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Palaeotectonic cross-sections through the Mid-Polish Trough

Ryszard WAGNER, Krzysztof LESZCZYŃSKI, Jędrzej POKORSKI and Krzysztof GUMULAK

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The Late Permian and Mesozoic evolution of the Mid-Polish Trough is analysed using a set of palaeotectonic cross-sections which are constrained by regional integrated depth-converted reflection seismic profiles. Results support the concept that the central and NW part of the Mid-Polish Trough can be subdivided into a Pomeranian and a Kuiavian segment. The Pomeranian segment is characterised by lower subsidence and a shallower depth to the base of the Zechstein (3500–4000 m) as compared with the Kuiavian segment. The Pomeranian basin was characterised by a nearly symmetrical structure and a single depocentre. In Kujawy, the basin displays a more complex structure with several local depocentres. In the Pomeranian segment, salt structures are poorly developed (salt pillows). These formed relatively late: during the latest Cretaceous and Early Paleocene. In the Kuiavian segment, salt structures include also salt diapirs which began to form at the end of the Muschelkalk, and were active later throughout Mesozoic times, as evidenced by lateral facies and thickness changes. During end Cretaceous and Paleocene basin inversion, the base of the Zechstein was uplifted by 3000–4000 m in the Kuiavian segment and by 2000–3000 m in the Pomeranian segment. The transition zone between the Pomeranian and Kuiavian segments, located in the area between Piła and Toruń, displays mixed features in its structure and geological evolution. Subsidence of the Mid-Polish Trough was controlled by multiple extensional pulses during which pre-existing crustal-scale faults were reactivated. Similarly, inversion of the Mid-Polish Trough involved reactivation of crustal faults. Segmentation of the Mid-Polish Trough can be related to factors including differences in its basement composition.

Ryszard Wagner, Krzysztof Leszczyński, Jędrzej Pokorski and Krzysztof Gumulak, Polish Geological Institute, Rakowiecka 4, PL-00-975 Warszawa, Poland; e-mail: rwag@pgi.waw.pl, kles@pgi.waw.pl, jpok@pgi.waw.pl *(received: March 6, 2002; accepted: June 26, 2002).*

Key words: Mid-Polish Trough, Zechstein-Mesozoic sedimentary cover, subsidence, salt structures, Late Cretaceous inversion.

INTRODUCTION

Palaeotectonic cross-sections were constructed by teams from the University of Mining and Metallurgy, Polish Geological Institute and Polish Oil and Gas Company within the framework of a regional research project that addressed the hydrocarbon potential of the Zechstein Main Dolomite. For the purpose of this project 13 palaeotectonic cross-sections were constructed on the basis of integrated and reprocessed, depth-converted reflection-seismic profiles, which were geophysically and geologically interpreted by specialist teams of Geofizyka Toruń, the Geological Bureau Geonafta and the Polish Geological Institute. These cross-sections run perpendicular to the axis of the Mid-Polish Trough i.e. across the central part of the Permian basin. They are spaced at 20–70 km intervals and provide a three-dimensional image of the geological structure of the Mid-Polish Trough (Fig. 1).

The seismic profiles were interpreted only down to the base of Zechstein, as sub-Zechstein reflections are recognisable only on some of them. Reconstruction of the evolution of almost all of the Permian-Mesozoic succession, except for the initial phase during deposition of the Upper Rotliegend, was possible owing to the interpretation of seismic images down to the base of the Zechstein. The initial phase is shown in Figure 2.

The essential aim of this report is the subsidence analysis of the Pomeranian and Kuiavian segments of the Mid-Polish Trough during Permian and Mesozoic times. The analysis was performed for several major phases of basin evolution and includes a reconstruction of the original thicknesses of Zechstein and Mesozoic deposits along the regional seismic profiles. It should be noted that these thicknesses have not been corrected for compaction and thus the results are approximate.

Only the central parts of 5 palaeotectonic cross-sections were selected for publication (Fig. 1). Of these, 2 cross-sections are typical of the Pomeranian segment of the Mid-Polish Trough (Figs. 3 and 4), 1 cross-section is situated in the transition zone between these two segments (Fig. 5) and 2 represent

