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Mesozoic thickness pattern in the Mid-Polish Trough

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The Mid-Polish Trough (MPT) is well recorded in the distribution of thickness of the Mesozoic sediments. Its shape was most distinctly delineated in the Early Triassic, and Early to Middle Jurassic, when thickness gradients attaining 100 m/km were reached. However, because the regional faults bordering the MPT were not active throughout its history, the existence of Mid-Polish Rift has not been confirmed. The strongest thickness gradients may have been caused by the periodical activity of the sub-Zechstein faults, which did not penetrate the Mesozoic strata due to the damping effect of plastic Zechstein salts. On the contrary, local faults, forming (mainly during the Late Triassic) syn-sedimentary grabens, are a common feature in the MPT and its surroundings. Transversal subdivision of the MPT and its slopes into at least two segments (Pomeranian and Kuiavian) is clearly visible in the thickness pattern. It is expressed by the presence of separate depocentres, reversal of asymmetry, differences in stratigraphical sequences observed on the palaeomorphological terraces south-west of the MPT, and by the structural variations after the inversion. The scale of inversion, which transformed the MPT into the Mid-Polish Swell (MPS), is unclear and needs further investigations. Estimation of the thickness of the Upper Cretaceous sediments removed by erosion is a key problem in this respect. It should take into account both, the effects of the regional inversion and the local changes resulting from the last stage of strong salt displacements.

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Key words: western and central Poland, Mid-Polish Trough, Mesozoic thickness, tectonics, palaeogeography.

INTRODUCTION AND GEOLOGICAL SETTING

The aim of this paper is to analyse changes of the present thickness distribution of the individual series in the Mesozoic succession of the Mid-Polish Trough (MPT) and its surroundings. Such an analysis is the first step to reconstruction of the primary thickness, and to further estimations of the rates of sedimentation and subsidence.

The MPT is the deepest (10 km) and the largest (700 km long and up to 100 km wide) basin in a group of inverted Mesozoic basins of the Western and Central Europe (Ziegler, 1990). It is an elongated structure, formed in the Late Permian, along the southwestern edge of the East European Craton (EEC), between the present Baltic coast and Carpathian front (Fig. 1). Its base raises towards north-west (Danish Basin) and south-east (Holy Cross Mts area). In the latter direction it was periodically connected with the Tethyan domain. Initiation of the subsidence was a combined effect of trans-tensional tectonic stresses along the southwestern border of the EEC, and of crustal cooling (Dadlez *et al*., 1995; van Wees *et al*., 2000). MPT was inverted in the latest Cretaceous and the beginning of Tertiary as a result of vertical movements, probably caused by compression in the lower crust, triggered by stress generated in the forefield of the Alpine–Carpathian fold belt forming at that time (Ziegler, 1990). A regional tectonic unit of the Mid-Polish Swell (MPS) emerged then from the MPT. It was intensely eroded, mainly in the beginning of Tertiary. As a result, dominantly Lower Jurassic rocks appear at the sub-Cenozoic surface in the Pomeranian segment of the MPS (northwestern Poland), while in its Kuiavian segment (central Poland) the Upper Jurassic rocks dominate. Both are contrasting sharply with the Upper Cretaceous sediments filling in the adjacent synclines. In the depression between the Pomeranian and Kuiavian segments the Lower Cretaceous strata occur at this surface.

While the older parts of Mesozoic (Triassic and partly Lower Jurassic) may be a subject of direct thickness analysis, the younger, eroded parts (partly Lower Jurassic to Cretaceous), may be interpreted only indirectly because of the post-inversion erosion. Isopachs of the Upper Jurassic and Lower Cretaceous in the Kuiavian segment run roughly parallel to the axis of the MPT and to the present erosional boundaries of both series. In the Pomeranian segment, isopachs of Jurassic and Lower Cretaceous run obliquely to the erosional boundaries indicating a gradual thickness decrease towards the

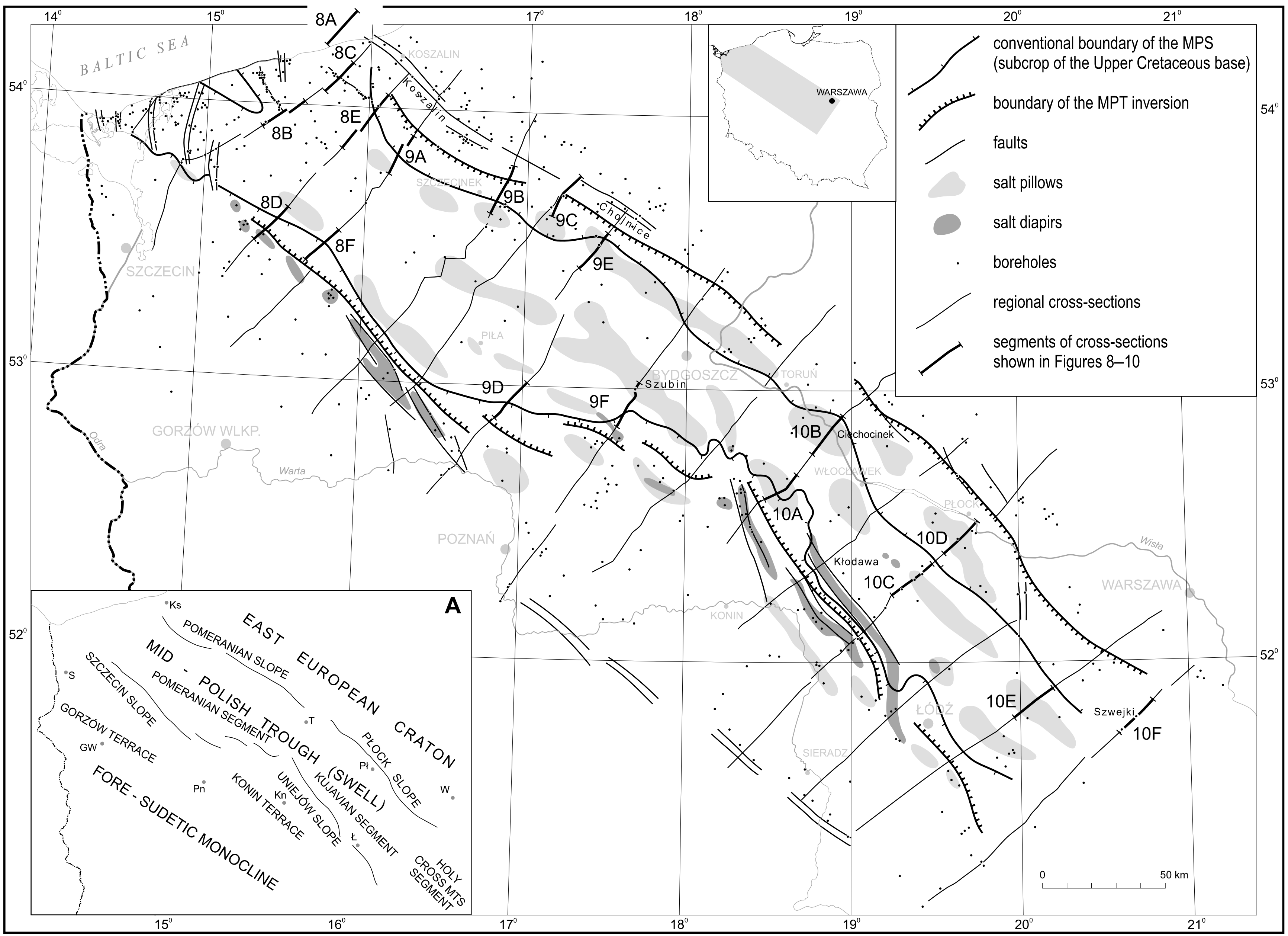

Fig. 1. Locality map

A — Regional units discussed in the text; GW — Gorzów Wielkopolski, Kn — Konin, Ks — Koszalin, Ł — Łódź, Pł — Płock, Pn — Poznań, S — Szczecin, T — Toruń, W — Warszawa north-west, along the axis of the trough. In both cases, the extrapolation of primary thickness pattern from neighbouring areas into the MPS is relatively simple. The reconstruction of syn- and post-inversion Upper Cretaceous thickness is ambiguous and depends on the assumption whether the uplift of the MPS started in the Maastrichtian or earlier (after the Turonian — see the discussion between Świdrowska and Hakenberg, 1999*a*, *b* and Leszczyński and Dadlez, 1999). In the first case, the subsidence continued throughout the Late Cretaceous, and the primary Upper Cretaceous thickness could be greater than in the neighbouring units, where the Upper Cretaceous rocks escaped erosion. In the second variant, the Upper Cretaceous profile should be thinner than in the surrounding units.

PREVIOUS WORK

Small scale thickness maps of the Mesozoic stratigraphic units have been published, among others, in the special issue of "Kwartalnik Geologiczny", edited by Marek (1988), and in the monograph on the epicontinental Permian and Mesozoic in Poland, edited by Marek and Pajchlowa (1997). The most recent interpretation is given in the palaeogeographical atlas, edited by Dadlez *et al.* (1998). This paper is the first to use seismic cross-sections in the thickness evaluation.

DATA

This analysis has been based on two sources. The first comprised thickness maps of the Mesozoic series, compiled during 1992–1998 as a basis for transformations of Bouguer gravity anomalies (author's unpublished data); these maps were slightly modified in the successive years. The second source included a number of perpendicular regional geological cross-sections of the MPT, constructed during 1997–1999 (Dadlez, 2001). The maps are presented in Figures 2–7, the examples of cross-section segments (location in Fig. 1) are shown in Figures 8–10.

