015). The authors correlate the biostratigraphical zonations with the belemnites/echinoids zonation described from North Germany (Schulz *et al.* 1984) (Text-fig. 2). The inoceramid biostratigraphy of the Campanian and Lower Maastrichtian of the Miechów Synclinorium was presented by Jurkowska (2014; see also Jurkowska and Uchman 2013; Jurkowska *et al*. 2015).

GEOLOGICAL SETTING

The Miechów Synclinorium is the SE part of the Szczecin-Łódź-Miechów Synclinorium. To the SW the synclinorium passes gradually into the Silesian-Cracow Homocline, and to the NE into the Holy Cross segment of the Mid-Polish Anticlinorium (Text-fig. 1). The Cretaceous of the Miechów Synclinorium, represented by the Albian through the Lower Maastrichtian, overlies the Jurassic substrate unconfomably and, in its central and southern parts, it is covered by the Miocene of the Carpathian Foredeep (Pożaryski 1977). The Cretaceous succession of the Miechów Synclinorium is distinctly two-fold (Text-fig. 3). Its lower, Albian through Santonian part, is composed of siliciclastic and carbonate units, relatively thin and stratigraphically largely incomplete (Sujkowski 1926, 1934; Różycki 1937, 1938; Kowalski 1948; Marcinowski 1974; Walaszczyk 1992). At least the Upper Coniacian, Santonian and basal Campanian seems to be complete in the northern part of the Miechów Synclinorium (Walaszczyk 1992; Remin 2004, 2010). The upper part, the Campanian and Lower Maastrichtian, is composed of a monotonous succession of siliceous limestones (opokas) with marly horizons. The total thickness of the Campanian–Maastrichtian succession is about 300 m in the south-western part of the Miechów Synclinorium, and 500 m in its north-eastern part.

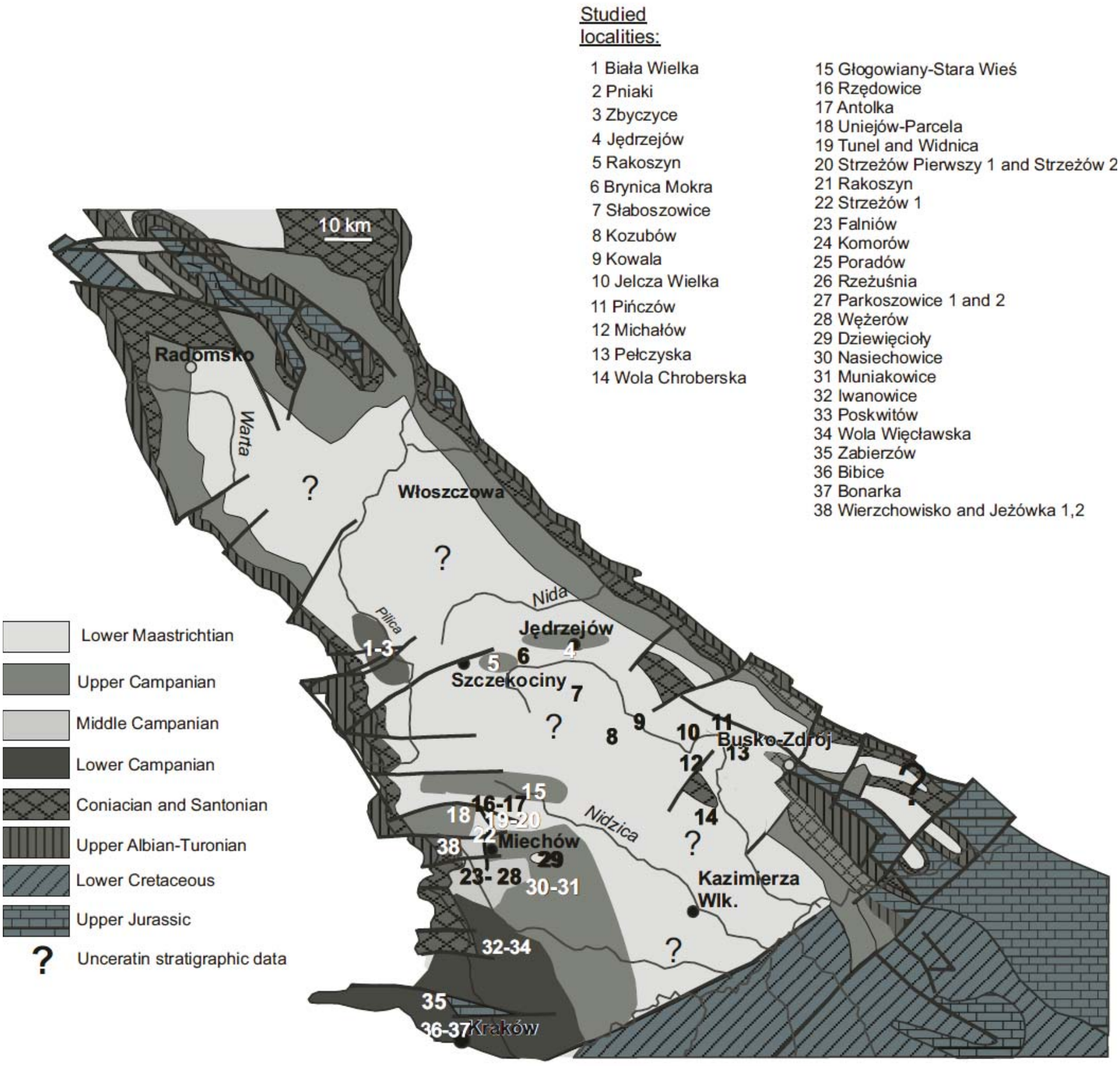
The so-called mid-Cretaceous transgression in extra-Carpathian Poland started in the Middle Albian, covering rapidly most of its territory (Pożaryski 1960, Marcinowski 1974). The initial facies variability of the Albian and Cenomanian was quickly followed by facies unification during the Early Turonian. With the exception of the Sudetes Mountains area, where siliciclastic sedimentation prevailed until the Santonian, the rest of the area is characterized by carbonate facies; limestones are restricted to the Kraków Swell area, while in other regions, opoka-marly facies dominate (Marcinowski 1974; Walaszczyk 1992).

STAGE AND SUBSTAGE SUBDIVISION

With the exception of the base of the Maastrichtian Stage, all other stage and substage definitions of the Campanian and Maastrichtian are still provisionary. The current, widely followed recommendations (see Ogg and Hinnov 2012) were agreed mostly during the 1995 Brussels' Symposium on Cretaceous Stage Boundaries (Rawson *et al.* 1996). As no formal requirements exist, however, definitions accepted in this paper, are shortly commented below.

The base of the Campanian was provisionally defined with the last occurrence of the stemless, pandemic crinoid species *Marsupites testudinarius* (Schlotheim, 1820) (Hancock and Gale 1996; see also Gale *et al.* 2008). As, however, this crinoid maybe limited to some environments, the base of the reversed polarity Chron C33r, which approximates the crinoid level, is evenly considered as the primary boundary marker (see comments in Ogg and Hinnov 2012).

According to the Brussels Symposium (e.g., Rawson *et al.* 1996), the tripartite subdivision of the Campanian stage is recommended. There are no formal definitions of particular substages, and the US Western Interior subdivision scheme (e.g., Cobban *et al.* 2006) is recommended (see Ogg and Hinnov 2012), and followed herein. The bases of the middle and upper Campanian substages in the US Western Interior ammonite



Text-fig. 3. Geological map of the Miechów Synclinorium (Dadlez *et al*. 2000; modified) with studied localities

scheme are defined with the first appearances of ammonites, *Baculites obtusus* and *Didymoceras nebrascense*, respectively (e.g., Cobban 1994; Cobban *et al.* 2006; see also Ogg and Hinnov, 2012). Due to the endemic character of these ammonites, the biostratigraphic position of these boundaries in the European Campanian is interpreted with inoceramids (Walaszczyk *et al.* 2001, 2002a, b; Odin and Walaszczyk 2003; Walaszczyk 2004). Accordingly, the base of the middle Campanian lies within the ‘*I*’. *azerbaydjanensis* – ‘*I*’. *vorhelmensis* Zone, and the base of the upper Campanian within the ‘*I*’. *tenuilineatus* Zone (see also Ogg and Hinnov 2012).

The Campanian/Maastrichtian boundary, one of the Cretaceous stage boundaries already approved by the International Commission on Stratigraphy (Ogg and Hinnov 2012), is defined as a statistical average of twelve bioevents recognized in the Campanian-Maastrichtian boundary interval in the Tercis les Bains (SW France) stratotypic section (Odin 1996, 2001; Odin and Lamaurelle 2001). In inoceramid terms this boundary correlates to the upper part of the ‘*Inoceramus*’ *redbirdensis* Zone, and approximates the FO of inoceramid species *Endocostea typica* (Walaszczyk *et al.* 2002; Odin and Walaszczyk 2003; see also Ogg and Hinnov 2012). This new definition places the base of the Maastrichtian in the lower part of the *Belemnella obusta* Zone (e.g., Niebuhr *et al*. 2011; Keutgen *et al*. 2012), which is distinctly higher than the FAD of *Belemnella lanceolata* (Schlotheim, 1813), the traditional marker of the Campanian–Maastrichtian boundary in the Boreal Realm (e.g., Birkelund 1957; Schulz *et al*. 1984).

The Maastrichtian Stage is commonly subdivided into two substages (Odin 1996; Ogg and Hinnov 2012). In the Boreal Europe, the base of the upper Maastrichtian is traditionally placed at the base of the belemnite zone of *Belemnitella junior* (see e.g., Schulz *et al.* 1984), which is correlated to the base of the potential ammonite marker of this boundary, i.e., *Menuites fresvillensis* (Suenes) (see e.g., Odin 1996; see also Walaszczyk *et al*. 2010). In inoceramid terms, this boundary corresponds to the top, or lies within the upper part of the *Trochoceramus radiosus* Zone (see Walaszczyk *et al*. 2009, 2010; Walaszczyk and Kennedy 2011).