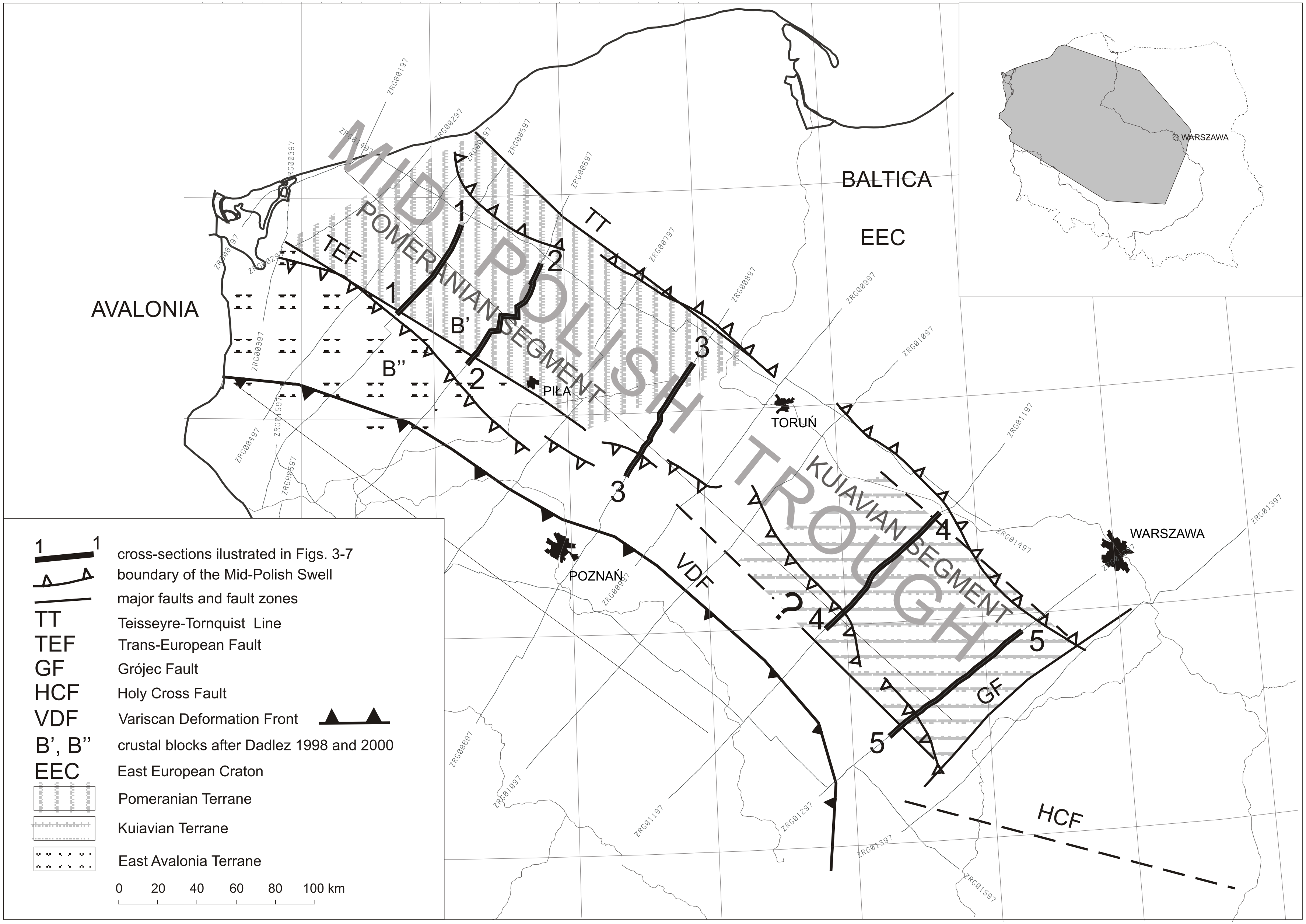


Fig 1. Tectonic sketch with location of cross-sections (after Dadlez, 1998, 2000, 2001 and Guterch *et al*., 1999, modified)

the Kuiavian segment (Figs. 6 and 7). Due to the considerable length of the cross-sections analysed, Figures 3–7 illustrate only their central portions, covering the area of the Mid-Polish Trough that is characterised by the most intense salt movements and the greatest degree of basin inversion. The palaeotectonic evolution is therefore not presented against a broader regional background.

The cross-sections are given at the same vertical and horizontal scale so that structural features and stratal dips are maintained.

Two papers, providing sets of geological cross-sections across the Mid-Polish Trough, have recently been published. The first one shows 19 regional cross-sections crossing the entire Mid-Polish Trough and neighbouring areas (Dadlez, 2001). The second one shows 10 cross-sections with a seismic image background, through the Kuiavian segment of the Mid-Polish Trough (Dziewińska *et al*., 2001). Some of these geological cross-sections coincide with the palaeotectonic cross-sections presented in this paper. The terminology for salt structures was adopted from Dadlez (2001).