A total of 530 boreholes were used for the construction of the maps. Each map is based on a smaller number of boreholes, because some of them were too shallow to reach the deeper parts of the Mesozoic succession, and some — located in the MPS area — did not provide information about the eroded strata. Cross-sections are in average 140 km long; their total length — within the boundaries of the MPT and its surroundings — is over 2100 km.

The stratigraphic subdivision of the borehole sections is simplified compared to the standard column (Table 1). The reason for this simplification is the fact, that only the earliest deep boreholes, completed in the Polish Lowlands in the late 1950's, were fully cored enabling the detailed biostratigraphic division. Later on, the coring was more sparse (every 100 m or less). In some

Table 1

Comparison of stratigraphic schemes

STANDARD STRATIGRAPHIC SCHEME	SIMPLIFIED LITHOSTRATIGRAPHIC SCHEME (THIS PAPER)
Upper Cretaceous	Upper Cretaceous
Lower Cretaceous	Lower Cretaceous
Upper Jurassic	Upper Jurassic
Middle Jurassic	Middle Jurassic
Lower Jurassic	Lower Jurassic
Rhaetian and Keuper–Upper Triassic	Rhaetian and Keuper Ceratites Beds
Muschelkalk–Middle Triassic	Muschelkalk
Bunter–Lower Triassic	Marly Beds Bunter
Permian	Zechstein

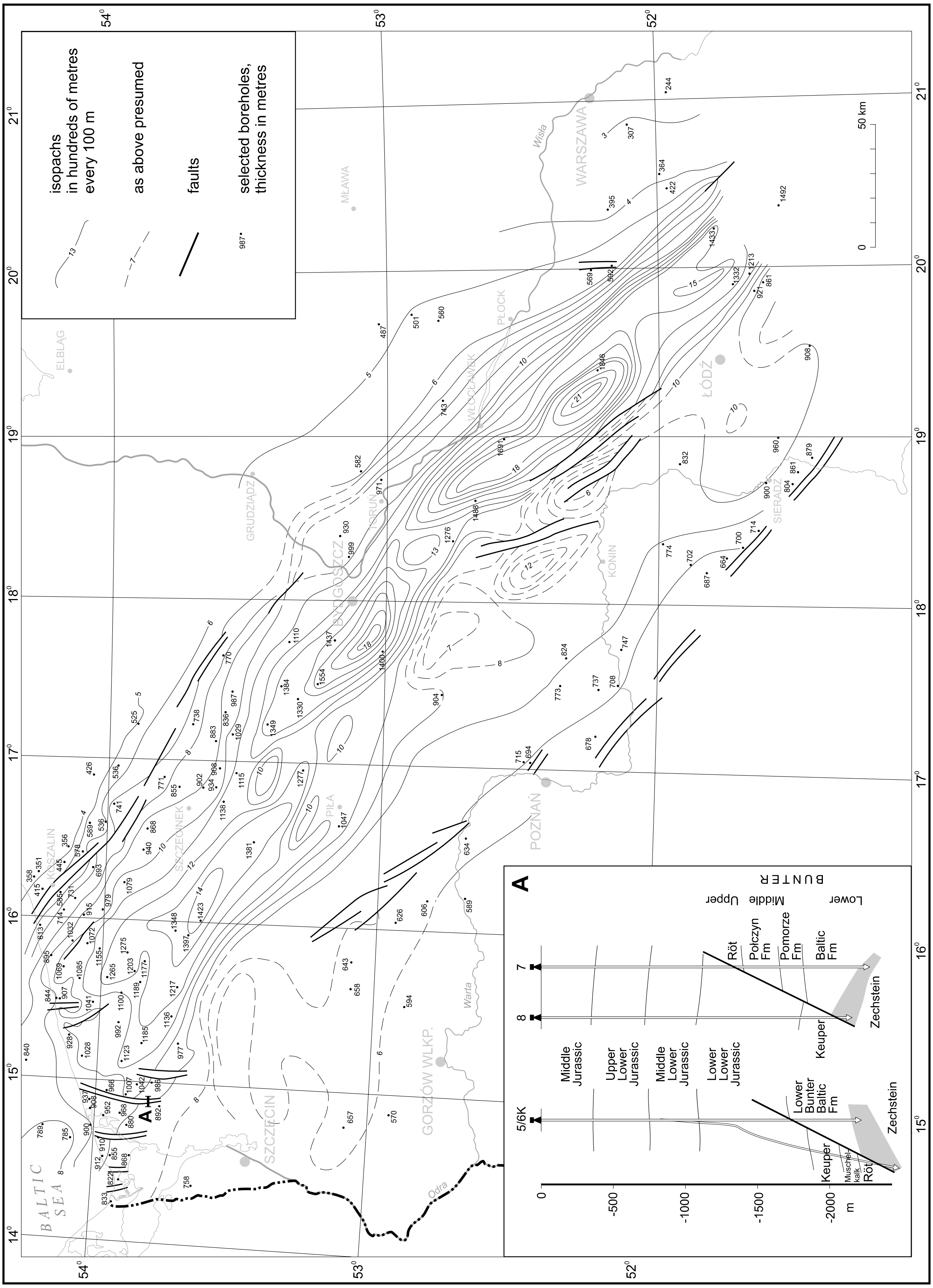

Fig. 2. Bunter thickness

A — tectonics in the Wysoka Kamieńska Graben

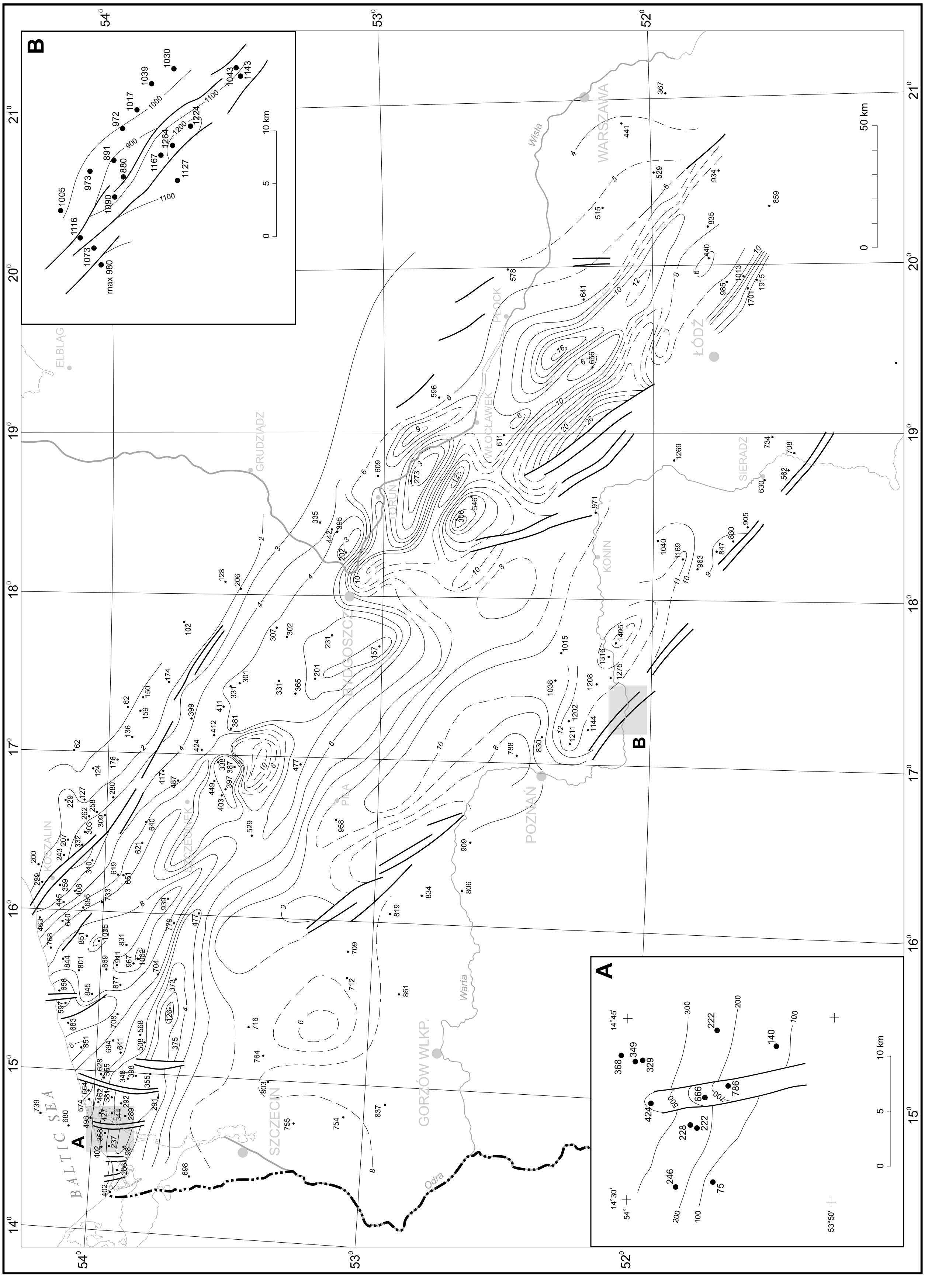

Fig. 3. Muschelkalk and Keuper thickness

A — Keuper thickness in the Laska Graben; B — Keuper thickness in the Klęka Graben (after Kwolek, 2000, modified); thickness in boreholes in metres; other explanations as in Figure 2 cases, no core was taken from the Mesozoic strata at all. Thus, the lithostratigraphic subdivision based on the geophysical logs was only possible. Therefore, the bio- and chronostratigraphic boundaries, which are different to lithostratigraphic boundaries, could not be determined in every borehole. Since the intention of the regional thickness analysis is to correlate stratigraphic boundaries in all boreholes — proceeding step by step from one section to another — the adopted boundaries are in fact lithostratigraphic. Boundary corrections in relation to chronostratigraphy are described in the following chapters.