LOCALITIES AND CAMPANIAN-MAASTRICHTIAN SUCCESSION

The Campanian-Lower Maastrichtian succession in the Miechów Synclinorium is accessible in a series of natural and artificial (abandoned quarries) exposures. The exposures are concentrated in the southern part of the area (Text-fig. 3). The tectonics of the Campanian and Maastrichtian of the study area is not well recognized. Previous authors (Sujkowski 1926, 1934; Rutkowski 1965; Jurkiewicz 1970; Łyczewska 1971, 1972; Kwapisz 1978; Szajn 1980; Walczowski 1984; Baran 1985; Bukowy 1968; Woiński 1991; Boratyn and Brud 1993; Rutkowski and Mądry 1994) reported many uncertain faults; some of them were recognized during the fieldwork.

Lower Campanian

The Lower Campanian succession starts with grey marls, and overlies the Santonian glauconitic marls (Bonarka, Zabierzów) or, unconformably, the Upper Jurassic limestones (Rutkowski 1965). In the upper part, opokas with marly horizons and cherts dominate. Chert nodules are either chaotic (Bonarka, Biała Wielka, Iwanowice, Zabierzów) or occur in horizons (Wierzchowisko, Jeżówka 1 and Jeżówka 2). Two bentonite horizons are noticed (Wierzchowisko and Jeżówka 2) in the lower part of the Lower Campanian. The *Sphaeroceramus sarumensis–Cataceramus dariensis* inoceramid Zone was recognized by its index taxa; the level of the *Sphenoceramus patootensiformis* Zone was documented by foraminifera (Jurkowska *et al.* 2015).

Microfacially the Lower Campanian opokas represent wackestone/packstone with foraminifera and spicules of siliceous sponges (Text-fig. 4a, b). There are also sponge fragments, echinoids and bivalves. An admixture of detrital quartz and glauconite is insignificant. The marls, which occur as interbeds in opokas, represent wackestone with foraminifera and spicules, and have a slightly higher content of detrital quartz and glauconite in comparison to opoka.

All Campanian–Lower Maastrichtian localities are briefly characterized below in alphabetical order. Their stratigraphic position is shown in Text-fig. 5 and their geographical location in Text-fig. 3.

Biała Wielka [N 50° 41′ 17.19″; E 19° 39′ 42.52″]; working quarry in the *S. sarumensis-C. dariensis* Zone opokas with marly intercalations (Jurkowska *et al.* 2015). Fossils are common, especially sponges and bivalves; inoceramid bivalves are rare.

Bibice; historical outcrop of Małecki (1989), Zapałowicz-Bilan *et al*. (2009), c. 10 km N of Kraków. Based on archival collection of rock samples and inoceramids, the outcrop represents opokas with cherts of the *S. sarumensis-C. dariensis* Zone.

Bonarka [N 50°2′17.39″; E 19°57′15.44″]; historical, abandoned quarry (currently nature reserve), now within the town of Kraków, in the uppermost Santonian–Lower Campanian *S. patootensiformis* Zone (Jurkowska *et al.* 2015), represented by grey marls and opokas with marly interlayers (see e.g., Smoleński 1906; Panow 1934; Alexandrowicz 1954; Barczyk 1956; Gradziński 1972; Kudrewicz and Olszewska-Nejbert 1997). The grey marls yielded abundant echinoids, belemnites and crinoids (*Marsupites testudinarius* in the lower part); the opokas contain common sponges and bivalves.

Iwanowice [N 50° 11′4. 74″; E 19°59′3.43″]; natural exposure in the eastern part of the village (Słomniki area) in the *S. sarumensis-C. dariensis* (Jurkowska *et al.* 2015) Zone opokas with marly interlayers. Rare fossils are dominated by sponges and bivalves with sporadic *Cataceramus balticus*.

Jeżówka 1 [N 50°24′41.37″; E 19°50′12.42″]; abandoned quarry. The lower part of the section, capped by glauconitic limestone, represents the *S. sarumensis -C. dariensis* Zone. The glauconitic limestone contains common sponges, echinoids (*Galeola* sp.), ammonites, crinoids and bivalves. The overlying opoka series belongs to the upper part of the *Cataceramus beckumen-*

sis Zone (see Jagt *et al.* 2004; Dubicka 2015). It contains rare sponges, echinoids and inoceramids (*C. dariensis*), as well as ammonites and belemnites.

Jeżówka 2 [N 50°24′50.98″; E 19°49′4.43″]; natural exposure of opokas with cherts and marly horizons. The lower part, assigned to the *S. patootensiformis* Zone and basal *S. sarumensis-C. dariensis* Zone (Jurkowska *et al.* 2015), contains a bentonite horizon. The fossils are quite abundant, mainly sponges echinoids, bivalves (inoceramids are rare, mainly imprints). The marly horizons yielded additionally echinoids, belemnites and solitary corals.

Pniaki [N 50° 41′ 17.19″; E 19° 39′ 42.52″]; abandoned quarry of the *S. patootensiformis* Zone opoka with thin marly intercalations (Jurkowska *et al.* 2015). It provided relatively common sponges, bivalves and rare echinoids.

Poskwitów [N 50° 13′ 24. 57″; E 20° 0′ 41. 77″]; temporary road-cutting along the main street in the village (described by Mączyńska 1968, and Kudrewicz and Olszewska-Nejbert 1997). It is composed of marly opokas with cherts of the *S. sarumensis-C. dariensis* Zone. Opokas contain common echinoids and sponges; single specimens of *C. dariensis* were found.

Wierzchowisko [N 50°22′ 9.35″; E 19°49′5.21″]; abandoned quarry in the *S. patootensiformis* and *S. sarumensis-C. dariensis* Zone (see Jagt *et al*. 2004; Jurkowska *et al.* 2015; Dubicka 2015). The exposed succession is represented by opokas with marly intercalations; a single chert horizon occurs in the middle of the succession. Rare sponges and echinoids were noticed.

Wola Więcławska [N 50°10′ 51.67″; E 20° 0′ 58.61″]; natural exposure in the *S. sarumensis -C. dariensis* Zone opoka with marly intercalations. In the middle of the succession, marly horizons with numerous inoceramids (*C. balticus*) occur. Sponges, echinoids and large *S. sarumensis* inoceramids were noted in the opokas.

Zabierzów [N 50° 6′ 50. 08″; E 19° 47′ 15. 76″]; inactive reclaimed quarry. Glauconitic horizons documented in the lower part of the succession represent the Upper Santonian (Alexandrowicz 1956; Rutkowski 1965; Świerczewska-Gładysz 2010). The Santonian/Lower Campanian boundary runs in grey marls (Rutkowski 1965) overlying the glauconitic horizon. The next series of opokas with cherts represents probably the *S. patootensiformis* Zone.

Zbyczyce [N 50° 41′ 28. 13″; E 19° 37′ 28. 66″]; historical outcrop in the *S. patootensiformis* Zone (Jurkowska *et al.* 2015) opoka of Hurcewicz (1966). Fossils are relatively rare, dominated by sponges and inoceramid imprints.

Middle Campanian

The Middle Campanian succession starts with opokas with marly interlayers (Rzeżuśnia, Falniów, Parkoszowice 1, 2 and Poradów). Cherts occur chaotically only in the lower part of the Rzeżuśnia succession. Two inoceramid zones were documented in the Middle Campanian: *'I'. azerbaydjanensis- 'I'. vorhelmensis* Zone (also documented near Busko Zdrój, in the NE part of the Miechów Synclinorium by Walaszczyk *et al.* 2008) and *'I'. tenuilineatus* Zone. The *Cataceramus subcompressus* Zone has not been documented by inoceramids, however an ammonite equivalent, *Bostrychoceras polyplocum* Zone, was reported by Rutkowski (1965).

Microfacially, opokas are represented by packstone with foraminifera and spicules (Text-fig. 4c, d). The other organic components comprise fragments of bivalves and echinoids. An admixture of detrital quartz (<0.1 mm) and glauconite (0.2 mm) grains is significant.

Falniów [N 50° 22′ 32. 54′ E 19° 57′ 56. 35′]; natural exposure at the NW end of the village on the fields behind the houses. The *'I'. azerbaydjanensis- 'I'. vorhelmensis* Zone opokas with marly horizons and rich sponges and echinoids, are exposed. The middle part of the succession contains horizons with abundant baculitid ammonites and inoceramids (*'I'. azerbaydjanensis* and *'I'. vorhelmensis*) with glauconitic coatings.

Parkoszowice 1 [N 50° 18′ 59. 39′; E 20° 3′ 36. 86″]; abandoned quarry in the eastern bank of the Piotrówka stream in the village. The quarry exposes the *I'. tenuilineatus* Zone opokas with marly interlayers. In the lower part of the section, horizons with baculitids occur. In the topmost part of the quarry, glauconitic marly opoka horizons with oysters, massive sponges, ichnofossils and gastropods were noticed. Fossils of sponges, ammonites, bivalves and gastropods are common throughout the section. *'I'. tenuilineatus* specimens are common, especially in the lower part of the succession. *Cataceramus goldfussianus* (d'Orbigny, 1847) and '*Inoceramus*' *nebrascensis* Owen, 1852 were also found.

Parkoszowice 2 [N 50° 18′ 53. 96′; E 20° 3′ 19. 12″]; natural exposure on the eastern bank of the Piotrówka stream in the village of Parkoszowice in the *I'. tenuilin-*

eatus opokas with marly horizons. Fossils are abundant, including mainly the inoceramids *C. goldfussianus* and *'Inoceramus' borilensis* Jolkicev, 1962.

Rzeżuśnia [N 50° 20′ 9.98″; E 19° 58′ 15.53″]; abandoned quarry in the eastern end of the village represents *I'. azerbaydjanensis- 'I'. vorhelmensis* opokas with marly interlayers (Jagt *et al*. 2004). In the lower part of the succession, opokas with cherts occur. Fossils are quite common: sponges, inoceramids ['*I*'. *vorhelmensis* (Walaszczyk, 1997)*,* '*I*'. *azerbaydjanensis* Aliev, 1939 and *C. balticus* (Böhm, 1907)], echinoids, ammonites and belemnites. Two horizons with mass-occurrence inoceramids and baculitids with glauconitic coatings were observed.

Poradów [N 50°20'5.12"; E 20°3'5.95"]; natural exposure in the '*I*'. *tenuilineatus*, (Jurkowska *et al.* 2015) Zone marly opoka with marly horizons. Fossils are common: sponges, echinoids, bivalves and belemnites. In the lower part of the succession there is a horizon with fragments of huge platyceramid inoceramids.

Upper Campanian

The Upper Campanian is represented by sandy opokas with grey marl horizons. Three inoceramid Zones are documented: *Sphaeroceramus pertenuiformis*, *'Inoceramus' inkermanensis* and '*Inoceramus' costaceus* – *'Inoceramus' redbirdensis*. The *'Inoceramus' altus* Zone has not been documented.