PALAEOTECTONIC EVOLUTION OF THE MID-POLISH TROUGH

Evolution of the Mid-Polish Trough, which is superimposed on the southwestern edge of the East European Craton and the northeastern boundary of the Variscides, began during the late Early Permian with the deposition of the Upper Rotliegend series. At that time it formed a 700 km-long, narrow, and periodically strongly subsiding, sedimentary basin. Its development was preceded by a widespread uplift that commenced during the latest Carboniferous and culminated during the Early Permian, as manifested by the gradual reduction of the area of sedimentation (Wagner, 1994). The gradual contraction of sedimentary basins and the change in sedimentary regime from marine to continental started in the late Namurian and successively intensified during the Westphalian. During Stephanian and earliest Rotliegend time, continental sedimentation was restricted to small, isolated intra-montane and foreland basins displaying the characteristics of grabens and half-grabens (Wojewoda and Mastalerz, 1989; Kiersnowski, 1991; Pokorski, 1997). Widespread uplift of the area which subsequently evolved into the Permian basin was accompanied by intense magmatic activity and the deposition of thick effusive rocks, mainly along the western margin of the future Mid-Polish Trough (Fig. 2A). This magmatic activity resulted in a weakening and thinning of the crust and mantle-lithosphere (Dadlez *et al*., 1998; Van Wees *et al*., 2000). Between the Early Permian and the initial phase of the formation of the Mid-Polish Trough (Late Permian) there was probably a sedimentary gap spanning several to around 10 My.

During the deposition of the Upper Rotliegend (Drawa Subgroup) an initially asymmetric sedimentary basin appeared between the Variscan deformation front and the Teisseyre-Tornquist zone (T-T) (Pokorski, 1997, 1998*b*; Dadlez *et al*., 1998). This basin (Fig. 2B) occupied the Pomeranian segment of the Mid-Polish Trough and terminated to the south-east in the transition zone towards the Kuiavian segment. The development of the Mid-Polish Trough commenced in its axial zone with the deposition of the Drawa Subgroup. The trough showed maximum subsidence rates during the Late Permian-Early Triassic (Wagner, 1994; Pokorski, 1997). Following this initial phase, the basin began to expand progressively. During deposition of the Noteć Subgroup (upper part of the Upper Rotliegend) the basin widened considerably and sedimentation gradually overstepped flanking areas, with the Variscan Platform showing evidence for strong downwarp (Fig. 2C). However, the axial trough still remained the zone of maximum subsidence with sedimentation being dominated by sandstones, mudstones and claystones. The basin also expanded towards the north-east, but Noteć Subgroup deposits overstepped the margin of the Precambrian Platform only in northern Poland and around Warszawa. Moreover, small, local basins developed in shallow topographic lows on this platform (Pokorski, 1997, 1998*b*). Similar tendencies are also evident regarding later phases of the basin evolution. During the Zechstein (Fig. 2D) and the deposition of the Lower and Middle Buntsandstein the basin gradually widened whilst the Mid-Polish Trough depocentre subsided rapidly with sedimentation keeping in pace with subsidence. During the first phase of evolution of the Mid-Polish Trough, i.e. during 25 My years, up to 4000 m of Upper Rotliegend, Zechstein and Lower and Middle Buntsandstein deposits (50% of the entire Permian and Mesozoic cover) accumulated in its axial parts. Sedimentation of the remaining 4000 m of Mesozoic deposits lasted almost 160 My years (Wagner, 1994; Dadlez *et al*. ed., 1998).

The development of the Mid-Polish Trough was most probably controlled by a combination of thermal subsidence and a succession of extensional and transtensional tectonic pulses (Ziegler, 1990; Wagner, 1994; Dadlez *et al*., 1995, 1998; Van Wees *et al*., 2000; Dadlez, 2001). The paper by Van Wees *et al*. (2000) discusses an alternative theory of a "delayed infill" to explain the possibility of accumulation of such huge thicknesses of deposits during a short time. This theory assumes the Early Permian development of an intracontinental depression which subsided below the global sea-level, and its filling during the Late Permian. This hypothesis is difficult to accept since Rotliegend continental deposits of the North-German Basin contain a record of several marine ingressions, identified both within salt and terrigenous deposits near the boundary with the Zechstein. The Zechstein transgression was very rapid although it was not catastrophic (Wagner, 1994).

