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CRETACEOUS BASIN EVOLUTION IN THE LUBLIN AREA ALONG THE TEISSEYRE–TORNQUIST ZONE (SE POLAND)

Maciej HAKENBERG & Jolanta ŚWIDROWSKA

Institute of Geological Sciences, Polish Academy of Sciences, Twarda 51/55, 00-826 Warszawa, Poland

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Abstract: The Cretaceous basin of the Lublin area belongs to the SE part of the Mid-Polish Trough and its NE border extending on the East European Craton. Our study is based on isopach maps of seven time intervals, from Neocomian to Early Maastrichtian. Several main lithofacies have been distinguished whose areal extents were plotted on thickness pattern maps. The isopach and lithofacies maps helped to delimit the basin depocenter, providing information on vertical motions of the basin basement and synsedimentary reactivation of older fault zones. The areal extents of the siliceous and chalk lithofacies have been shown to be controlled by the positions of discontinuity zones in the crystalline basement.

Two stages of accelerated subsidence have been established: in Turonian and Early Maastrichtian times. Regional comparisons of accumulation rates and their accelerations during these time spans gave possibility to distinguish the roles of eustatic and tectonic factors in the process of augmenting the basin capacity. Some remarks concerning Early Maastrichtian timing of the inversion onset are also presented.

Key words: isopachs, lithofacies, subsidence, basin development, Cretaceous, Mid-Polish Trough, Teisseyre–Tornquist Zone.

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INTRODUCTION

This study covers the part of Poland comprised between the boundary with Ukraine in the east and southeast, the erosional limit of Jurassic and Cretaceous outcrops in the southwest, the meridian of Radom in the west and the parallel of Łuków in the north (Fig. 1). The Mid-Polish Trough formed along the Teisseyre–Tornquist Zone, above the contact of the West European Palaeozoic Platform with the Precambrian East European Craton.

The aim of this paper is to present sedimentary evolution of Cretaceous deposits in the basin of the southeast segment of the Mid-Polish Trough and its northeast margin, extending over the East European Craton. This analysis of the pattern of lithofacies and their thickness, and in consequence of subsidence, in the area adjacent from the northeast to the zone of the proper trough, which extended in the place of the present Lower San Anticlinorium in late Jurassic time (Niemczycka & Brochwicz, 1988; Kutek, 1994; Hakenberg & Świdrowska, 1997), may serve as a basis for further considerations on the Cretaceous palaeotectonic evolution of this area. The deposits of the opposite south western limb of the basin are partly buried beneath the overthrust units of the Outer Carpathians. Where these deposits were had been encountered by drilling, they were described in an earlier publication by the present authors (Hakenberg & Świdrowska, 1998). The purpose and the methods used in this paper are similar to those used in that paper, dealing with the area of the Holy Cross Mountains (Góry Świętokrzyskie).

From the point of view of the deep geological structure, the area so defined lies within two major tectonic units (Fig. 1): the Precambrian East European Craton and the Palaeozoic West European Platform (Żelichowski, 1972, 1979; Książkiewicz *et al.*, 1977; Znosko, 1979, 1998). A fragment of the south eastern part of the East European Craton is distinguished as the Marginal Depression (Żelichowski, 1972). It is bounded on the northeast by the Kock Fault (see Fig. 10) that lowers the top of the Precambrian basement by 1–3 km (see Znosko, 1998). Farther to the east, within the Włodawa Graben, Kumów Elevation and Terebin Depression, the course of this fault in Precambrian rocks is less well known. The south western boundary of the Marginal Depression (see Fig. 10) is the Ursynów–Kazimierz Dolny–Wysokie–Rawa Ruska Fault (Żelichowski, 1972, 1974; Pożaryski & Dembowski, 1983; Znosko, 1998). The Marginal Depression is overlain by the Lublin Graben filled with Carboniferous and Devonian strata and underlain by older Palaeozoic rocks (Żelichowski, 1972, 1979). The north eastern boundary of the younger Palaeozoic graben is the Żelechów–Kock–Wasylów Fault (Żelichowski, 1972). To the northeast of it lies the Łuków–Hrubieszów Eleva-

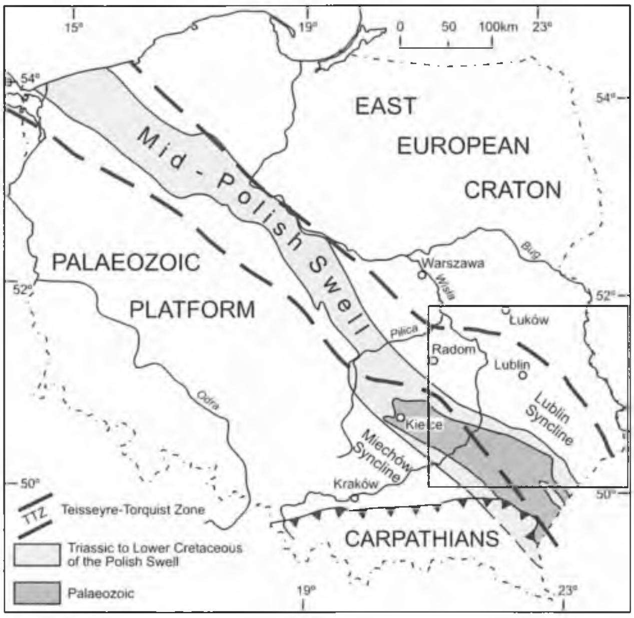

Fig. 1. Location of the study area relative to the major structural units of Poland. Line with solid triangles – frontal thrusts of the Carpathians

tion, which forms, together with the Lublin Graben, the Bug Trough (Porzycki, 1988).

The Jurassic and Cretaceous rocks build a gentle structure described as the Lublin Syncline, and farther southeast, in the Podolia area, as the Lwów Syncline (Żelichowski, 1972; Khiznyakov & Żelichowski, 1974; Pożaryski, 1979). It was formed during the Laramian inversion, when its present south western limb formed by uplift of the Holy Cross part of the Mid-Polish Trough. The limbs of the Lublin Syncline extend beyond the young Palaeozoic Lublin Graben. In the south western part of the discussed area the Jurassic and Cretaceous sediments cover the Radom–Kraśnik Uplift, attributed to the Caledonian tectonic storey (Żelichowski, 1972, 1979), and in the north eastern part overlie the margin of the East European Craton.

Biostratigraphical zonation of the Cretaceous sediments of the Lublin area, based on ammonites, belemnites, inoceramids and foraminifers, was established mainly by: Samsonowicz (1925), Pożaryski (1938, 1948, 1956, 1960), Pożaryska (1956), Cieśliński (1959a, 1960, 1965), Witwicka (1976), Błaszkiewicz (1980), Peryt (1983), Pożaryska & Witwicka (1983), Walaszczyk (1987, 1992), Gawor-Biedowa (1992).

The lithology and stratigraphy was the subject of papers by Krassowska (1976, 1977, 1981b, 1982, 1986, 1989), Wyrwicka (1980) and Marek (1983). Petrography of the Cretaeous rocks of the Lublin area was studied by Sujkowski (1931), Uberna (1967), Harapińska-Depciuch (1972), Harasimiuk (1975) and Wyrwicka (1977, 1980).

The evolution of sedimentation and palaeogeography in Cretaceous time were analysed mainly in papers by Cieśliński (1959b, 1976), Marcinowski & Radwański (1983), Marcinowski & Walaszczyk (1985), Machalski & Walaszczyk (1987), Kutek *et al.* (1989), Marcinowski & Wiedmann (1990), Walaszczyk (1987, 1992).

Comprehensive analyses of the Cretaceous deposits outside the Carpathian part of Poland, including the Lublin area, are present in the papers by Pożaryski (1962), Jaskowiak-Schoeneichowa & Krassowska (1988), Marek (1988, 1997) and Krassowka (1997). Reviews of earlier works were presented by Pożaryski (1956) and Cieśliński & Pożaryski (1970).

Geological structure of the Precambrian and Palaeozoic basement in the Lublin area was the subject of studies by Pożaryski (1957), Żelichowski (1972, 1974, 1979, 1984), Żelichowski & Kozłowski (1983), Khizhnyakov & Żelichowski (1974), Porzycki (1988) and Znosko (1979, 1984, 1998). Tectonics of Mesozoic strata was studied mainly by Pożaryski (1948, 1956, 1957, 1997) and Pawłowski (1961); many observations on this topic are also included in the papers by Żelichowski quoted above.

The basic analytical material (logs of exposures and boreholes) on stratigraphy and lithology of the Cretaceous strata of the Lublin Syncline, used in this paper, was taken mainly from studies by Krassowska (1965, 1976, 1977, 1981a, b, 1982, 1986, 1989), and also by Cieśliński (1959a), Lendzion (1960, 1969), Moryc & Waśniowska (1965), Cieśliński & Pożaryski (1970), Geroch *et al.* (1972), Krassowska & Witwicka (1983), Kijakowa & Moryc (1991), Moryc (1996, 1997), Olszewska (1999) and from logs of deep boreholes drilled by Polish Geological Institute (Profile ..., 1973–1989). Archived descriptions of PIG boreholes were also used to a large extent. Many of these papers, especially those by A. Krassowska and S. Cieśliński, include many valuable data on conditions of sedimentation and palaeogeography.

The length of time corresponding to the stratigraphical hiatus at the base of the Cretaceous varies largely over the area, in consequence of differentiated evolution of individual pre-Cretaceous tectonic units. The gap is greatest – ca. 230 My – near Hrubieszów, where Cenomanian strata directly overlie the Upper Carboniferous (Żelichowski, 1972; Krassowska, 1976). Over the East European Craton, where Cretaceous strata directly overlie the Jurassic ones, the gap corresponds to ca. 54 My (Cenomanian overlying Middle Oxfordian – Krassowska, 1976; Niemczycka, 1976). In the area of Dębica (Fig. 2), close to the axis of subsidence, the hiatus disappears, as a continuous transition was observed there between the Tithonian and Berriasian strata (Olszewska, 1999).

LITHOLOGY AND STRATIGRAPHY

Neocomian strata occur in a narrow belt near the erosional boundary with the Upper Jurassic in the south western limb of the Lublin Syncline and are known only from a few boreholes: Szelina, Potok IG-1, Ruda Janowska, Dyle IG-1, Józefów, Narol IG-1, Narol PIG-2, Babczyn 2 and Basznia 1 (Fig. 2).