Apart from a significant erosion in the MPS, thickness analysis is constrained by the following factors:

— irregularity of borehole distribution. Majority of boreholes is concentrated along the northeastern slope of the MPT (Fig. 1). Moreover, some of them are grouped on local anticlines, and are not useful for regional analysis. Only a small number of boreholes is located in the centre of the MPT;

— reliability of seismic sections. While the boundaries of the Triassic and within this system, as well as the base of the Upper Cretaceous are reliable, the seismic subdivision of the Jurassic system is, in some cases, doubtful;

— distance between cross-sections. Average distance between the neighbouring cross-sections is 30 km. In areas of more complicated tectonics (e.g. in areas affected by salt tectonics) such distribution is too sparse for correlation of structural and thickness details.

Areas with doubtful interpretation are marked on the maps (Figs. 2–7) by long-dashed lines. Short-dashed lines indicate the areas of erosion.

2D decompaction procedure along cross-sections has not been performed. The application of this procedure would not influence significantly the distribution of the regional thicknesses. In general, the thickness contrasts between the axis of the MPT and its slopes should be increased, particularly in the case of shaly successions such as the Lower Bunter, the Keuper and the Middle Jurassic, which were compacted most strongly. Examples of 1D decompaction in drilled sequences and in "synthetic boreholes" were shown by Dadlez *et al.* (1995).

Information on stratigraphic sequences (particularly on stratigraphic gaps) of individual series was derived from the cross-sections included in the recent palaeogeographical atlas of Poland (Wagner, 1998 — Zechstein; Iwanow, 1998 — Triassic; Feldman-Olszewska, 1998 — Lower and Middle Jurassic; Gaździcka, 1998 — Upper Jurassic; Leszczyński, 1998 — Cretaceous).

Palaeomorphological terms are used for the regional units characterised by similar thickness distribution (Fig. 1A). The EEC slope, located north-east of the axial part of the MPT, is divided into two parts — the Pomeranian Slope and the Płock Slope. To the south-west, the MPT is bordered by the Szczecin Slope and the Uniejów Slope. Deep synclines, containing Upper Cretaceous sediments, developed over these slopes during the later inversion. Two terraces — the Gorzów Terrace and the Konin Terrace existed further to the south-west.

THICKNESS ANALYSIS

Thickness distribution in the area discussed is characterised by:

— regional increase towards the axis of the MPT (except for the Middle–Upper Triassic);

— local, broader and gradual reductions above non-pierced salt anticlines (salt pillows);

— local narrow zones of more rapid thickness changes within either syn-sedimentary grabens, or above the pierced salt diapirs; these changes have not been shown on the main maps because of the scale; selected examples are shown on the inset maps at a larger scale (Figs. 2–7).

SUBSTRATE OF THE MESOZOIC SUCCESSION

Mesozoic strata in the entire area lie over the salt-bearing Upper Permian Zechstein. The present contact in most of the area is modelled by salt tectonics which had a decisive influence on the Mesozoic thickness distribution. Only the Peri-Baltic region, and the north-east and south-west margins of the MPT, were not affected by the salt movements.

BUNTER

The lithostratigraphic boundary between the Zechstein and the Bunter is drawn at the sharp contact of the Zechstein salts or anhydrites with the overlying clastic Bunter rocks. It is different to the boundary between Permian and Triassic, which runs somewhat higher (Pieńkowski, 1987; Nawrocki *et al.*, 1993; Wagner, 1994).

In general, in the MPT, there is no stratigraphic gap between the lowest Triassic (Lower Bunter sub-series) and the highest Zechstein. Only exceptionally — in small areas above the mobilised salt diapirs — the salts are covered by various Mesozoic strata (e.g. Fig. 8D — Oświno) or, in extreme cases, even by the Quaternary. In spite of high relief (attaining amplitude of thousands of metres) between the tops of salt pillows and bottoms of the dividing synclines, the Zechstein/Bunter contact is concordant. Bunter sequence does not contain significant stratigraphic gaps. It is composed mainly of shaly Lower Bunter known as Baltic Formation (Szyperko-Śliwczyńska, 1980); the Middle Bunter begins with shales, followed by prevailing sandstones (Pomorze and Połczyn formations). The Upper Bunter (Röt — Barwice Formation) is composed of interlayered clastics, dolomites and anhydrites. Thickness changes of these sub-series are proportional to the changes of the entire series.

Bunter thickness pattern (Fig. 2) shows a gradual increase towards the axis of the MPT, from about 400–600 m on the EEC, 600–800 m on the Gorzów Terrace, and 700–900 m on the Konin Terrace, to 1400–1800 m in the centre of the MPT, where three depocentres are recognised. Such thickness distribution emphasises the continuity of the Late Permian subsidence with the most complete sedimentation in the MPT (Pokorski, 1998 — Rotliegend; Wagner, 1994, 1998 — Zechsteine). Maximum thickness gradients in the Kuiavian segment approach 100 m/km. In the Pomeranian segment, they are less pronounced and reach 20 m/km. Syn-sedimentary activity of faults is locally noted along the Koszalin–Chojnice Zone (Fig. 9C). It is possible, that a local depocentre, with thickness exceeding 1200 m, existed also on the Konin Terrace. This hypothesis, however, is based on a single cross-section and therefore is less certain.

It is likely, that the Early Triassic salt movements, and the formation of salt pillows, occurred locally in the central Kuiavian region, causing the thickness increase to more than 2000 m (Fig. 2; see also Dadlez, 2001, cross-section 14). Salt displacements may have commenced already during the Middle Bunter, as soon as the thickness of the salt overburden and its lithostatic pressure attained a critical value, capable to mobilise the underlying salts (Dadlez, 2001).

Although the Bunter sequences in grabens were later tectonically disturbed (Fig. 2A), the reconstruction of the total thickness (based on compilation of partial sequences) indicates, that the thickness of graben sediments is similar to the regional values. This indicates, that the grabens were not initiated at that time.

MUSCHELKALK AND KEUPER

Muschelkalk is characterised by carbonate sedimentation with some anhydrites in the entre of the basin. Its boundaries, due to distinctive signature of carbonates, are clearly visible on geophysical logs. Finer sub-divisions include two units: so-called "Marly Beds" in the lowermost part and below the pure carbonates, and equivalents of the "Ceratites Beds" (mainly marls) in the uppermost part, above the pure carbonates. Because the boundaries of these two units (each of them reaching a maximum thickness of 20 m) in geophysical logs are not clear, both units are here excluded from the Muschelkalk and are incorporated into the Bunter and Keuper respectively. The complete stratigraphic section of the Keuper includes the Lower Keuper, Lower Gypsiferous Beds, Schilfsandstein and the Upper Gypsiferous Beds. The last three units comprise Carnian, and together form the Upper Keuper (Gajewska, 1978). These strata are disconformably to unconformably overlain by dominantly shaly sediments of the Norian (Jarkowo and Zbąszynek Beds) and Rhaetian stages. Equivalents of the Norian and Rhaetian stages are here included into the Keuper.

Because the Muschelkalk thickness changes in a regular pattern, increasing from some 100 m in the north to about 250 m in the south, the Muschelkalk and Keuper units are shown together on one map. Thus, thickness changes given in Figure 3 refer mainly to the Keuper.

Contrary to the Bunter and Muschelkalk, the thickness of Keuper is highly variable (Fig. 3). The cause of this is twofold. Firstly, it is related to the non-salt intra-basinal highs, such as the area near the western part of the Baltic coast, where thickness is reduced to 100–250 m, in contrast to 600–800 m in the surrounding terrane (Fig. 3; see also Dadlez, 2001, cross-section 4). Secondly, the initial salt displacements, of a variable character, appear on the most of the MPT. Some of them comprise broader areas, such as east of Bydgoszcz, where a plateau with thickness 150–350 m, hosting later salt pillows, had been developed (Fig. 3). In other cases (e.g. the Kuiavian segment), the thickness changes indicate an immediate local development of salt pillows. Thickness contrasts caused by the salt pillows may be as much as 1000 m. The largest thickness gradients occur at the Kuiavian segment, where they reach more than 100 m/km (Figs. 3, 10B, C and E). Asymmetric shape of the syncline adjacent to the Kłodawa salt diapir (south of Włocławek — Fig. 3; see also Dadlez, 2001, cross-sections 13 and 14), and the maximum Keuper thickness of 2600 m indicate, that this diapir pierced into the basin bottom at that time.

The intense local tectonic movements disturbed the regional picture so much, that the MPT depocentre is visible only at places (northwestern part of the Pomeranian segment, part of the Kuiavian segment south of Płock — Fig. 3). Syn-sedimentary tectonic movements of the Koszalin–Chojnice Zone were as likely as in the Bunter times (Fig. 8A).