Alternatively, the Mid-Polish Trough has been interpreted by Kutek (2001) and Karnkowski (1999) as a rifted basin. Although this view is acceptable for the first phase of basin formation, no convincing evidence for rifting, at least in the Pomeranian and Kuiavian segments of the Mid-Polish Trough, can be found for the subsequent history of the basin (Dadlez *et al*., 1998; Dadlez, 2001). Also Van Wees *et al*. (2000) agree that there is no convincing evidence for Permian and Triassic rifting throughout the basin.

Late Permian and Early Triassic geological processes were probably controlled by thermal subsidence that followed Permo-Carboniferous lithospheric thinning and regional uplift,

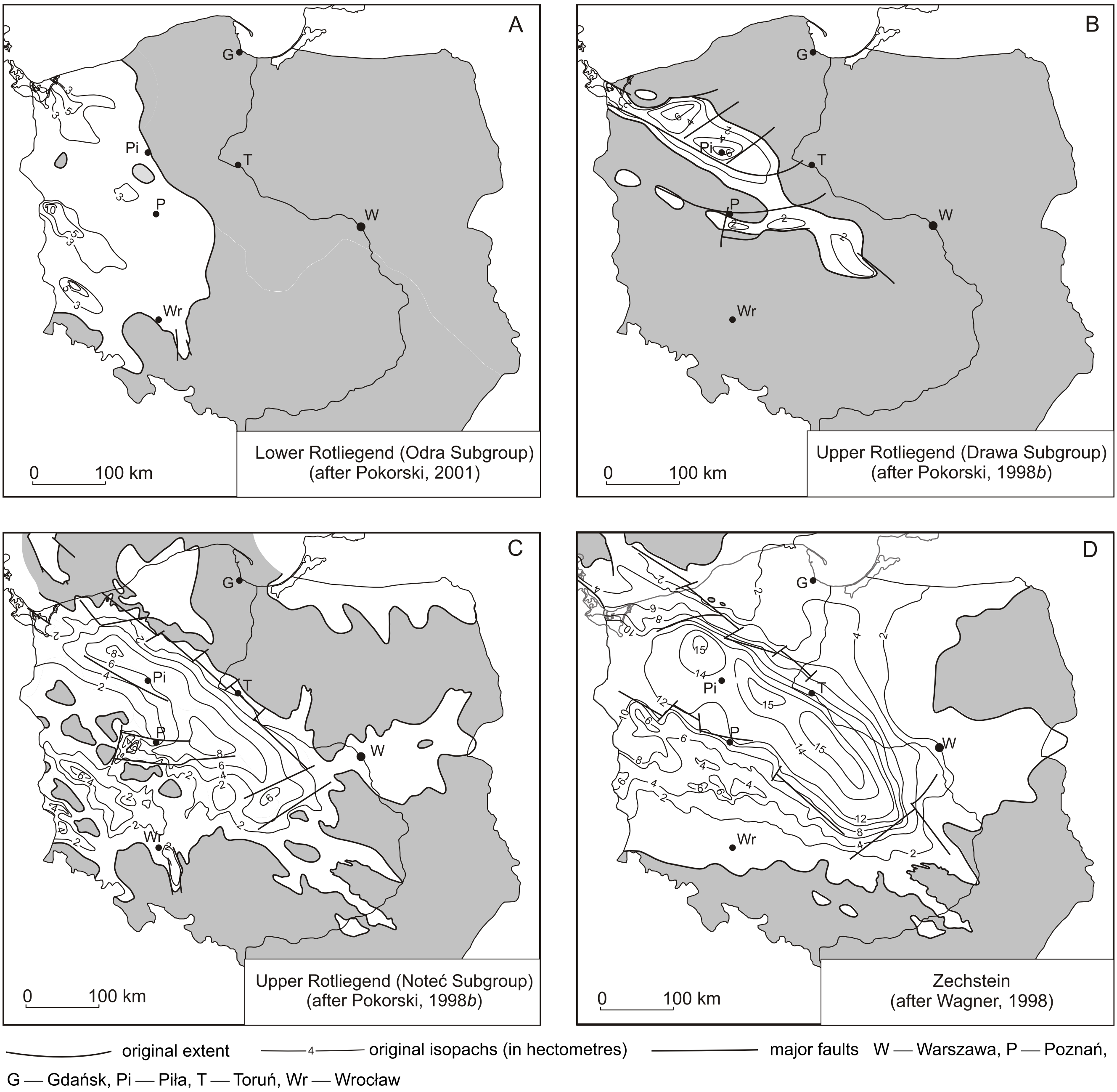


Fig. 2. Palaeotectonic maps of the Permian

as shown by the pre-Rotliegend geological structure of the Permian basin (Wagner, 1994).