The Neocomian strata are proven by microfauna in three boreholes: Szelina (Cieśliński & Pożaryski, 1970), Basznia 1 (Moryc & Waśniowska, 1965) and Narol PIG 2 (Marek & Leszczyński, 1992). Upper Valanginian age was determined at Narol, Valanginian–Hauterivian at Basznia

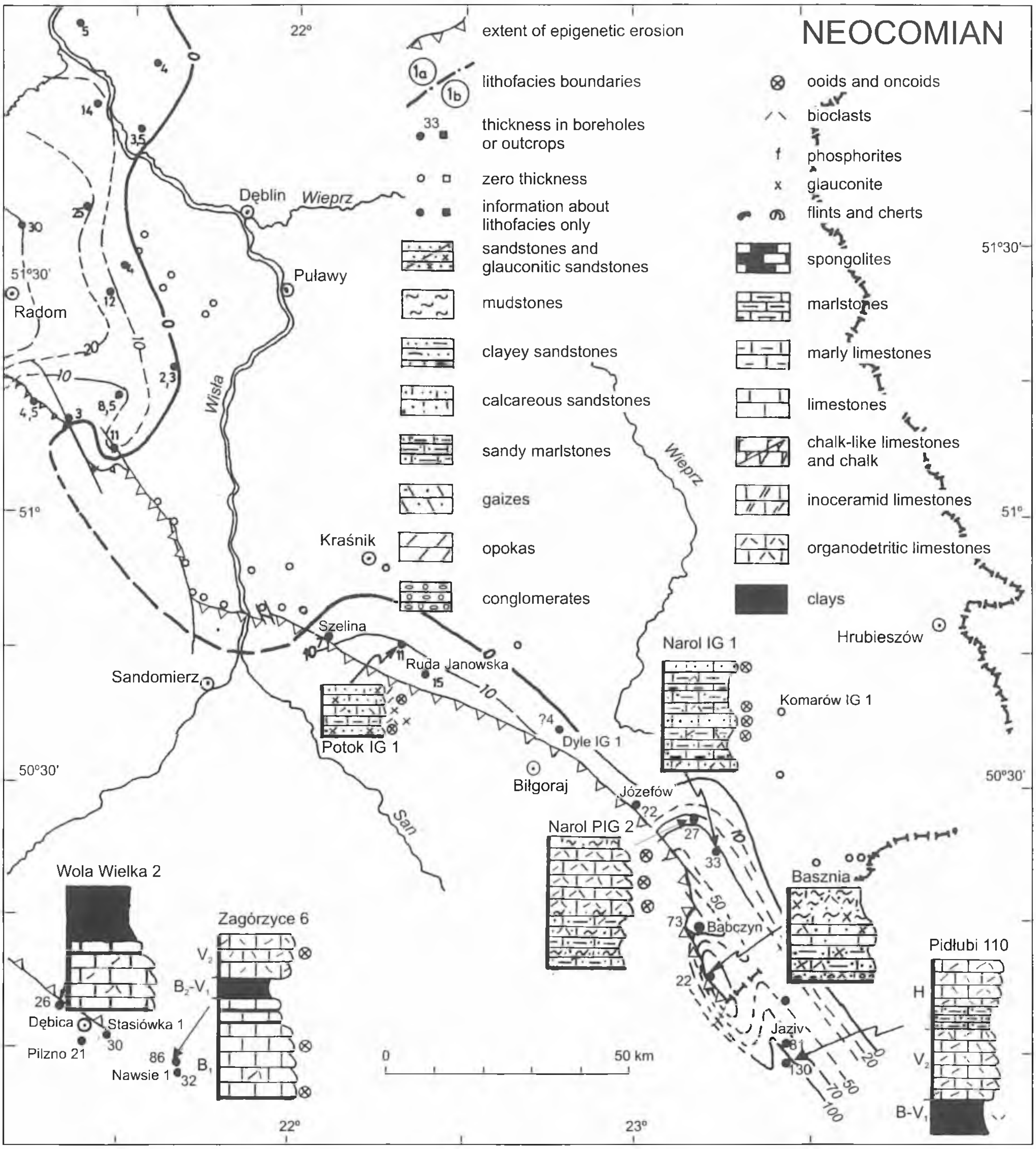

Fig. 2. Thickness pattern and characteristic lithological sequences of Neocomian deposits. Schematic, characteristic profiles not to vertical scale. B_1 – Lower Berriasian, B_2–V_1 – Lower Valanginian – Upper Berriasian, V_2 – Upper Valanginian, H – Hauterivian

and Neocomian at Szelina. In the other boreholes the Neocomian age was attributed on the grounds of the position in the sequence and lithological analogies to the stratigraphically documented boreholes. The Neocomian sediments are sandy-muddy-calcareous with oolites, bioclastic material and locally glauconite. The north western part of the studied area, represented by boreholes Szelina and Potok IG 1, clearly stands out with its higher content of terrigenous material. The sections of Neocomian deposits from the area near Dębica, on the south western side of the Lower San Anticlinorium, have been also taken into account, as the results of their stratigraphical studies have been recently published (Moryc, 1997; Olszewska, 1999). These include: Wola Wielka 2, Pilzno 21, Stasiówka 1, Nawsie 1, Zagórzyce 6 (Fig. 2). The sequence of Lower Cretaceous strata is there tripartite (Fig. 3): the lower and upper units of

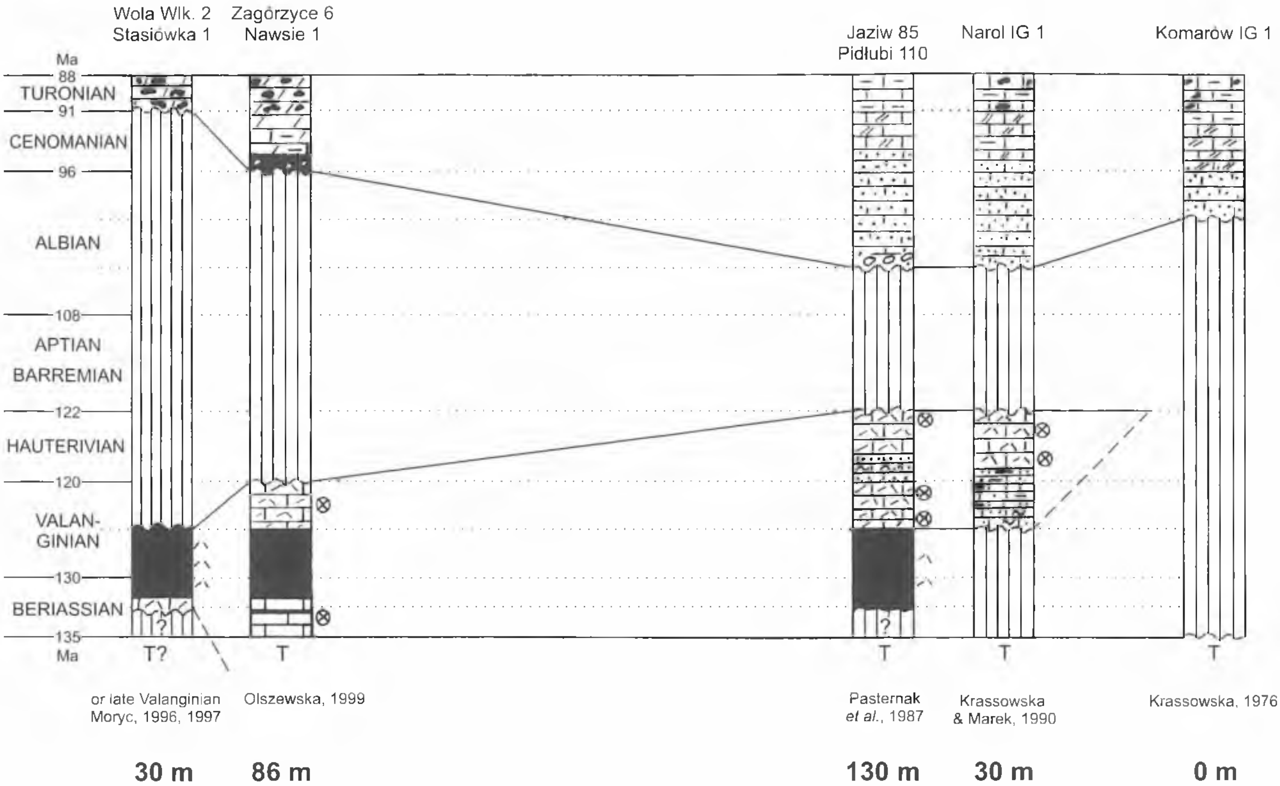

Fig. 3. Chronostratigraphic correlation of Lower Cretaceous deposits and hiatuses across the central part of the Mid-Polish Trough. T – Tithonian. Thicknesses of Neocomian beds belonging to 5 boreholes are located below each of profile. Lithology as in Fig. 2

oolitic-bioclastic limestones are separated by a mudstone-claystone layer rich in organic debris. Microfauna in the clayey series and the overlying limestones indicates a Valanginian (Geroch *et al.*, 1972; Kijakowa & Moryc, 1991), possibly late Valanginian age (Moryc, 1997). A recent study by Olszewska (1999) constrains the age of the mudstone-claystone series in boreholes Zagórzyce 6 and Nawsie 1 to the late Berriasian–early Valanginian. This, combined with the findings of *Calpionella alpina* in the lower limestone series, suggests the continuity of Late Jurassic–Early Cretaceous sedimentation (Olszewska, 1999). It is possible, however, that the Lower Cretaceous strata in boreholes Wola Wielka 2 and Stasiówka 1 represent the same time interval, and the Upper Valanginian deposits were removed during a break in sedimentation that lasted longer in that area (Fig. 3). The thickness of the Neocomian strata varies from 0 to 90 m.

The Albian strata (see Fig. 4) are represented by sandstones with glauconite, marly and phosphorite-bearing in the upper part. They include intercalations of spongolites and gaizes in the south western part of the area. Their thickness varies from 0 to ca. 20 m.

The Cenomanian sediments (see Fig. 5) are clastic inoceramid-bearing limestones and marly limestones with some phosphorites, small amounts of glauconite and siliciclastic material, whose amount decreases upsection and gradually towards the northeast. West of the Vistula river cherts appear. The higher parts of the sections in the southwest include intercalations of opokas and gaizes. The thickness varies from a few to 20 m, over most part of the area they are around 10 m.

The Turonian sediments (see Fig. 6) in the northeast are represented by chalk and chalk-like limestones with cherts, in the central part of the area passing to limestones with abundant cherts and containing olisteginids and dispersed inoceramid fibres. These limestones include marly limestone intercalations farther to the southwest. In the south easternmost part of the area, the mentioned rocks include also intercalations of opokas and thin layers of sandy limestones at base. The content of broken inoceramian shells decreases towards the southeast. The thickness varies from ca. 70 m in the north, to more than 200 m in the south western part of the area.

The Coniacian and Santonian strata (see Fig. 7) contain increasing proportions of argillaceous material; marly limestones and marlstones appear as intercalations over the whole area. Cherts are much less common than in the Turonian sediments. The siliceous lithofacies (gaizes and opokas) enlarged its extent to the southeast, covering the area of Biłgoraj and Tomaszów Lubelski. The thickness varies from ca. 60 m in the northeast to ca. 360 m in the south western part.

The deposits of the Campanian and Early Maastrichtian stages (see Figs 8, 9) are lithologically similar to those of the Santonian, and the boundaries of the three lithofacies zones vary only slightly. The thickness of the Campanian varies from 50 m in the northeast to ca. 550 m in the southwest, and of the Lower Maastrichtian from ca. 50 m in the northeast to ca. 260 m in the southwest.

The Upper Maastrichtian strata are covered with the lowermost Palaeocene, hence their thickness is not altered by post-Laramian erosion. They occur only along the axis of the Lublin Syncline near Kazimierz, Puławy, Nałęczów, Dęblin, Abramów, Świdnik and Lublin (Harasimiuk, 1980, 1983; Krassowska, 1986). Though these sediments locally exceed 320 m in thickness (the maximum value among the all substages – Harasimiuk, 1975), their lateral extent is too small to permit an analysis of their facies or thickness variation to a degree comparable with the older Cretaceous units.