Upper Campanian opokas represent bioclastic wackestone (in the lower part of the succession) and packstone with spicules and foraminifera (in the upper part) (Text-fig. 4 e, f). They also contain sponges, bivalves, echinoids and high admixture of detrital quartz (0.1–0.3 mm) and glauconite grains (0.3 mm).

Głogowiany-Stara Wieś [N 50° 27′ 58.23″; E 20° 6′ 48.11″]; abandoned quarry in the eastern end of the village. A section of 4.5-m-thick highly bioturbated marly opokas with sandy opoka horizons was described. Fossils are common, but preserved fragmentarily (sponges, bivalves and ammonites). '*Inoceramus*' *alaeformis* Zekeli, 1852, and huge representatives of *Platyceramus* sp. were found.

Jędrzejów [N 50° 31′ 5.05″; E 20° 17′ 4.76″]; temporary road-cutting in the northern part of the town of Jędrzejów. The succession is composed of sandy opokas and marls of the *'I.' inkermanensis* and '*I.' costaceus- 'I.' redbirdensis* zones (Świerczewska-Gładysz and Jurkowska 2013). The *'I.' inkermanensis* Zone is very fossiliferous with abundant sponges, inoceramids (*'I.' inkermanensis,* '*Inoceramus*' *cobbani* Walaszczyk *et al.* 2002a, and '*Inoceramus*' *magniumbonatus* Douglas, 1942), echinoids, belemnites, large gastropods and plants (*Debeya haldemiana,* Debey ex Saporta and Marion, 1873, and *Debeya* cf. *paulinae* sp. nov., Halamski 2013). In the upper part ('*I.' costaceus- 'I.' redbirdensis* Zone) of the section, fossils become rare and there are only single representatives of inoceramids ('*I.' costaceus, E.* aff. *typica)*.

Komorów; historical locality of Hurcewicz (1960; and probably of Rutkowski 1965), near Miechów. Based on inoceramids (archival specimens), the section represents the *Sphaeroceramus pertenuiformis* Zone (Jurkowska *et al.* 2015).

Muniakowice [N 50° 17′ 7.99″; E 20° 7′ 10.85″]; seven abandoned quarries in the southern end of the village. Rocks are exposed in two of them only. Sandy opokas (*'I.' inkermanensis*) with a marly horizon were described (from the topmost part of the succession). Fossils are abundant: mainly sponges, bivalves and ammonites. 'The inoceramid fauna is characterized by '*I.' inkermanensis* and *'I'. magniumbonatus* (Douglas, 1942).

Nasiechowice [N 50° 18′ 30.09″; E 20° 8′ 2.28″]; abandoned quarry in the southern slope of the village of Nasiechowice. Only a 2-m-thick opoka bed with marl horizons in the lower part, and glauconitic marly opokas, highly bioturbated in the upper part, are available for observation. Specimens of *'I.' redbirdensis* were found in opokas below the glauconitic horizon.

Rakoszyn [N 50° 38′ 40.64″; E 20° 5′ 50.78″]; temporary road-cutting along the main road from Rakoszyn to Trzciniec, in Upper Campanian sandy opokas. A single specimen of *'I.' nebrascensis* and rare sponges and echinoids were only found.

Strzeżów 1 [N 50° 22′ 28. 3″; E 20 24′ 7.38″]; inactive quarry in the '*I.' inkermanensis*- *'I.' costaecus* sandy opokas with marl horizons. Fossils are frequent: sponges, bivalves (pectenids), belemnites, gastropods and echinoids. The rich inoceramid fauna includes: '*I.' inkermanensis*, *'I'. costaecus*, *C. balticus*, *Inoceramus pierrensis* (Walaszczyk, Cobban and Harris 2001).

Uniejów-Parcela [N 50° 25′ 41.9″; E 19° 56′ 51.13″]; outcrop of marly opokas in the lower part, and sandy opokas in the upper part. In the middle of the succession, there is a horizon with phosphorite concretions in the lower part, and with glauconitic grains, quartz and phosphorite concretions in the upper part. All sponges, bivalves and belemnites detected in the horizon are preserved incomplete. The topmost part of the horizon is represented by highly bioturbated opokas with abundant inoceramids (*C. goldfussianus*) and pectenids. The ichnofossils are filled with green, carbonate clasts. Above the horizon, 6-m-thick sandy opokas can be observed. Inoceramids are represented by *C. goldfussianus*, which are very common and probably indicate the *S. pertenuiformis* Zone (similar situations were described in the Middle Vistula Valley by Walaszczyk 2004).

Wężerów [N 50° 16′ 14.51″; E 20° 3′ 5.49″]; exposure behind the buildings in the eastern part of the village. It exposes a 3-m-thick succession of opokas with marly horizons, of the *S. pertenuiformis* Zone. Fossils are rich, including mainly bivalves, sponges, gastropods and echinoids. Inoceramids are represented by *S. pertenuiformis* and *Cataceramus ellipticus* (Giers, 1964).

Lower Maastrichtian

The Lower Maastrichtian is represented by sandy opokas (with a variable content of detrital quartz, generally increasing towards the top) with marly interlayers (sandy marly opokas were found only in the SE part of the study area). Two inoceramid zones were documented: *Endocostea typica* and *Trochoceramus radiosus*. The stratigraphic position of the sections of Antolka, Widnica, Tunel, Słaboszowice and Michałów is based on lithological correlation to the sections of Strzeżów 2 and Wola Chroberska, from which *Trochoceramus radiosus* (archival collections) was described (Walaszczyk *et al.* 1996).

Microfacially, opokas from the lower part of the Lower Maastrichtian represent packstone with foraminifera and spicules (Text-fig. 4g, h), and high admixture of detrital quartz (0.1–0.2 mm). Opokas from the upper part of the succession represent wackestone with spicules and foraminifera. Detrital quartz in this part of the succession is abundant and the size of quartz grains increases upwards (Antolka and Tunel: <0.3 mm, and Strzeżów 2 and Widnica: 0.3–0.6 mm).

Antolka [N 50° 24′ 26.28″; E 20° 5′ 28.66″]; abandoned quarry near the road to Cisie. It exposes a 5-m-thick succession of highly sandy, yellow opokas with marly interlayers. Only traces of deep-burrowing bivalves (*Lucina* sp.) and ichnofossils were found. Behind the quarry, along the road to Cisie, there is a small exposure of white sandy opokas with frequent small *Cataceramus subcircularis* (Meek, 1876).

Brynica Mokra [N 50° 39′ 30.20″; E 20° 10 48.63″]; temporary road-cutting along the main road in the village. A 2-m-thick section of sandy and marly opokas with numerous inocerams, sponges, echinoids and belemnites was described. Inoceramids are very frequent and dominated by *C. subcircularis,* indicating the upper part of the *E. typica* Zone.

Dziewięcioły [N 50°18′ 22.21″; E 20°10′ 28.71″]; abandoned quarry along the main road in the village. It exposes sandy opokas with frequent inoceramids and single ammonites. Horizons with mass-occurrence of inoceramids dominated by *C. subcircularis, Cataceramus barabini* (Morton, 1834), *Cataceramus glendivensis* Walaszczyk, Cobban and Harries, 2001 were described from the middle and the top parts of the succession. The opokas represent the upper part of the *E. typica* Zone.

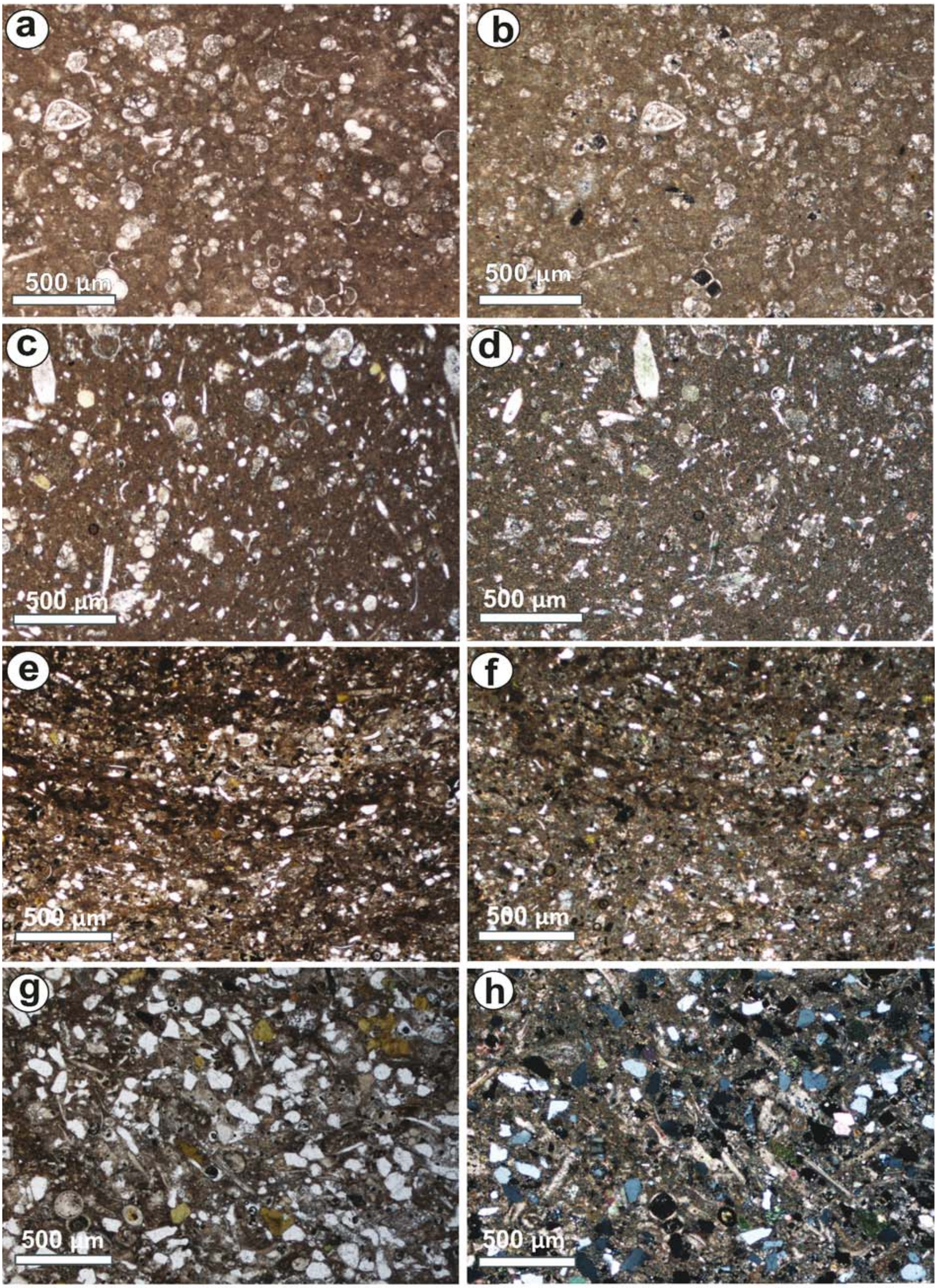
Jelcza Wielka [N 50° 30′ 47″; E 20° 24′ 52.24″]; abandoned quarry in the village of Jelcza Wielka (in previous publications referred to as Wrocieryż). Foraminiferal stratigraphy of the exposed highly sandy opokas was provided by Dubicka and Peryt (2012), and it correlates with the *T. radiosus* Zone. Specimens of the scaphitid ammonite *Hoploscaphites constrictus* were also described from the section (Machalski, personal communication 2014).