According to Dadlez *et al*. (1995), two further strong pulses of accelerated tectonic subsidence occurred during the Late Jurassic and in mid-Cretaceous times (during the Turonian, according to Leszczyński, 2000*b*). However, these pulses were weaker than the Late Permian-Early Triassic ones, though they resulted in a considerable increase in thicknesses of Mesozoic deposits (Dadlez *et al*., 1998). Up to 10–12 km of Upper Permian and Mesozoic deposits in total accumulated in the Mid-Polish Trough.

At the Late Cretaceous/Paleocene transition the Mid-Polish Trough was inverted, resulting in the development of the Mid-Polish Swell.

The Mid-Polish Trough shows a distinct segmentation into the Pomeranian and Kuiavian segments. These segments, which are separated by a transition zone (Dadlez, 2001), differed from each other in subsidence rates during the sedimentation of the Zechstein-Mesozoic succession, the depth to the base of Zechstein, the basin architecture, the type of salt structures, and the timing of their formation and synsedimentary tectonic activity.

Causes of the segmentation can be sought in differences within the geological structure of the Palaeozoic substratum of the basin and possibly also of the crystalline crust (Dadlez, 2001).

In the Pomeranian and transition segments, in SW parts of the cross-sections 2 (Fig. 4) and 3 (Fig. 5), salt-pillows formed at a late phase during the evolution of the Mid-Polish Trough. These salt-pillows subsequently evolved during the Late Cretaceous and Paleocene into the Ińsko and Człopa diapirs. Tectonic activity in the area of salt pillow formation may have been associated with variations in the geological structure of the crystalline crust, which were identified on refraction profiles LT-7 (Guterch *et al.*,1994, 1999) and P2 (Guterch *et al.*, 1999). In the LT-7 profile, under a thick cover (about 12 km) of rocks with velocities less than 6 kms^{-1} (Caledonides, Dadlez, 1997), two blocks were recognised: a southwestern block composed of a laminated crust (B" — Fig. 1) and a northeastern block with a cratonic-type crust (block B'). The boundary between them is indicated after Dadlez (1998). According to Dadlez (2000) these blocks may represent a proximal terrane (or terranes) which were detached, displaced and then rejoined with Baltica. However, it is also possible that the southwestern block has an Avalonia-type crust, and the boundary between the blocks separates the proximal Pomeranian terrane from an East Avalonia terrane (or terranes). The contact zone between these crustal blocks has been referred to the Trans-European Fault (TEF) (Berthelsen,1992; Młynarski *et al.*, 2000) and, at Upper Rotliegend levels (Drawa Subgroup), as the SW boundary of the Mid-Polish rift (Pokorski, 1998*a*). By contrast, the low velocity layer (5.75–5.89 kms^{-1}, Caledonides) is missing beneath the Kuiavian segment, and crystalline crust (approximately 10 km in thickness, velocities from 6–6.1 kms^{-1}) lies directly beneath the sedimentary cover (Grad *et al.*, 1999). In this segment both the thickness of the crystalline crust and the depth of the Moho (more than 40 km) indicate that it probably consists of modified cratonic crustal material (presumably allochthonous). The Pomeranian and East Avalonian crustal blocks of the Pomeranian segment probably do not extend into the Kuiavian segment (terrane), whilst the SW zone of salt tectonics (Gopło-Pabianice Zone — Dadlez, 1998) appears to coincide with the boundary between these two units of the crystalline crust.

REGIONAL PALAEOTECTONIC CROSS-SECTIONS

Palaeotectonic reconstructions of the regional seismic sections were developed for 4 evolutionary phases of the Polish Lowlands. These phases retrace the main phases in the subsidence history of the Zechstein-Mesozoic basin, the development of salt structures and inversion processes.

— phase I — beginning of Zechstein to end Muschelkalk;

— phase II — from Keuper times to the end of the Early Cretaceous;

— phase III — Late Cretaceous;

— phase IV — present configuration, after inversion and the development of the Mid-Polish Swell.

PHASE I — ZECHSTEIN-MUSCHELKALK

Phase I defines the palaeostructural position of the base Zechstein at the end of Muschelkalk sedimentation by when the first period of maximum subsidence rate terminated in the Polish Lowlands (Late Permian and Early Triassic). Salt movements had not yet started, except in section 4 (Fig. 6).

As the top of the Muschelkalk corresponds to one of the most prominent regional seismic marker horizons, the Muschelkalk was included in this phase, although the period of rapid subsidence had already terminated at the end of the Middle Buntsandstein.