COURSE OF SEDIMENTATION AND FACIES PATTERN

The Neocomian position of the Mid-Polish Trough in its Holy Cross part was outlined in the papers by Głazek & Kutek (1970), Kutek & Głazek (1972), Raczyńska (1979), Hakenberg (1986), Kutek *et al.* (1989), Kutek & Marcinowski (1996), Marek (1988, 1997), Marek & Pajchlowa (1997), Moryc (1997), Hakenberg and Świdrowska (1998). A zone of increased subsidence existed in the south westernmost part of the studied area, which was a prolonagation of the Holy Cross segment of the Mid-Polish Trough. The remaining, much larger part of the studied area lied on the western palaeoslope of the East European Craton and was subject to subsidence whose rate decreased towards the northeast and correspondingly, it has stratigraphic gaps, increasing in this directions. The area of deposition of the Neocomian strata was limited to the axial part of the trough, so these sediments are now preserved in two narrow zones on both sides of the Lower San Anticlinorium. Directions of clastic supply in the Neocomian deposits are difficult to determine because of the narrowness of the zones of their occurrence. It is possible that the material was supplied from the northeast, from the side of the East European Craton (see Pasternak *et al.*, 1987).

The Hauterivian sediments close the Jurassic sedimentation cycle (Kutek, 1994) which has began in this area in Middle Jurassic or, exceptionally, in Oxfordian time (Niemczycka, 1976). A time section perpendicular to the elongation of the Mid-Polish Trough (Fig. 3) illustrates deposition and stratigraphical hiatuses at the break of the two cycles. The continuity of sedimentation across the Jurassic/Cretaceous boundary was probably maintained along the basin axis, as is indicated by the results of recent studies by Olszewska (1999), but the precise delineation of the extent of the Late Tithonian–Berriasian basin is hitherto uncertain. The youngest sediments (Hauterivian) belonging to the older cycle occur closer to the East European Craton (Fig. 3) and there also appear sediments of the new, mainly Late Cretaceous, sedimentary cycle. It seems thus likely that the axis of maximum subsidence was situated asymmetrically, closer to the north eastern margin of the basin.

After a break in deposition, lasting at least ten to twenty million years (Barremian, Aptian and Early Albian – Fig. 3) another Cretaceous transgression has began. The lithofacies regions in the successive younger Cretaceous stages were distinguished taking into account the proportions of chalk, siliceous material of sponge origin and terrigenous material in the sections. These criteria were used to distinguish the main lithofacies (see Figs 4–9), deemed important for palaeogeographical interpretations.

The oldest faunistically proven deposits, described as the Middle Albian, occur in the Annopol section and in Podolia (Samsonowicz, 1925; Kokoszyńska, 1931; Cieśliński, 1959a, 1976; Marcinowski & Walaszczyk, 1985; Pasternak *et al.*, 1987; Marcinowski & Radwański, 1989; Marcinowski & Wiedmann, 1990). The location of these exposures between the interpreted position of the Mid-Polish Trough axis and the areas lacking the Albian sediments indicates that the Albian transgression spread in the northeasterly direction (see Cieśliński, 1976; Marcinowski & Wiedmann, 1990). Carbonate-free sands were laid down during the Albian transgression in the areas flooded earlier. In the course of time and progress of transgression, calcium carbonate appeared in sediments, so that the Albian sediments are carbonate-free at the lower and calcareous in the upper parts of the sections (facies region 1b in Fig. 4). As a result, the Albian sections in the eastern and central regions, originally lying higher, consist mostly or exclusively of calcareous sandstones (facies region 1a in Fig. 4). These regions are adjacent to the areas devoid of the Albian deposits, considered as the emergent areas with erosion prevailing and found (Krassowska, 1976, 1989; Pietruszka & Wilgat, 1981) near Hrubieszów, north of Włodawa and between Kraśnik and Lublin (Fig. 4).

Three small areas with reduced thickness of lithofacies 1a, not related to the areas of prevailing denudation, occupy an exceptional position. They are located along the south western margin of the post-erosional extent of the Albian sediments. These areas coincide with the zones where Mesozoic strata display now stronger deformation, with anticlines, flexures and longitudinal faults along the boundary between the Jurassic and Cretaceous outcrops. This may suggest that a group of synsedimentary listric faults were active in the south western part of the basin, whose hanging limbs supported zones of shallow water, with higher energy of water movements.

The occurrence of phosphorites in the Albian sections is probably related to slower deposition (of hardground type) and relative abundance of faunal remains in the basin bottom, supplying phosphophorus compounds (Uberna, 1967; Annopol section – Marcinowski & Radwański, 1983; Marcinowski & Walaszczyk, 1985; Walaszczyk, 1987).

The rocks of type of non-calcareous gaizes and spongolites that form a small lithofacies region west of the Vistula (2a in Fig. 4) were laid down in conditions favourable for sponges, at greater depths than the other sediments.

In Cenomanian time, sedimenation expanded over the whole studied area (Fig. 5). The facies distribution was controlled by, along with subsidence, the directions of terrigenous supply. The least amount of the terrigenous material was found in the north eastern area (1c in Fig. 5), where the slightly marly bottom part is overlain by limestones consisting almost entirely of broken inoceramid shells (Krassowska, 1976, 1989). The supply of fine argillaceous material to the central part of the studied area was already noticeable and numerous intercalations of marly limestones were laid down among the bioclastic inoceramid limestones (1b in Fig. 5). A distinctly higher amount of terrigenous material,

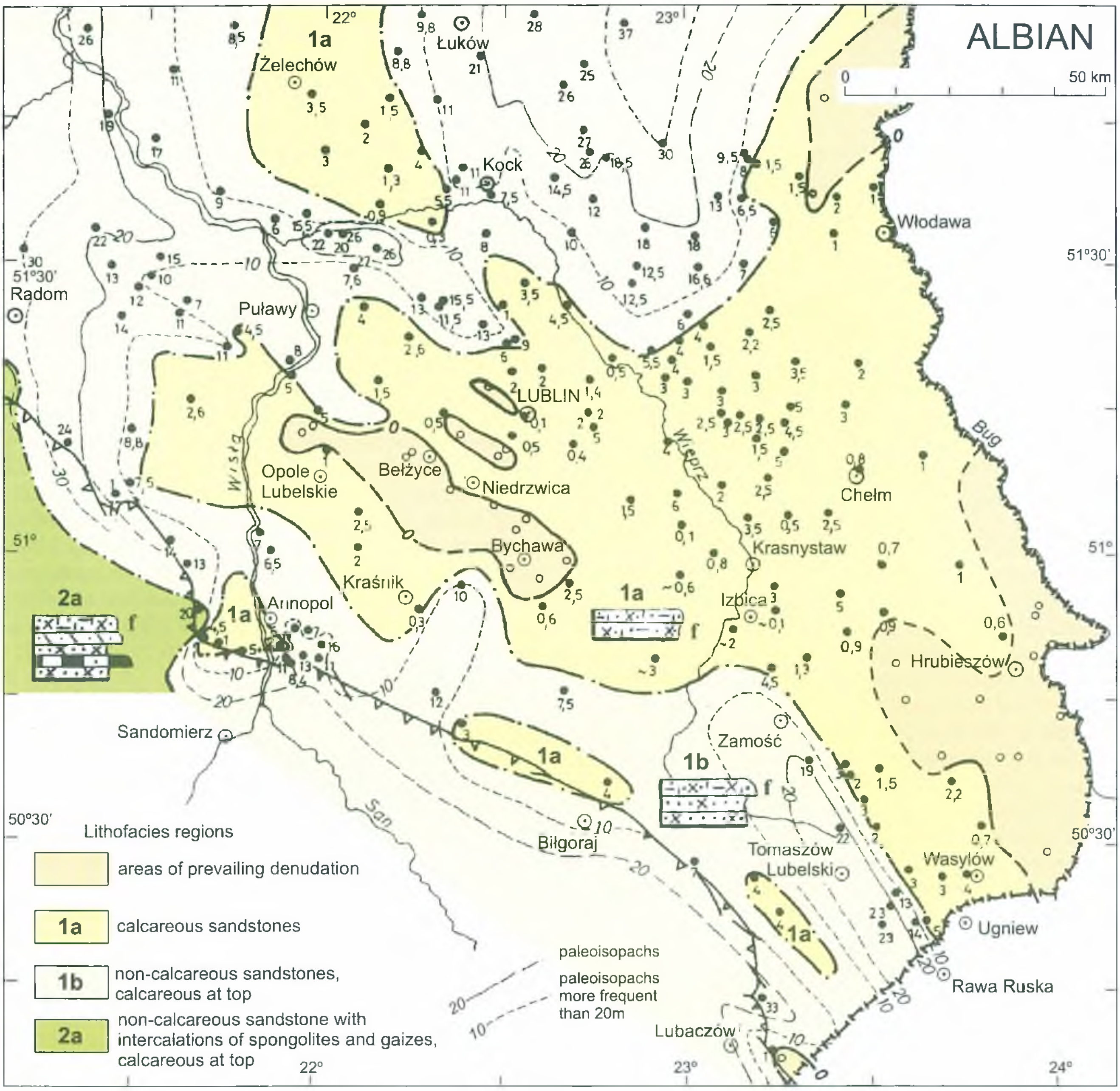

Fig. 4. Thickness and facies pattern of Albian deposits. Colours mark extents of individual facies realms shown in columns 1a, 1b, 2a; other explanations in Fig. 2 and in the text

including sand, was found in a small area north of the confluence of the San and the Vistula (1a in Fig. 5a). This area underwent little subsidence and possibly had shallower waters than the surrounding areas. The material could be deposited due to transverse transport of sand from deep to shallower zones, where longitudinal, SE–NW flowing, currents were active (region 2a). Sediments similar to those in region 1b occurs in one of the regions lying farther to the southwest (1d in Fig. 5), which is considered as representing a deeper part of the basin because of the presence of cherts. A still deeper part of the basin is represented by region 2a (Fig. 5), where marly limestones and marls are intercalated with opokas and gaizes, and the amount of terrigenous material – sand and clay – is significant.