Kowala [N 50° 28′ 46.03″ E 20° 32′ 50.53″]; natural exposure on the left bank of the Nida River in the village of Kowala. It exposes sandy opokas of the *E. typica* Zone, with frequent *C. subcircularis* and single echinoids.

Kozubów [N 50° 26′ 15.3″; E 20° 29 ′43. 38″]; natural exposure in the NW slope in the village of Kozubów. It reveals the upper part of *E. typica* Zone sandy opokas with highly bioturbated limestones and marl horizons. Abundant inoceramid fauna occurs in opokas, dominated by *C. subcircularis*, *C. barabini* and *Cataceramus balticus* (Böhm, 1907).

Michałów [N 50° 29′ 51.72″; E 20° 27′ 51.23″]; abandoned quarry in Lower Maastrichtian highly sandy opokas with marly horizons. Based on geological mapping data and a lithological comparison with Jelcza Wielka, the rocks probably represent the *T. radiosus* Zone.

Pełczyska [N 50° 21′ 34.58″; E 20° 33′ 40.14″]; natural outcrop in the *E. typica* Zone marly opokas. Rich fauna includes sponges, bivalves, belemnites and ichnofossils. Mass occurrence of small inoceramids of *En-*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docostea typica Withfiled, 1877 and *Cataceramus subcircularis* is observed.

Pińczów [N 50° 32′ 13.41″ E 20° 32′ 16.69″]; natural exposure along the road from Pińczów to Kije. It exposes sandy opokas of the *E. typica* Zone. The opokas contain a rich inoceramid fauna dominated by *C. subcircularis*.

Rzędowice [N 50° 26′ 21.11″; 20° 5′ 22.64″]; natural outcrop in the southern bank of the village. Thick succession of highly sandy; yellow opokas of the *T. radiosus* Zone was described. Only rare specimens of *T. radiosus* were noticed.

Słaboszowice [N 50° 34′ 50.51″; E 20° 11′ 22.29″]; inactive quarry in the southern bank of the village. Yellow, highly sandy opokas were described. Only fragments of prismatic shells of inoceramds were found. Based on lithological similarities, the opoka probably represent the *T. radiosus* Zone.

Strzeżów Pierwszy 1 [N 50° 22′ 47.56″; E 20° 9′ 30. 16″]; temporary road-cutting along the main road in the Strzeżów Pierwszy. The succession starts with glauconitic marls and marly opokas with phosphorite concretions and common fossils (*Spondylus* bivalves, belemnites, echinoids), but preserved incomplete. Marls are highly bioturbated. The marls are overlain by white sandy opokas with abundant inoceramids dominated by *C. subcircularis* and *C. barabini*, sponges, *Spondylus* bivalves and small echinoids. The overlying opoka contains only one specimen of *Spyridoceramus tegulatus* (Von Hagenov, 1842) form A and *T. radiosus* (archival collection of Warsaw University see Walaszczyk *et al.* 1996). White sandy opokas are separated from yellow highly sandy opokas by horizons with phosphorite concretions, detrital quartz and glauconitic grains. The collected and archival specimens indicate that the section represents the upper part of the *E. typica* Zone-*T. radiosus* Zone (yellow highly sandy opokas).

Strzeżów 2 [N 50° 22′ 56.6″; E 20° 25′ 7.34″]; three inactive quarries on the opposite side of the main road in Strzeżów Pierwszy yellow highly sandy opokas with marly horizons represent the *T. radiosus* Zone. Fossils are rare, only adapted for deep burrowing bivalves *Lucina* sp. and ichnofossils were noticed.

Tunel [N 50° 26′ 3.79″; E 19° 59′ 33.34″]; natural exposure near the railway station in Tunel. It exposes *T. radiosus* Zone sandy and highly sandy opokas with marly horizons. Only single fossils of bivalves (*Lucina* sp.) and ichnofossils can be found.

Widnica [N 50° 23′ 56.31″; E 20° 1′ 39.95″]; abandoned quarry. Highly sandy opokas with marly horizons were described from the *T. radiosus* Zone. Fossils are uncommon: only single bivalves and prisms of inoceramid shells were found.

Wola Chroberska [N 50° 23′5 8.49″; E 20° 31′ 16. 72″]; natural exposure along the road from Wola Chroberska to Odrzywół, mentioned by Łyczewska (1965) and Mazurek (1924). It exposes the *T. radiosus* Zone highly sandy opokas. Fossils are relatively rare, only some fragments of inocerams were found. Archival specimens of *T. radiosus* from this section are stored at Warsaw University (Walaszczyk *et al.* 1996).

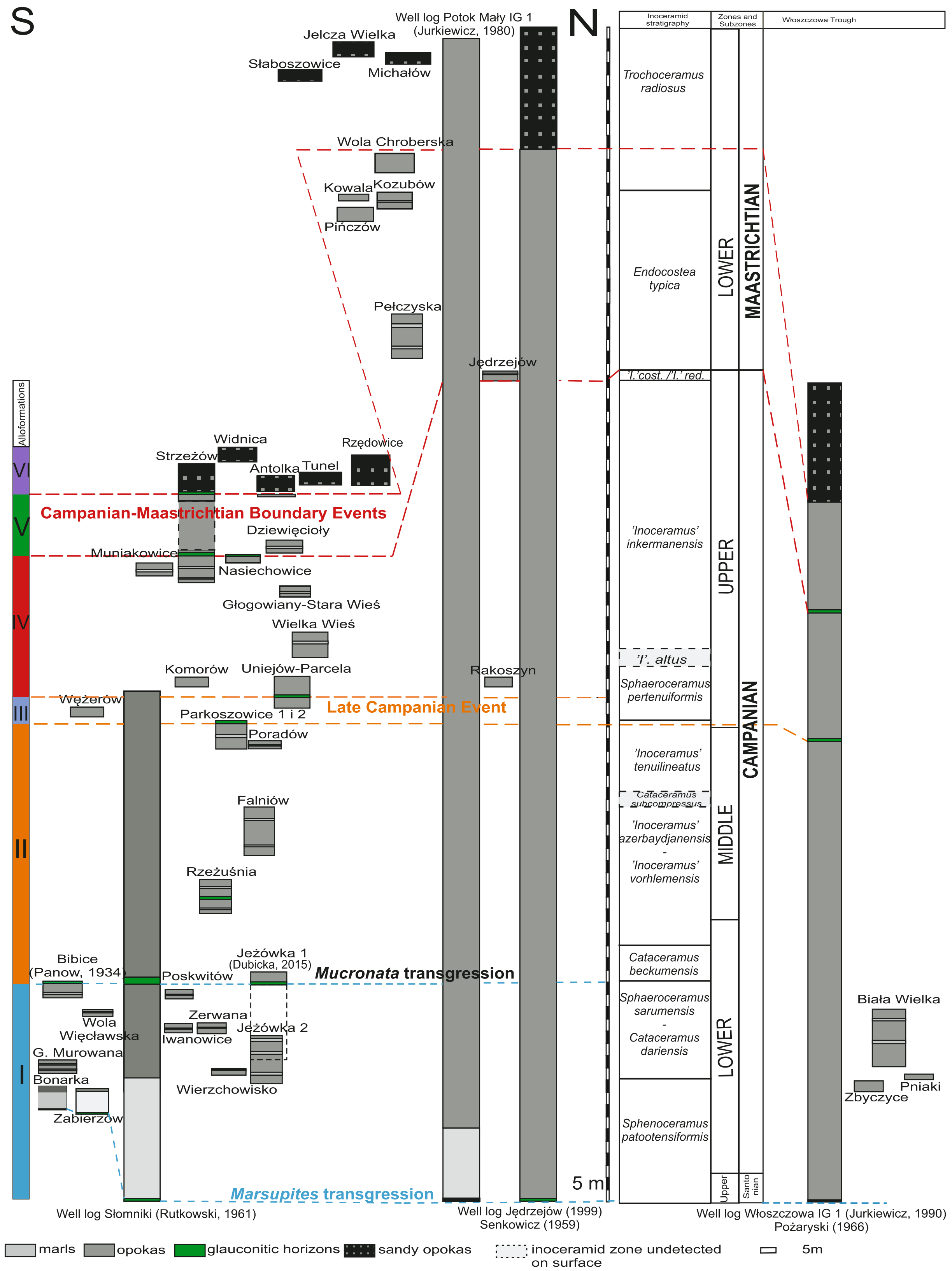
INOCERAMID BIOZONATION

Inoceramid biostratigraphy enables application of unified zonation recognized recently in the Western Interior (US) (Walaszczyk *et al.* 2001), Tercis (France) (Walaszczyk *et al.* 2002a), northern Germany (Walaszczyk 1997) and in the Middle Vistula River section (Walaszczyk 2004).

In inoceramid terms, the studied succession comprises an interval from the *S. patootensiformis* Zone up to the *T. radiosus* Zone. The Lower Campanian inoceramid succession can be compared with sections in northern Germany (Walaszczyk 1997). Inoceramids in this part of the succession are rare and the state of their recognition is poor. The inoceramid record of the Upper Campanian and Lower Maastrichtian of the study area can be directly compared to the succession known from the Middle Vistula River section (Walaszczyk 2004) and from Tercis (Walaszczyk *et al.* 2002a). Although it requires further studies, it seems that inoceramid diversity (actually richness) is lower than in the Middle Vistula area.