An analysis of this phase requires the reconstruction of the original thicknesses of the Zechstein salts in areas which were affected by halotectonic deformations. This reconstruction was performed on the basis of the analysis of regional salt thickness variations within the 2-D geological space (Wagner, 1998) of the seismic-geological section. This interpretation may be affected by some errors in balancing salt volumes on a local scale. These errors can influence the interpreted magnitude of post-Cretaceous erosion of Mesozoic deposits.

In the Pomeranian segment of the Mid-Polish Trough subsidence rates were regular and strong. In its axial zone, the base of Zechstein subsided to a depth of approximately 3000 m (cross-section 1 — Fig. 3; cross-section 2 — Fig. 4). The margins of the Mid-Polish Trough were asymmetric with greater thickness gradients in the north-east. Listric faults, separating basement blocks (Antonowicz *et al.*, 1994), were active in this area (beyond the area illustrated on the cross-sections).

The transition zone between the Pomeranian and Kuiavian segments underwent a similar evolution during phase I (cross-section 3 — Fig. 5).

The different evolution of the Kuiavian segment manifested itself in higher and more varied subsidence. Local depocentres formed within the basin, with some of them showing the characteristics of tectonic grabens or half-grabens. The Krośniewice Depression, where the base of the Zechstein reached a depth of 4000 m, provides an example. Initial salt structures, subsequently evolving into the Wojszyce Salt-pillow and the Kłodawa Diapir, were probably already active at this phase. These were presumably the first salt movements in the Polish Lowlands (cross-section 4 — Fig. 6). This is the exception mentioned above, as incipient salt movements were accentuated on a regional scale during the Late Triassic — before the Norian (Dadlez, 2001). Zones of strong subsidence are more pronounced in the Kuiavian segment than in the Pomeranian segment.

PHASE II — KEUPER-EARLY CRETACEOUS

Phase II in the development of the Mid-Polish Trough defines the position of the base of the Zechstein at the end of the Early Cretaceous and after the second, much weaker, subsidence pulse which occurred during the Early and Late Jurassic. This phase covers a long time period as the seismic records do not allow its subdivision and reflectors associated with Jurassic intervals are discontinuous. Therefore the very good quality base Upper Cretaceous marker horizon was chosen as the phase II/phase III boundary.