The progress of the transgression in Turonian time is marked by the decrease in the amount of terrigenous material. Sand was supplied in small amounts only from the south western part of the area (2a in Fig. 6). The pattern of spatial distribution of the facies regions confirms the earlier suggested direction of terrigenous supply from the southwest, furnishing material to the marly limestone intercalations in the limestones and bioclastic inoceramian limestones (facies regions 1c and 2a in Fig. 6). The terrigenous material, even its finest fraction, hardly reached the region situated in the northeast (1a – chalk and 1b – bioclastic inoceramian limestones in Fig. 6; Krassowska, 1976, 1989). In the farther north eastern region 1a, the scarcity of siliciclastic material, calm sedimentation and small subsidence,

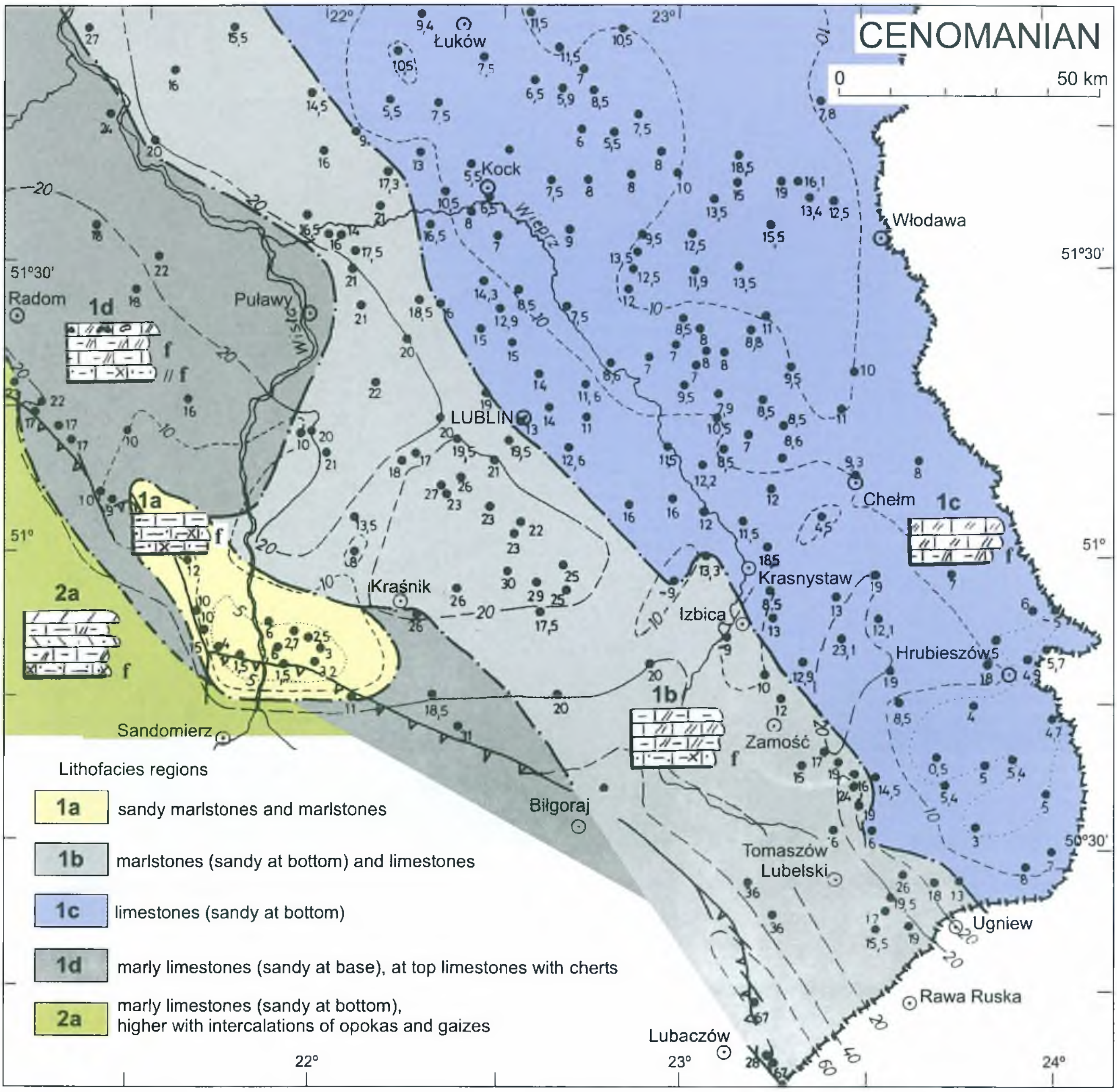

Fig. 5. Thickness and facies pattern of Cenomanian deposits. Explanations see Figs. 2, 4 and text

all favoured development and accumulation of coccoliths, which are the main component of the chalk present there. Sediments rich in silica of sponge origin (cherts in the whole area and additionally opokas in the south western region 2a) were found in all lithofacies regions. This suggests some degree of facies unification, related to the generally high stand of global sea-level (cf. Hancock, 1989). The differences in depth were preserved: the greatest depths in the south western and the lowest in the north eastern parts of the studied area.

The Coniacian–Santonian, Campanian and Lower Maastrichtian sections do not reveal the predominance of biogenic, bioclastic and chert-bearing limestones. One of the facies characteristics which distinguishes the Cretaceous stages younger than Turonian is the higher amount of the fine, argillaceous terrigenous material. It is present in the marlstones and marly limestones abundant in the central and south western lithofacies regions (Coniacian/Santonian – Fig. 7, 1b, 2a; Campanian – Fig. 8, 1b, 2a; Early Maastrichtian – Fig. 9, 1c, 2a). The north eastern region (1a in Figs 7–9) was reached by only scarce siliciclastic material and deposition of chalk and chalk-like limestones persisted there, similarly as in Turonian time. During the Early Maastrichtian (Fig. 9), region 1c (rich in marly rocks) was reduced in extent (see also Wyrwicka, 1980), while region 1b was intermediate between 1a and 1c, with intermittently increased supply of argillaceous material. During the breaks in its supply conditions favourable for development of coccoliths persisted in the area.

The Campanian and Lower Maastrichtian deposits in

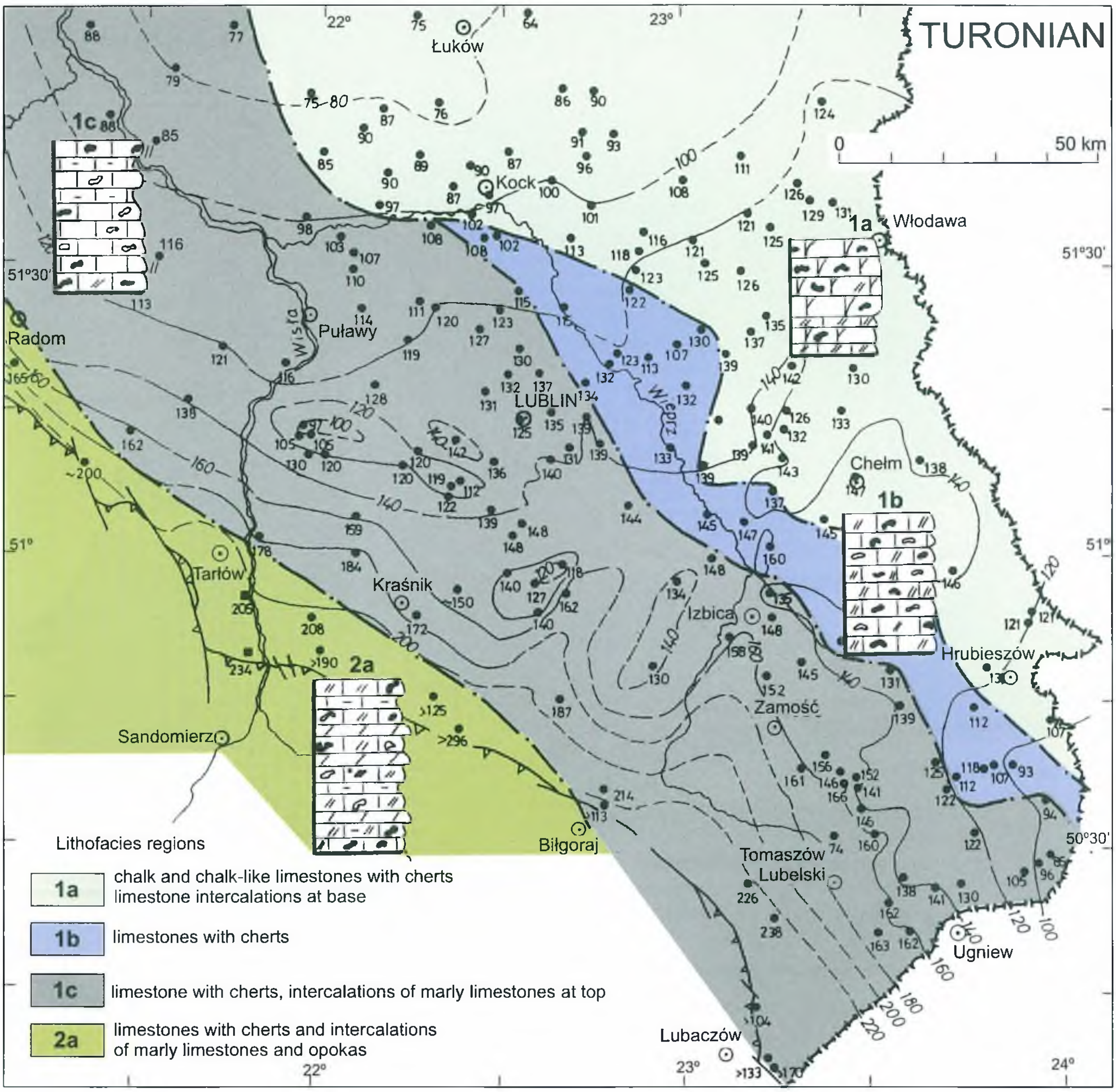

Fig. 6. Thickness and facies pattern of Turonian deposits. Explanations see Figs. 2, 4 and text

the central and north eastern facies regions (1a, 1b, 1c in Figs 8 and 9) contain much less cherts. We interpret this as a result of some shallowing of the basin in these regions. The farthest south western region (2a in Figs 7–9) remained deepest relative to the other regions (relatively numerous intercalations of gaizes and opokas).

Beginning from the Turonian, the siliceous lithofacies steadily expanded towards the northeast. This was probably related to the eustatic rise in sea level, which could even attain 650 m relative to the Albian level (Hancock, 1989).

It should be noted that lithofacies enriched in biogenic silica are always thickest, hence they probably were laid down at locations closest to the axis of maximum subsidence. Another lithofacies characteristic of the Late Cretaceous sedimentation – chalk – was typical of the zone of lowest thickness and was laid down in the north eastern part of the studied area. Between the two mentioned extremally situated zones, deposits of calcareous and marly facies were laid down (Fig. 10). The south western limit of the chalk extended (from Turonian through Campanian time) near the Żelechów–Kock Fault Zone, extending southeast to the vicinities of Hrubieszów. The line so defined (see Fig. 10) was accepted by Pożaryski (1963, p. 7) as the north eastern boundary of the Marginal Syclinorium, understood as a synclinal structure of the Mesozoic cover and related to the "break in inclination of the platform slope... and sudden increase in thickness towards the southwest with filling in this direction of the numerous stratigraphic gaps." Already in 1957 Pożaryski has drawn attention to the deep, related to crystalline basement, tectonic control of the of the chalk fa-

