Integrated biostratigraphy of the Santonian through Maastrichtian (Upper Cretaceous) of extra-Carpathian Poland

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ABSTRACT:


The biostratigraphic importance, current zonations, and potential for the recognition of the standard chronostratigraphic boundaries of five palaeontological groups (benthic foraminifers, ammonites, belemnites, inoceramid bivalves and echinoids), critical for the stratigraphy of the Santonian through Maastrichtian (Upper Cretaceous) of extra-Carpathian Poland, are presented and discussed. The summary is based on recent studies in selected sections of southern Poland (Nida Synclinorium; Pulawy Trough including the Middle Vistula River composite section; and Mielnik and Kornica sections of south-eastern Mazury-Podlasie Homocline) and of western Ukraine (Dubivtsi). The new zonation based on benthic forams is presented for the entire interval studied. Zonations for ammonites, belemnites and inoceramid bivalves are compiled. All stage boundaries, as currently defined or understood, may easily be constrained or precisely located with the groups discussed: the base of the Santonian with the First Occurrence (FO) of the inoceramid Cladoceramus undulatoplicatus; the base of the Campanian with the Last Occurrence (LO) of the crinoid Marsupites testudinarius and approximated by the range of the foraminifer Stensioeina pommerana; and the base of the Maastrichtian approximated by the FO of the inoceramid bivalve Endocostea typica and the FO of the belemnite Belemnella vistulensis. The positions of substage boundaries, as currently understood, are constrained in terms of the groups discussed.

Key words: Upper Cretaceous; Extra-Carpathian Poland; Biostratigraphy; Correlation; Chronostratigraphy.

INTRODUCTION

Much has changed in the stratigraphical understanding and resolution of Upper Cretaceous stratigraphy since the publication of the biostratigraphic summary on the Upper Cretaceous of extra-Carpathian Poland (Blaszkiewicz and Szymakowska 1984 in the Atlas of Cretaceous fossils by the Polish Geological Survey in 1984, with its English edition in 1989). The critical factor has been the change in approach; from the study of the stage and substage contents to the study of their boundaries, envisioned the best by the two symposia on Cretaceous Stage Boundaries, in Copenhagen in 1983 (Birkelund et al. 1984) and in Brussels in 1995 (Rawson et al. 1996). The symposia were followed by intensive studies by members, and associates, of the stratigraphical working groups, established and devoted to select the
most appropriate stratotype sections, and to recognize the stratigraphic successions and subdivisions of particular stages. As a result, most of the Upper Cretaceous stages already have formally designated stratotypes (Odin and Laumerelle 2001; Kennedy et al. 2004, 2005; Lamolda et al. 2014) and those which are left have been intensively studied (Gale et al. 2007; Walaszczyk et al. 2010, 2012). Much work has been done also on the substages (discussion in Ogg and Hinnov 2012).

During these two decades, intensive works have been conducted on the biostratigraphy of the Upper Cretaceous of extra-Carpathian Poland. The selected best sections in the country were re-investigated with the aim of integrating the results based on critical macro- and microfossils. Although there are still biostratigraphic groups and other, non-biostratigraphic tools, which will contribute to the final scheme of the Upper Cretaceous subdivision of extra-Carpathian Poland, the results of recent studies have improved markedly the former biostratigraphic summary.

The present paper summarizes the current biostratigraphies and biostratigraphic recognition of the Santonian–Maastrichtian (Upper Cretaceous) chronostratigraphy of extra-Carpathian Poland. We have integrated the results inferred from benthic foraminifers, ammonites, belemnites, inoceramid bivalves, and echinoids. The results are based primarily on surficial sections, which provided parallel records of at least two groups included into the analysis. The critical sections studied are located in south-eastern Poland: the Lublin area, including the Middle Vistula River section, the Nida Synclinorium, and selected sections in the eastern part of the country (Text-figs 1, 2).

The main aim of the present account is to update and summarise the biostratigraphical subdivisions of the Santonian through Maastrichtian of extra-Carpathian Poland and to present the practically applicable biostratigraphic definitions of chronostratigraphic boundaries (at stage and substage levels), as currently understood. Nevertheless, the record of the palaeontological

Text-fig. 1. Geological sketch-map of extra-Carpathian Poland, without Cenozoic deposits; tectonic units after Żelaźniewicz et al. 2011. Localities studied are in bold; Middle Vistula River section is presented Text-fig. 2.
The present summary on the biostratigraphy of the Coniacian through Maastrichtian of extra-Carpathian Poland integrates the results based on benthic foraminifers, ammonites, belemnites, inoceramid bivalves and echinoids. Not every group allows for the subdivision of the entire succession, either because of their limited occurrence or because they are still insufficiently recognized. Inevitably, the groups with the most complete record are foraminifers, ammonites and inoceramid bivalves. The belemnites and echinoids, although spanning the entire interval studied, provide sufficiently good palaeontological documentation only in parts of their ranges.

**Benthic foraminifers (Z. Dubicka)**

Like today, Foraminifera were the most common and abundant calcareous shell marine microorganisms during the Late Cretaceous. Combined with their high fossilization potential, foraminifers provide the most complete and sufficiently good fossil record to trace the details of their evolutionary changes (e.g. Pearson and Ezard 2014).

Foraminifera occupied almost all marine environments from marginal marine to deep seas and from poles to the tropics, representing both the benthic and planktonic modes of life. Planktonic forms are commonly believed to be particularly effective for interregional biostratigraphic correlations, since their planktonic behavior affects their high dispersal potential. However, there are many factors which influence their distribution, including physical barriers, depth, salinity, and temperature of ambient waters, food availability
and related features such as primary production, upwelling and water currents (Hemleben et al. 1989; Sen Gupta 2002; Schiebel and Hemleben 2005). Recent planktonic foraminiferal communities are attributed to five major bioprovinces (tropical, subtropical, temperate, subpolar, and polar) which approximately follow the water temperature and salinity zonal pattern (Bé 1977; Boltovskoy and Wright 1979). The species diversity decreases generally pole-wards. At least four palaeobiogeographic provinces are distinguished among Late Cretaceous planktonic foraminifera (Hart 2000): Tropical (Tethyan), Transitional, Boreal (N) and Austral (S), of which the tropical is taxonomically the most diverse.

During the Late Cretaceous the area of extra-Carpathian Poland belonged to the Foraminiferal Transitional Province, located between the Tethyan and Boreal provinces (Pożaryska and Peryt 1979). Therefore, the foraminiferal assemblages of epicontinental Poland are taxonomically much more depleted than Tethyan–Central Atlantic assemblages, missing the most of the characteristic forms of the latter area. Consequently, the standard globotruncanid and heterohelicid zonations (i.a., Robaszynski and Caron 1979, 1995; Robaszynski et al. 1984; Huber et al. 2008; Pérez-Rodríguez et al. 2012; Ogg and Hinov 2012), based mainly on Tethyan-Central Atlantic species, cannot be applied. Actually, this standard zonation works only, and to a limited extent, in the Cenomanian and Turonian (see Peryt 1980, 1983; Peryt and Wyrwicka 1991, 1993; Peryt et al. 1994; Dubicka and Machalski 2016), being almost totally useless in the later part of the epoch. In consequence, new local planktonic foraminiferal zonations were established (Peryt 1980; Gawor-Biedowa 1992; Dubicka and Peryt 2012a, b). Regrettably however, these zones, based on species with relatively long vertical ranges, have rather moderate chronostratigraphic potential. Nevertheless, some of the planktonic foraminiferal events can be used for local and even interregional correlations [e.g., the first occurrence of *Globotruncanina linneaina* pill-box-like morphotypes close to the Coniacian–Santonian boundary and the extinction of marginotruncanids within the Santonian–Campanian boundary interval; their stratigraphic positions correspond to the coeval events recorded in the stratotype Olazaguita section (Lamolda and Paul 2007; Lamolda et al. 1999, 2014) and in the Waxahachie Dam Spillway section, the GSSP candidate section for the base of the Campanian Stage (Gale et al. 2007)].

Instead, with the exception of very shallow coastal sediments, benthic foraminifera are common to abundant in almost all marine facies of the European epicontinental Cretaceous. They are mostly represented by calcareous forms of the Rotaliida, including buliminids (supra-ordinal classification follows Pawlowski et al. 2013) and the Lagenida, whereas representatives of the Milolida are less frequent. Agglutinated taxa are in general rarer in more calcareous facies, however, their abundance and diversity increase significantly in oxygen-poor and organic-rich sediments (e.g. Bernhard 1986; Dubicka et al. 2014). They seem to be able to overcome the problems of carbonate undersaturation and the difficulty of secreting calcium carbonate in such environments (e.g. Bernhard 1986). Moreover, agglutinated forms dominate the foraminiferal assemblages of very shallow sandy facies (e.g., the Albian sands and marly sands of the Amnopol succession – see Dubicka and Machalski 2016). In general, the taxonomic composition of Late Cretaceous benthic foraminifera is very similar across the entire epicontinental Europe, giving an opportunity of direct bio-correlations between regions. The available data suggest, moreover, that the majority of first appearances recognized in most of the taxa reflect actual evolutionary events. Several evolutionary lineages of arenobuliminids, bolivinoidids, gavelinellids, globorotalitids or stenioecinids have been recognized in these sediments (Vasilenko 1961; Carter and Hart 1977; Edwards 1981; Hart and Swiecick 1988; Bailey et al. 2009; Dubicka and Peryt 2014, 2016; Dubicka 2015).


**Ammonites and belemnites (Z. Remin)**

Ammonites and belemnites are critical groups for the biostratigraphy of the Upper Cretaceous of the entire North European Province. Both groups, because of their fast evolution, yielded several traditional zonal index fossils in the interval studied, however, the overall stratigraphic subdivision and resolution offered by ammonites and belemnites in the Cretaceous of extra-Carpathian Poland differ markedly in particular intervals.
The critical study on the Campanian-Maastrichtian ammonites of extra-Carpathian Poland is the monograph by Błaszkiewicz (1980), based on the fossiliferous and apparently continuous succession of the Middle Vistula River section (Text-figs 1, 2). Although his study was revised and amended in a series of subsequent papers (Burnet et al. 1992; Kennedy et al. 1992, Hancock and Kennedy 1993; Machalski 1996, 2005a, b; Machalski and Jagt 1998; Jagt et al. 1999; Landman et al. 2010; Machalski 2012a, b), the general succession recognized has been confirmed. The studies on the Campanian ammonites in the Miechów Trough (Jagt et al. 2004 and Machalski et al. 2004) and on the Campanian and Maastrichtian of the Roztocze region (SE Poland) (Machalski 2005a, b, 2012b; Kin 2010; Remin et al. 2015) supplemented and extended the stratigraphic knowledge of the Campanian–Maastrichtian ammonites in Poland. Topmost Coniacian and Santonian ammonites from Poland are known from the fossiliferous Lipnik–Kije section in the north-eastern Nida Synclinorium (Remin 2004, 2010; and also Remin et al. 2016); only a few reports from the Middle Vistula River section (Kurlenda 1966), North Sudetic (Milewicz et al. 1968; Milewicz 1988) and from borehole material of the Polish Lowlands (Jaskowiak-Schoenichowa 1979, 1981) are known outside this area.