South-west of the MPT, the Keuper thicknesses are also considerable, and often greater than in the MPT itself. The Gorzów Terrace is characterised by the values of 700–900 m, and the Konin Terrace by values of 900–1300 m. A local depocentre, with thickness of up to 1400 m, occurs in the southwestern part of the latter. Such thickness distribution, together with the regular thickness increase of the Muschelkalk to the south, is probably caused by a downwarping of the basin bottom towards the Tethys; the first break-ups of the continental crust took place there at that time.

Late Triassic is also the time of foundation of several syn-sedimentary grabens. This is evidenced by local thickness increases. The Klęka Graben (Fig. 3B) contains more than 1200 m of Keuper deposits. The Laska Graben (Fig. 3A), which opens to the south, and where thickness increases to 700 m, cuts across the northern limb of the earlier mentioned peri-Baltic local high.

Stratigraphic analysis of the reduced Keuper sequences above the salt pillows proved, that salt movements began in the lower part of the Middle Keuper, and culminated before the Norian. It is reflected by the discordant contact (recorded also in seismic sections) between the latter and various members of the Keuper or even the Muschelkalk (Figs. 9F and 10C). The same also applies to the non-salt high near the Baltic coast. This unconformity proves that significant tectonic impulses occurred in the latest Triassic. The start of the graben formation was probably coeval with those events.

LOWER JURASSIC

In the MPT, the boundary between the Rhaetian and the Hettangian stages runs across the non-marine sediments with very poor biostratigraphic control, based mainly on palynomorphs. The Rhaetian species occur in mixed clastic (sand and shale) sediments within the MPT, and in the thin package of clayey strata along its southwestern surroundings. The lithostratigraphic boundary between the Triassic shales and the sandstone dominated Lower Jurassic series is easy to determine on geophysical logs. This boundary, accepted for the MPT, differs from the true Triassic/Jurassic boundary, which may be located as much as 100 m higher in the sequence. South of the MPT, the lithostratigraphic contact coincides with the chronostratigraphic boundary.

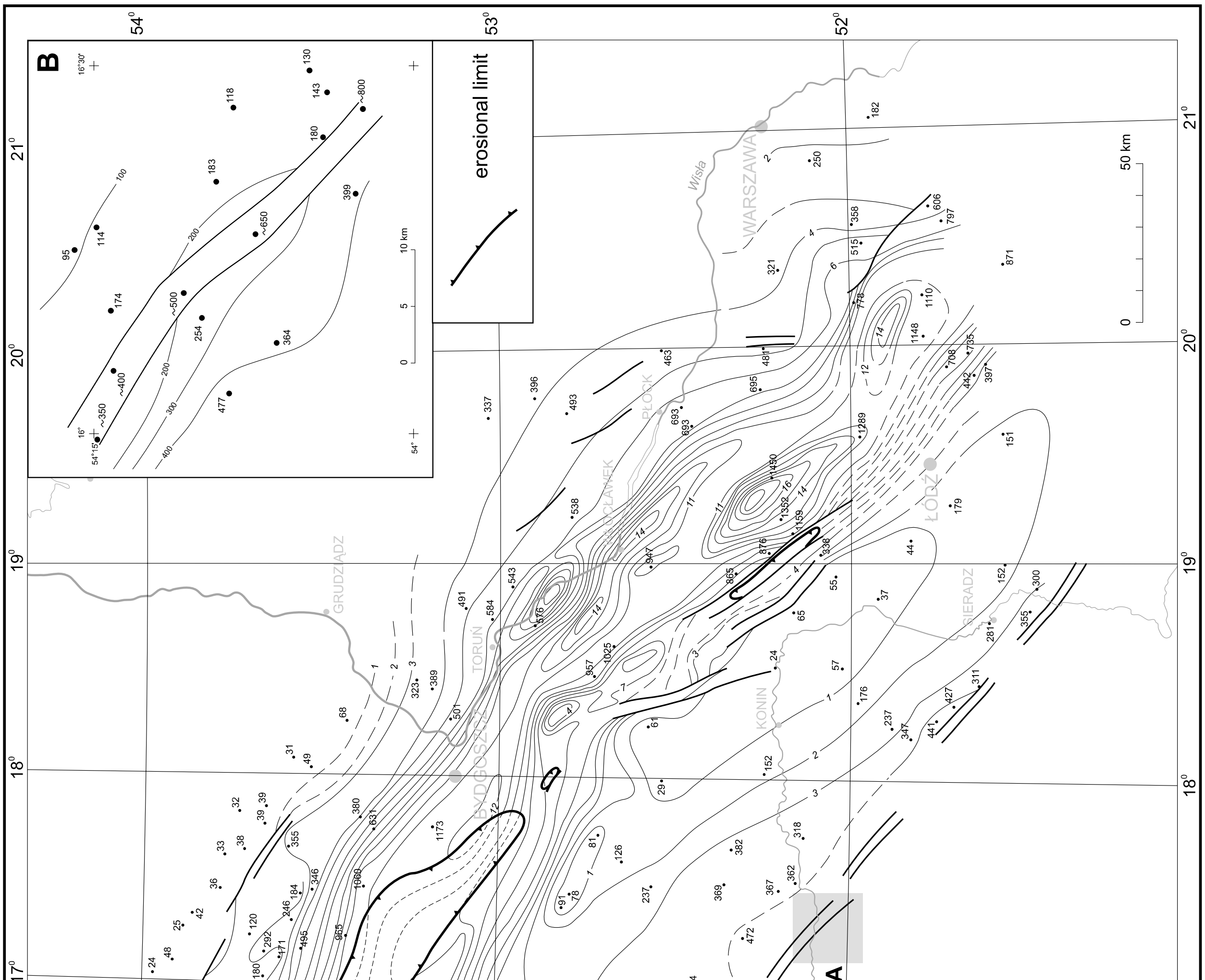

Fig. 4. Lower Jurassic thickness

A — thickness in the Klęka Graben; B — thickness in the Koszalin Graben; other explanations as in Figure 2

The Lower Jurassic section is dominated by non-marine deposits. In the western part of Poland, a marine transgression proceeded eastward from the German Basin in the early Pliensbachian, followed by smaller brackish transgression in the early Toarcian. These events were recorded in several lithostratigraphic units. Such a sub-division in the central part of the MPT is rather doubtful because of largely limnic origin of the sediments.

At the start of the Early Jurassic, the became again as distinct as in the Early Triassic (Fig. 4). From the north-east, in the Pomeranian segment, the MPT was bordered by the Koszalin–Chojnice Zone, which displayed syn-sedimentary activity. At its northeastern side, the Lower Jurassic sections are reduced to less than 50 m, (Fig. 8A), and are composed of sandstones deposited during the earliest Jurassic. An exception is the area near the Baltic coast where the succession is more complete (Fig. 8B and C). A syn-sedimentary graben (Fig. 4B), with a sedimentary sequence 2–3 times thicker compared to its surroundings, exists in the Koszalin–Chojnice Zone. A notable thickness increase towards the MTP axis occurs south-west of the Koszalin–Chojnice Zone. It is more gradual near the Baltic coast (300–900 m; gradient about 20 m/km — Figs. 4 and 8E), and more rapid further south-east (200–1000 m), where the gradient reaches 40 m/km (Figs. 4 and 9E). In the Kuiavian segment, the thickness increase across the EEC slope is more gradual, and ranges from 300–600 m. In all cases the sequence is complete. The gradients on the Szczecin Slope are comparable to the latter or greater (Fig. 8F).

The Lower Jurassic succession on the Gorzów Terrace differs from that on the Konin Terrace. Within the former the sequence is complete, varying from 300–400 m. On the Konin Terrace an intra-basinal high (Wielkopolska Ridge of Dadlez and Franczyk, 1976; see also Dadlez 2001, cross-section 13), with thickness of less than 100 m was developed, and the sequence lacks the upper part because the Upper Liassic strata were eroded during the earliest Middle Jurassic. This high adjoins directly the MPT. Thickness contrast here is significant and may approach 70 m/km, probably resulting from the synsedimentary faulting. At the opposite side of this high, thickness increases gradually to about 400 m. The sedimentation here is complicated by the continued activity of the Kłęka Graben (Fig. 4A), where thickness attains 500–600 m.

Between both these border areas, in the MPT, two depocentres were developed. In the Pomeranian segment, the reconstructed thickness exceeds 1100 m, and in the Kuiavian segment the observed thickness amounts to at least 1400 m. In the latter area, the continuation of the salt pillows growth, accompanying the regional subsidence of the MPT, is recorded. (Fig. 10B — Ciechocinek). Thickness gradients on the slopes of salt pillows attain values of 100 m/km, similar to the gradients during the earlier Late Triassic.

MIDDLE JURASSIC

The largest discrepancy between the chronostratigraphic, and adopted in this report lithostratigraphic boundaries occurs at the contact between the Lower and Middle Jurassic. The Middle Jurassic is characterised by a major eustatic transgression, which firstly encroached upon the Kuiavian part of the MPT. On the geophysical logs, a distinctive signature of this event coincides with the base of the Upper Aalenian shales. The Lower Aalenian(?) beds form marginal deposits preceding the main transgression, but their age is uncertain as they do not host any index fossils. Further north-west along the MPT, the transgression came later. Near the Baltic coast it occurred at the beginning of the Late Bajocian (Strenoceras Beds). Lithostratigraphically — like in the Kuiavian segment — this boundary is marked by a sharp contact between the shales and the underlying sandstones. The latter strata, although lacking any biostratigraphic evidence, are considered as an equivalent of the Lower Bajocian and Aalenian. If such assumption is correct, the difference between this interpretation and the here accepted lithostratigraphic boundary may be as much as a few hundreds metres. In the marginal parts of the MPT, the Middle Jurassic transgression appeared even later, in the latest Bajocian or at the beginning of the Bathonian. The lithostratigraphic base of marine shales remains here as distinct as in the previous areas. Contrary to the other areas, however, the stratigraphic gap probably existing here, and including the earlier periods of Middle Jurassic, resulted in negligible difference between the chrono- and lithostratigraphic boundary. As the stages of the Middle Jurassic succession are relatively well defined by ammonites, this dominantly shaly sequence is not divided into lithostratigraphic units.