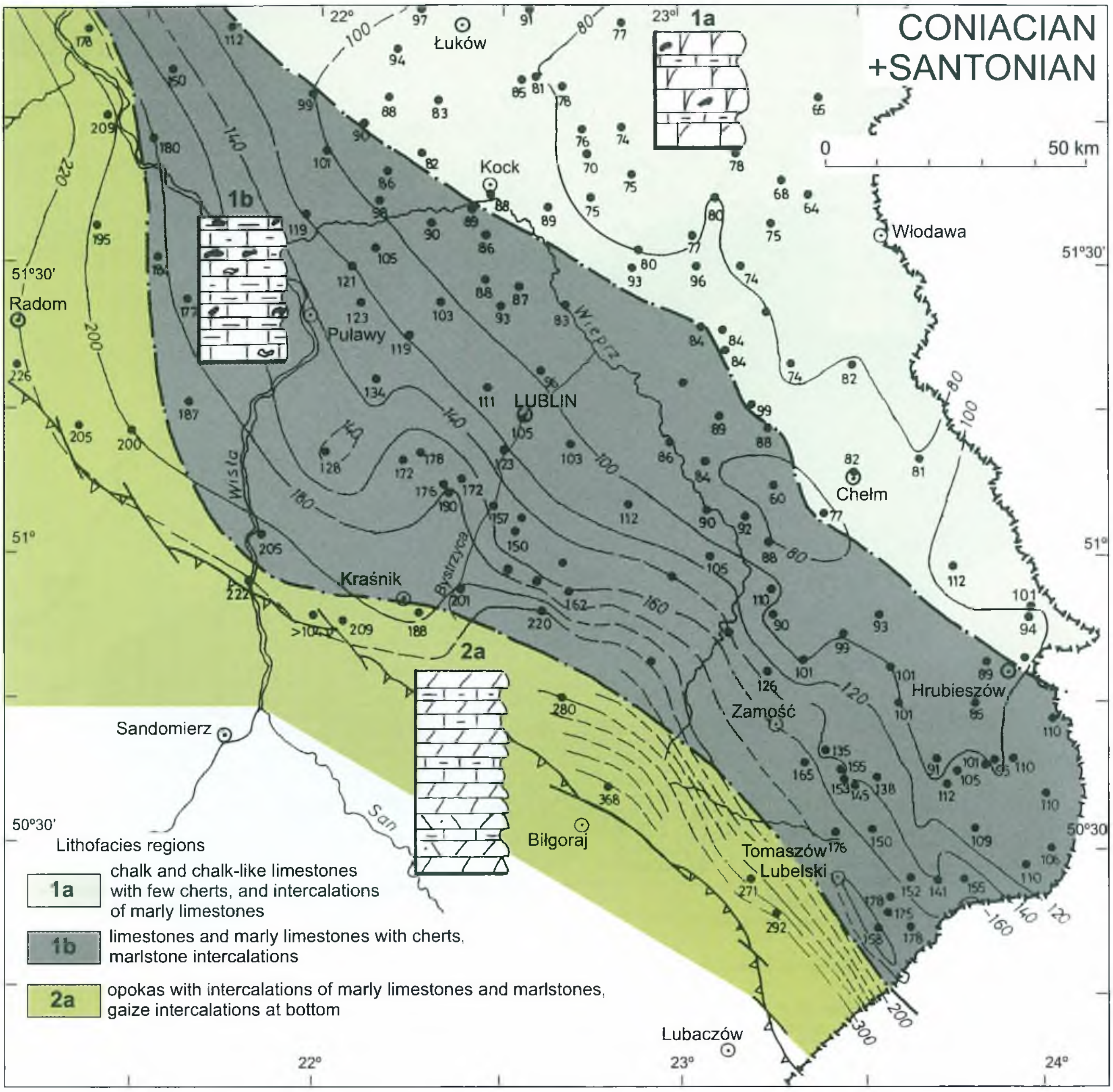

Fig. 7. Thickness and facies pattern of Coniacian–Santonian deposits. Explanations see Figs. 2, 4 and text

cies extent. An equivalent of the Żelechów–Kock–Hrubieszów Fault may be traced on the Ukrainian side as two adjacent parallel faults: the Novy Volyn and Krasnograd Faults (cf. Kruglov & Khizhnyakov, 1985).

The north eastern boundary of the siliceous lithofacies (from Coniacian through Early Maastrichtian time) runs through Roztocze, near the north eastern boundary of this region, controlled by the edge of the lower step in the crystalline basement of the East European Craton. This relation has been already pointed out by Pożaryska & Witwicka (1983).

The continuous supply of terrigenous material from the southwest to the area of the north eastern slope of the basin from Albian through Maastrichtian was the result of currents flowing transversally to the basin slope. These could not be the same currents that supplied material to the basin, as the position of the trough axis in the southwest is documented by the earlier appearance of the oldest trangressive sediments, expansion of the transgressions to the sides of the trough, a higher thickness and lithofacies laid down in deeper parts of the basin. The source area for the Late Cretaceous supply has been thought in the eastern part of the Ukrainian Shield (see palaeogeographical maps in Najdin, 1959; Pasternak *et al.*, 1987). Rivers could transport products of weathering to its southern slopes, from where the terrigenous material could be transported by longitudinal currents farther to the northwest. The presence of a land barrier on the margin of the epicontinental area of Europe, that would separate the studied basin from the Tethys basin can not be ruled out.

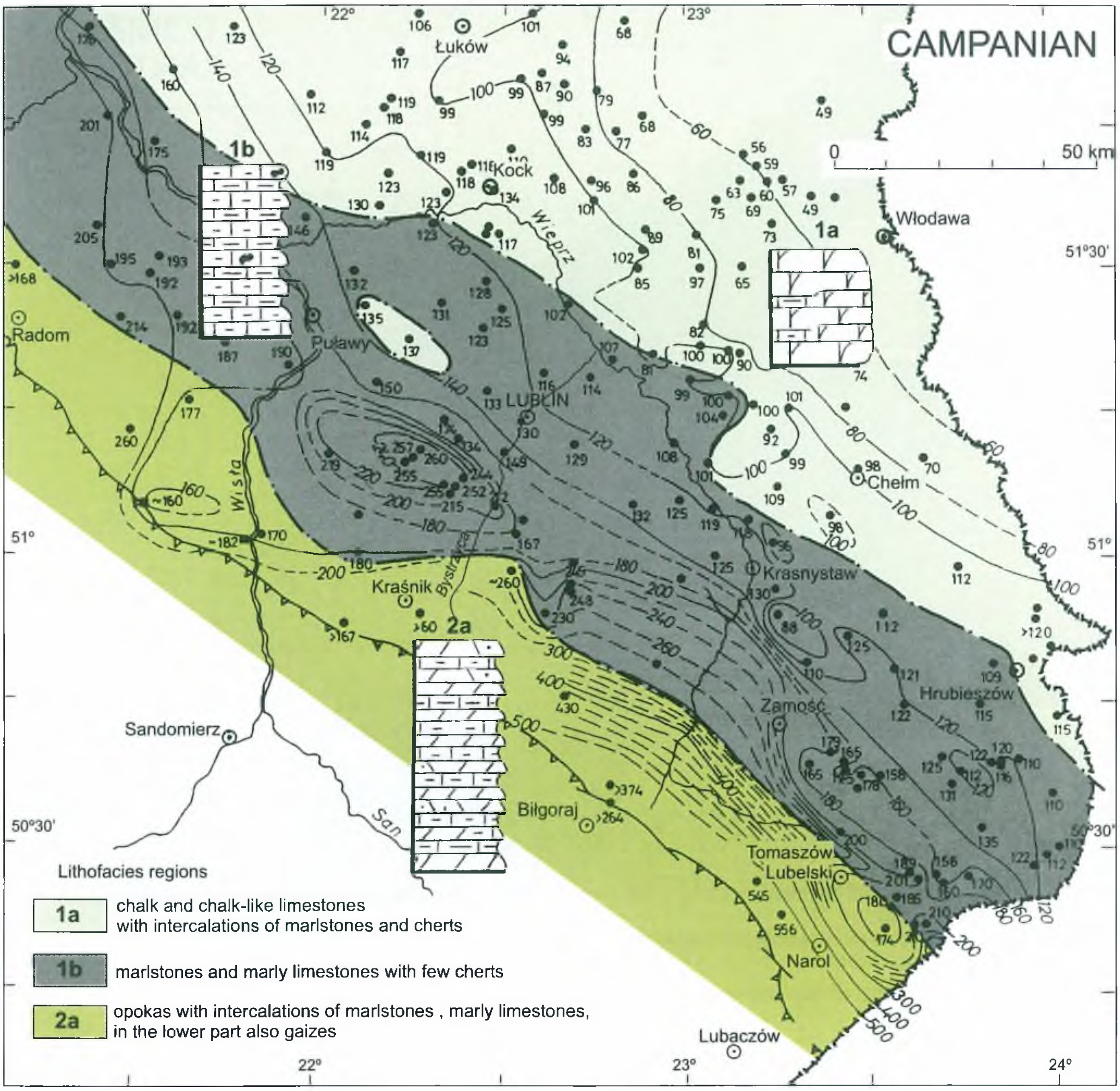

Fig. 8. Thickness and facies pattern of Campanian deposits. Explanations see Figs. 2, 4 and text

Sixteen logs of relatively well studied boreholes sections have been selected along the cross-section lines (Fig. 11) drawn approximately perpendicular to the present-day tectonic units (Fig. 10). These tectonic units include: (i) the Kock Fault that separates (ii) the most elevated north eastern part of the East European Craton from (iii) the Lublin Graben in the Palaeozoic structural pattern (prolongation of the fault towards Wasylów) and in the Mesozoic structural pattern from (iv) the Lublin Syncline (prolongation of the Kock Fault towards Hrubieszów); the Lublin Graben is bounded on the southwest by (v) the Ursynów–Kazimierz Dolny–Wysokie–Rawa Ruska Fault that separates it from (vi) the Radom–Kraśnik Uplift. A comparison of the three cross-sections confirms the persistence of the main lithofacies boundaries throughout the whole Late Cretaceous. It also reveals some more detailed facts that could not be all noticed on the maps.

The sections B and C reveal increased thickness of Turonian limestones in the zone near Łęczna 2 and between the boreholes Grabowiec and Terebin. This takes place near the Kock Fault and the fault's influence should also account for the persistence of limestone lithofacies, characteristic of Turonian, during Coniacian time (Łęczna). A probable cause of the increased carbonate productivity could be the presence of a submerged ridge above the active Kock Fault and favourable hydrodynamic conditions; also, increased fertility of water due to endogenic supply can not be ruled out.

The sections A and B show that the stable lithofacies pattern was altered in Early Maastrichtian time. First, the siliceous lithofacies expanded to the northeast and then, at the end of the Early Maastrichtian, it withdrew toward the axis