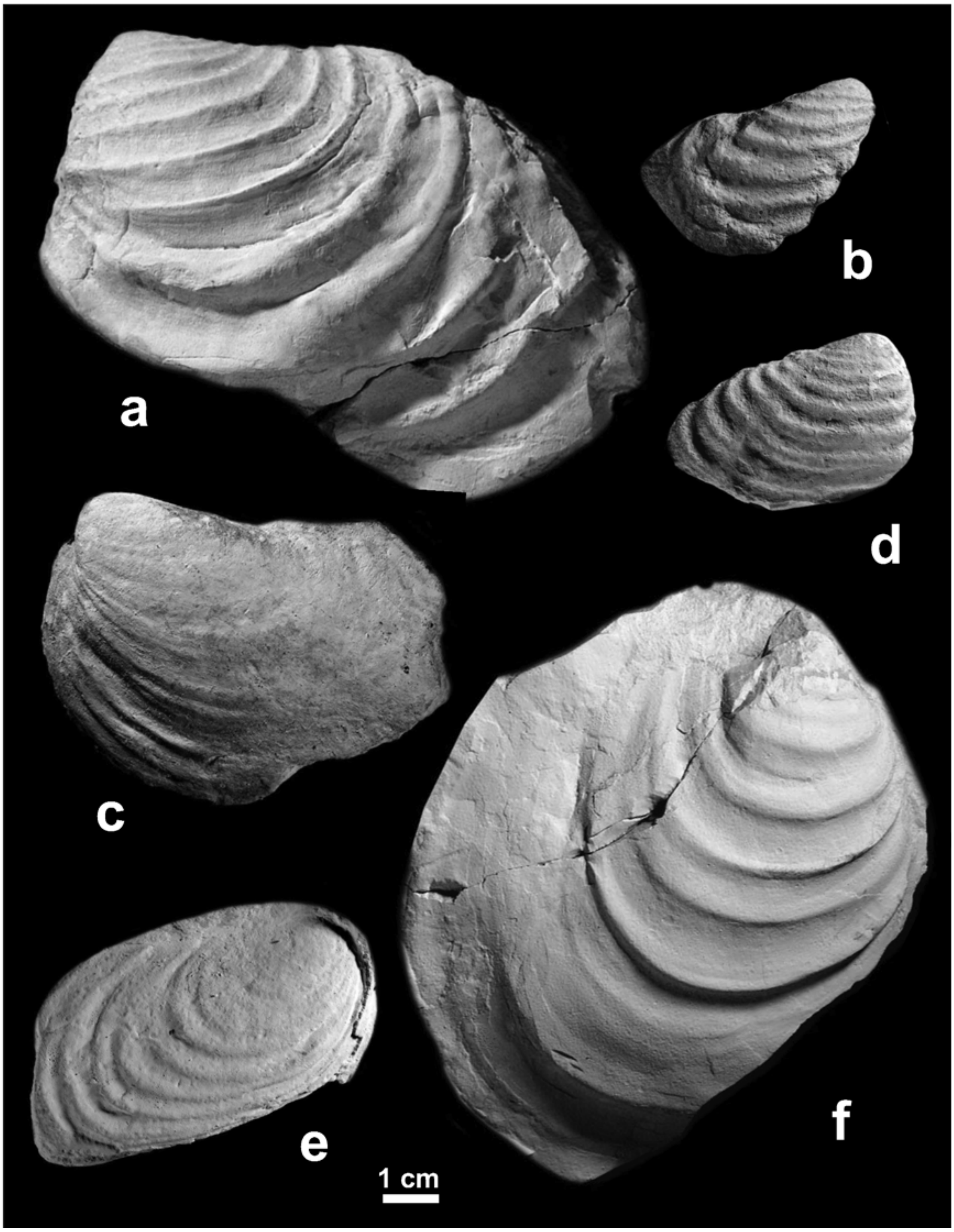
Sphenoceramus patootensiformis interval Zone. The base of the zone is defined by the FO of the index taxon, and the top by the FO of *S. sarumensis* and/or *C. dariensis* (see Walaszczyk 1997). This zone corresponds to the upper part of the *Marsupites/granulata*, *granulataquadrata*, *lingua-granulata* and the lower part of the

Text-fig. 4. **a, b** – Packstone with numerous foraminifera and spicules from Wierzchowisko, *S. sarumensis-C. dariensis* Zone (Lower Campanian) (a) crossed nicols (b). **c, d** – Bioclastic packstone with quartz grains from Parkoszowice 1, *'I.' tenuilineatus* Zone (Middle Campanian) (c) crossed nicols (d). **e, f** – Bioclastic packstone with abundant quartz grains from Strzeżów 1, *'I.' inkermanensis* Zone (Upper Campanian) (e) crossed nicols (f). **g, h** – Bioclastic packstone with numerous quartz and glauconitic grains from Strzeżów Pierwszy 1, *T. radiosus* Zone (Lower Maastrichtian) (g) crossed nicols (h)



Text-fig. 5. Lithology and inoceramid biostratigraphy of the studied sections *pilula* Zone (Walaszczyk 1997; Jagt *et al.* 2004). In the study area, this zone was recognized by micropalaeontological equivalents (Jurkowska *et al.* 2015)

Spaheroceramus sarumensis–Cataceramus dariensis interval Zone. The base of the zone is defined by the FO of the index taxa, and the top by the FO of *C. becku-*



Text-fig. 6. **a** – *Cataceramus dariensis* (Dobrov and Pavlova, 1959), Bibice, *S. sarumensis–C. dariensis* Zone; ING UJ/220P/I/1, × 0.97. **b** – '*Inoceramus*' *vorhelmensis* (Walaszczyk, 1997), Rzeżuśnia, '*I.*' *azerbaydjanensis*– '*I.*' *vorhelmensis*; ING UJ/220P/I/4, × 0.97. **c** – '*Inoceramus*' *tenuilineatus* Hall and Meek, 1856, Parkoszowice 1, *'I.' tenuilineatus* Zone; ING UJ/220P/I/8, × 0.97. **d** – '*Inoceramus*' *azerbaydjanensis* Aliev, 1939, Rzeżuśnia, '*I.*' *azerbaydjanensis*– '*I.*' *vorhelmensis* Zone; ING UJ/220P/I/15, × 0.97. **e** – '*Inoceramus*' *borilensis* Jolkicev, 1962, Parkoszowice 1, '*I.*' *tenuilineatus* Zone; ING UJ/220P/I/20, x 0.97. **f** – *Cataceramus copetdagensis* (Arzumanova, 1965), Bibice, *S. sarumensis–C. dariensis* Zone; ING UJ/220P/I/21, × 0.97

mensis (Walaszczyk 1997). This zone corresponds to the upper part of the *pilula, senonensis, papillosa, conica-gracilis* and *gracilis/senior* zones (Walaszczyk 1997). In the study area, the zone was documented by *C. dariensis* (Text-fig. 6a) and micropalaeontological equivalents (Jurkowska *et al.* 2015). Horizons with mass occurrence of *C. balticus* and *C. copetdagensis* (Text-fig. 6f) were found in this zone.

Catacearmus beckumensis interval Zone. The base of the zone is defined by the FO of the index taxon, and the top by the FO of the *'I.' azerbaydjanensis*-*'I.' vorhelmensis* assemblage (Walaszczyk 1997). The presence of this zone was suggested by Jagt *et al.* (2004) above the glauconitic horizon in the Jeżówka 1 section. This zone corresponds to the *conica/mucronata* Zone.

'Inoceramus' azerbaydjanensis-vorhelmensis interval Zone. The base of the zone is defined by the FO of the index taxon, and the top by the FO of *C. subcompressus* (Walaszczyk 2004). This zone corresponds to the *stobaei/bisiplana* and *vulgaris/bisiplana* zones (Jagt *et al.* 2004). In the study area the zone was identified by the index taxon (Text-fig. 6b, d), which coincides with *C. balticus* and *C. ellipticus*.

'Inoceramus' tenuilineatus interval Zone. The base of the zone is defined by the FO of the index taxon (Text-fig. 6 c), and the top by the FO of *S. pertenuiformis* (Walaszczyk 2004) (Text-fig. 7e). This zone was identified by the index taxon and correlated with the lower part of the *Didymoceras donezianum* ammonite Zone (Błaszkiewicz 1980; Walaszczyk 2004). *I. borilensis* (Text-fig. 6e)*, C. goldfussianus* (Text-fig. 7a), '*I.*' *nebrascensis* (Text-fig. 7 b) and fragments of huge platyceramids were also found. Inoceramid fauna occurs in horizons. The lower part of the '*I*'*. tenuilineatus* Zone has not been found in the study area and the uppermost part is absent due to a sedimentary gap (glauconitic horizon), thus the lowermost Upper Campanian was determined by the FO of *S. pertenuiformis*.

Sphaeroceramus pertenuiformis interval Zone. The base of the zone is defined by the FO of the index taxon (Text-fig. 7e), and the top by the FO of *'I.' altus* (Walaszczyk 2004). This zone was identified by finds of the index taxon and correlated with the upper part of the *D. donezianum* Zone (Błaszkiewicz 1980; Walaszczyk 2004). *C. ellipticus* (Text-fig. 7f) and abundant *C. goldfussianus* were also found.