During the Middle Jurassic, the MPT still formed a distinct feature. To the north-east its boundary is defined by the 200 m isopach in the Pomeranian segment, and by the 300–500 m isopachs in the Kuiavian segment (Fig. 5). On the opposite side, the boundary is marked roughly by the 200–300 m isopachs. Farther south-west, at the Gorzów Terrace, thinner, less than 100 m thick sequences are observed. On the Konin Terrace, the intra-basinal Wielkopolska Ridge, also has thickness of less than 100 m. The reduction of thickness in these two areas partly results from the fact that the Middle Jurassic sequence begins here with Bathonian (locally only with the uppermost Bajocian Parkinsoni Beds). Thus, the stratigraphic gap comprises at least the Aalenian and much of the Bajocian.

In the MPT two depocentres existed as before (Fig. 5): at the boundary of the Pomeranian and Kuiavian segments (thickness of more than 900 m), and in the Kuiavian segment (thickness exceeding 1000 m). A south-east shift of the maximum subsidence is accentuated. Thickness gradients across the slopes of the MPT are smaller than in case of Lower Jurassic and amount to maximum of 50 m/km (Figs. 8A, B, D and 10A and D).

Some activity, although considerably weaker is noted in the earlier formed grabens (Fig. 5A). Elsewhere it ceased (e.g. Kłęka Graben). New grabens and half-grabens were formed (Fig. 5B and C). Salt displacements stopped at a regional scale, but mild, short-period movements could still occur (Dadlez, 2002).

UPPER JURASSIC

In the Kuiavian part and the adjacent areas, transition from the Middle to Upper Jurassic is characterised by change from siliciclastic to carbonate sedimentation. A condensed bed (so called Nodular Bed) forms a significant horizon in the Upper Callovian–lowermost Oxfordian strata in this area. This horizon is easily recognisable on the geophysical logs. In the Pomeranian area, the transition between the Middle and Upper Jurassic is lo-

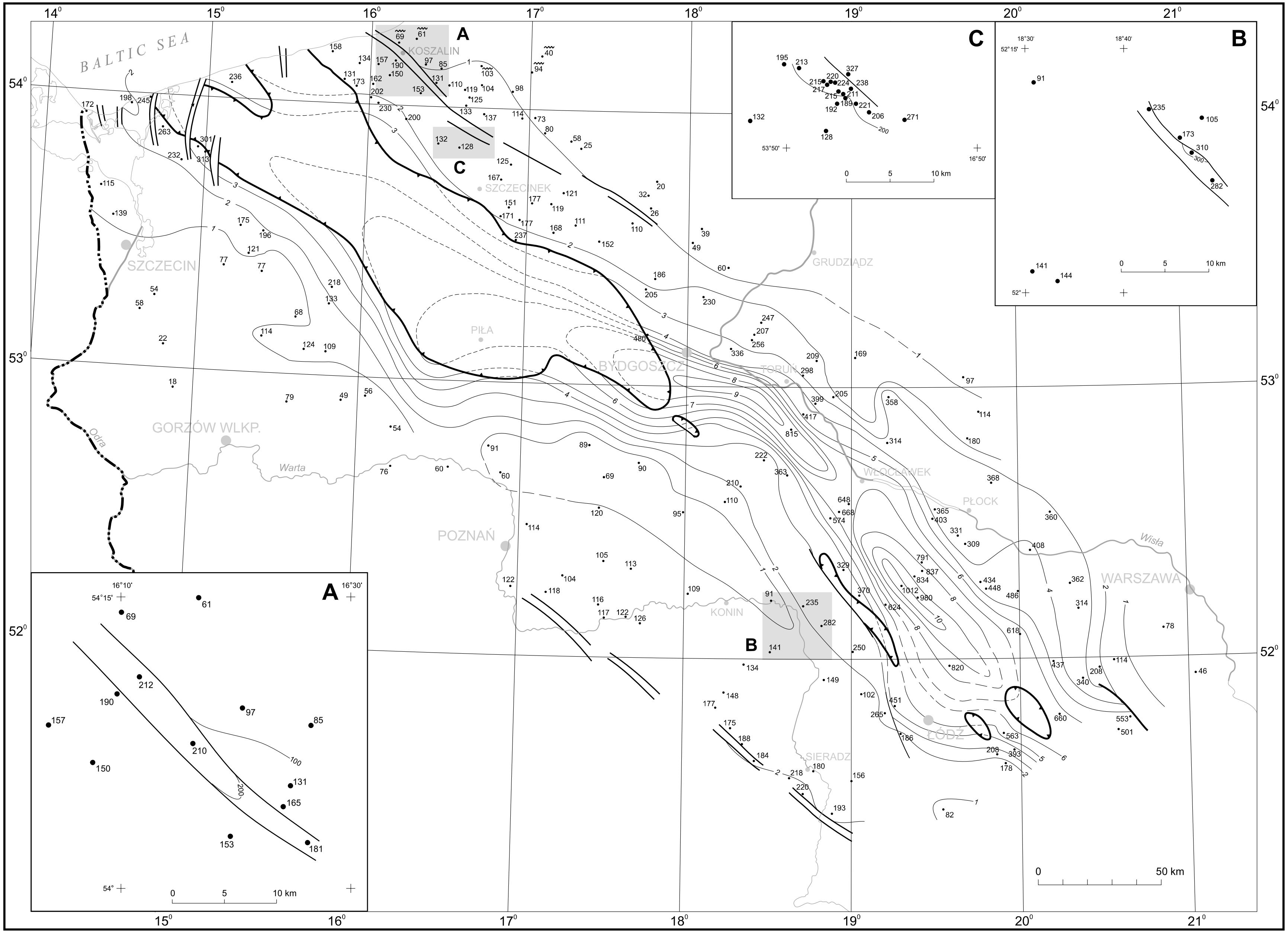

Fig. 5. Middle Jurassic thickness

A — thickness in the Koszalin Graben; B — thickness in the Wierzchowo Anticline; C — thickness in the Brda Graben; other explanations as in Figures 2 and 4

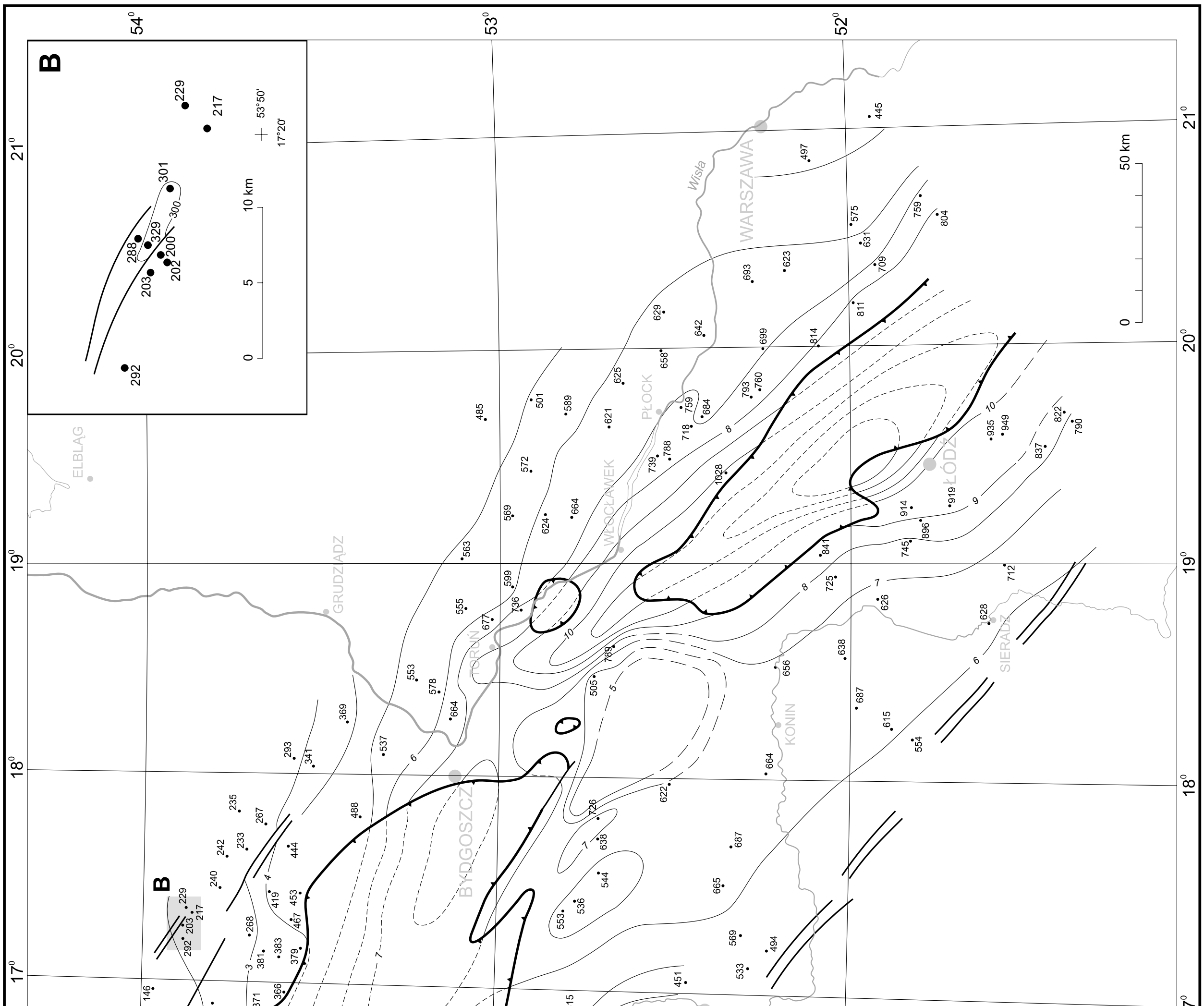

Fig. 6. Upper Jurassic thickness

A — thickness in the Wierzchowo Anticline; B — thickness in the Brda Graben; other explanations as in Figures 2 and 4