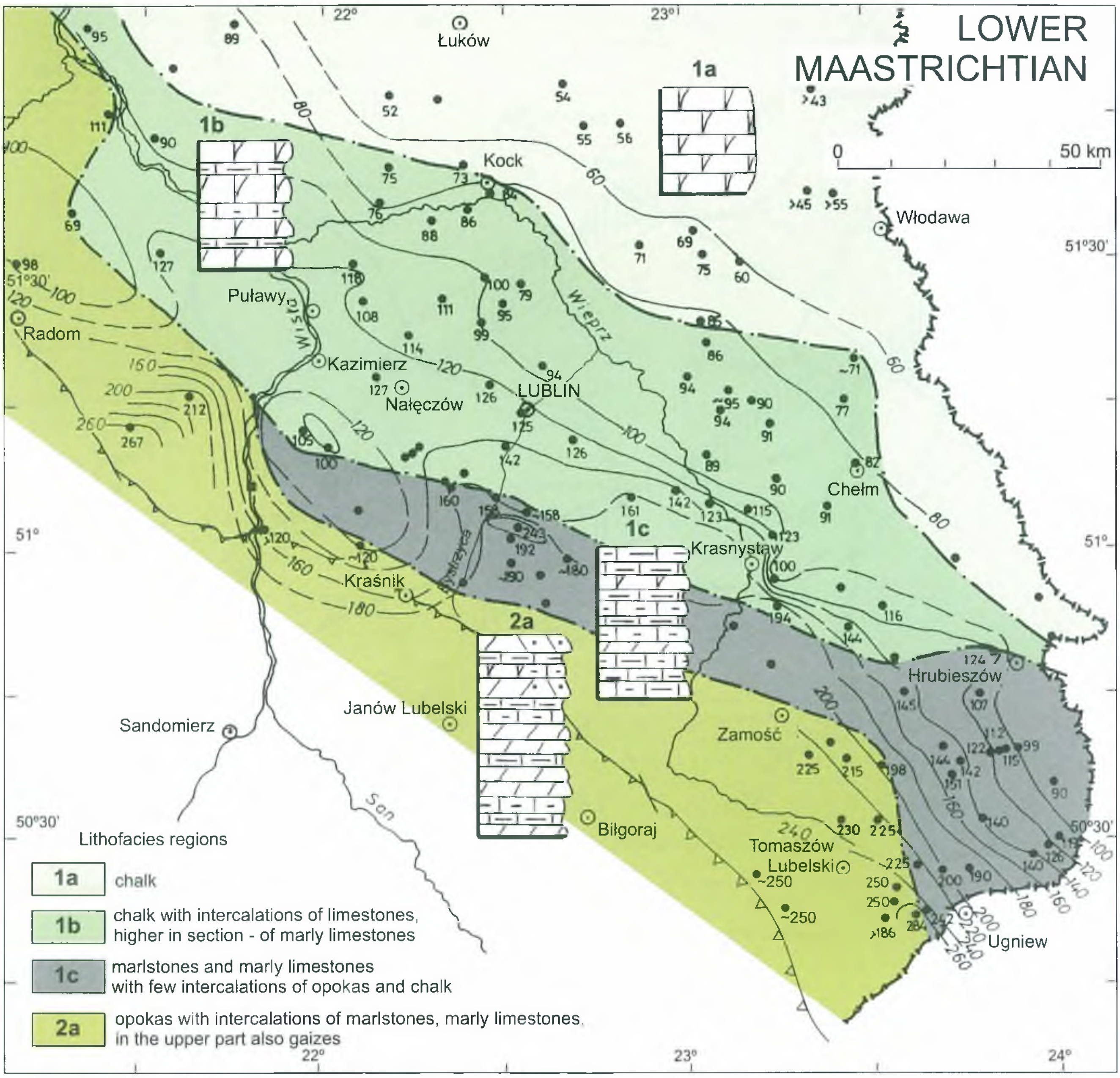

Fig. 9. Thickness and facies pattern of Lower Maastrichtian deposits. Explanations see Figs. 2, 4 and text

of the Holy Cross segment of the trough (to the southwest), behind which the area of chalk facies was expanding. This fact may be interpreted as a narrowing of the deeper basin area, coupled with the expansion of the area deprived of clastic supply from land. Both these phenomena occurring at the end of Early Maastrichtian could be caused by a barrier rising between Bąkowa and Ciepielów and between Stróża and Bystrzyca, which separated the chalk lithofacies area from the area of the trough proper.

A clear expansion of the siliceous lithofacies to the northeast occurred along the third cross-section line (C). Sedimentation of opokas persisted in the zone of the present-day Lublin Syncline until the end of the Early Maastrichtian. Chalk lithofacies did not increase its extent to the southwest. This could be due to stronger subsidence in this part of the basin than in the northwest (cross-sections A and B) and the increased supply of terrigenous material at that time along the southern margin of the Ukrainian Shield. This is implied by the presence of sandy gaizes (Narol borehole) and the expansion of the marlstone lithofacies near the state boundary (Fig. 9).

THICKNESS PATTERN AND SYNSEDIMENTARY BASEMENT MOVEMENTS

The presented thickness maps of the Cretaceous stages (Figs 4–9) indirectly demonstrate how the accumulation rate varied in any time interval and where zones synsedimentary tectonic movements in the basement could be located, based on the increased thickness gradients. Accelera-

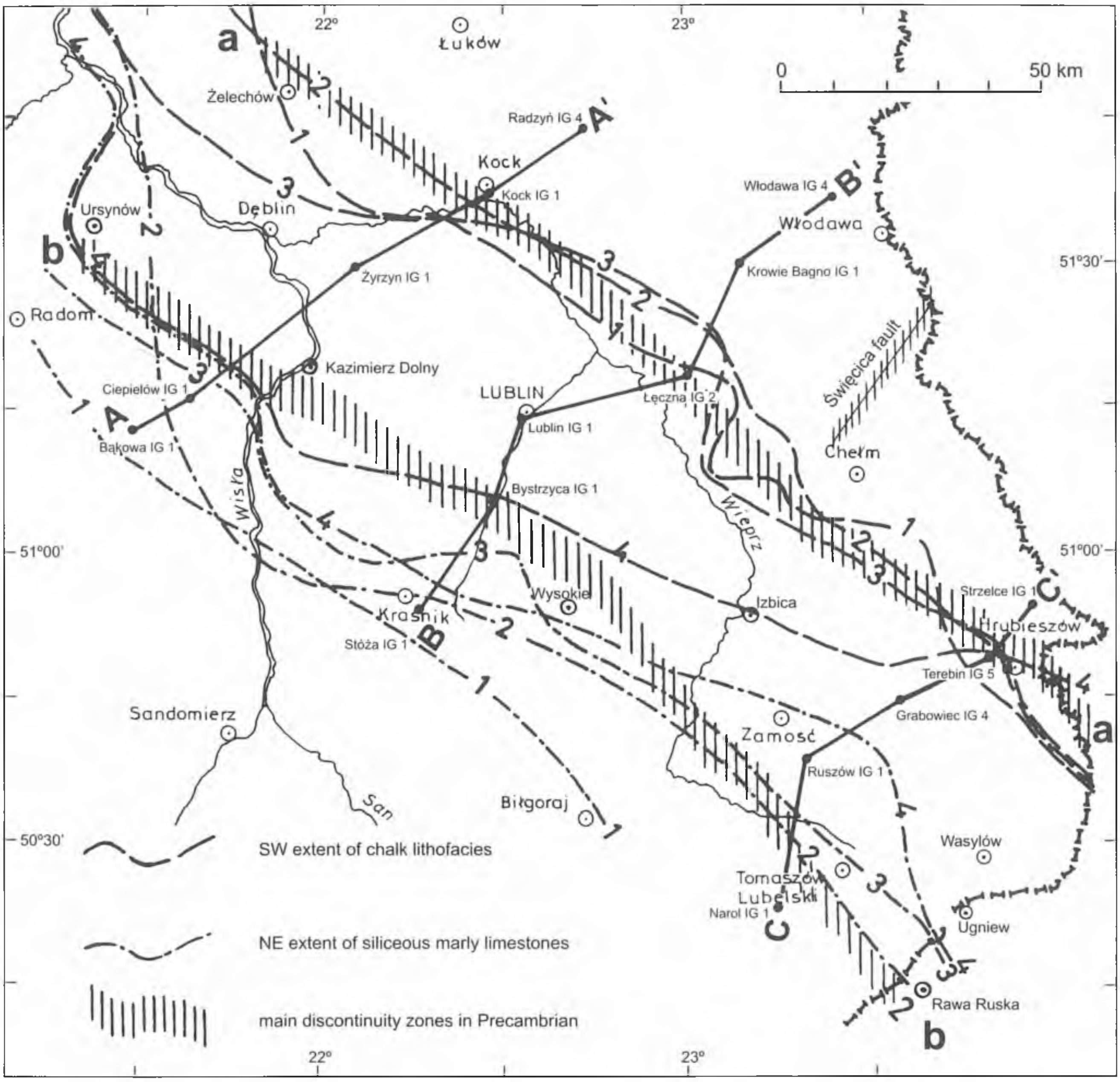

Fig. 10. Late Cretaceous changes in extent of chalk and siliceous marly lithofacies: 1 – Turonian, 2 – Coniacian/Santonian, 3 – Campanian, 4 – Early Maastrichtian; main discontinuity zones in Precambrian (partly after Znosko, 1998; other explanation in the text): a – Żelechów–Kock–Hrubieszów, b – Ursynów–Kazimierz Dolny–Rawa Ruska

tions in basin subsidence, observed on maps (Figs 4–9) and expressed in more dense arrangement of isopachs, are attributed to the activity of synsedimentary faults in the basement (cf. Hakenberg & Świdrowska, 1998).

The thickness of the Albian strata is very low (Fig. 4). An exceptionally stable triangular area may be distinguished in the central part, reaching to the Vistula and the Bug and farther east. In the west, to the line of the Wieprz, subsidence was controlled by WNW–ESE trending Palaeozoic faults and folds. The sediment-free zone north of Kraśnik, coincides with the Palaeozoic anticlinal structure Opole Lubelskie–Niedrzwica–Bychawa; perpendicular directions can be also discerned. Farther east, between the Wieprz and the Bug, the influence of the basement is less visible, though the submeridional extent of the zone of zero thickness is generally parallel to the structural trends in the basement (from Precambrian through Jurassic – cf. Pożaryski & Dembowski, 1983). The south eastern area features the presence of active zones of downbending of the basin bottom and its division into NW–SE oriented parallel zones of lower and higher subsidence. Subsidence was highest along the Izbica–Zamość–Ugniew Fault. The western boundary of this area lies in the Wieprz valley south of Krasnystaw (Fig. 4), which may be predisposed by a tectonic disturbance in the basement. It lies in the prolongation of the Święcica Fault (see Fig. 10), active from Early Palaeozoic time, whose course was reinterpreted using the recent seismic surveys (Wnuk & Świerczewska, 1994).

A zone of NW–SE trending longitudinal faults, bounding the axial part of the trough, ran probably along the south western boundary of the studied area.

A thickness pattern similar to the Albian one persisted through the Cenomanian (Fig. 5) only south of Hrubieszów and north of the San and Vistula confluence, where areas of low subsidence are present (thickness usually below 6 m). In the south eastern and the western areas, the trends are reversed: the Cenomanian depocentres are located in the zones of thinner Albian sediments. A similar trend was observed in the Holy Cross segment (Hakenberg, 1978, 1986; Świdrowska & Hakenberg, 2000). Cenomanian sediments are relatively thick, (up to 30 m) in the western part of the area, between Kraśnik and Lublin. The zones of greatest subsidence are located in the southeast: near the Izbica–Zamość–Ugniew Fault and the NW–SE trending faults northeast of Lubaczów. The last depositional centre (60 m) seems to be deepening towards Ukraine.

The thickness is much greater in Turonian sediments (Fig. 6): from 70 to 240 m in the south western part of the area, most frequently 100–140 m. The generally latitudinal pattern of isopachs changes to a NW–SE trending one east of the meridional segment of the Wieprz river. Isopachs are there closer spaced, pointing to the synsedimentary activity of the Izbica–Zamość–Ugniew Fault. A series of large transverse faults which delineate the Tarłów Graben is also well discernible.

The thickness of the Coniacian–Santonian strata (Fig. 7) varies from ca. 60 m in the northeast to more than 350 m near Biłgoraj; on the prevailing area it falls within 80–160 m. The general trend of isopachs is uniform over the whole area – NW–SE, typical of the Mesozoic structures. Subsidence was markedly accelerated near the fault running beneath the inner margin of Roztocze, southwest of Tomaszów Lubelski.

The thickness of Campanian strata (Fig. 8) vary from ca. 50 m in the northeast to more than 550 m near Narol in the southeast; they usually fall within 100–200 m. Isopachs in the central part of the Lublin region trend NW–SE, similarly as before. The most variable pattern of isopachs is present in the southwest, where three segments may be distinguished in the basin slope. The western segment, down to the line of the Bystrzyca river, features rejuvenation of the WNW–ESE trending Palaeozoic structures. The Bełżyce–Niedrzwica structure was depressed. A zone of increased subsidence in the southwest is not evident here. The eastern sector, between the Wieprz valley and the state boundary, comprises a zone of very high thickness gradient – 350 m in 10 km. The middle segment, between the Bystrzyca and the Wieprz is also a zone of rapid increase in thickness towards the southwest, but over a wider area.