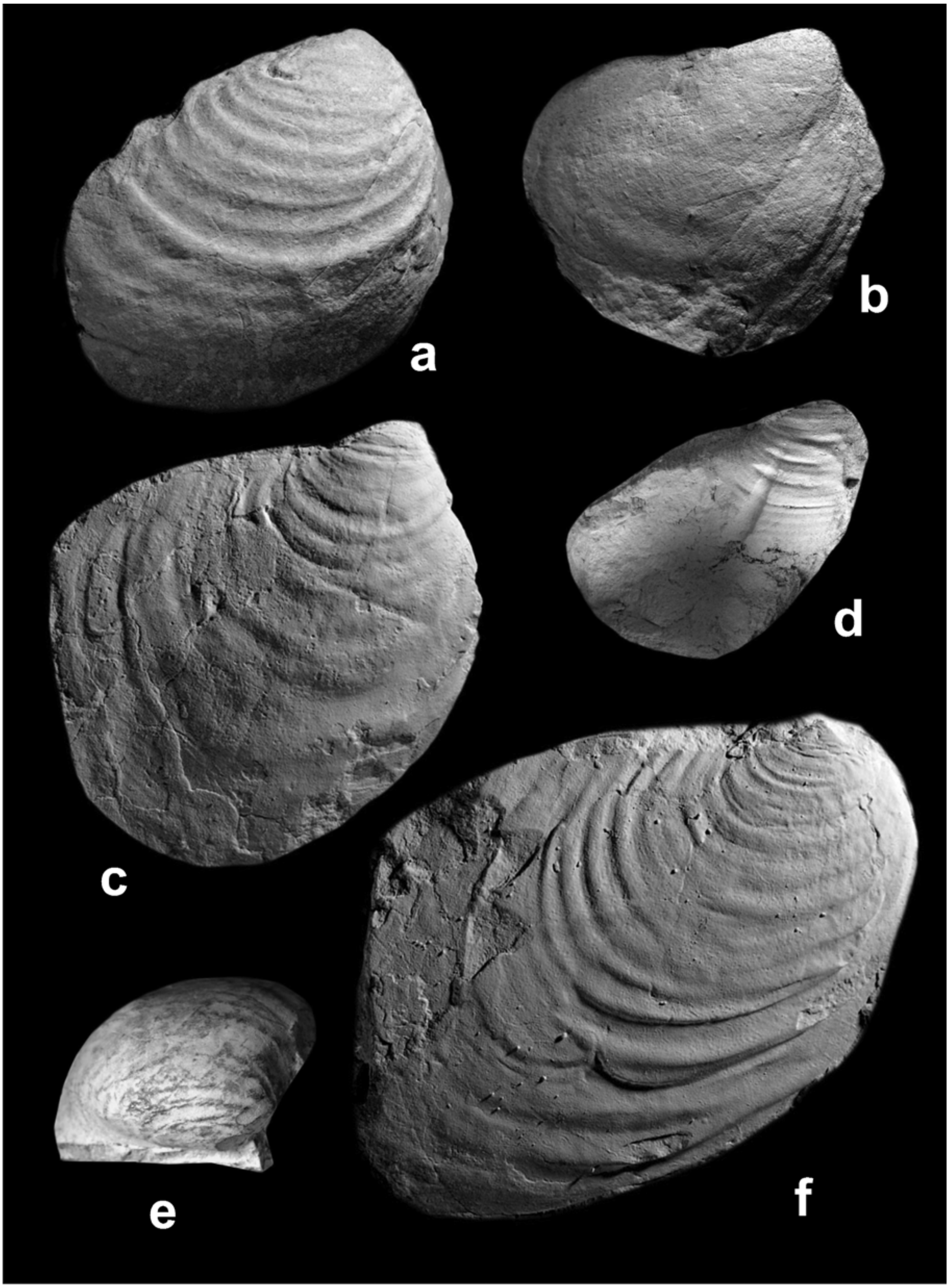
'Inoceramus' inkermanensis interval Zone. The zone ranges between the FO of the index taxon (Text-fig. 7c) and the FO of *'I.' costaecus* (Walaszczyk 2004). This zone is documented by numerous inoceramids: *'I'. inkermanensis* (Text-fig. 7c), *I. balticus*, *'I'. smirnovi* (Text-fig. 8a) and *'I'. magniumbonatus* (Text-fig. 8b). The *'I.' inkermanensis* Zone corresponds to the middle and upper parts of the *Nostoceras hyatti* ammonite Zone (Walaszczyk 2004).

'Inoceramus' costaecus and ***'Inoceramus' redbirdensis*** Zones. This interval is between the FO of *'I.' costaecus* (Text-fig. 9b) and the FO of *E. typica* (Walaszczyk 2004). The two index taxa occur in the succession; *'I.' costaecus* appears first and is followed by *'I.' redbirdensis* (Text-fig. 9f) appears after the FO of *'I.' costaecus*. This zone corresponds to the interval from the *Belemnella lanceolata* up to middle part of the *Belemnella vistulensis* Zone (Remin 2012; compare also Keutgen *et al.* 2012 for zonation based on different methodology) and presumably to the basal part of the *B. occidentalis* Zone of Błaszkiewicz (1980) (see also: Walaszczyk 2004). The FO of *E. typica* was accepted as the beginning of the Lower Maastrichtian (Ogg and Hinnov 2012).

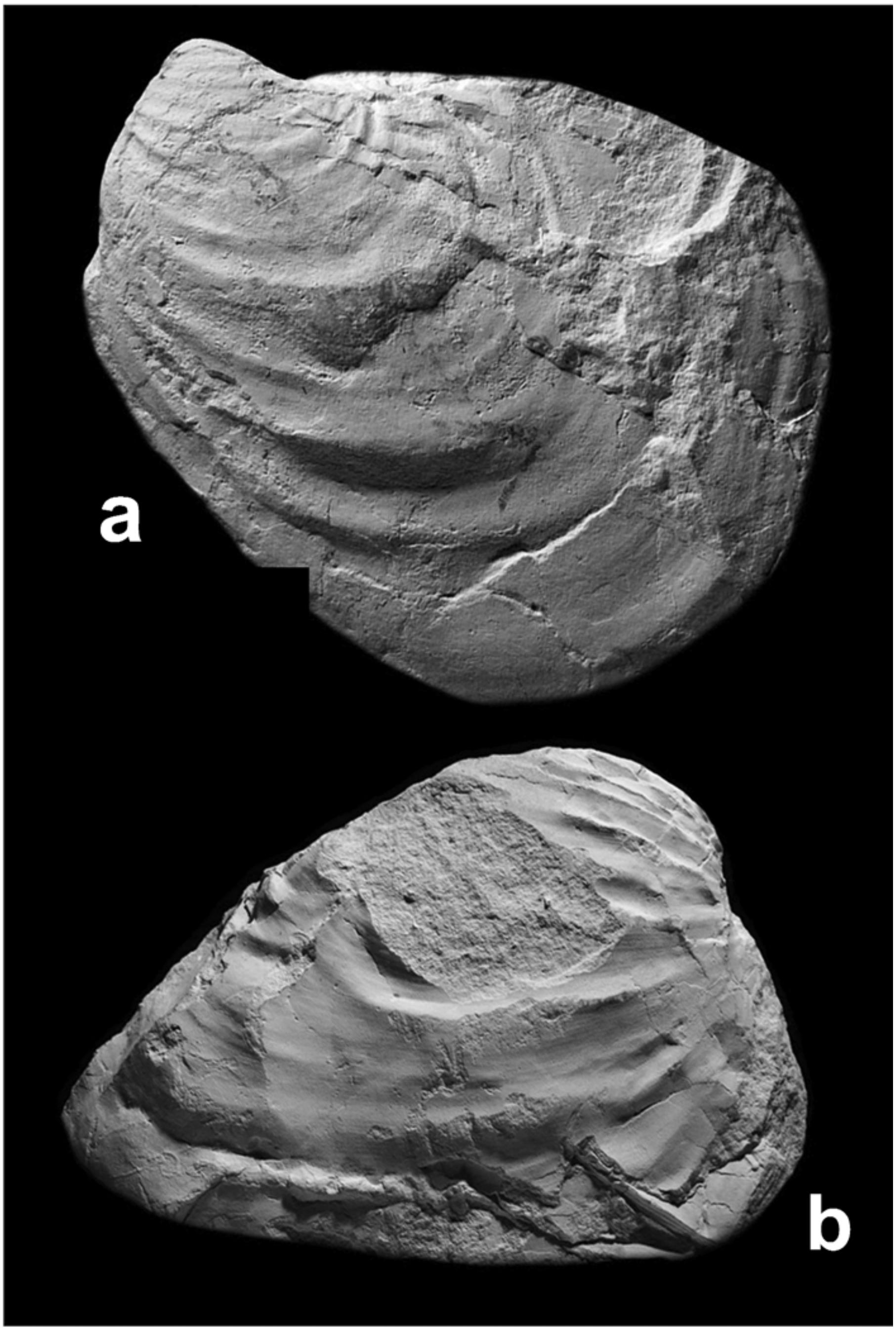
Endocostea typica interval Zone. The zone ranges between the FO of the index taxon (Text-fig. 7d) and the FO of *T. radiosus* (Walaszczyk 2004). Horizons with mass occurrence of small (< 4 cm) inoceramids are characteristic of this zone (Walaszczyk 2004). The lower part of the zone with *E. typica* (Text-fig. 7d) and *C. subcircularis* (Text-fig. 9d, e) was recognized in Pełczyska. In the remaining part of the study area only the upper part of the zone was identified. *E. typica* disappears in the upper part of the zone, but *C. barabini, C. glendivensis* (Text-fig. 9c) and *C. balticus* appear instead. The *E. typica* Zone corresponds to the *Belemnella obtusa* Zone of Remin (2012) without its basal part which is equal to the upper part of the *Belemnella vistulensis* B. sp. G and B. sp. F zones (compare, Remin 2012).

Trochoceramus radiosus interval Zone. This interval is between the FO of *T. radiosus* and the FO of *'Inoceramus' ianjonaensis* Sornay, 1973 (Walaszczyk *et al.* 2002a, b, 2010).

Two specimens from the archival collection of Alojzy Mazurek come from the Wola Chroberska and Strzeżów sections (Walaszczyk *et al.* 1996). One specimen was collected by the author in the Rzędowice section. *S. tegulatus* forma A (Text-fig. 9a) were also noted in the *T. radiosus* Zone. This zone corresponds to at least to the upper part of the *Belemnella obtusa* Zone (Remin 2012).