In the case of the Santonian–Maastrichtian belemnites, the early recognition of their stratigraphic significance is best expressed in the old stratigraphic subdivision of Stolley (1897), into “granulaten-“,”quadraten-“ and “mucronaten-Kreide”, based on the succession of the respective belemnite species groups. The belemnite subdivisions are, however, of geographically limited application. This is well exemplified by biostratigraphic schemes based on the genera Belemnitella and Belemnella as used in Western and Eastern Europe, which apply different zonal markers and/or present different understanding of apparently the same taxa. The Santonian through Maastrichtian belemnites of Poland (based on the material from the Middle Vistula River section) were monographed by Kongiel (1962). However, because of various reasons his taxonomic concepts have never gained wider acceptance. The revision of the rich Middle Vistula River material was recently accomplished by Remin (2007, 2008, 2012, 2015), who applied an artificial neural networks method, coupled with a unified biometric procedure. The direct comparison of Remin’s methodology with the classic Schulz 1979 procedure for the topmost Campanian–southern Maastrichtian Belemnella (see Keutgen et al. 2012) and for the topmost Maastrichtian Bln. kazimiroviensis (Skolozdrojowa, 1932) (Keutgen et al. 2016) showed quite divergent results, and the lack of any possibility of a simple transformation between both schemes.

**Inoceramid bivalves (I. Walaszczyk)**

For decades, the upper–middle Coniacian and Santonian inoceramids of Europe have intensively been studied and their biogeographic and evolutionary patterns are well recognized (see e.g., Heinz 1928; Seitz 1935, 1961, 1965; Tröger 1974; Kauffman 1977; Tröger and Christensen 1991; Walaszczyk 1992). There is a distinct biogeographic pattern within the group in the late Coniacian and in the Santonian. The latest Coniacian and Santonian (up to early Campanian) are characterised by Sphenoceramus, the genus typical of more boreal areas, whereas the southern areas are dominated by the genera Platyceramus, Cladoceramus and Cordiceramus. In central Europe the boundary between both biogeographic areas approximates to the palaeogeographic northern boundary of the Tethys. In the early and middle parts of the late Coniacian this biogeographic pattern is not as distinct, as, however, the genus Magadiceramus, the marker and dominant genus of this interval is rare or absent in more northerly parts of the European Biogeographic Province (see e.g., Tröger and Christensen 1991), where the genera Volvic eramus and Sphenoceramus dominate.

Late Cretaceous inoceramid bivalves have long been recognized as a widely spread and fast evolving group with, consequently, very high stratigraphic potential (e.g., Tröger 1967; Kauffman 1977). As long as wide geographic distribution and fast evolution were recognized among lineages of the early Late Cretaceous (Cenomanian through Santonian), the late Late Cretaceous (Campanian–Maastrichtian) clades were regarded as characterized by higher provincialism and, first of all, much slower evolution (e.g., Dhondt 1983b, 1992; Voigt 1996). Nevertheless, the preliminary analysis of the diversity curves and of evolutionary rates among European inoceramids (Walaszczyk 1996), as well as stratigraphical summaries on inoceramids from the US Western Interior (Kauffman et al. 1994) and from Japan (Toshimitsu et al. 1995), suggested that the late Late Cretaceous inoceramids kept the same trend throughout the epoch, until their final extinction. Subsequent studies on the Western Interior material (Walaszczyk et al. 2001) and European faunas (from Tercis: Walaszczyk et al. 2002; Odin and Walaszczyk 2003; and from the Middle Vistula section: Walaszczyk 2004; as well as slightly earlier reports from various parts of Europe: Walaszczyk et al. 1996; Walaszczyk 1997) confirmed the preliminary results. Recently, the group was successfully applied to the biostratigraphic
study of the Campanian and Maastrichtian of the Nida Synclinorium (Jurkowska 2016; see also Jurkowska et al. 2015).

With a few exceptions, the Campanian and Maastrichtian inoceramids of Poland represent uniform faunas characteristic of the entire Euramerican Biogeographic Region. The final extinction of true inoceramids is dated as early late Maastrichtian (Walaszczyk et al. 2009, 2010; Walaszczyk and Kennedy 2011). The later part of the Maastrichtian is characterised by ‘tegulated’ inoceramids, Spyridoceras tegulatus (von Hagenow, 1842) and Tenuipteria argentea (Conrad, 1858) (see e.g., Speden 1970; Dhondt 1983a; Abdel-Gawad 1986). These forms, regarded as separate from ‘true’ Inoceramidae, based on the characteristics of their ligamental plate, seem, however, to be much closer to the latter than earlier assumed. The regularity of ligamental pits is lost in a number of late Campanian and early Maastrichtian inoceramid lineages and this feature should not be regarded as critical at the genus-level taxonomy.

Until the early late Maastrichtian, the time of the extinction of the ‘true’ inoceramids, the group was evolutionarily vigorous, with high taxonomic diversity and morphological disparity. Inoceramids, even in their present state of recognition, allow the subdivision of the entire Santonian–Maastrichtian interval with a resolution comparable to that of ammonites and benthic forams (as presented in this paper), with still a huge potential for further, more detailed subdivisions.

Echinoids (D. Olszewska-Nejbert)

Echinoids are common in the Upper Cretaceous successions of the North European Biogeographic Province. Although usually considered as of secondary stratigraphical importance, in some intervals the group is potentially of great stratigraphical value.

During the Late Cretaceous, most of the present area of Poland was located within the North European Province, stretching from the western tips of Central Asia (Kopeth-Dagh and and Mangyshlak Mts in Turkmenistan and Kazakhstan) to Ireland in the west (extra-Alpine area). In the Santonian–Maastrichtian the province was dominated by irregular echinoids, with regular forms rather rare (Ernst 1970b). The stratigraphically useful irregular echinoids are first of all holasteroids (Offaster, Galeola Echinocorys), spatangoids (Micraster), and holectipoids (Conulus and Galerites).

Most of the published echinoid reports are accompanied by precise stratigraphies (e.g. Ernst 1970b, 1972, 1975; Smith and Wright 1999, 2003; Jagt 2000; Jagt et al. 2004; Olszewska-Nejbert 2007; Schlüter and Wiese 2010). Consequently, it was possible to show that some genera, as e.g. Micraster (Ernst 1970c, 1972; Olszewska-Nejbert 2007) or Offaster-Galeola (Ernst 1971) are fast-evolving lineages, other are complex, and the rate of evolution of some others, is not clear at all. This is the case with e.g., Echinocorys, a key echinoid genus for the late Late Cretaceous biostratigraphy. This genus retained a very conservative architectural plan during its entire Late Cretaceous history, and displays a very weak morphological expression of its evolutionary changes. Consequently, the genus is understood by some researchers as a single large species complex (Wright 1864-1882; Wilcox 1953; Smith and Wright 2003). Some other investigators do see phenotypic changes in its successive populations (e.g. Ernst 1970b, Jagt 2000, Smith and Wright 2003), arguing about stratigraphical value of the genus (Wright 1864-1882; Smith and Wright 2003). Ernst and Schulz (1974), Jagt et al. (2004) and Olszewska-Nejbert (2007) proposed the use of the concept of Echinocorys ‘species groups’, which would give a stratigraphically recognizable succession of morphotypes, and this concept is also adopted herein. A similar problem applies to some Campanian Micraster, where the ‘group’ concept, although informal, gives a preliminary solution to the taxonomy of these poorly understood clades (e.g. Jagt 2000; Jagt et al. 2004).

Echinoids are marine benthic fauna, with a strong dependence on the consistency and grain size of the substrate, as well as some other factors, such as water depth or temperature (e.g. Ernst 1970a, b; Smith 1984; Olszewska-Nejbert 2007). Numerous regular echinoids prefer nearshore settings, with a coarse-grained substrate or hard rocky bottom covered by algae mats. Irregular echinoids favor more distal and quieter environments in deeper parts of the basin. During the Late Cretaceous, with the CaCO₃ content increasing above 55–60%, holasteroids and spatangoids dominated the echinoid assemblages (Ernst 1970b). This type of substrate is found in most of the Santonian–Maastrichtian seas of extra-Carpathian Poland (Jaskowiak-Schoeneichowa and Krassowska 1988; Walaszczyk 1992; Leszczyński 1997, 2012). The echinoid faunas known from the Upper Cretaceous of extra-Carpathian Poland represent echinoids known from the entire North European Province (Stokes 1975; Jagt 2000; Jagt et al. 2004; Smith and Wright 1999, 2003, 2012; Olszewska-Nejbert 2007).

Although echinoids are known from various regions of extra-Carpathian Poland (Text-fig. 1), the most representative areas for the particular intervals, discussed in this paper, are: Santonian of the western flank of the
Nida Synclinorium (Hynda and Mączyńska 1979; Kudrewicz 1992); Campanian and Maastrichtian of the Nida Synclinorium (Mączyńska 1968, 1989; Jagt et al. 2004), Campanian and Maastrichtian of the Middle Vistula section (Mączyńska 1989), and the chalk succession of eastern Poland (Olszewska 1987; Langner 1990). The Coniacian-Maastrichtian echinoids from the Middle Vistula River and from the entire Lublin area have not received sufficient palaeontological documentation.