The thickness pattern in the Maastrichtian (Fig. 9) is in clear contrast to those in the older Cretaceous stages, though the minimum values of thickness are noted in the northeast (about 50 m) and the maximum ones in the southwest (up to ca. 260 m), similarly as earlier. A differentiation of the basin appears transversal to the general isopach trend. In the western segment, between Radom and Kraśnik, two elevations are discernible with thickness below 100 m, which separate the area of the siliceous lithofacies from the area of the chalk lithofacies. Eastward of the upper, fault-controlled (Harasimiuk, 1980) segment of the Bystrzyca, the pattern is completely different as the 200 m isopach is shifted relatively far to the northeast. The area situated between Janów Lubelski, Biłgoraj, Krasnystaw, and Ugniew and Tomaszów Lubelski was subject to intense subsidence.

Analysis of the thickness changes in vertical plan (Fig. 11) requires separate discussion of the individual cross-section lines.

The A-A' line coincides with the Holy Cross segment of the trough in its south western part. The thickness gradients do not indicate the presence of active faults. The East European Craton as a whole was subsiding faster in the southwest direction. A departure from the uniform subsidence is discernible only in the Campanian and Lower Maastrichtian strata, on the grounds of a higher increase in thickness over the short distance between Ciepielów and Bąkowa. This fragment of the north eastern margin of the trough was subsiding faster than the zone situated farther to the northeast and represented in the cross-section between Ciepielów and Radzyń. The stronger downbending of the south western margin of the craton has began probably earlier, already in Santonian time, as the appearance of sponge facies in this stage at Bąkowa may be interpreted as due to the basin deepening not compensated by supply of argillaceous and carbonate material. The facies change precedes here the increased supply of sediment in the axial part of the trough.

The B-B' line provides similar data on subsidence: a steady, slow increase in thickness to the southwest is accelerated in the Santonian strata as is shown by the presence of siliceous lithofacies and in the Campanian, as is shown by the increase in sediment thickness. The changes in the Lower Maastrichtian can not be shown here.

Along the C-C' line a pattern of subsidence is clearly different than in the other two cross-sections. The north eastern segment displays an increased gradient in the thickness of the Lower Maastrichtian strata between Strzelce and Terebin, in the prolongation of the Kock Fault, which was probably reactivated over this segment. Thickness variations between Terebin and Grabowiec are minimal; rapid increases appear at Ruszów and Narol, southwest of the Izbica–Ugniew Fault and another fault parallel to it, running southwest of Tomaszów Lubelski. The influence of these faults is greatest in the Campanian, though even earlier they became manifest in both, thickness and facies.

RATE OF SUBSIDENCE

An analysis of sediment thickness growth with time, without taking into account compaction, changes in basin depth and eustatic changes in sea-level, leads to conclusions on the rate of accumulation rather than on the rate of subsidence. However, if we accept that this is proportional to the rate of subsidence (for a stable sea-level) and if we treat it as a relative value used for comparison within one basin, than such a simplification may be accepted as a substitute.

In order to compare the rates of subsidence at various times and the variation in subsidence rate with time (accel-

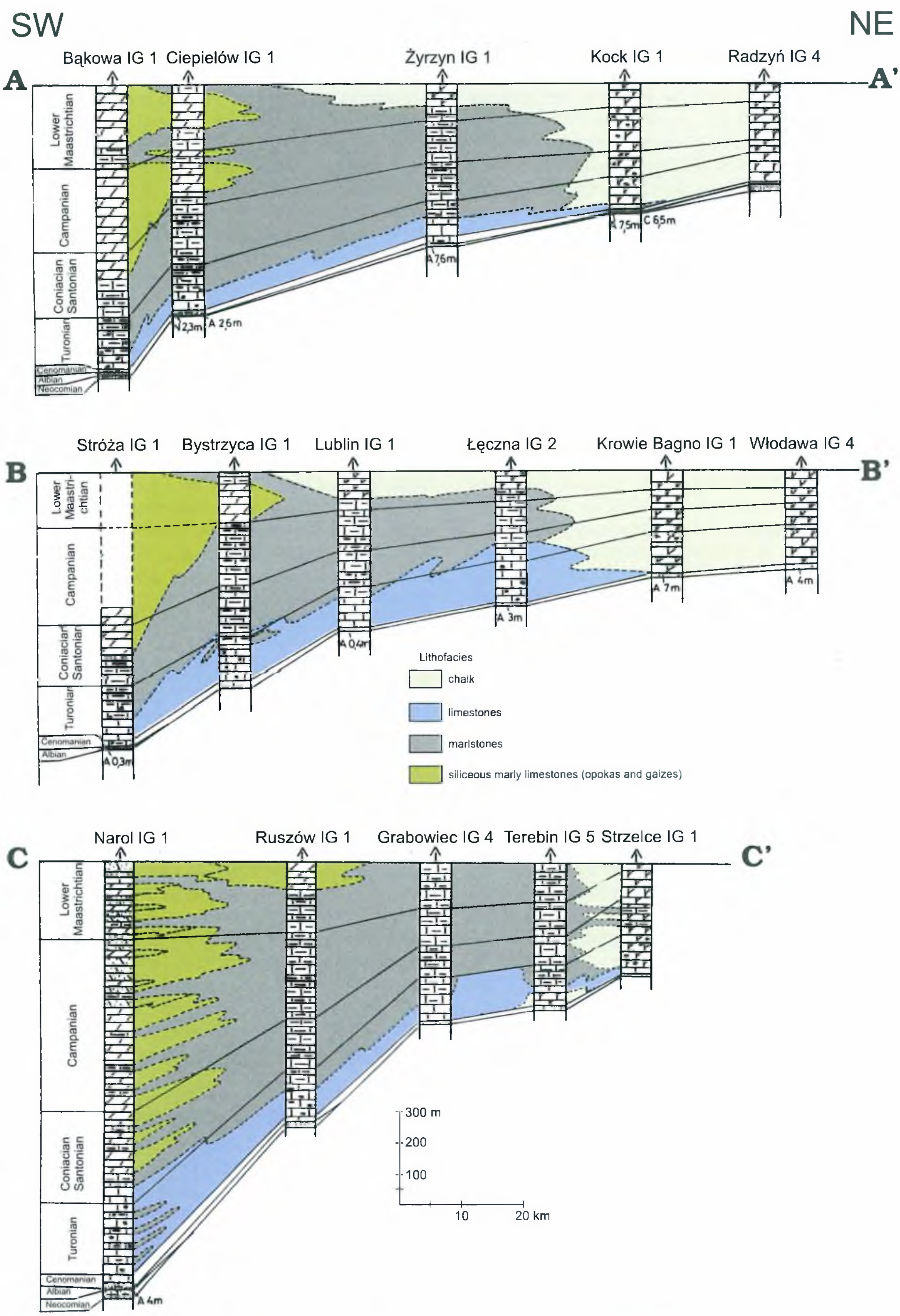

Fig. 11. Thickness and lithofacies pattern of Cretaceous deposits at the end of Early Maastrichtian along palaeotectonic cross-sections. Thicknesses of: N – Neocomian, A – Albian, C – Cenomanian

eration), subsidence curves have been plotted (Fig. 12). Nine boreholes were selected, three from each of the three cross-sections showing facies and thickness of the deposits, to demonstrate the subsidence in various palaeotectonic regions, labelled with numbers 1 to 3: 1) the north eastern limb of the trough situated close to the longitudinal fault zones bounding the proper trough – boreholes Bąkowa, Stróża, Narol, 2) the East European Craton with its thick young Palaeozoic sedimentary cover (Lublin Graben), situated south west of Kock Fault, where the crystalline basement lies at a great depth – boreholes Żyrzyn, Lublin and Grabowiec, 3) the East European Craton northeast of the Kock Fault, where the crystalline basement lies at shallow depths – boreholes Radzyń, Krowie Bagno and Strzelce.

The subsidence rate, expressed in the diagram by the slope of the curve, in most part of the area (regions 1 and 2) has attained similarly high values still twice in Late Cretaceous time: in the Turonian and Early Maastrichtian. Northeast of the Kock Fault (region 3), the subsidence rate was greatest in Turonian, and much lower in Early Maastrichtian.

A comparison of the Turonian subsidence rate in various areas (regions 3 and 2, along cross-sections A, B, and C in Fig. 12) shows that the differences are very small; only the segments of the curve corresponding to the south western region 1 show slightly steeper slopes. The degree of relative lowering of the craton which formed the north eastern limb of the trough, was similar; only its south western margin was subject to greater subsidence. This trend is more clear in the southeast (Narol). The Kock Fault did not influence the rate of sediment accumulation.

The subsidence rate in the Early Maastrichtian changes steadily along each of the cross-section lines. The whole studied area was subject to stronger subsidence in the southwest (progressive steepening of the curve from the region 3 to 1), which means that a uniform cause provoked uneven response within the basement.

The subsidence curves reveal also changes in subsidence rate, including its important accelerations. Acceleration of subsidence is expressed in the increase in slope of a curve segment,