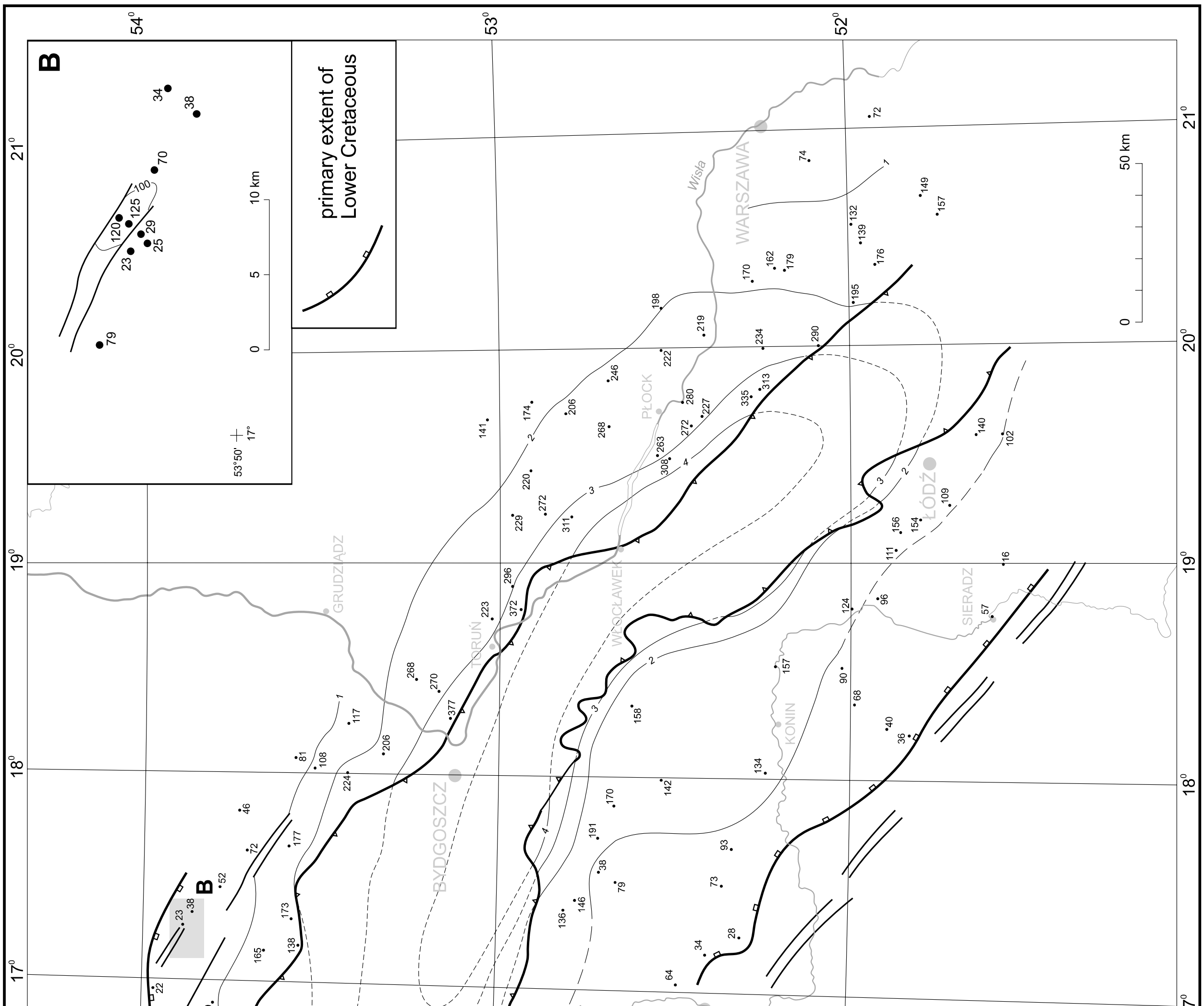

Fig. 7. Lower Cretaceous thickness

A — thickness in the Wierzchowo Anticline; B — thickness in the Brda Graben; other explanations as in Figure 2