BIOZONATIONS

Among the groups discussed in this paper, the benthic foraminifers, inoceramid bivalves, ammonites and belemnites allow for a well-defined biozonation within the entire or in most of the Santonian through Maastrichtian interval of extra-Carpathian Poland. Besides benthic foraminifers, for which the original biozonation is presented in this paper, the schemes based on other groups are compiled from recent extensive studies and discussions (Peryt 1980, Błaszkiewicz 1980; Keutgen et al. 2004; Remin et al. 2015). The first biostratigraphic study on the Late Cretaceous benthic foraminifera of extra-Carpathian Poland was published by Pożaryska (1954). Her study was based on the Middle Vistula River succession, and she was able to successfully correlate her foraminiferal ranges with Pożaryski’s (1938) macrofossil zonation. Subsequent studies, published between 1950 and 1990, were mainly based on borehole material (Bieda 1958; Witwicka 1958; Gawor-Biedowa and Witwicka 1960; Gawor-Biedowa 1972, 1992; Pożaryska and Witwicka 1983; Gawor-Biedowa et al. 1984; Peryt 1988). Unfortunately, the zonation worked out on the borehole material was not directly correlated to the macrofossil standard zonation and consequently, its chronostratigraphic interpretation was difficult. The recent restudy of selected sections with well-constrained chronostratigraphy (Dubicka 2012, 2015; Dubicka and Peryt 2011, 2012, b; 2014, 2016; Jurkowska et al. 2015; Peryt and Dubicka 2015; Machalski et al. 2016) allowed for the precise and rigorous correlations between micro- and macrofossil zonations. The summary on the recent development in the benthic foraminiferal zonation and its correlation to the chronostratigraphic standard is presented below.

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The particular zones (Text-fig. 3), with their definitions, are discussed (in ascending order). The index taxa are illustrated in Text-figs 5–8.

Stensioeina exsulca Partial-range Zone. The base of the zone is defined by the Last Occurrence (LO) of Protostensioeina granulata (Olbertz, 1942) and its top by the First Occurrence (FO) of Protostensioeina polonica (Witwicka, 1958). At the base of the zone Gavelinella vombensis (Brotzen, 1945), Loxostomum eleyi (Cushman, 1927), and the genus Neoflabellina appear. In the upper part of the zone appears Protostensioeina sp. E. The zone ranges from the upper part of the V. involutus Zone through to the upper part of the Magadiceramus subquadratus Zone. The zone is established based on the Ukrainian sections of the Dubivtsi I quarry (marls) and the Dubivtsi II quarry (lower half of the first exploitation level).

Protostensioeina bohemica Total-range Zone. This is the index taxon range zone. The top of the Zone is associated with the disappearance of all members of the
Text-fig. 3. Chronostratigraphy; ammonite, belemnite, inoceramid bivalve, and benthic foraminifera zonations; and vertical ranges of critical sections for the Santonian through Maastrichtian of extra-Carpathian Poland.
*P. granulata* group (see Dubicka and Peryt 2014). The zone corresponds to the upper part of the *Magadiceramus subquadratus* Zone and the lowermost part of the *Cladoceramus undulatoplicatus* Zone, thus coinciding with the Coniacian–Santonian boundary interval. The zone was recognized in the Ukrainian section of Dubivtsi II quarry (the middle and upper parts of the first exploitation level).

*Gavelinella vombensis* Partial-range Zone. The base of the zone is defined by the LO of *P. bohemica* (Jirová, 1958), and its top by the FO of *Stensioeina perfecta* Koch, 1977, the oldest member of the *Stensioeina* perfecta (“thick stensioenids”) lineage (see Dubicka and Peryt 2014). The zone corresponds to the lower part of the *Cladoceramus undulatoplicatus* Zone. The zone was recognized in the Ukrainian section of Dubivtsi II quarry (uppermost part of the fourth exploitation level).

*Stensioeina perfecta–Gavelinella vombensis* Concurrent-range Zone. This is the interval between the FO of the index taxon and the LO of *G. vombensis*. The zone spans the upper part of the *Cladoceramus undulatoplicatus* Zone, and upper boundaries of both zones seem to be coeval; the LO of *G. vombensis* Zone is thus a good foraminiferal proxy for the lower/middle Santonian. It was best studied in the Ukrainian section of Dubivtsi II quarry (upper middle Santonian, and corresponds to the upper part of the *Sphe-noeceramus pinniformis* inoceramid Zone. It was best studied in the Ukrainian section of Dubivtsi II quarry (middle part of the third up to the middle part of the fourth exploitation levels) (see Dubicka and Peryt 2014).

*Stensioeina gracilis* Interval Zone. The zone ranges between the FO of the index taxon (base) and the FO of *Bolivinoides strigillatus* (Chapman, 1892) (top). The zone corresponds to the lower part of the *Cordiceramus muelleri* inoceramid Zone, which defines the lower upper Santonian. It is best accessible in the Ukrainian section of Dubivtsi II quarry (upper part of fourth exploitation level) (see Dubicka and Peryt 2014).

*Stensioeina pommerana* Subzone. This is the subzone of the *B. strigillatus* Zone. It ranges between the FO of true *Stensioeina pommerana* Brotzen, 1936 and the FO of *B. culverensis*. The subzone is best accessible in the Ukrainian section of Dubivtsi II quarry (fifth and basal sixth exploitation levels) (see Dubicka and Peryt 2016) and in the Lipnik-Kije section, in the NE Nida Synclinorium.

*Bolivinoides culverensis* Interval Zone. The base of the zone is defined by the FO of the index taxon and its top by the FO of its descendant, *Bolivinoides culverensis* Barr, 1967. The zone spans the upper upper Santonian and basal Campanian (upper part of the *Cordiceramus muelleri* and basal *Sphenoceramus patootensiformis* zones). The zone is well accessible in the Ukrainian section of Dubivtsi II quarry (fifth and basal sixth exploitation levels) (see Dubicka and Peryt 2016) and in the Lipnik-Kije section, in the NE Nida Synclinorium.

*Gavelinella praestelligera* Interval Zone. Its base is defined by the FO of the index taxon, the oldest member of the *Gavelinella stelligera* lineage, and its upper boundary of the *Gavelinella pertusa* (Marsson, 1878). The zone spans the middle part of the middle Santonian. It was best studied in the Ukrainian section of Dubivtsi II quarry (lower part of the third exploitation level).

*Gavelinella pertusa* Interval Zone. The zone ranges between the FO of the index taxon (base) and the FO of *Stensioeina gracilis* Brotzen, 1945 (top). The zone spans the upper middle Santonian, and corresponds to the *Sphe-noeceramus pinniformis* inoceramid Zone. It was best studied in the Ukrainian section of Dubivtsi II quarry (middle part of the third up to the middle part of the fourth exploitation levels) (see Dubicka and Peryt 2014).
Bolivinoides granulatus—Stensioeina gracilis Concurrent-range Zone. The zone is characterised by the co-occurrence of the index taxa. It spans the middle lower Campanian (uppermost part of the S. patootensisiformis and a lower part of the Sphaeroceramus sarmiensis-Cataceramus darsiensis zones) (semonensis, conica/papillosa/ papillosa and the lower part of gracilis/micronat zones in the belemnite/echinoid zonation). The zone is well exposed in the Wierzchowisko, Bonarka–Tesco and Jeżówka 1 sections of the Nida Synclinorium (see Dubicka 2015).

Bolivinoides decoratus Partial-range Zone. The base of the zone is defined by the LO of Stensioeina gracilis Brotzen, 1945 and its top by the FO of Gavelinella monterelensis (Marie, 1941) and of the plano-convex morphology of C. voltzianus (d’Orbigny, 1840) (C. voltzianus morphotype B – see Dubicka 2015). The index taxon appears slightly above the base of the zone. The zone corresponds to the gracilis/micronata belemnite Zone. The top of the zone approximates the lower/upper Campanian boundary in the two-fold subdivision. It is known from the Mielnik I section of the Mazury–Podlasie Homoclino (see Dubicka 2015).

Gavelinella monterelensis–Gavelinella costulata Concurrent-range Zone. The zone is defined by the LO of Stensioeina gracilis Brotzen, 1945 and its top by the FO of Gavelinella costulata (Marie, 1941) morphotype D (planispiral; see Dubicka 2015) disappears. The zone approximates the C. becumensis inoceramid Zone, and the conica/micronata echinoid/belemnite Zone. It is best exposed in the middle part of the Mielnik I section (Mazury–Podlasie Homoclino) and in the upper part (above the hardground) of the Jeżówka 1 section (Nida Synclinorium) (see Dubicka 2015).

Gavelinella annae Partial-range Zone. The base of the zone is defined by the LO of Gavelinella costulata (Marie, 1941) and its top by the FO of Globorotalites emdyanensis Vasilenko, 1961. It corresponds to the ‘Inoceramus’ azerbajdjanensis – ‘Inoceramus’ vorhelmensis inoceramid Zone. It is best represented in the upper part of the Mielnik I section (Mazury–Podlasie Homoclino) and in the Rzęuśnia section (Nida Synclinorium) (see Dubicka 2015).

Globorotalites emdyanensis Interval Zone. This is the interval between the FO of the index taxon and the FO of Bolivina incrassate Reuss, 1851. Higher in the zone Bolivinoides miliaris Hiltermann and Koch, 1950 appears. The zone begins in the upper part of the ‘Inoceramus’ azerbajdjanensis – ‘Inoceramus’ vorhelmensis Zone, whereas its top coincides with the top of the C. subcompressus inoceramid Zone. This zone is exposed in the Sulejów and Dorotka section of the Middle Vistula River section.

Bolivina incrassata–Globorotalites michelinianus Concurrent-range Zone. The zone is defined by the co-occurrence of both index taxa. The lower part of the zone is additionally characterized by the occurrence of the relatively short-ranging taxon Bolivinoides sp. 1, followed by its successor B. sidestradensis in the middle part of the Zone. It corresponds to the ‘Inoceramus’ tenuilineatus inoceramid Zone and the lower part the Didymoceras donezianum ammonite Zone. It is best exposed in Leśne Chalupy, Ciszyca Kolonia and Ciszyca in the Middle Vistula River section (see Peryt and Dubicka 2015) and in the Szozdy section, Roztocze Hills.

Bolivinoides miliaris Partial-range Zone. The base of the zone is defined by the LO of Globorotalites michelinianus (d’Orbigny, 1840) and its top by the FO of Angulogavelinella gracilis (Marsson, 1878). It corresponds to the lower part of the Sphaeroceramus pertenuiformis inoceramid Zone and the upper part of the Didymoceras donezianum ammonite Zone. The zone is known only from the Wola Pawłowska section of the Middle Vistula River section (see Peryt and Dubicka 2015).

Angulogavelinella gracilis–Gavelinella monterelensis Concurrent-range Zone. The zone is defined by the co-occurrence of both index taxa. Bolivinoides intermedius Dubicka and Peryt, 2016 appears in the zone. It corresponds to the lower part of the Belemnittella najdini–Belemnittella posterior belemnite Zone and to the upper part of the Sphaeroceramus pertenuiformis and the lowermost part of the ‘Inoceramus’ altus inoceramid zones. The zone is best exposed in the sections of Łopoczno and of the lowest part of the Pawłowice Cementery of the Middle Vistula River section, as well as in the Gnatowice section of the Nida Synclinorium (see Peryt and Dubicka 2015).