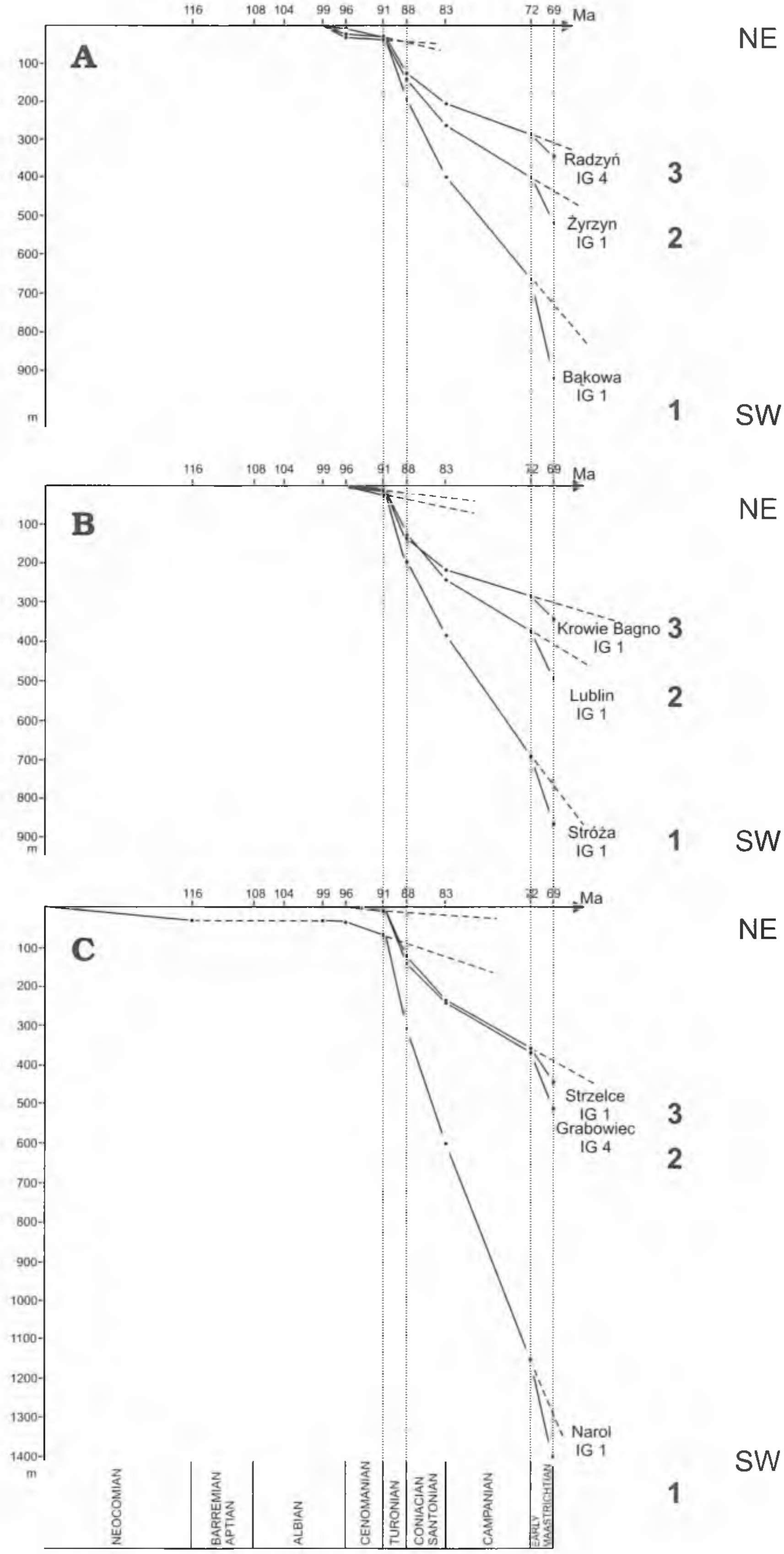

Fig. 12. Curves showing changing accumulation rates along the A, B and C cross-sections (location in Fig. 10); 1, 2, 3 – palaeotectonic realms; dashed lines shown to enhance the increase in the rate of accumulation manifest in the angular difference between the adjacent sections of the curves (relative to Cenomanian and Campanian, respectively); numeric scale after Odin & Odin (1990); other explanations in text

relative to the preceding segment; its measure is the difference in slope angle between the two segments of the curve. Acceleration of subsidence occurred twice within each of the analysed points: in the Turonian and in early Maastrichtian; the Turonian one was greater.

The Turonian acceleration was uniform along the whole cross-section lines – it does not display any variation relative to the tectonic position. Thus the underlying cause did not act selectively – the whole area reacted in a similar way. The reason could be a sea-level rise or a change in general tectonic regime (for instance a stronger extension), which nevertheless did not generate faults and did not activate the old discontinuities. However, a possibility that both causes were superposed can not be ruled out. A similar acceleration of subsidence rate in the Turonian over the whole area seems to indicate a significant role of the eustatic factor in the enlargement of the basin area and in uniform isostatic response of the basin basement.

The Early Maastrichtian acceleration is differentiated along the cross-sections: it is greatest in the central points (2) of the cross-sections B and C, that is above the Palaeozoic Lublin Graben. Along the section A it is greatest in borehole Bąkowa situated in the southwest (1). The factor which caused the acceleration of the sediment accumulation rate did not evoke then a uniform response – this may imply either a differentiated response of the basement to a uniform cause or a regionally differentiated intensity of the causal factor. The different pattern of subsidence rate in the Early Maastrichtian suggests that the causal factor could not be of eustatic nature. Downwarping was greatest in the southwest (region 1), while greater acceleration occurred above the axis of the Late Palaeozoic Lublin Graben. As the generally greater Turonian acceleration in subsidence rate did not cause a differentiated response in the basement, than the weaker but regionally differentiated Early Maastrichtian acceleration was probably due to the role of tectonic factor in the augmenting of the depositional capacity of the basin. The Lublin Graben area was subject to a stronger downbending and after inversion it became the central part of the Marginal Depression. This seems to be a manifestation of the beginning of the formation of the Marginal Syncline, which in turn may be an equally good argument for the beginning of inversion as the difficult to ascertain (because of later removal of Cretaceous deposits) beginning of the formation of elevation in the central part of the trough. This is confirmed by the observation at Narol, situated both, near the area which was uplifted towards the end of Cretaceous time and close to the area which was subjected to downbending in the Early Maastrichtian (Grabowiec on cross-section C). At Narol, the Early Maastrichtian acceleration is smallest. We observe a reversal in the trend of sediment accumulation during the Early Maastrichtian, which may be interpreted as heralding the oncoming process of inversion.

The regional comparison of the values of accumulation rate acceleration at various times may thus provide opportunity for a distinction between the role played by eustatic (Turonian) and tectonic (Early Maastrichtian) factors in the process of augmenting the depositional capacity of the basin.

CONCLUSIONS

1. The thickness of deposits, both in the Jurassic–Lower Cretaceous and the Albian–Upper Cretaceous (including Lower Maastrichtian) megacycles, increases to the southwest. Therefore, the axis of maximum subsidence lied southwest of the present-day erosional limit of Cretaceous deposits.

2. The occurrence of the Middle Albian transgressive sediments, limited to the extremal southwest part of the studied area, shows the lowest part of the basin.

3. Siliceous lithofacies appeared in the southwest in Albian time, then spread to the northeast and lasted through the Early Maastrichtian. Its occurrence, related to the zone of maximum subsidence and conditions favourable for siliceous sponges (depths of several hundred metres, inclined slopes), delineate the zone lying closest to the trough axis relative to the other facies.

4. The supply of terrigenous material to the north eastern slope of the basin during the Albian through Maastrichtian time interval was from the southwest to the northeast, that is from the direction of the trough axis (located by the appearance of transgression, its spreading to the trough limbs, greater thickness and deeper facies) and was caused by currents transverse to the basin slope. These currents, however, can not be considered as the currents supplying material to the basin from source areas. The proven source area was the south eastern part of the Ukrainian Shield, which suggests supply of terrigenous material by longitudinal currents from the southeast in the Polish part of the trough.

5. Chalk was laid down from Turonian through Early Maastrichtian time, always farthest from the trough axis, in the NE part of the studied area, where subsidence was smallest and terrigenous supply lowest.

6. The limits of extent of chalk facies to the southwest and siliceous facies to the northeast lie above the zones of deep faults lowering the top of the crystalline basement of the East European Craton: one above the Żelechów–Kock–Hrubieszów Fault Zone which marks the upper escarpment of the crystalline basement, another above the Kazimierz Dolny–Wysokie–Rawa Ruska Fault Zone, accepted as the south western boundary of the craton.

7. The control of the lithofacies pattern by the dislocation course proves the role of tectonic factor in controlling the basin depth.

8. The rate of sediment accumulation was subject to two episodes of strong acceleration: in the Turonian and Early Maastrichtian. A regional comparison of the values of acceleration in sediment accumulation rate in both time intervals implies a greater role of the eustatic factor in the Turonian and of tectonic factor in the Early Maastrichtian in the augmenting of the depositional capacity of the basin.

9. The Early Maastrichtian acceleration in subsidence rate occurred along the axis of the present-day Lublin Syncline, which may be interpreted as the beginning of the process of inversion.

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Streszczenie

EWOLUCJA BASENU KREDOWEGO NA OBSZARZE LUBELSKIM WZDŁUŻ STREFY TEISSEYRE'A–TORNQUISTA (SE POLSKA)

Maciej Hakenberg & Jolanta Świdrowska

Celem tej pracy jest przedstawienie rozwoju depozycji osadów kredowych w lubelskim basenie sedymentacyjnym na podstawie analizy rozkładu litofacji i miąższości. Basen ten był położony na północno-wschodnim skłonie bruzdy śródpolskiej, a dalej na północny wschód na jej przedpolu rozciągającym się na kratonie wschodnioeuropejskim. Bruzda śródpolska powstała wzdłuż strefy Teisseyre'a–Tornquista ponad strefą kontaktu platformy paleozoicznej a prekambryjskim kratonem wschodnioeuropejskim (Fig. 1).

Posługując się istniejącymi publikacjami i materiałami archiwalnymi zestawiono mapy izopachyt dla siedmiu przedziałów czasowych od neokomu po wczesny mastrycht (Fig. 2 i 4–9). Wyróżnionych zostało kilka głównych litofacji, których granice zaznaczono ma mapach miąższości. Analiza miąższości osadów, należących zarówno do megacyklu jurajsko-dolnokredowego (neokom – Fig. 2 i 3), jak i cyklu albsko-górnokredowego (włącznie z dolnym mastrychtem – Fig.4–9), wykazała, że rosną one ku południowemu zachodowi. Tak więc oś maksymalnej subsydencji była położona na południowy zachód od obecnego erozyjnego zasięgu występowania osadów kredowych. O położeniu osi dodatkowo świadczy występowanie transgresywnych osadów środkowego albu, ograniczone do skrajnie południowo-zachodniej części badanego obszaru. Wyznaczona zostaje w ten sposób najniżej położona część dostępnego badaniami basenu.

Dopływ materiału terygenicznego w strefę NE skłonu basenu następował konsekwentnie od albu do mastrychtu z SW ku NE, od strony osi bruzdy (wyznaczonej pojawieniem się transgresji, jej rozprzestrzenieniem na skrzydła bruzdy, większymi miąższoś-

ciami i głębszymi facjami) i było skutkiem prądów poprzecznych do nachylenia dna basenu. Prądy te nie mogą być traktowane jako prądy dostarczające materiał klastyczny do zbiornika z obszarów alimentacyjnych. Takim denudowanym obszarem była południowo-wschodnia część tarczy ukraińskiej. Sugeruje to na polskim odcinku bruzdy dostawę materiału terygenicznego z południowego wschodu prądami podłużnymi. Na południowym zachodzie w albie pojawiła się litofacja krzemionkowa, która następnie rozszerzyła swój zasięg ku NE i trwała do wczesnego mastrychtu włącznie. Jej występowanie, związane ze strefą największej subsydencji i korzystnymi warunkami życia gąbek krzemiokowych (głębokości kilku setek metrów, nachylone stoki), wyznacza strefę położoną najbliżej osi bruzdy w stosunku do pozostałych litofacji. Inna ważna litofacja – kreda pisząca osadzała się od turonu do wczesnego mastrychtu włącznie zawsze w maksymalnej odległości od osi bruzdy, w NE części opracowywanego terenu (Fig. 10 i 11). Obszar ten charakteryzował się najmniejszą subsydencją i najmniejszym dopływem materiału trygenicznego. Południowo-zachodni zasięg litofacji kredy piszącej i północno-wschodni litofacji krzemionkowej leżą nad wgłębnymi strefami dyslokacyjnymi obniżającymi strop krystaliniku kratonu wschodnioeuropejskiego: pierwsza nad strefą dyslokacyjną Żelechów–Kock–Hrubieszów, wyznaczającą górną skarpę krystaliniku, a druga nad strefą dyslokacyjną Kazimierz Dolny–Wysokie–Rawa Ruska, uznawaną za SW granicę tego kratonu (Fig. 10). Uzależnienie rozkładu litofacji od przebiegu dyslokacji dowodzi roli czynnika tektonicznego w kształtowaniu głębokości zbiornika.

Tempo akumulacji osadów dwukrotnie uległo silnemu przyspieszeniu: w turonie i we wczesnym mastrychcie. Regionalne porównanie wielkości przyspieszenia tempa trwałej akumulacji osadów w tych dwóch przedziałach czasowych sugeruje większy udział czynnika eustatycznego w turonie, a tektonicznego we wczesnym mastrychcie w procesie zwiększenia sedymentacyjnej objętości basenu (Fig. 12). We wczesnym mastrychcie największe przyspieszenie subsydencji nastąpiło w osi obecnej synkliny lubelskiej, co można interpretować jako początek procesu inwersji.