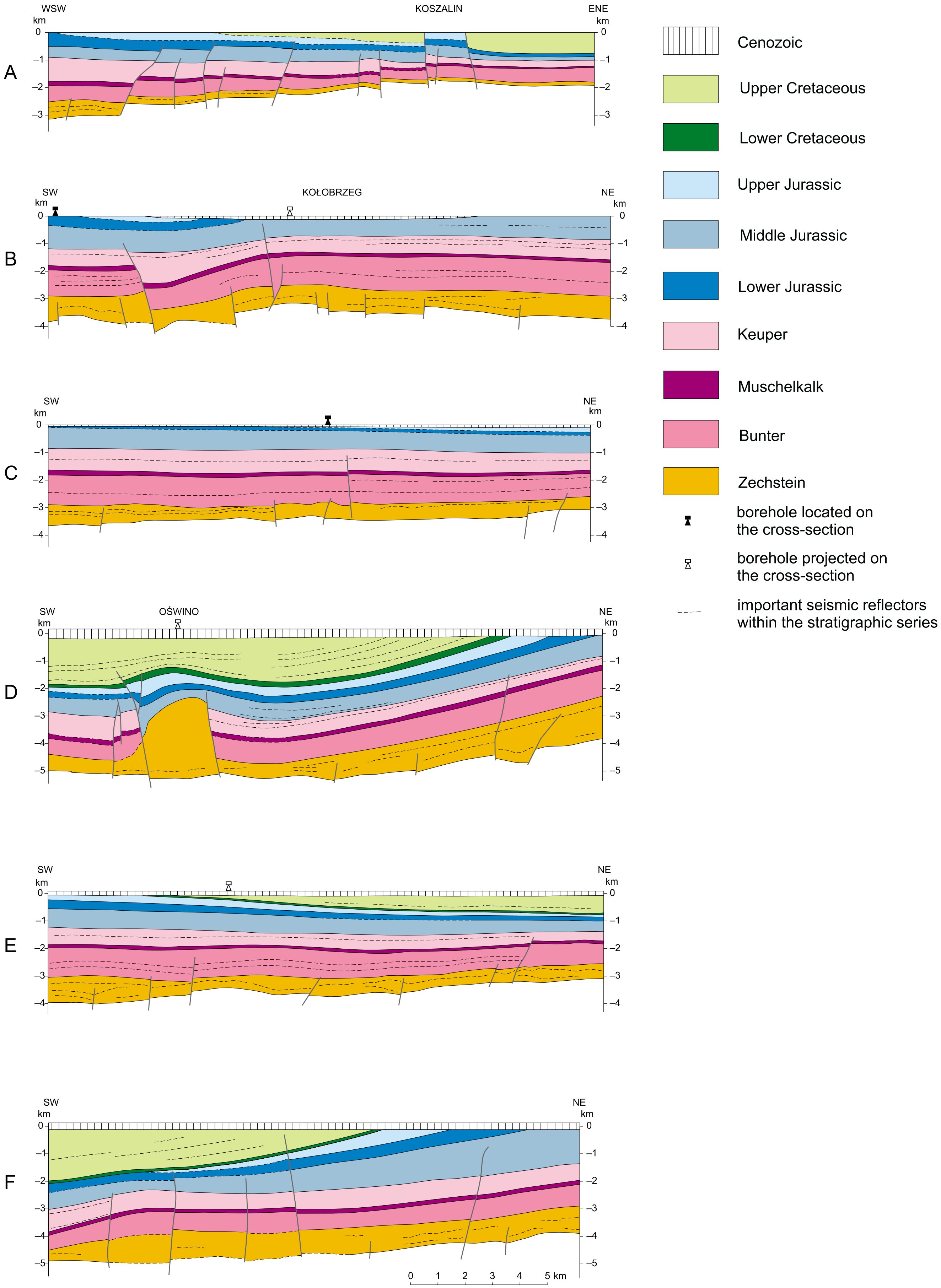

Fig. 8. Cross-sections, Pomeranian segment of the MPT, northwestern part

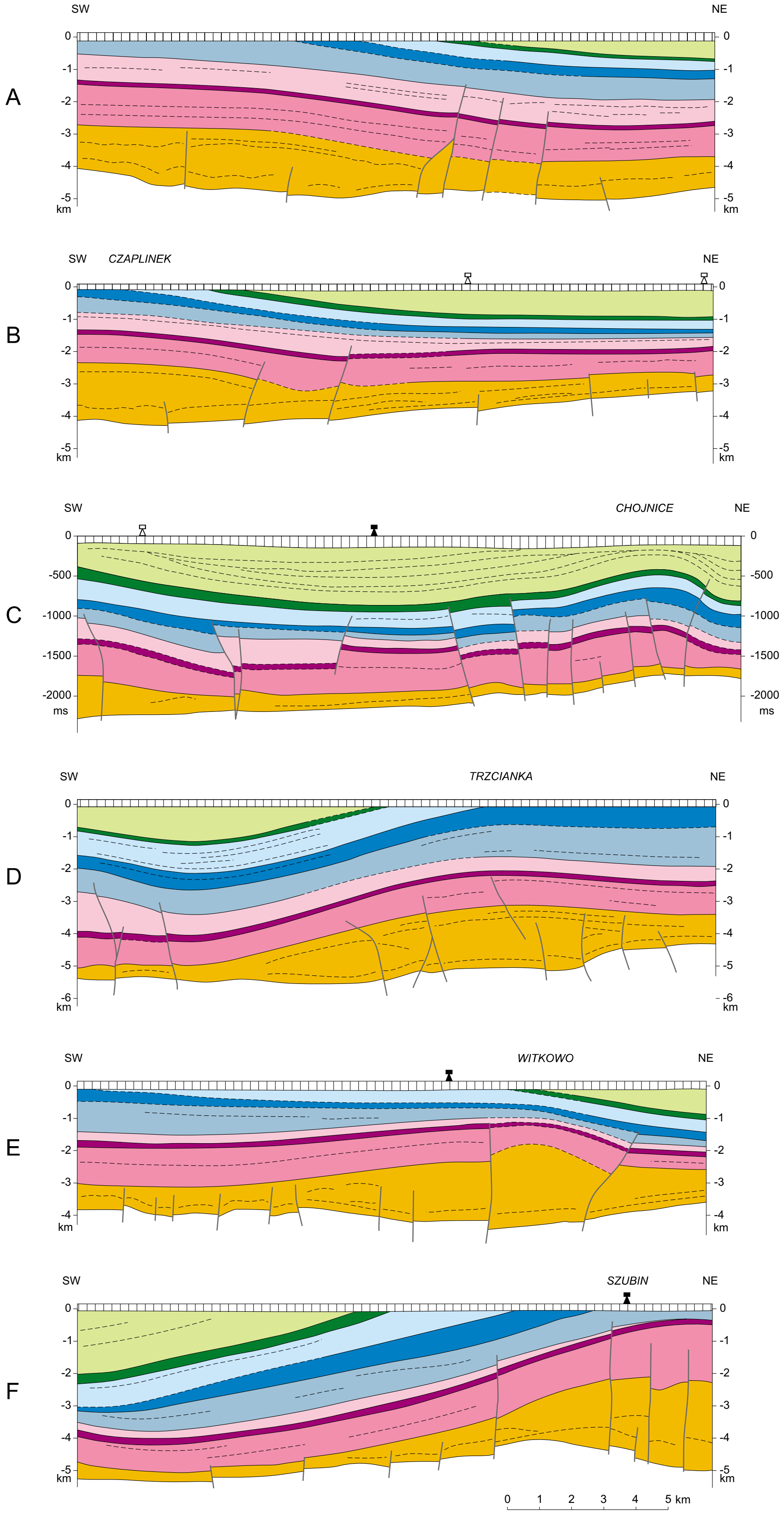

Fig. 9. Cross-sections, Pomeranian segment of the MPT, southeastern part

Explanations as in Figure 8

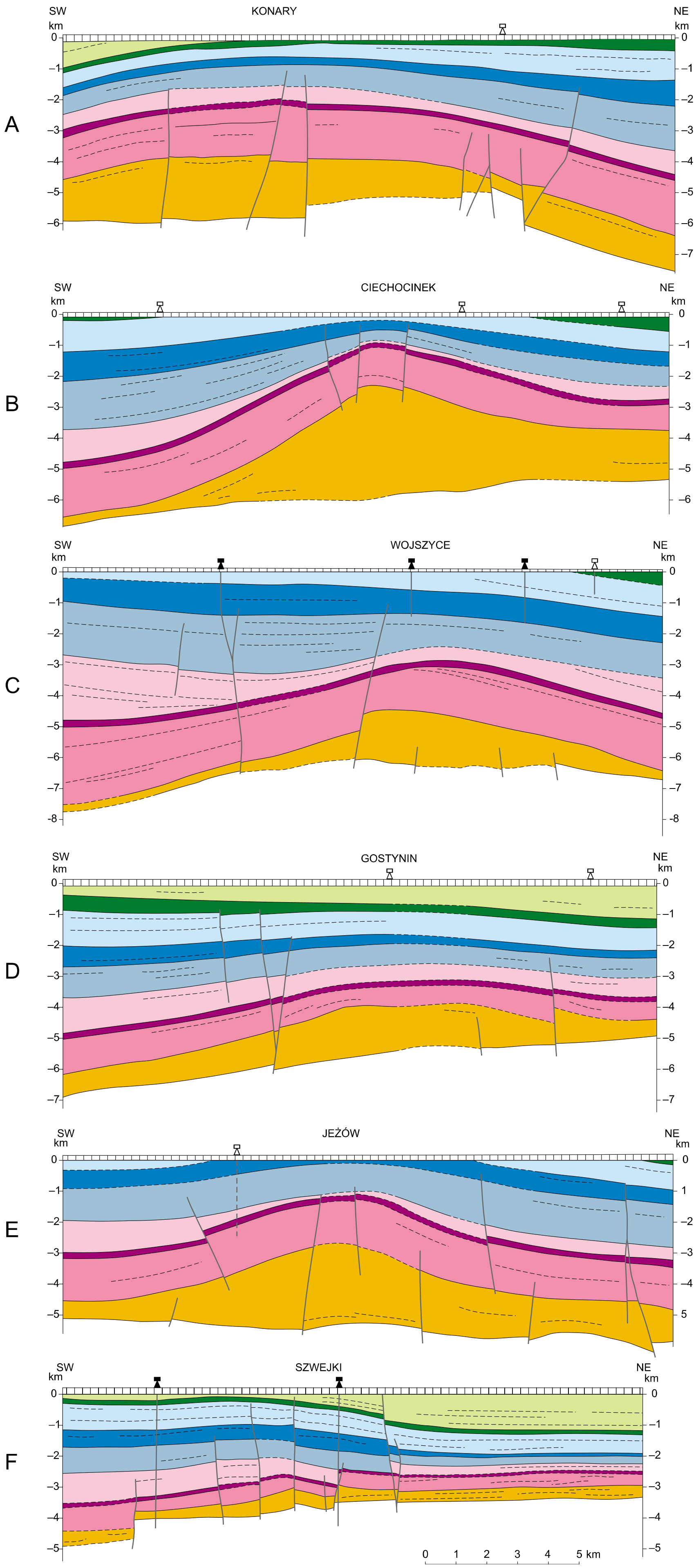

Fig. 10. Cross-sections, Kuiavian segment of the MPT

Explanations as in Figure 8

cated in the clastic deposits, and is identified by the shale package yielding the Upper Callovian ammonites. Its top is no more than a few metres away from the chronostratigraphic boundary.

The presence of MPT is well reflected in the thickness distribution (Fig. 6), but the thickness gradients are usually smaller than in the earlier periods (maximum 25 m/km — Figs. 9A, B and 10D). Stronger gradients are rare (Fig. 10A). Two depocentres — one in the southeastern part of the Pomeranian segment (thickness >800 m), and the other in the Kuiavian segment (reconstructed thickness >1300 m) — are clearly visible. Along the EEC slope the thickness increases gradually and obliquely to its strike, from about 100 m in the peri-Baltic area, to nearly 700 m in the Kuiavian segment. Reduced thickness on the Gorzów Terrace (<100 m in majority of the area) is due to the pre-Early Cretaceous or the earliest Cretaceous erosion. On the contrary, the complete sequence on the Konin Terrace is 600–800 m thick. Observed local differentiation south of Bydgoszcz (Fig. 6 — thickness reduction to <500 m) is not certain and may simply result from the paucity of data. A new generation of syn-sedimentary grabens continued to develop (Figure 6A and B). A system of coeval grabens located north of Warsaw on the EEC is not shown, because it lies beyond the limits of the map. No traces of salt movements were recorded.

LOWER CRETACEOUS

The lithostratigrapic boundary between the Jurassic and Cretaceous is easy to recognise. It is marked by the contrast between marls, limestones and evaporites of the uppermost Jurassic, and siliciclastics (sandstones and shales) of the Lower Cretaceous. Recent investigations proved, that the biostratigraphic boundary between the Upper Jurassic and Lower Cretaceous is located several metres below the lithostratigraphic boundary.

The Early Cretaceous coincided with the maximum reduction of sedimentation and subsidence rates. They are of an order smaller than, for example, during the Bunter period (10 m/my versus 125 m/my — see also the subsidence analysis in Dadlez *et al*., 1995). This difference may be even greater considering the compaction of the Bunter shales in the centre of the MPT. Small thickness gradients occur on both sides of the MPT (Figs. 7, 8E, F, 9D and 10D). They are similar to the Upper Jurassic ones and average 15 m/km. A division of the MPT into two segments is no longer observed. The maximum reconstructed thickness is over 400 m. Like during the Late Jurassic, an increase in thickness along the northeastern border is observed. It rises from 20–200 m in the Pomeranian segment to 200–300 m in the Kuiavian segment. Thicknesses on the Gorzów Terrace are also smaller (>100 m) than on the Konin Terrace (maximum 200 m). This difference is caused by the fact that the Gorzów Terrace section begins with the Hauterivian, and the reduction in thickness at least partly results from the stratigraphic gap, while the Konin Terrace section is more complete. Syn-sedimentary grabens (Fig. 7B) and local depocentres connected with them (Fig. 7A) are active as before.