Bolivinoides intermedius Partial-range Zone. The base of the zone is defined by the LO of Gavelinella monterelensis (Marie, 1941), and its top by the FO of Bolivina decurrens (Ehrenberg, 1854). The zone spans the lower part of the Nostoceras hyatti ammonite Zone and most of the Inoceramus altus inoceramid Zone (except its basal part). It is best accessible in the lower third of Piotrawin Quarry and in the Pawłowice North section of the Middle Vistula River section (see Peryt and Dubicka 2015).
Text-fig. 6. 1 – Angulogavelinella gracilis (Marsson, 1878), Kłudzie, MWGUW ZI/67/36.02; 2 – Bolivina incrassata Reuss, 1851, Kłudzie, MWGUW ZI/67/36.04; 3 – Anomalinoidea gunkinoensis (Neckaja, 1948), Chełm, MWGUW ZI/67/36.35; 4 – Bolivina decurrens (Ehrenberg, 1854), Chełm, MWGUW ZI/67/36.56; 5 – Eouvigerina cretae (Ehrenberg, 1854), Dubivtsi, ZPAL F63/29/48; 6 – Eouvigerina cretae (Ehrenberg, 1854), Dubivtsi, ZPAL F63/32/38; 7 – Gavelinella acuta (Plummer, 1926), Chełm, MWGUW ZI/67/36.34; 8 – Gavelinella chenomonta (d’Orbigny, 1840), Mielnik, MWGUW ZI/67/36.18; 9 – Gavelinella montevilense (Marie, 1941), Dorotka, MWGUW ZI/67/36.01; 10 – Neoflabellina reticulata (Reuss, 1851), Chotcza, MWGUW ZI/67/36.18; 11 – Gavelinella annae (Pawaryska, 1954), Mielnik, MWGUW ZI/67/36.29. Scale bars – 100 µm
Bolivina decurrens–Globorotalites emdyensis Concurrent-range Zone. This zone is defined by the co-occurrence of both index species. It spans the middle part of the Nostoceras hyatti ammonite Zone and the lower part of the ‘Inoceramus’ inkermanensis Inoceramid Zone. It is best exposed in the Sadkowice and Sadowice North sections, as well as in the upper third of Piotravian Quarry (all in the Middle Vistula River section) (see Peryt and Dubicka 2015).

Osangularia navarrona Partial-range Zone. This ranges between the LO of G. emdyensis and the FO of Neoflabellina reticulata (Reuss, 1851). The zone corresponds to the upper part of the ‘Inoceramus’ inkermanensis and ‘Inoceramus’ costaeus Inoceramid zones. It spans the upper part of the Nostoceras hyatti ammonite Zone and the Belemnella lanceolata + Belemnella inflata belemnite zones. It is best accessible in the Raj, Raj North and Kamięt sections and in the topmost part of the Piotravian quarry of the Middle Vistula River composite section (see Peryt and Dubicka 2015).

Neoflabellina reticulata Interval Zone. The base of the zone is defined by the FO of the index taxon and its top by the FO of Anomalinoideas gankinoensis (Neckaja, 1948). In inoceramid terms, it ranges from the upper part of the ‘Inoceramus’ redbirdensis Zone to the lower part of the Trochoceramus radiosus Zone. It is best exposed in the Kludzie and Dziurków sections, of the Middle Vistula River section.

Anomalinoideas gankinoensis–Angulogavelinella gracilis Concurrent-range Zone. The zone is defined by the co-occurrence of both index species. It corresponds to the upper part of the Belemnella occidentalis Zone (sensu Błaszkiewicz 1980). It is known from the Ukrainian section of Kamyankopli (‘Lvivskaya svita’ of Gavrilyshin et al. 1991) and from the lower part of the Boiska section of the Middle Vistula River section (see Dubicka and Peryt 2012).

Bolivinoides giganteus Interval Zone. The base of the zone is defined by the LO of A. gracilis and its top by a level of the temporal disappearance of S. pommerana. It corresponds to the basal part of the Belemnitella junior belemnite Zone of the basal upper Maastrichtian. The zone was recorded in the Boiska and Jarentowskie Pole sections of the Middle Vistula River section (see Dubicka and Peryt 2012).

Gavelinella acuta Interval Zone. The base of the zone is defined by the temporal disappearance of S. pommerana whereas its top is marked by the FO of Bolivinoides draco (Marsson, 1878). It corresponds to the Hoploscaphites constrictus ivivenisis ammonite Zone. The zone is known from the Chotcza and Lucimia sections of the Middle Vistula River section, as well as from the Chełm Quarry of the Lublin Upland (see Dubicka and Peryt 2011).

Bolivinoides draco Interval Zone. The base of the zone is defined by the FO of the index taxon and its top by the FO of Bolivinoides vistulae Pożarska, 1954. It corresponds to the lower part of the Hoploscaphites constrictus crassus ammonite Zone. It is accessible in the Podgórz 1, Podgórz 2, and Dobre sections of the Middle Vistula River section.

Bolivinoides vistulae Interval Zone. The base of the zone is defined by the FO of the index taxon and its top is marked by the disappearance of most of the Cretaceous planktonic foraminifers. The zone corresponds to the upper part of the Hoploscaphites constrictus crassus and Hoploscaphites constrictus johnjagi ammonite zones. It is exposed in the quarries of Kazimierz Dolny and Nasiłów in the Middle Vistula River section, and in the Melgiew and Lechówka sections of the Lublin Upland (see Peryt and Dubicka 2012; Machalski et al. 2016).

Ammonite zonation (Z. Remin)

Paratexanites serratominarginatus Interval Zone. The base of the zone is defined by the FO of the index taxon. This taxon has not been found in Poland; however, the presence of the zone is confirmed by Protexanites (Protexanites) bourgeoisianus (d’Orbigny, 1850) accompanied by Parapuzosia (Parapuzosia) aff. corbarica (de Grossouvre, 1894). As indicated by Kennedy (1984) and Kennedy et al. (1995), the main occurrence of P. (P.) bourgeoisianus falls within the P. serratominarginatus Zone. Similarly, P. (P.) corbarica also first appears in this zone. The upper boundary of the zone is defined by the FO of Texanites pseudotexanus (de Grossouvre, 1894). This zone was best exposed in the temporary Lipnik–Kije section in the SW margin of the Holy Cross Mountains (Remin 2010).

Texanites pseudotexanus Interval Zone. The base of the zone is defined by the FO of its index taxon. In the Lipnik–Kije section the base of the zone is drawn at the FO of T. cf. pseudotexanus. This zone corresponds to the uppermost part of the Magadiceramus subquadra tus and Sphenoceramus pachti Inoceramid zones (Text-fig. 3). Its upper boundary is defined by the entry of Kitchinutes enscheris Lommerzheim, 1995 and Nowakites
savini de Grossouvre, 1850, the event, which seems to coincide with the FO of Cladoceramus undulatoplicatus (Roemer, 1852), the inoceramid marker of the base of the Santonian (Text-fig. 3). The T. pseudotexanus Zone was best exposed in the Lipnik–Kije section in the SW margin of the Holy Cross Mountains (Remin 2010); currently these ephemeral outcrops are no longer accessible.

Kitchinites emscheris–Nowakites savini Interval Zone. The base of the zone is defined by the FO of its index taxon. As its base correlates well with the FO of the inoceramid basal Santonian marker, C. undulatoplicatus, the base of the zone can be taken as the base of the Santonian Stage in ammonite terms. The zone corresponds to the lower and lower middle Santonian, the Cl. undulatoplicatus Zone and the lower part of the Cordiceramus ssp. Zone, in inoceramid terms. It is an equivalent of the K. emscheris Zone of the Münsterland Cretaceous Basin, Germany (Kaplan and Kennedy 2000), and of the Nowakites carezi and Texanites gallicus subzones in Corbières, France (Kennedy et al. 1995).

Upper Santonian–lower Campanian. Because of the absence of stratigraphically important taxa no ammonite zones are distinguished in this interval.

Neancyloceras phaleratum Interval Zone. The base of the zone is defined by the FO of Trachyscaphites spiniger spiniger (Schlüter, 1872) and its top by the LO of the index taxon. Its upper boundary approximates the base of the succeeding B. polyplocum Zone. According to Błaszkiewicz (1980), the subspecies posterior (Błaszkiewicz, 1980) of T. spiniger ranges into B. polyplocum Zone. The N. phaleratum Zone corresponds to the lower part of the middle Campanian. In the Middle Vistula River section, it is accessible in the villages of Okół and Sulejów.

Bostrychoceras polyplocum Interval Zone. The base of the zone is defined by the FO of the index taxon, and its top by the FO of Menuites portlocki posterior (Błaszkiewicz, 1980). The index taxon ranges through the entire zone and, most probably, passes into the basal part of the Didymoceras donezianum Zone. The zone yielded also (according to Błaszkiewicz 1980): Pachydiscus koeneni de Grossouvre, 1894, Menuites portlocki (Sharpe, 1855), Trachyscaphites pulcherrimus (Roemer, 1841), Hoploscaphites greenlandicus (Donovan, 1953) and Anapachydiscus wittekindi (Schlüter, 1872). In the Middle Vistula River section, it is accessible between the villages of Sulejów and Dorotka. This zone is also accessible in some sections in the Roztocze Hills in SE Poland (Remin et al. 2015).

Didymoceras donezianum Interval Zone. The base of the zone is defined by the FO of Menuites portlocki posterior (Błaszkiewicz, 1980), and its top by the FO of Jelezykes nodosus (Owen) [=Acanthoscaphites quadrirhipinosis Błaszkiewicz, 1980 (see Kennedy et al. 1992)]. The index species dominates in the lower portion of the zone. The zone yielded also (according to Błaszkiewicz 1980): Acanthoscaphites tuberculatus (Giebel, 1849), T. pulcherrimus, H. greenlandicus, Pachydiscus cf. oldhami (Sharpe, 1855), and A. wittekindi. The zone is well exposed between the villages of Dorotka and Ciszycyan in the Middle Vistula River section. The zone is also exposed in the Nida Synclinorium (Błaszkiewicz 1980; Jurkowska 2016) and in the Roztocze Hills (Remin et al. 2015).

Nostoceras hyatti [= N. pozaryskii of Błaszkiewicz, 1980] Interval Zone. The base of the zone is defined by the FO J. nodosus and its top by the FO of Pachydiscus neubergicus (von Hauser, 1858). The index taxon first appears higher than J. nodosus and seems to range to the very top of the zone. In the Middle Vistula River section, it is accessible between the villages of Pawłowice and Raj, on the western bank and between Kamień and the Piotrawin Quarry, on the eastern bank of the river (Text-fig. 2). This zone is also accessible in selected locations in the Nida Synclinorium (Błaszkiewicz 1980; Jurkowska 2016) and in the Roztocze Hills in SE Poland (Remin, unpublished data).