Text-fig. 7. **a** – *Cataceramus goldfussianus* (d' Orbigny, 1847), Parkoszowice 2, '*I.*' *tenuilineatus* Zone; ING UJ/220P/I/25, × 1. **b** – '*Inoceramus*' *nebrascensis* Owen, 1852, Parkoszowice 2, '*I.*' *tenuilineatus* Zone; ING UJ/220P/I/35, × 1. **c** – '*Inoceramus*' *inkermanensis* Dobrov and Pavlova, 1959, Jędrzejów, '*I.*' *inkermanensis* Zone; ING UJ/220P/I/36, × 1. **d** – *Endocostea typica* Withfield, 1877, Pełczyska, *E. typica* Zone; ING UJ/220P/I/44, × 1. **e** – *Sphaeroceramus pertenuiformis* Walaszczyk, Cobban and Harries, 2001, Wężerów, *S. pertenuiformis* Zone; ING UJ/220P/I/46, x 1. **f** – *Cataceramus ellipticus* (Giers, 1964), Wężerów, *S. pertenuiformis* Zone; ING UJ/220P/I/47, × 1

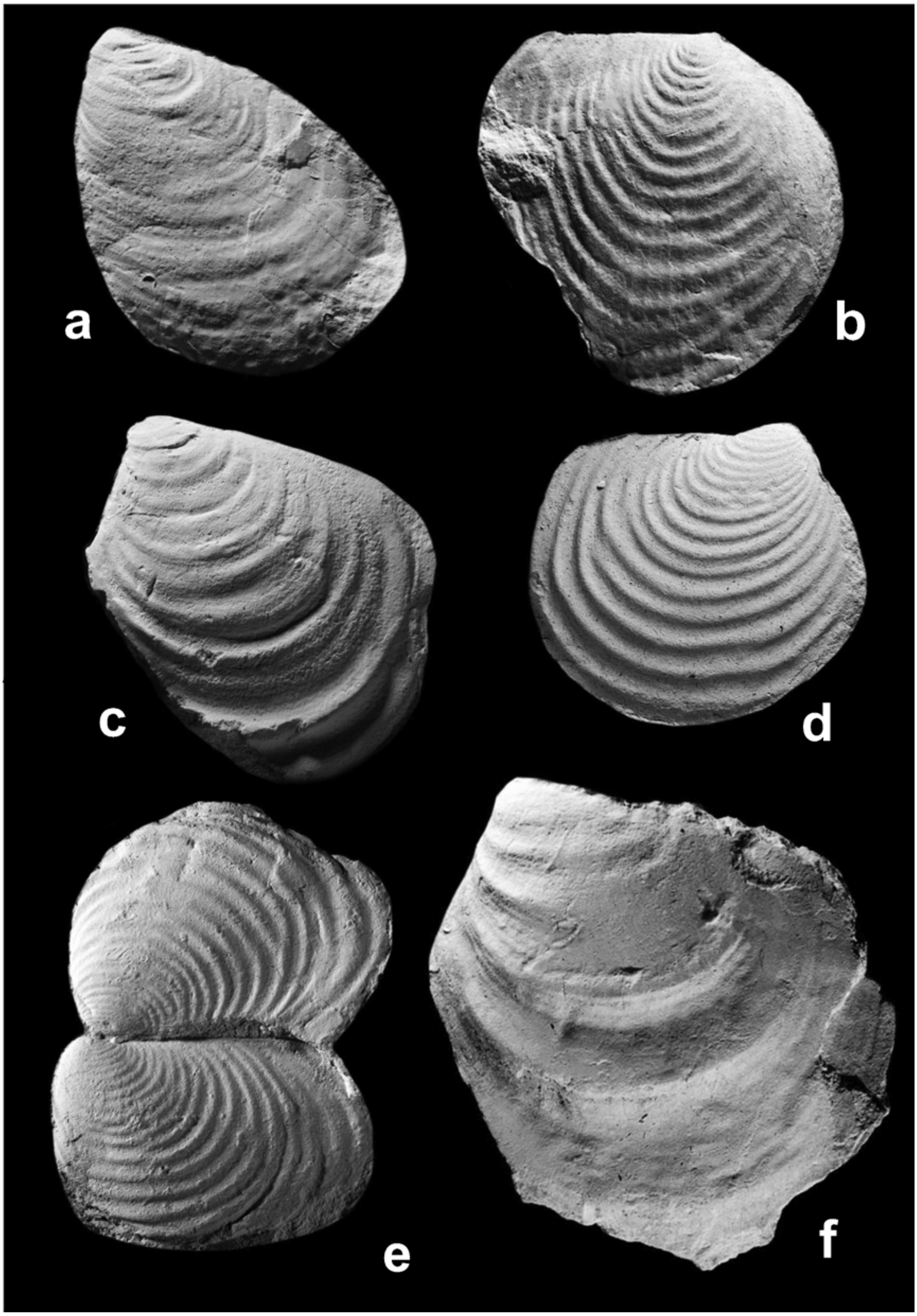


Text-fig. 8. **a** – '*Inoceramus*' *smirnovi* Walaszczyk, 2004, Jędrzejów, '*I.*' *inkermanensis* Zone; ING UJ/220P/I/48, × 1. **b** – '*Inoceramus*' *magniumbonatus* Walaszczyk, 2004, Jędrzejów, '*I.*' *inkermanensis* Zone; ING UJ/220P/I/49, × 1

EVOLUTION OF THE STUDY AREA DURING THE CAMPANIAN AND MAASTRICHTIAN

Global sea-level changes

Five unconformities represented by horizons of slower sedimentation rate, enriched with quartz, glauconitic grains and/or phosphorite concretions were recognized in the studied succession (Text-fig. 5). The contents of glauconitic grains, quartz and phosphorite concretions are different for each horizon. Four of them were recognized earlier, and used to subdivide the Campanian–Maastrichtian succession into three units (Rutkowski 1965, Table. 1). Biostratigraphic analysis al-



Text-fig. 9. **a** – *Spyridoceramus tegulatus* (von Hagenow, 1842) form A, Strzeżów Pierwszy 2, ? *T. radiosus* Zone**;** ING UJ/220P/I/51, × 1. **b** – '*Inoceramus*' *costaecus* Khalafova, 1966, Jędrzejów, '*I.*' *costaecus*– '*I.*' *redbirdensis* Zone*;* ING UJ/220P/I/52, × 1. **c** – *Cataceramus*? *glendivensis* Walaszczyk, Cobban and Harries, 2001, Dziewięcioły, *E. typica* Zone; ING UJ/220P/I/72, × 1. **d, e** – *Cataceramus subcircularis* (Meek, 1876), Dziewięcioły, *E. typica* Zone*;* ING UJ/220P/I/126, × 1. **f** – '*Inoceramus*' *redbirdensis* Walaszczyk, Cobban and Harries, 2001, Nasiechowice, '*I.*' *costaecus*– '*I.*' *redbirdensis* Zone*;* ING UJ/220P/I/127, × 1 lows determining the stratigraphic position of the horizons, to correlate them with eustatic sea-level trends.

***Marsupites* transgression** (Text-fig. 5). The oldest glauconitic horizon was described from the western part of the Miechów Synclinorium: Zabierzów, Bonarka (Gradziński 1972), Korzkiew (Kurdrewicz and Olszewska-Nejbert 1997), Wielkanoc (Świerczewska-Gładysz and Olszewska-Nejbert 2009), Słomniki core (Rutkowski 1961), Potok Mały IG1 (Jurkiewicz 1980), Jędrzejów IG1 (Jurkiewicz 1999), Włoszczowa IG1 (Pożaryski 1966; Jurkiewicz 1990). The horizon is 0.5–1.0 m thick and is enriched with glauconitic grains and inoceramid prisms. Świerczewska-Gładysz and Olszewska-Nejbert (2009) described redeposited (Middle Coniacian and Middle Santonian) sponges in the glauconitic marls from the quarry of Wielkanoc. Bukowy (1956), Alexandrowicz (1960) and Rutkowski (1965) included the glauconitic marls into the Santonian (see Walaszczyk 1992 who included the glauconitic marls into the upper Santonian, *S. patootensiformis* Zone) based on finds of the crinoid *Marsupites testudinarius* in grey marls above the horizon. In the central and NE part of the synclinorium, the equivalent of the glauconitic marls is a sandy horizon, known from the Jaronowice IG1 (Jurkiewicz 1976) and Książ Wielki IG1 (Jurkiewicz 1991) borehole cores and from the Kije section (Walaszczyk 1992; Remin 2004).

This horizon could be interpreted as a record of the *Marsupites* transgression recognized in Europe (Niebuhr 1995; Ernst and Wood 2000). Based on carbon stable-isotope variation through the Campanian–Maastrichtian, Jarvis *et al.* (2002, 2006) recognized the *Marsupites* transgression in Tunisia, France and England. The transgression was also reported from Madagascar (Walaszczyk *et al.* 2014).

***Mucronata* transgression** (Niebuhr 1995) (= Middle Campanian Event, Jarvis *et al.* 2002; 2006) (Text-fig. 5). The glauconitic horizon from Jeżówka 1 was also recognized from Grzegorzowice Wielkie, Lipna Wola (Rutkowski 1965), and Bibice (Panow 1934). It is also known from boreholes drilled in the SE part of the synclinorium (Heller and Moryc 1984). The horizon consists of limestone clasts with glauconitic coatings contained in marly deposits; the thickness of the horizon is about 40 cm. It is underlain by limestone with *Thalassinoides* burrows. The horizon could have been produced by the *Mucronata* transgression, described from Germany (Niebuhr 1995), Tunisia, France, England (Jarvis *et al.* 2002; 2006), and Spain (Küchler 2000). The transgression started at the beginning of the *B. mucronata* Zone (the Early–Late Campanian boundary in traditional European subdivision).

Late Campanian Event (Voigt *et al.* 2012) (= Late Campanian Grobkreide Event; Niebuhr *et al.* 2011) (Text-fig. 5). The horizon from Parkoszowice 1 consists of 3-m-thick marly opokas with glauconitic grains. Common oysters (*Pycnodonte* sp.), gastropods and large sponges were reported. This horizon, which is an effect of slower or absence of sedimentation, could be connected with the Late Campanian Event (LCE) described by Voigt *et al.* (2012) from France, England, Italy and Germany (Niebuhr *et al.* 2011), which is manifested by a negative $\delta^{13}C$ excursion. In Tercis (France), the LCE was recognized between the interval without any ammonite and inoceramid documentation and the *'I.' altus* Zone (Odin and Lamurelle 2001; Walaszczyk *et al.* 2002a). The horizon from Parkoszowice 1 represents the *'I.' tenuilineatus* Zone and is older than the LCE, although it could be producd by an event connected with LCE. Such is the case with the horizon identified in Uniejów-Parcela. This horizon starts with a boundary enriched with quartz grains, phosphorite concretions and glauconitic grains. The upper part is highly bioturbated and the bioturbation is infilled with glauconitic clasts and phosphorite concretions.