UPPER CRETACEOUS

A distinct lithostratigraphic marker, accepted here as the Lower/Upper Cretaceous boundary, runs at the base of a conspicuous gamma ray anomaly caused by the occurrence of an increased potassium in glauconites and phosphorites of the Upper Albian trangressive beds. The chronostratigraphic Lower/Upper Cretaceous boundary is located a few metres higher.

A map of the Upper Cretaceous thickness has not been prepared because of difficulties specified in the next chapter (point 7).

DISCUSSION AND CONCLUSIONS

1. The Mid-Polish Trough is well recorded in the thickness pattern of the Mesozoic stratigraphic columns. It was most distinct in the Early Triassic and in the Early to Middle Jurassic, when the thickness gradients on its slopes attained 100 m/km. During the Late Jurassic and Early Cretaceous the gradients were smaller, reaching a maximum of 20 m/km. In the Late Triassic, the thickness distribution was more complex, because it was disturbed during the first stage of strong Zechstein salt displacements. Thicknesses of all the Mesozoic series decrease along the MPT both, to the north-west and south-east from its central Kuiavian part. In general, the MPT is shaped like a bottom of a boat, which rises steeply towards its sides, and more gently towards its bow and stern. However, this boat is wrecked because it is broken in its midst (see point 4 below).

2. The idea of the Mid-Polish “Rift” (Kutek, 1997) has not been confirmed, because no regional faults bordering the MPT and active throughout its development have been recognised. The exceptions are the Koszalin–Chojnice Zone (Fig. 8C) and the area of Szwejki (Fig. 10F), where the activity of such faults during the Late Triassic and Early and Middle Jurassic was likely. The fault near Szwejki is a northwestern-most extension of the Nowe Miasto–Iłża fault bordering the Holy Cross Mountains segment of the MPT from the north-east (Hakenberg and Świdrowska, 1997). Elsewhere, the syn-sedimentary faults may have acted at shorter distances and in some periods only. The boundaries of the MPT are distinctly defined by the increased thickness gradients mentioned above. They are probably caused by the activity of deep-seated, sub-Zechstein faults, which did not propagate upwards into the Mesozoic. This interpretation is best explained by the model of a decoupled basin (Krzywiec, 2002*a*), where Zechstein salt acted as a plastic lubricant precluding the transmission of brittle deformations into the overlying post-Zechstein strata. This process has been known in German literature (F. Kockel, pers. comm.) and called there Puffertektonik (buffer tectonics). The exception is the marginal part of the trough (e.g. the Koszalin–Chojnice Zone), where the salts were not thick enough to be mobilised.

3. On the contrary, local syn-sedimentary grabens and half-grabens are common features of the MPT and its surroundings (see also Dadlez, 2001). They started to form in the Late Triassic, and continued to develop in the Early Jurassic. A second generation of grabens developed in the Middle-Late Jurassic and Early Cretaceous. The grabens are probably rooted in single sub-Zechstein faults.

4. The longitudinal division of the MPT into several segments was described earlier by Dadlez (1994, 1997), but without considering the thickness pattern. It is now confirmed by the thickness distribution shown on the maps. A longitudinal division into at least two distinctive parts was observed in the

MPT and its surroundings. This division includes the Pomeranian segment and the Kuiavian segment of the MPT; the Pomeranian Slope and the Płock Slope north-east of the MPT along the EEC edge; and the Gorzów Terace and the Konin Terrace along the southwestern border of the MPT. The following arguments support such a division:

a) Two separate depocentres were active from the Early Triassic to the Late Jurassic within the MPT. Both segments of the MPT are asymmetric, but in a reverse sense. Asymmetry is again best expressed during the Early and Middle Jurassic. The northeastern boundary of the Pomeranian segment is steeper than the southwestern one. Conversely, the southwestern boundary of the Kuiavian segment is steeper than the northeastern boundary.

b) Along the northeastern slope of the MPT, a NW–SE thickness increase from the Kuiavian to the Pomeranian segment is observed, beginning in the Late Triassic, and best pronounced during the Jurasssic and Early Cretaceous.

c) On the opposite side of the MPT, the Jurassic sedimentation and subsidence on both terraces differed significantly. While on the Gorzów Terace the Early Jurassic sedimentation was continuous, on the Konin Terrace thickness was strongly stratigraphically reduced due to delay in commencement of the Lower Jurassic sedimentation and the pre-Middle Jurassic erosion, which removed part of the Lower Jurassic sequence. Consequently two stages of uplift can be identified. During the Middle Jurassic, the evolution of both terraces was similar. At the end of the Late Jurassic, the Gorzów Terace experienced a marked uplift, causing the erosion of the upper part of the sequence. In the Early Cretaceous, sedimentation rate on the Gorzów Terace was small compared to the Konin Terrace.

d) After the inversion, the division of the MPS was expressed by the eastward shift of the Kuiavian segment against the Pomeranian segment. This was accompanied by a similar shift of the salt diapirs adjoining the MPS from the south-west (Fig. 1).

5. Subordinate segmentation of the MPT can also be proposed. For example, the peri-Baltic part of the Pomeranian segment can be distinguished by:

a) existence of two embayments with increased thickness from the Early Triassic to the Early Jurasic;

b) lack of salt tectonics except for local peri-fault injections;

c) maximum uplift of the Zechstein basement;

d) bifurcation into two anticlines (Kamień and Kołobrzeg).

Similarly, the southeastern part of the Kuiavian segment (south of the Kłodawa diapir) may also represent a separate unit.

6. It is likely, that this segmentation reflects the structure of the Permian–Mesozoic basement, containing a system of dextral strike-slip faults formed during the Late Variscan events. This system was rejuvenated in Permian and Mesozoic in a dip-slip regime (Dadlez, 1994). It is also possible, that it is even deeper system, reaching the crystalline crust (Dadlez, 2000). Thus, the differentiation of Mesozoic sedimentation and tectonics could be a mild reflection of the earlier events.

7. The scale of inversion, which transformed the MPT into the MPS, is the key unresolved problem for the estimation of subsidence.

The maximum Upper Cretaceous thickness in the synclines directly adjoining the MPS to the south-west exceeds 2000 m. The thickness to the north-east ranges from 800 to more than 1000 m. Interpretation of the primary thickness in the eroded parts of the MPS depends on the assumption of timing of the commencement of inversion. If the inversion began at the end of the Late Cretaceous (*fide* Świdrowska and Hakenberg, 1999*a*), then the subsidence should continue during this period, and the thickness in the MPT could reach at least average thicknesses of that on both sides of the present MPS. It could be even greater than on its southwestern side. However, if the inversion started earlier, before the Coniacian, the thickness along the present MPS should be smaller. Leszczyński (1998, map 71) showed an extreme interpretation, proposing the minimum thickness in the MPS of less than 200 m.

Three arguments speak in favour of the latter concept:

a) The pre-Coniacian uplift of the local anticlines in the troughs adjoining the MPS is noted above the salt diapirs towards south-west (Leszczyński, 2002), and within the anticlines of the Koszalin–Chojnice Zone towards north-east (Jaskowiak-Schoeneich, 1976). The uplift is also recorded in some seismic sections (Fig. 9C). It is most likely that the regional unit (MPS), lying between those local structures, experienced the coeval uplift. Seismic data along the MPS limbs are not decisive in this respect, particularly on the deeply eroded southwestern limb. Some sections in the northeastern limb suggest an intra-Upper Cretaceous unconformity (Krzywiec, 2002*b*; see also Fig. 9C). Leszczyński (2002) pointed out also to the reversal of proportions between the pre-Coniacian and post-Turonian thickness on both sides of the MPS arguing, that it is an evidence for the incipient inversion.

b) The indirect thickness estimates of eroded Upper Cretaceous sediments, based on the analysis of compaction of the Bunter shales (Dadlez *et al.*, 1997), have indicated smaller values on the MPS, except for the Kołobrzeg Anticline. The same data suggest the renewed mobility of salt pillows in the Pomeranian segment of the MPS. Clastic input from the uplifting Kłodawa diapir is argued by Leszczyński (2000).

c) The postulated pre-Coniacian tectonic movements are in agreement with the timing of the initial inversion in the neighbouring basins (Danish Basin — Liboriussen *et al.*, 1987; Lower Saxony Basin — Baldschuhn *et al.*, 1991; Kockel, in press).

Further work aimed at the reconstruction of the Upper Cretaceous sediment thickness removed by erosion needs more borehole information and application of modern research methods such as investigations of vitrinite reflectance and apatite fission tracks. Only a small number of available deep boreholes, particularly in the Kuiavian segment, is suitable for such research. Three possible scenarios should be considered during this work:

— smaller thickness in the MTP area comparing with its surroundings,

— larger thickness in the MTP area comparing with its surroundings,

— similar thickness in the MTP area and its surroundings.

A renewed mobility of salt pillows and diapirs also has to be taken into account. It can be done by application of a computer program containing various models of the volume of eroded deposits considering both, the regional and the local scale (inversion of the MPT accompanied by growth of salt structures).

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