Pachydiscus neubergicus Zone. The base of the zone is defined by the FO of the index species, and its top by the FO of Acanthoscaphites tridens (Kner, 1848) (compare Machalski 2012b). As noted by Machalski (2012a), the lowest well-localised specimen of P. neubergicus in the Middle Vistula River section comes from the bottom part of the Dziurków section, which corresponds to the lower part of the Endocosta typica inoceramid Zone (as recognized by Walaszczzyk 2004). Loose specimens of P. neubergicus are known from Khudzie and Kamień North, and come, most probably, from the upper part of the ‘Inoceramus’ redbirdensis Zone (compare Machalski 2012b).

Acanthoscaphites tridens Zone. The base of this zone is defined by the FO of the index species sensu Kin (2010), i.e. comprising large representatives of Acanthoscaphites with siphonal tubercles, and excluding the stratigraphically older forms which lack siphonal tuberculation (compare Machalski 2012b). The top of the zone is marked by the FO of Hoploscaphites constric tus livens Machalski, 2005. The zone was best exposed in Hrebenne, in the temporary excavations during
the constructions of the boundary post at the Polish-Ukrainian boundary. The part exposed belongs to the *Trocho ceramus radiosus* inoceramid Zone (Roztocze Hills, SE Poland) (Kin 2010). The zone is also available in the Bliżów section (Roztocze Hills area) in the upper part of the *E. typica* inoceramid Zone (Kin 2011). It is not exposed in the Middle Vistula River section (Machalski 2012b).

In the upper Maastrichtian, Machalski (2005b) recognized 13 scaphitid species/subspecies, with the newly named *H. constrictus lvivensis* and *H. c. johnjagti* Machalski, 2005. Machalski (2012b) used the chronosubspecies of *H. constrictus* to define three successive lineage zones. In ascending order, these are: *H. constrictus lvivensis* Zone, *H. c. crassus* Zone, and *H. c. johnjagti* Zone. As pointed out by Machalski (2005a, b; 2012b), the youngest member of the *H. constrictus* lineage is expected to be the most important and useful ammonite proxy for the recognition of the topmost Maastrichtian. Other scaphitids of the interval, because of their limited occurrences and poor documentation, are of limited biostratigraphic use.

**Hoploscaphites constrictus lvivensis** Zone. The base of this zone is defined by the FO of the index subspecies and its top by the FO of *Hoploscaphites constrictus crassus* (Łopuski 1911) as defined by Błaszkiewicz (1980) and Machalski (2005b). It is documented in sections in eastern Poland (Chelm) and Ukraine (near Lviv) where it corresponds to the lower part of the Belemnella junior Zone (*Spyridoceramus tegulatus–Belemnella junior Zone sensu germanico*; see Machalski 2005b; Dubicka and Peryt 2011). It seems that the base of the *lvivensis* Zone corresponds closely to the base of the upper Maastrichtian as understood herein (see discussion below).

**Hoploscaphites constrictus crassus** Zone. The base of this zone is defined by the FO of the index taxon and its top by the FO of *H. c. johnjagti*. The base of the zone is accessible in the locality Podgórz, in the Middle Vistula River section (Błaszkiewicz 1980; Machalski 2005b). It is widely distributed in central and eastern Poland (compare Machalski 2012b) and represents the highest ammonite zone recognized in the Middle Vistula River section (Machalski 2005a, b). The lower part of the zone is exposed in Kazimierz Dolny (Middle Vistula River section) and Rejowiec in eastern Poland. The part exposed belongs to the *Belemnella kazimiroviensis* Zone, albeit without the very last Maastrichtian levels. It is best exposed in the environs of Kazimierz Dolny, Bochotnica and Nasiłów, and Rejowiec in eastern Poland.

**Hoploscaphites constrictus johnjagti** Taxon-range Zone. This is the range zone of the index taxon. In Poland its top coincides with the top of the Maastrichtian stage (Machalski 2005b; 2012b). In Denmark and possibly in The Netherlands, this zone seems to extend into the basal Paleogene (compare Machalski 2012b). In Poland the zone is known from a single locality only, namely Melgiew near Lublin (Machalski 2005b; 2012b). Machalski (2012b) suggested that *H. c. johnjagti* is of great potential for recognition of the terminal Maastrichtian in the Boreal Realm and possibly in Central Asia (Machalski 2005b; 2012b). In belemnite terms it corresponds to the very top of the *Belemnella kazimiroviensis* Zone.

**Menuites terminus** Taxon-range Zone. This is the range zone of its index taxon. It is exposed in sections near Kazimierz Dolny and Nasiłów of the Middle Vistula River section (Machalski and Jagt 1998).

**Belemnite zonation** (Z. Remin)

The Santonian belemnite fauna is relatively rare. In the Vistula section belemnites are represented by the genera *Actinocamax* and *Gonioteuthis*. *Actinocamax verus* seems to occur throughout the Santonian (Kongiel 1962; Błaszkiewicz 1980) and ranges into the lower Campanian (Błaszkiewicz 1980). Within the *G. granulata* lineage, Kongiel (1962) distinguished *G. westfalicagranulata* (Stolley, 1897), *G. pseudopropinquaque* Kongiel, 1962, and *G. granulata* (Blainville, 1827), however he did not propose any formal zonation. Such a faunal composition supports the recognition of at least two standard zones, i.e. of *G. westfalicagranulata* and *G. granulata*, mainly in the middle and upper portions of the Santonian Stage (Kongiel 1962; Błaszkiewicz 1980).

Surprisingly, the Lipnik–Kije section, spanning the entire Santonian and basal Campanian, has not yielded any belemnite.

**Lower Campanian.** The Middle Vistula River section offers representatives of the genera *Actinocamax* and *Gonioteuthis*. Błaszkiewicz (1980) distinguished the zones of *G. g. granulata* and of *G. quadrata* in this interval. According to the recent belemnite subdivision as
recognized in NW Europe (compare Christensen 1990, 1997a, b), the *G. g. granulata* Zone is late Santonian in age. The *G. quadrata* lineage may be subdivided into: *G. granulata* (*Stolley*, 1897), *G. quadrata* (*Stolley*, 1897), *G. quadrata* (*Stolley*, 1897), and *G. quadrata gracilis*. In a similar manner to the situation with the Santonian *G. granulata* lineage, Kongiel (1962) did not propose any subdivision based on the *quadrata* lineage. Both groups were, however, successfully applied to the biozonation of the Santonian and Campanian in NW Europe (see e.g., Christensen 1990, 1997a, b). *G. quadrata sensu stricto* is known from the lower Campanian of the Wierzchowisko section in the SW part of the Nida Synclinorium (Jagt et al. 2004).

**Belemnitella langei** Interval Zone. The base of the zone is defined by the FO of the index taxon, and its top by the simultaneous FOs of *B. minor* I Jeletzky, 1951, *B. posterior* Kongiel, 1962, and *B. najdini* Kongiel, 1962. Only two *Belemnitella* species, i.e. *B. langei* and *B. mucronata* (*Schlotheim*, 1813) occur in this zone. In the Middle Vistula River section the lower boundary of the zone is not exposed. Its upper boundary is located between the Wola Pawłowska section and the base of the Pawłowiec Cemetery section in the western bank of the river (see Text-fig. 3).

**Belemnitella minor** I Interval Zone. The base of the zone is defined by the FO of the index taxon and its top by the simultaneous FOs of *B. minor* I Jeletzky, 1951, *B. posterior* Kongiel, 1962, and *B. najdini* Kongiel, 1962. Five *Belemnitella* species were recognized in this zone. In the Middle Vistula River section the lower boundary of the zone is not exposed, being located somewhere in an interval between the base of the succession exposed in the Pawłowiec Cemetery section and the Wola Pawłowska section, in the western bank of the river. Its top is located between the Sadkowice N and Raj sections, and the entire succession exposed in the huge Piotrawin Quarry section belongs to this zone.

**Belemnitella minor** II Interval Zone. The base of the zone is defined by the FO of the index taxon; its top by the LOs of *B. najdini* and *B. langei*. Five *Belemnitella* species have been recognized in this zone. In terms of the *Belemnella* zonation, the zone corresponds to the entire *Belemnella lanceolata* and *Belemnella inflata* zones. In the Middle Vistula River section the lower boundary is located in the Raj section, and its top is located at the “boundary marl”, well exposed in the sections of Podole, Kludzie S and Kludzie N, in the western bank of the river (Text-fig. 3).

**Belemnitella najdini–Belemnitella posterior** Concurrent Range Zone. The base of the zone is defined by the FO of the index taxon or by the simultaneous entry of *B. minor* I; its top by the LO of *B. najdini* in addition to the LO of *B. langei*, which seem to disappear simultaneously. The upper part of this zone corresponds to the *Belemnella lanceolata* and *Belemnella inflata* zones.

**Belemnella lanceolata** Interval Zone. The base of the zone is defined by the FO of the index taxon; its top by the FO of *Belemnella inflata* (*Arkhanelsky*, 1912). In the Middle Vistula River section, the base of the zone is exposed at the top of the Raj section, and its upper boundary is located somewhere between the Raj and Raj N sections.

**Belemnella inflata** Interval Zone. Its base is defined by the FO of the index taxon; its top by the FO of *Belemnella obtusa* Schulz, 1979, or the entry of *B. vistulensis* (Kongiel, 1962). The zone is well documented in the Middle Vistula River section.

**Belemnella obtusa** Interval Zone. The FO of the index taxon or the entry of *B. vistulensis*, define the base of this zone. Its upper boundary is defined by the FO of *B. sumensis*. The zone is subdivided into the *Belemnella vistulensis*, *Belemnella* sp. G and *Belemnella* sp. F subzones defined as interval range subzones (see Remin 2012).

In the Middle Vistula River section, the base of the *B. obtusa* Zone is placed immediately above the “boundary marl”, well exposed at Podole, Kludzie S and Kludzie N, and the belemnite assemblages below and above this level differ significantly. Higher parts of the zone are exposed in the Dziurków and Przedmieście sections (Text-figs 1, 2). Its upper boundary is not exposed.

**Upper lower Maastrichtian.** The classic *Belemnella* zones distinguished in Germany by Schulz (1979), i.e., *Bln. sumensis* Jeletzky, 1949, *Bln. cimbica* Birkelund, 1957, and *Bln. fastigata* Schulz, 1979, have not been recognized in the Polish sections yet, due to the lack of equivalent exposures. Provisionally, the *Bln. sumensis/Acanthoscaphites tridens* Zone was recognized in eastern Poland, i.e. in Hrebenne (Text-fig. 1), however, neither the upper nor the lower boundary of the zone could be studied.