Campanian–Maastrichtian Boundary Events (=CMBE) (Text-fig. 5)**.** It was described by Jung *et al.* (2012) from the Pacific, France, England and Egypt (Jarvis *et al.* 2002), and is manifested by a strong negative $\delta^{13}C$ excursion, which is an effect of supposed cooling. The horizon recognized in Nasiechowice and Strzeżów Pierwszy 1 from the upper part of the *'I.' redbirdensis* Zone and the lower part of the *E. typica* Zone could be associated with the CMBE. The correlation of these events on a global scale is controversial due to lack of precise stratigraphic data. Jarvis *et al.* (2002) determine the start of the negative $\delta^{13}C$ excursion in the *Gansserina gansseri* foraminiferal Zone, which correlates with the *Belemnella lanceolata* belemnite Zone and the *'I.' redbirdensis* to *E. typica* Zones (Ogg and Hinnov 2012). Jung *et al.* (2012) show many small $\delta^{13}C$ peaks during the CMBE and extended the CMBE to the *T. radiosus* Zone (see also Voigt *et al.* 2012). Voigt *et al.* (2012) connect the CMBE with global tectonic movements rather than climate cooling. In these terms, the upper horizon from Strzeżów Pierwszy 1 could be a result of a short-term sea-level pulse.

The older horizon from Nasiechowice and Strzeżów Pierwszy 1 comprises a 1.5-m-thick marly opoka enriched with glauconitic grains, quartz and fragmentarily preserved fossils (only *Spondylus* sp. are preserved whole). The horizon is strongly bioturbated and the sediment infilling ichnofossil burrows does not contain glauconite grains. The younger horizon from Strzeżów Pierwszy 1 is characterized by opokas with quartz, phosphorite concretions and rare glauconitic grains.

Alloformations

Inoceramid biostratigraphy is the most useful method for chronostratigraphic analysis of the Campanian and Maastrichtian of the Miechów Synclinorium. Its usefulness is limited to the exposed successions; inoceramids are rarely found in cores. For the reconstruction of the depositional architecture of the study area, a more precise chronostratigrapic analysis is needed.

The described horizons are useful for distinguishing alloformations in the Campanian and Maastrichtian of the Miechów Synclinorium. All of them are correlated with global eustatic sea-level changes, which makes them isochronous in the area studied.

Six alloformations have been distinguished in accordance with the Polish Rules of Stratigraphy (Racki and Narkiewicz 2006). Most of them represent third-order eustatic sea-level changes (Haq *et al.* 1987).

Alloformation I

The lower boundary is defined by Santonian glauconitic marls (or sandy marl horizon), and the upper one by the Lower Campanian horizon with limestone in glauconitic coatings. The lower horizon is well examined in the western part of the Miechów Synclinorium and in cores (see section: '*Marsupites* transgression'). In the NW part of the study area it correlates with the sandy marl horizon (Remin 2004). The glauconitic marls are overlain by grey marls and opokas with cherts. Locally, the grey marls lie on Jurassic limestones (Rutkowski 1965).

The thickness of alloformation I is variable: 2–10 m in the western part (Gradziński 1972, Świerczewska-Gładysz 2010, Jurkiewicz 1974), 40–45 m in the central (Rutkowski 1961, Jurkiewicz 1976, Jurkiewicz 1990) and eastern parts of the Miechów Synclinorium (Heller and Moryc 1984).

The opokas contain abundant fossils represented by epibenthos (sponges, bivalves) and endobenthos (echinoids); nektonic organisms (ammonites and belemnites) are rare.

Microfacially, the opokas represent wackestone/packstone with spicules and foraminifers. Fragments of sponges, echinoids and bivalves also occur. Quartz and glauconite are rare.

Alloformation I represents the upper part of the *S. pinniformis* Zone to the *S. sarumensis*-*C. dariensis* Zone.

Alloformation II

The limestone in glauconitic coatings recognized in the Jeżówka 1 section indicates the lower boundary of alloformation II, and the upper boundary is marked by the glauconitic horizon known from Parkoszowice I.

The horizon from the Jeżówka 1 section was also found in Lipna Wola, Grzegorzowice Wielkie (Rutkowski 1965) and Bibice (Panow 1934) and from cores in the SE part of the Miechów Synclinorium (Heller and Moryc 1984).

The thickness of alloformation II is about 100 m. Alloformation II is represented by marly opokas with cherts (in its lower part) and opokas with marly horizons (in its upper part). The fossils are abundant: sponges, inoceramids, baculitids. In the lower part of alloformation II, there are two horizons of abundant baculitids and inoceramids in glauconitic coatings (Rzeżuśnia section).

Microfacially, the opokas represent packstone with foraminifers and spicules, the quartz content is insignificant.

Alloformation II is correlated with the *C. beckumensis* – *'I.' tenuilineatus* zones.

Alloformation III

The lower boundary of alloformation III is indicated by the glauconitic horizon from the Parkoszowice 1 section, and the upper boundary by the glauconitic-phosphorite horizon from the Uniejów-Parcela section. The glauconitic horizon from the Parkoszowice 1 section was also noticed in the Włoszczowa Trough by Pożaryski (1966).

The thickness of alloformation III is estimated in the southern part of the Miechów Synclinorium at 10 m, and in the northern part at 30–60 m.

Alloformation III consists of fossiliferous opokas with marly horizons. Microfacially, it is represented by bioclastic wackestone/packstone with quartz (0.1–0.2 mm) and glauconitic grains (0.1 mm).

Alloformation III spans the interval of the upper part of the *'I.' tenuilineatus* Zone to the *S. pertenuiformis* Zone.

Alloformation IV

Alloformation IV has been distinguished between the glauconitic-phosphorite horizon from the Uniejów-Parcela section and the glauconitic horizon from Strzeżów Pierwszy 1. The former was also described by Pożaryski (1966) from the northern part of the Miechów Synclinorium.

Alloformation IV is represented by fossiliferous, sandy opokas with marly horizons. Microfacially, the opokas represent bioclastic wackestone/packstone with abundant quartz grains (0.1–0.3 mm).

Alloformation IV spans between the *S. pertenuiformis* and *E. typica* zones (including a gap comprising the *'I'.altus* Zone).

Alloformation V

The lower boundary is indicated by the glauconitic horizon examined in the Strzeżów Pierwszy 1 section, and the upper boundary by the phosphorite horizon known from the Strzeżów Pierwszy 1 section.

Alloformation V consists of white sandy opokas with marly horizons. The lower part of the succession was recognized only in the Pełczyska section and is represented by fossiliferous marly opokas. Microfacially, the opokas are packstone with spicules and foraminifers; the admixture of quartz and glauconite grains is high.

The thickness of alloformation V is variable: about 60 m in the SW part of the Miechów Synclinorium, and about 130 m in the NE.

Alloformation V spans between the *E. typica* Zone to the lower part of the *T. radiosus* Zone.

Alloformation VI

The youngest alloformation was defined between the phosphorite horizon described from Strzeżów Pierwszy 1 and the youngest Maastrichtian deposits available in the Miechów Synclinorium.

Alloformation VI consists of sandy, yellow opokas with marly interlayers. Fossils are rare, represented by single inoceramids and other bivalves (*Lucina* sp.). Microfacially, the opokas represent packstone with spicules, foraminifers. The admixture of quartz grains (0.2–0.5 mm) is significant.

The thickness of alloformation VI is about 20–30 m in the SW part of the Miechów Synclinorium, and reach up about to 50 m in the NE part.

The alloformation is represented by the *T. radiosus* Zone.

Evolution of the study area

The chronostratigraphic and microfacies analyses provide a basis to analyze the thickness and facies changes in the Campanian and Maastrichtian in the study area. The thickness of particular chronostratigraphic units within the Campanian and Lower Maastrichtian increases progressively towards the axis of the Mid-Polish Anticlinorium, which suggests that the inversion of the Danish-Polish Trough could not have started before the Late Maastrichtian, which is in agreement with suggestions presented earlier by Kutek and Głazek (1972), and Świdrowska and Hakenberg (1999). It is significantly later than in the NE border of the Holy Cross Mountains, where the geophysical data show that the uplift movement started in the Late Turonian?–Early Coniacian (Krzywiec 2002, 2006; Krzywiec *et al.* 2009; see also Dadlez *et al.* 1997; Leszczyński 2010). Signs of synsedimentary uplit tectonics during this time were not noted in the Miechów Synclinorium.

Five unconformity horizons, representing third-order eustatic sea-level changes (Haq *et al.* 1987), well recorded in European successions (Jarvis *et al.* 2006, Niebuhr *et al.* 2011), have been identified.

The lowest quartz content is found in opokas and marls of alloformations I and II, and it increases in alloformations III and IV; in opokas and marls of alloformation V and VI it is abundant. It is difficult to indicate the sediment provenance area; further investigations are necessary. Up-section, but not lateral, changes in the size of quartz grains in the Lower Maastrichtian sandy opokas described by Rutkowski (1960) were observed also by the present author. These could not be interpreted as an indicator of a sediment supply area. An area lying S/SW from the studied sections was indicated as a good provenance area for the S part of the Miechów Synclinorium (Kutek and Głazek 1972; Hakenberg and Świdrowska 1998; Świdrowska and Hakenberg 1999). Also the area lying N/NE from the Miechów Synclinorium, in the Holy Cross Mountains, was pointed out as a supplementary area (Małopolska Land; Jaskowiak-Schoeneichowa and Krassowska 1988). The data from leaf floras from the Miechów Synclinorium also suggest that, during the Campanian, there must have existed uplifted areas in the Holy Cross part of the Danish-Polish Trough (Halamski 2013). The leaf flora and a greater input of quartz were interpreted as a sign of the beginning of inversion of the Danish-Polish Trough. New data presented in this paper show that tectonic evolution of the study area could be more complicated. It is difficult to estimate whether the quartz content was an effect of eustatic sea-level changes or tectonic movements in the Danish-Polish Trough (Walaszczyk and Remin 2015).

CONCLUSIONS

1. In the Campanian–Lower Maastrichtian deposits of the Miechów Synclinorium, nine inoceramid zones, excluding *C. beckumensis, C. subcompressus* and *'I.' altus,* were identified by finds of the index taxa.
2. Five glauconitic horizons enriched with quartz and

phosphorite nodules correlate with eustatic sea-level peaks well recognized in Europe.
3. Unconformity horizons allow the determination of six alloformations which are isochronous within the Miechów Synclinorium.
4. The thickness of particular alloformation units increases progressively toward the axis of the Danish-Polish Trough, which indicates that the inversion of the trough in the Miechów Synclinorium could not have started before the Late Maastrichtian.
5. The increasing quartz input in the Campanian–Lower Maastrichtian could be an effect of eustatic or tectonic movements in the Danish-Polish Trough.

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