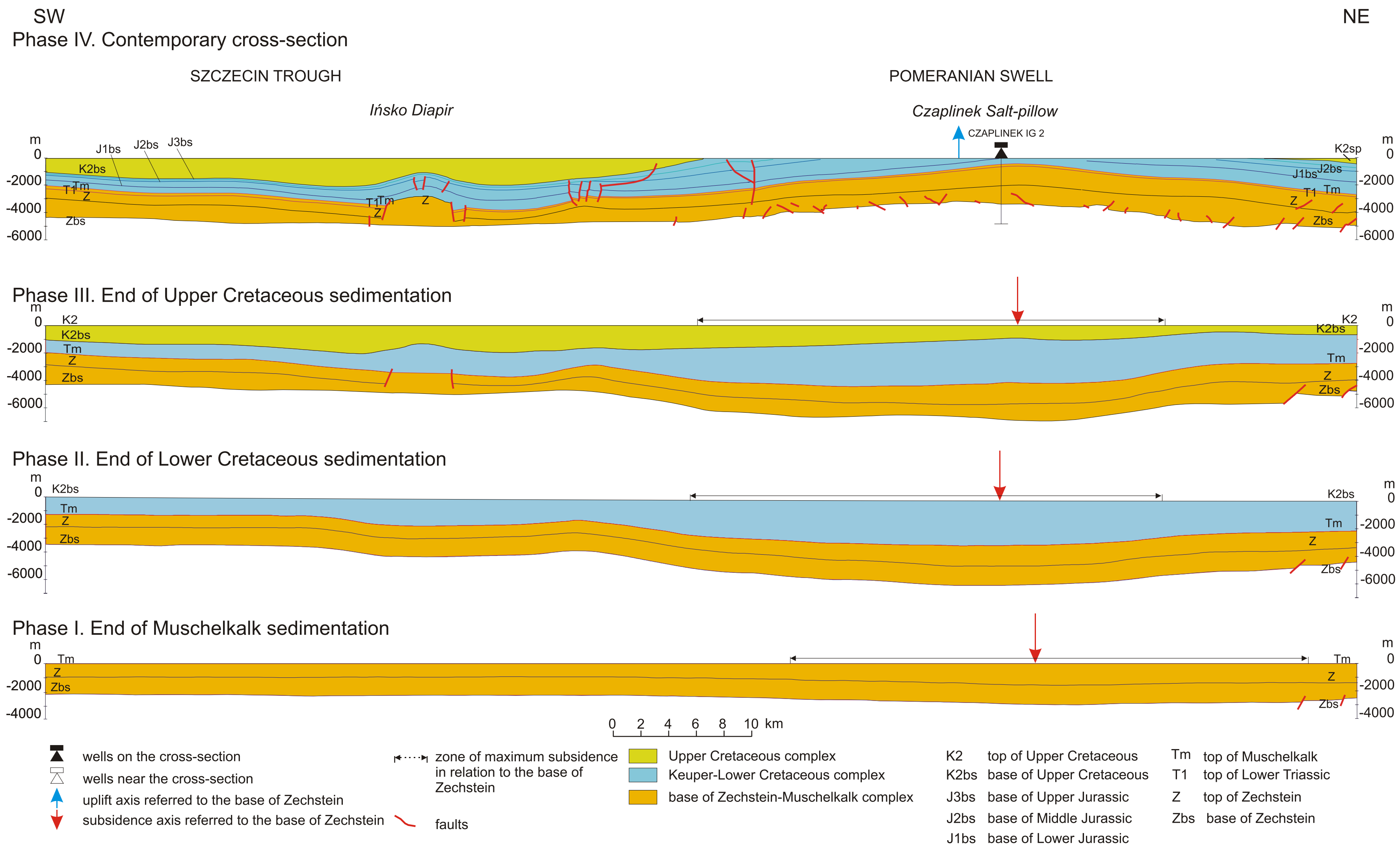
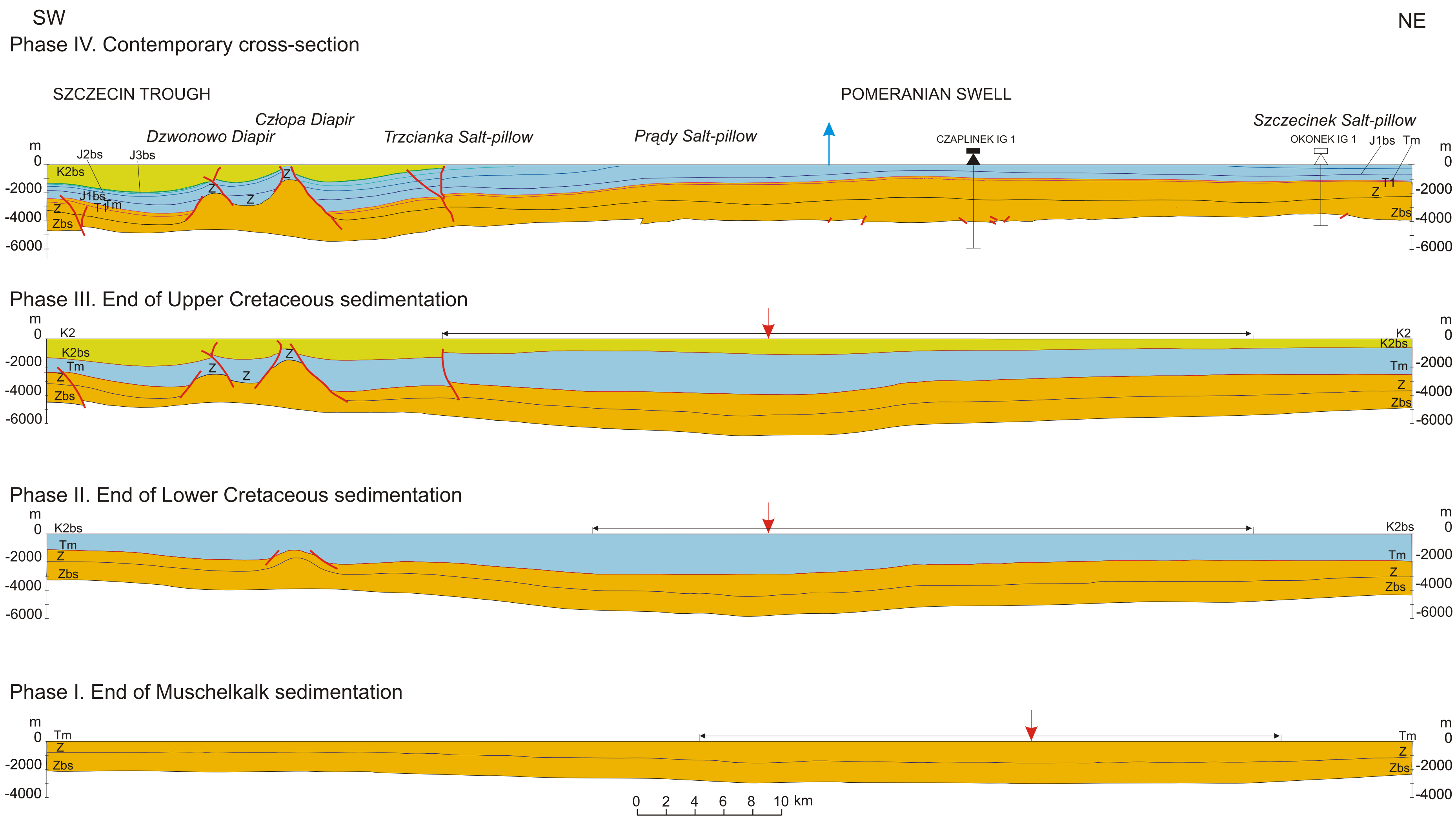