**Belemnella junior** Zone. The base of the zone is defined by the FO of its index taxon; its top by the FO of *Belemnella kazimiroviensis* (*Skolozdrówna*, 1932). In the Middle Vistula River section the base of the zone is exposed in the Boiska section, north of Sołeć. The top
is located in the environs of Męćmierz (Text-figs 1, 2). It is also available in few locations in the Lublin Up-
lands, i.e. at Pogórz and Chełm (compare Machalski 2005b).

**Belennella kazimiroviensis Zone.** This is the youngest
Maastrichtian belemnite zone. In the Vistula section, the
base of the zone is exposed in the section of Męćmierz,
south of Kazimierz Dolny, and its top is exposed further
north in the Bochotnica and Nasiłów sections (Text-fig.
2). Equivalent strata of the zone are also available further
east in the Melgiew and Rejowiec sections.

**Inoceramid zonation** (I. Walaszczyk)

The topmost Coniacian through Maastrichtian in-
oceramid biozonation, as applicable to the successions
of extra-Carpathian Poland, is listed, defined and com-
mented on shortly below. Most of the zones may be re-
garded as standard zones, applicable for the entire
Euramerican biogeographic region. Others, however,
are based on taxa with limited geographic distribution,
or the understanding of the zones varies.

**Magadiceramus subquadratus** Interval Zone. The
base of the zone is defined by the FO of the index
taxon and its top by the FO of *Cladoceramus undulatoplicatus*.
The zone is potentially subdivided based on various
morphotypes of Romer’s species (treated usually as
subspecies; the nominal one, *crenulatus* and *creniso-
triaus* – see e.g., Walaszczyk and Cobban 2006). This
subzonal subdivision is not established in any section
in Poland.

**Cladoceramus undulatoplicatus** Taxon-range Zone.
This is the index taxon range zone. In Poland, the zone
is poorly documented, however, it has been reported
from the Lipnik-Kije section (Remin 2004) and from the
North Sudetic Trough (Mitura et al. 1969; Milewicz
*et al.* 1968; Milewicz 1988).

**Cordiceramus cordiformis** Partial-range Zone. The base
of the zone is defined by the LO of *C. undulatoplicatus*,
and its top by the FO of *Cordiceramus* ex gr. *muelleri*.

**Cordiceramus muelleri** Interval Zone. The base of the
zone is defined by the FO of the index species and its
top by the FO of *Sphenoceramus patoetniformis*
(Seitz, 1965) *lundbreckensis* (McLearn, 1929). The top of
the zone should approximate to the base of the *Mar-
supites testudinarius* Zone, which is the crinoid-based
topmost Santonian Zone. In extra-Carpathian Poland all
inoceramid taxa are well documented.

**Sphenoceramus patoetniformis** Taxon-range Zone. This is the long-ranging zone of the index
taxon, with a various sphenoceramids and *Cata-
ceramus* species [*C. baltica* (Böhm, 1909) should start
somewhere within the zone] present. The content
and evolution of inoceramids within the zone is
poorly understood.

**Sphaeroceramus sarumensis-Cataceramus dariensis**
Interval Zone. The base of the zone is defined by the
FO of any of the index taxa and its top by the FO of
*Cataceramus beckumensis* (Giers, 1964). The zone was
first documented in north German sections (Walaszczyk
1997) and recently in the Nida Synclinorium, in south-
ern Poland (Jurkowska 2016).

**Cataceramus beckumensis** Interval Zone. The base
of the zone is defined by the FO of the index species and
its top by the FO of *Inoceramus* azerbaydjanensis
(Aliev, 1939) and/or ‘I.’ vorhelmensis Walaszczyk,
1997. The zone, well documented in the Westphalian
sections (northern Germany) (Walaszczyk 1997), is
poorly documented in Poland.

‘Inoceramus’ azerbaydjanensis– ‘I.’ vorhelmensis Inte-
 rval Zone. The base of the zone is defined by the FO of
any of the index taxa and its top by the FO of *Cata-
ceramus subcompressus* (Meek and Hayden, 1860) [= *C.
haldemensis* (Giers, 1964)]. The zone is well docu-
mented in a number of sections in the Nida Synclinio-
rium (Jagt *et al.* 2004; Walaszczyk *et al.* 2010;
Jurkowska 2016).

**Cataceramus sub compressus** Partial-range Zone. The
base of the zone is defined by the LO of members of the
‘I.’ azerbaydjanensis–vorhelmensis group and its top
by the FO of *Inoceramus* ‘tenuilineatus’ Hall and
Meek, 1856. The basal part of the zone is poorly docu-
mented; its upper part is best accessible at Dorotka in
the Middle Vistula River section.

‘Inoceramus’ tenuilineatus Interval Zone. The base of
the zone is defined by the FO of the index species and
its top by the FO of *Sphaeroceramus pertenuiformis*
Walaszczyk, Cobban and Harries, 2001. The zone is
best exposed in the Kolonia Ciszycza and Ciszycza
Górska parts of the Middle Vistula River section as well
as in some sections of the Nida Synclinorium (see Ju-
rkowska 2016).

**Sphaeroceramus pertenuiformis** Interval Zone. The
zone begins at the FO of the index taxon and ranges to
the FO of ‘Inoceramus’ altus Meek, 1871.
The latter taxon was formerly referred to the genus *Inoceramus* costaecus Khalafova, 1966. The latter taxon was formerly referred to the genus *Trochoceramus* based on its radial ornament. It seems, however, that radial ornament appears independently in more than one lineage of the latest Campanian–early Maastrichtian inoceramids. Consequently, the species is left in open nomenclature.

*Inoceramus* costaecus Interval Zone. The zone begins at the FOs of the species and its top is marked by the FO of *Inoceramus* inkermanensis Dobrov and Pavlova, 1959.

*Inoceramus* inkermanensis Interval Zone. The zone begins at the FOs of the species and its top is marked by the FO of *Inoceramus* costaecus Khalafova, 1966. The latter taxon was formerly referred to the genus *Trochoceramus* based on its radial ornament. It seems, however, that radial ornament appears independently in more than one lineage of the latest Campanian–early Maastrichtian inoceramids. Consequently, the species is left in open nomenclature.


*Inoceramus* redbirdensis Interval Zone. This is the interval between the FOs of the index taxon and of *E. typica*. The Campanian–Maastrichtian boundary, as currently defined, is located in the upper part of this zone.

Endocostea typica Interval Zone. As defined herein, the zone may be treated as the range zone of its index taxon. *E. typica* is represented as the lower member of the *E. typica*–*E. barabini* lineage.

Cataceramus subcircularis Interval Zone. The base of the zone is defined by the LO of *E. typica*, and its top by the FO of *Trochoceramus radiatus* (Quaas, 1902). The zone is well represented in a number of sections of the Nida Synclinorium (see Jurkowska 2016) and in the Bliżów section, in eastern Poland.

Trochoceramus radiatus Taxon-range Zone. This is the range zone of the zonal index taxon. The zone was well documented in the village of Hrebenne, in eastern Poland (Kin 2010). The equivalent interval in the Middle Vistula River section is not exposed.

*Inoceramus* ianjonensis Taxon Range Zone. This is the taxon range zone of the index taxon. The zone has not been recognized in extra-Carpathian Poland yet.

Spyridoceramus tegulatus and Tenuipteria argentea zones. In Poland, the stratigraphy of tegulated inoceramids was intensively studied by Abdel-Gawad (1986). According to his data, correlated to the inoceramid zonation, as applied herein, *S. tegulatus* appears in the ‘I.’ redbirdensis Zone, somewhere close to the base of the Maastrichtian, as currently understood, and ranges high up into the Belenitella junior Zone. The zone of *T. argentea* correlates approximately to the topmost Maastrichtian belemnite zone of *Bln. kazimiroviensis*, although the base of the inoceramid zone is not precisely indicated.

**Echinoids (D. Olszewska-Nejburt)**

The group may be used in the formal biozonation only for part of the succession discussed in the present paper. Consequently, instead of the consequent presentation of the biozonation, a discussion on critical taxa for the biostratigraphy of the Santonian through Maastrichtian of extra-Carpathian Poland is provided. The selected forms are illustrated (Text-figs 9–11).

Echinoids are useful biostratigraphically in the Campanian, mostly in its lower and middle substages. Their importance was documented, and the formal zonation based on selected lineages was worked out, in northern Germany (Ernst 1971; Ernst et al. 1979). The most important are holasteroids ([*Offaster pilula* (Lamarck, 1816), *Galeola papillosa* (Leske, 1778), *Echinocorys* ex gr. subglobosa/turrita, *Echinocorys* ex gr. conica (Agassiz, 1847), *Echinocorys* ex gr. gibba], spatangoids ([*Micraster* (Gibbaster) ex gr. fastigatus/stolleyi, *Micraster* (Micraster) ex gr. schroederi/glyphus] and rare echinoids of the genus *Galrites*.

In the lower Campanian of Poland, *O. pilula* is best documented from the Nida Synclinorium (Text-fig. 10.2; Mączyńska 1989; Jagt et al. 2004), and reported also from the Middle Vistula section (Pozarski 1938). This species is known in the western and central parts of the North European Province, and is restricted to the lower lower Campanian of Germany (Ernst 1971, 1975; Jagt et al. 2004; Schlüter and Wiese 2010), England and Northern Ireland (Smith and Wright 2003).

Also reported from the upper lower Campanian of the Nida Synclinorium are *G. papillosa* (see Mączyńska 1989; Jagt et al. 2004). A single specimen of this species was found also in the upper lower Campanian of Mielnik, eastern Poland (Text-fig. 10.3). This species represents the zonal form of the topmost lower Campanian of the North European Province (Ernst 1971; Jagt et al. 2004; Smith and Wright 2003; Schlüter and Wiese 2010).

*Echinocorys* ex gr. *conica* (L. Agassiz, 1847), which seems to represent the smallest specimens of the genus (Text-fig. 10.4–6), was recently reported from the Nida Synclinorium (Jagt et al. 2004), as well as from Mielnik (Olszewska 1987) and Kornica (Langner 1990) in eastern Poland. Synonymous with this species is *Echinoco-
Another species, characteristic for the lower lower and lower middle Campanian is *Echinocorys* ex gr. *subglobosa* (Goldfuss, 1829) (Text-fig. 11.3). The group was reported from Rzeżuśnia in the Nida Synclinorium (Jagt et al. 2004), and dated for the 'Inoceramus' *azerbaydjanensis* - 'I.' *vorhelmensis* Zone (Jagt et al. 2004; see also Jurkowska 2016). The *Echinocorys turritus* of
Mączyńska (1989), reported by her from the same area (see comments in Jagt et al. 2004), seems to be synonymous with this group. This group includes also the *E. pyramidatus* of Mączyńska (1989), from the section of Chlina (a historical outcrop close to Jeżówka). Mączyńska’s specimens differ clearly from the *E. pyra-
midata ‘of authors’ (Lambert 1903; Smiser 1935a,b; Jagt 2000; Jagt et al. 2004).

*Micraster* (Gibbaster) ex gr. *fastigatus/stolleyi* is another group, moderately well known, reported from the lower–lower middle Campanian of Poland (Text-fig. 11.1-2; see Jagt et al. 2004). Both *M. (Gibbaster)* *fastigatus* and *M. (Isomicraster) stolleyi* were reported from a number of localities in the Nida Synclinorium (see Mączyńska 1968). This group, as understood herein, includes also *Micraster* (Gibbaster) *gibbus* of Mączyńska (1968), as well as her *Micraster* (Isomicraster) *dalloni* Lambert and *Micraster* (Isomicraster) *senonesis* Lambert.

Text-fig. 11. 1-2 – *Micraster* (Gibbaster) ex gr. *fastigatus/stolleyi*: 1 – MWGUW ZI/77/046, lower Campanian, Podkwiów, Nida Synclinorium, 2 – MWGUW ZI/77/047, lower upper (Middle) Campanian, Rzeżuśnia, Nida Synclinorium; 3 – *Echinocorys* ex gr. *subglobosa/turrita*, MWGUW ZI/77/045, lower upper (middle) Campanian, Rzeżuśnia, Nida Synclinorium; scale bar is 1 cm.
Another group of species, of more or less the same age, known from extra-Carpathian Poland, is the group of *Micraster* (Micraster) *schroederi/glyphus* (see Jagt et al. 2004). The following members of the group were described from various localities of the Nida Synclinorium by Mączyńska (1968, 1989): *Micraster* (Micraster) *schroederi Schroederi, Micraster* (Micraster) *schroederi planus*, and *Micraster* (Micraster) *glyphus*. Moreover, her *Micraster* (Micraster) *bronngarti, M. (M.) bibicensis, M. (Paramicraster) cracoviensis, M. (P.) latior*, and *M. (P.) sp.* are regarded conspecific with *Micraster glyphus* (Stokes 1975; Jagt et al. 2004).

The echinoids in the Maastrichtian of extra-Carpathian Poland are still poorly documented, although known to occur continuously in all regions discussed herein. Rare holocystoids, *Galerites vulgaris* (Leske) and *Galerites wollemani* (Lambert), and a single specimen of *Echinocorys magnus* (Nietsch, 1921), are reported from the Nida Synclinorium (Mączyńska 1989) and from the Lublin area [Mączyńska’s (1989) *E. magnus* may actually be *Echinocorys belgica* (Lambert, 1898), described originally from the lower Maastrichtian (Robaszyński et al. 2002) of Belgium and reported subsequently from the equivalent horizons of Norfolk (Peake and Hancock 1961, 1970)]. The two species described from the uppermost Maastrichtian of the Middle Vistula River section, i.e., *Echinogalerus bochotnicensis Kongiel* and *Hemicara pomeranum* Schlüter (see Mączyńska 1989), are poorly known indeed and require further study.

INTEGRATED BIO-CHRONOSTRATIGRAPHY

In the following, the discussion on the biostratigraphic constraints of stage and substage boundaries of the Santonian through Maastrichtian of extra-Carpathian Poland is provided. The discussion is not intended to be a general one on the stage boundaries and presents rather the state of bio-chronostratigraphic recognition of this interval in Poland.

Coniacian/Santonian boundary

This boundary is formally defined within the FO of the inoceramid species *Cladoceramus* (or *Platyceramus* as interpreted by others) *undulatopicatus* (see Lamolda and Hancock 1996). Its stratotype section in the eastern border of the ‘Cantera de Margas’ quarry, Olazagutía, in northern Spain, was recently approved by the International Subcommission on Cretaceous Stratigraphy and ratified by the International Union of Geological Sciences in January 2013 (Lamolda et al. 2014). The FO of *Cl. undulatopicatus* is widely recognized within the entire Euramerican biogeographic region (e.g., Seitz 1961; Gale et al. 2007; Lamolda et al. 2014), and was documented in the Lipnik–Kije section, southern Poland (Remin 2004), and in the Ukrainian section of Dubivtsi (e.g., Remin et al. 2016). *Sphenoceramus* ex gr. *pachti–cardioides*, the traditional inoceramid marker of this boundary (see e.g., Błaszkievicz and Szymakowska 1984, 1989; Błaszkievicz 1997) appears first slightly lower, in the uppermost Coniacian *Magadiceramus subquadatus* Zone. With the exception of some sphenoceramids, which cross the boundary unchanged, there is an almost total taxonomic turnover in inoceramid faunas at the boundary level (see e.g., Tröger 1974; Walaszczyk and Cobb 2006, 2007).

In foraminiferal terms, the base of the Santonian lies within the zone of *Protostensioeina bohemica*. At the upper boundary of the *P. bohemica* Zone all other members of the *P. granulata* group disappear, including *Protostensioeina sp. E*. The same assemblage of *Protostensioeina* was also reported from the Coniacian–Santonian boundary of the Seaford Head section (Hampton et al. 2007; Howe et al. 2007) [although two of the species reported by Howe et al. (2007) were incorrectly determined: their *Stensioeina granulata granulata* (fig. 6, Y-AA) should be *Protostensioeina bohemica* whereas their *Stensioeina granulata incondita* (fig. 6, BB-DD) is *Protostensioeina sp. E.*].

The FO of *Protostensioeina polonica*, the traditional marker of the base of the Santonian (see e.g., Witwicka 1958; Koch 1977, Pożaryska and Witwicka 1983, Gawor-Biedowa et al. 1984; Hart et al. 1989) is thus older and is actually latest Coniacian [as also documented in the Staffhorst Shaft section, norther Germany (Niebuhr et al. 1999), and in southern England (Bailey et al. 1983; Hampton et al. 2007; Howe et al. 2007)].

The ammonites at the Coniacian–Santonian transition are well documented from the Lipnik–Kije section, which yielded a diverse ammonite fauna, as well as inoceramids (Walaszczyk 1992; Remin 2004, 2010). The base of the Santonian corresponds to the boundary between the *Texanites pseudotexanus* Zone of the upper Coniacian and the *Kitchinities emscheris–Nowakites savini* Zone dated for the lower Santonian (Remin 2010).

In extra-Carpathian Poland, the Coniacian–Santonian boundary is directly available only in the Kije–Lipnik section (Remin 2004) and in the Ukrainian section of Dubivtsi (Dubicka 2012; Dubicka and Peryt 2014, 2016; Remin et al. 2016).
Santonian substages

There are no formally defined substages of the Santonian, however, a three-fold subdivision was recommended during the Brussels Symposium (see Lamolda and Hancock 1996). Among the biostratigraphic groups, discussed in Brussels as a potential Santonian subgroup marker, inoceramids are inevitably best represented in extra-Carpathian Poland. Consequently, and in accord with some previous proposals (see e.g., Niebuhr et al. 1999), the base of the middle and of the upper Santonian substages are defined here at a level of the LO of *Cl. undulatoplicatus* and the FO of *Cordiceramus muelleri* respectively. Both events are easily recognizable throughout at least the entire Euramerican Biogeographic Region (see e.g., Walaszczyk and Cobban 2006, 2007).

In foraminiferal terms, the base of the middle Santonian is close to the LO of *Gavelinella vombensis* (= *Gavelinella arnagerensis* Solikowski in the Anglo-Paris Basin). In equivalent stratigraphic positions, this event was also recognized in: (1) Lägerdorf, western Germany (Schönfeld 1990), at the boundary between the *coranginum/westfalica* and *rogalae/westfalica* zones (see Schultz et al. 1984); and (2) Seafood Head of southern England (Hampton et al. 2007), c. 2 m above the LO of *Cl. undulatoplicatus*. The base of the upper Santonian seems to be best defined by the FO of *Stensioeina gracilis* (see also the Staffhorst section, northern Germany, Niebuhr et al. 1999). The FO of *S. gracilis* at or close to the middle/upper Santonian boundary, as defined by the FO of the crinoid *Untacrinus socialis* was also recorded in various West European localities (Koch 1977; Bailey et al. 1983; Schönfeld 1990; Hampton et al. 2007).

The belemnites of the *G. granulata* lineage [in ascending order: *G. praewestfalica* Ernst and Schulz, 1974, *G. westfalica westfalica* (Schlüter, 1876), *G. westfalica granulata* (Stolley, 1897), *G. granulata* (Blainville, 1827)] are potentially of use in the Santonian subdivision (e.g., Christensen 1990, 1997a, b). The group is, however, poorly represented in the Santonian of extra-Carpathian Poland, with no reliable record available. Similarly, no ammonite proxies for the Santonian substages can be suggested.

The echinoids of the genera *Conulus*, *Echinocorys* and *Micraster* [e.g. *Conulus albogalerus*, *Echinocorys* ex gr. *scutata*, *Micraster maleckii* sensu Hynda and Mączyńska—*M. rogale* in authors’ concept] (Text-fig. 9) are potentially useful biostratigraphical proxies for the Santonian subdivision. The knowledge of their evolution and vertical ranges is, however, still insufficient to be practically applied.

In extra-Carpathian Poland, the Santonian succession is available in the railroad-cut section at Kije (see Walaszczyk 1992; Remin 2004). Other sections, with a rich and relatively complete palaeontological record of the stage, adding markedly to our data, are the Dubivtsi quarries in western Ukraine (SE of Lviv) (Dubicka 2012; Remin et al. 2016).

The Santonian–Campanian boundary

Although the Santonian–Campanian boundary has not been formally accepted yet, it is commonly defined by the extinction event of the crinoid *Marsupites testudinarius*. The boundary marker is well represented in numerous localities in Poland, mostly in the Nida Synclinorium (Roemer 1870; Smoleński 1906; Panow 1934; Kowalski 1948; Barczyk 1956; Walaszczyk 1992; Remin 2004).

The belemnite species *Goniotethis granulata quadrata*, which was shown to have its FO approximately coeval with the *Marsupites datum* (Ernst 1964), has not been studied in extra-Carpathian Poland, and there is no section that potentially could yield necessary material. Similarly, there is no good ammonite marker of this boundary (see discussion in Hancock and Gale 1996; see also comments in Walaszczyk 1992 about this boundary in southern Poland).

Inoceramids are very common in the boundary interval (see monographic description of the Santonian and lower Campanian inoceramids from northern Germany by Seitz 1961, 1965, 1967), however, none of the lineages give a firm biostratigraphic data. Walaszczyk (1992), based on the record from the Lipnik–Kije section, suggested that a morphotype that could be a good proxy of the base of the Campanian appears close to the boundary. He compared it to *Sphenoceramus alexandrovi* (Bodylevsky, 1959). This record from Lipnik–Kije has never been confirmed by finds from other sections.

In foraminiferal terms, this boundary is placed in the upper part of the *Bolivinoides strigillatus* Zone, slightly above the FO of true *S. pommerana* (possessing an umbilicus completely covered by wide flaps or plug) and below the FO of *B. culverensis* followed by the consistent occurrence of *Gavelinella* ex. gr. *clementiana*. The FO of *S. pommerana* corresponds stratigraphically to the coeval event recorded in the Lägerdorf section (north-western Germany), where it is a base of the *testudinarius/granulata* Zone, c. 3 m below the base of the Campanian (Schönfeld 1990). The FO of *B. strigillatus*, the oldest species of the *Bolivinoides* lineage, has been variably dated as late Santonian or earliest Campanian (White 1929; Cushman 1927; Edgell 1954; Reiss 1954; Koch 1977; Barr 1966,
and simultaneous appearances of ban (1994; see also Cobban Western Interior ammonite-based subdivision of Cobban et al. 1983; Hart et al. 1989; Schönfeld 1990; Niebuhr et al. 1999; Hampton et al. 2007). Accordingly, this event can be regarded as a good proxy of the latest Santonian. Additionally, the geographic range of this event may appear extensive, as Bolivinoides is characterized by its worldwide distribution (Dubicka and Peryt 2015 and literature cited therein) [The reason for such a wide and rapid dispersion of these foraminifera could be either their planktonic larvae or propagules (Alve 1999; Alve and Goldstein 2003, 2010) or tychopelagic mode of life (Darling et al. 2009; Dubicka in preparation)].

The best accessible section of the Santonian–Campanian boundary is near the village of Kije, in the northeastern part of the Nida Synclinorium (Waluszczyk 1992; Remin 2004). There are a number of sections in the south-western margin of the Nida Synclinorium, however, where these sections are strongly reduced/condensed (see summary in Waluszczyk 1992).

Campanian substages

In Europe, the Campanian stage was divided traditionally into two substages, with the boundary between them characterized by the significant change within the belemnite fauna, namely the extinction of the genus Goniotethis and the appearance of the Belemnella mucronata lineage, with a short-lived overlapping of their ranges. The boundary has been usually placed at the LO of Goniotethis (e.g., Jeletzky 1958; Schultz 1978; Ernst et al. 1979; Schultz et al. 1984).

In foraminiferal terms, the base of the upper Campanian (in the traditional European two-fold subdivision) lies at the base of the Angulogavelinella gracilis–Gavelinella monterelensis Zone with an almost simultaneous appearances of Gavelinella monterelensis and C. voltzianus (plano-convex morphotype) (Dubicka 2015). In an equivalent stratigraphic position, these events were also recognized in southern England (Bailey et al. 1983).

Because of the significant longevity of the stage, following the discussion during the Brussels’ 1995 Symposium, a three-fold subdivision, into the lower, middle and upper substages, was recommended (Hancock and Gale 1996). However, there are no formal proposals yet for substage definitions or their stratotypes (see Ogg and Hinnov 2012), and authors, if they wish to use the threefold subdivision in Europe, apply the US Western Interior ammonite-based subdivision of Cobban (1994; see also Cobban et al. 2006), with the middle and upper substages placed at the FO of Baculites obtusus Meek, 1876 and Didymoceras nebrascense (Meek and Hayden 1856) respectively. The lack of the North American ammonites in Europe precludes direct trans-Atlantic correlation. However, there are still some ammonites in common, and moreover, inoceramid bi-valves appear very useful in such a correlation.

The base of the North American middle Campanian, in terms of inoceramids, is located within the lower part of the ‘1.’ azerbaydjanensis–vorhelmensis Zone. This inoceramid zone corresponds to the stobaei/basiplana-vulgaris/basiplana zone (see Jagt et al. 2004; Walaszczyk et al. 2008a). Consequently, it seems that the base of the B. obtusus Zone, marking the base of the middle Campanian in the US Western Interior, corresponds to the base of the stobaei/basiplana Zone in Europe, or slightly higher. It is slightly higher than the base of the European traditional upper Campanian. The base of the middle Campanian would correspond also to the base of the ammonite zone of Trachycaplitites spiniger, which also appears in the stobaei/basiplana Zone (see e.g., Ernst et al. 1979; Schultz et al. 1984). There is no precise belemnite proxy. In benthic foraminiferal terms, this boundary is coeval with the base of the zone of Gavelinella annae. The base of the North American middle Campanian is thus clearly higher stratigraphically than the base of the European upper Campanian; actually both boundaries differ about the zone of conica/mucronata. The difference is bigger, when the base of the European upper Campanian is placed at the FO of Belemnella mucronata, which appears one zone earlier, marking the base of the gracilis/senior (=gracilis/mucronata) Zone.

The position of the base of the North American upper Campanian within the European succession defined with the FO of D. nebrascense, can again be determined by inoceramids. In inoceramid terms, this boundary is located in the upper part of the ‘1.’ tenuilinatus Zone, which corresponds to a middle part of the Didymoceras donezianum ammonite Zone. This position is not well constrained at all and, if the position of this boundary is retained, further studies on this part of the succession are needed. In terms of benthic foraminifera, this boundary should be located roughly within the B. incrassata–G. michelinianus Zone. Of interest may be a number of appearance/disappearance events within this zone, with the FOs of G. acuta and B. sidestrandensis, and the LO of Bolivinoides sp. 1 (‘pra’e’ sidestrandensis). There is no good belemnite or echinoid proxy recognized in this interval.

The middle–upper Campanian succession is best exposed in the Middle Vistula River section (Błaszkiewicz 1980; Walaszczyk 2004; Remin 2012,
The Campanian–Maastrichtian boundary

According to the formal definition, the base of the Maastrichtian stage is defined as an arithmetic mean of 12 bio-events (FOs and LOs of various micro- and macrofossils) and placed at level 115.2 m of the boundary stratotypic section at Tercis les Bains (near Dax, Landes) in SW France (Odin 2001; Odin and Laumurelle 2001). Its correlation to Poland is based on inoceramid bivalves and ammonites, and placed in the upper part of the inoceramid ‘I.’ redbirdensis Zone (Walaszczyk 2004) and in the basal part of the range of the ammonite Pachydiscus (Pachydiscus) neuberigicus (see Machalski 2012). In belemnite terms the boundary approximates to the base of the zone of Belemnella vistulensis or Belemnella obtusa (see Remin 2012; Keutgen et al. 2012). This newly defined boundary is distinctly higher than the traditional European (=Boreal) definition of the base of the Maastrichtian Stage, located at the FO of the belemnite Belemnella lanceolata (e.g. Arkhangelsky 1912; Jeletzky 1951a,b).

There is no precise proxy of this boundary among benthic foraminifera. Nevertheless, the FO of Neoflabellina reticulata (Reuss, 1851) was recognised close to this boundary (see also Hart et al. 1989; Schönfeld 1990; Olferev et al. 2007) and was even recommended as the secondary foraminiferal stage criterion for the base of the Maastrichtian during the Brussels’ 1995 Symposium (Odin 1996). In the Campanian–Maastrichtian boundary succession of the Middle Vistula River section (Walaszczyk 2012), this event was recorded from the basal part of the Kludzie section (Peryt and Dubicka 2015), dated to the Belemnella inflata Zone, which is the topmost Campanian belemnite zone in the present subdivision (see Remin 2012), and within the ‘I.’ redbirdensis inoceramid Zone which comprises the boundary (Walaszczyk 2004). The former report of N. reticulata from the Piotrawin succession (Peryt 2000), dated to a distinctly older level (‘I.’ inkermanensis Zone), results from differences in the taxonomic concepts applied to this foraminifer; for, into the concept of N. reticulata, Peryt (2000) also included N. praereticulata, its evolutionary ancestor.

The Campanian–Maastrichtian boundary is well exposed in a series of sections around the town of Solec, in the Middle Vistula River section (Walaszczyk 2012). The recent studies on the succession add much to the general knowledge of this interval (Remin 2012, 2015; Machalski 2012; Keutgen et al. 2012; Świerczewska-Gładysz 2012; Peryt and Dubicka 2015; Plasota et al. 2015). It is also easily accessible in the Nida Synclinorium (Jurkowska 2016).

Maastrichtian substages

In northern and central Europe, the base of the upper Maastrichtian is traditionally placed at the FO of Belenmitella junior (Nowak, 1913) and the boundary is defined accordingly in extra-Carpathian Poland (Blaszkiewicz 1980; Machalski 2005a, b). This level correlates closely to the base of the zone of Anapachydiscus fresvillensis, the commonly accepted ammonite marker of the upper Maastrichtian (see e.g., Ward and Kennedy 1993; Odin 1996). However, the extinction of ‘true’ inoceramids, quoted often as a good proxy of this boundary (Odin 1996) took place distinctly later (see e.g., Walaszczyk et al. 2009, 2010). This latter event, however, is well recorded in Europe, South Africa, and seemingly also in the North American Western Interior, being potentially a very good marker of the upper Maastrichtian (Walaszczyk et al. 2008b).

In foraminiferal terms, this boundary is located close to the LO of Angulogavelinella gracilis, the event which defines the boundary between the A. gankinoensis–A. gracilis and B. giganteus zones. The level is also slightly below the temporary disappearance of the genus Stensioeina. The lack of A. gracilis through almost the entire upper Maastrichtian of extra-Carpathian Poland was recognized by Pożaryska (1954) and Gawor-Biedowa (1992), and earlier it was reported from Sweden and north-western Germany (Brotzen 1945). Similarly, the temporary disappearance of stensioeinids in the earliest late Maastrichtian of Poland was previously reported by Witwicka (1958) and Gawor-Biedowa (1992); this event was also recognized from western and eastern Germany (Koch 1977; Frenzel 2000; Reich and Frenzel 2002) and from Russia (Naidin et al. 1984).

In extra-Carpathian Poland, the lower–upper Maastrichtian boundary interval is poorly exposed.

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