Fig. 3. Palaeotectonic cross-section 1



explanations as in Fig. 3

Fig. 4. Palaeotectonic cross-section 2

This phase expresses more distinctly the differences in the evolution of the Pomeranian and Kuiavian segments.

In the Pomeranian segment, the thickness increases of Keuper, Jurassic and Lower Cretaceous deposits towards the basin axis were gradual and the entire complex attained its maximum thickness of about 3200 m in the north and 2800 m in the south. The axes of depocentres shifted towards the SW as compared with their position during phase I. This is best illustrated in cross-section 2 (Fig. 4).

The development of an initial salt structure (subsequently the Człopa Diapir) is observed at this phase in the SW part of the cross-section 2 (Fig. 4). Further to the north, but in the same zone (cross-section 1 — Fig. 3), is an area (located SW of the maximum subsidence zone) in which thicknesses locally increased by about 200 m. This increase suggests that very weak salt movements were initiated within the zone in which the Ińsko Diapir subsequently developed. These two initial salt structures occupied similar positions relative to the contemporaneous depocentre and the axes of the Late Cretaceous-Early Tertiary inversion zone. These salt structures are located within a mobile, strongly faulted area which evolved into a depocentre during the Late Cretaceous.

Cross-section 3 (Fig. 5) is located in the transition zone between the Pomeranian and Kuiavian segments of the Mid-Polish Trough. At phase II, in contrast to phase I, the zone displayed much similarity to the Kuiavian segment. Intense salt movements commenced relatively early in this area — during the Early Jurassic or even the Rhaetian. The initial development of the Szubin, Damasławek and Janowiec salt structures can be observed here. The first piercing salt domes may have evolved near Damasławek at the end of phase II. Local salt-withdrawal depocentres formed during the Jurassic and Early Cretaceous in areas situated between these salt structures. Maximum subsidence zones are evident on either side of the Szubin Salt-pillow in which approximately 3000 m of Jurassic and Lower Cretaceous deposits accumulated.

The palaeotectonic evolution of the Kuiavian segment during phase II is best illustrated in cross-section 4 (Fig. 6). Development of the Wojszyce and Kłodawa salt structures, initiated during phase I, continued during Keuper-Early Cretaceous times. Other salt structures, located both to the north-east (Gostynin Salt-pillow) and the south-west (Ponętów Salt-pillow and probably Uniejów Salt-pillow), also developed in these times. Strong subsidence of areas situated between these salt structures controlled development of local depocentres filled mainly with Keuper and Jurassic deposits. A graben-type feature, filled with thick Keuper and Upper Jurassic deposits, was developed during the Keuper between the Ponętów and Kłodawa salt structures. Strong uplift of both of these structures occurred in the Keuper and the first piercing salt domes may have been formed in the area at that time (Dziewińska *et al.*, 2001). It is also possible that the Kłodawa salt structure started to rise a little earlier than Ponętów. At the end of phase II both of these structures, in particular the Kłodawa, pierced through Buntsandstein deposits. 6000 m of Keuper-Lower Cretaceous deposits accumulated in the area between the rising Kłodawa Diapir and the Wojszyce Salt-pillow, whereas, between the Wojszyce and Gostynin salt-pillows, about 5000 m were deposited. The greatest increase in thickness occurred in the Keuper and Early, Middle and Late Jurassic. In the Poddębice Trough, located between the Kłodawa Diapir and the Ponętów Salt-pillow, Keuper-Lower Cretaceous deposits attained a thickness of over 3000 m. At the end of phase II the base of Zechstein had subsided to maximum depth of approximately 9000 m in the axial part of the Kuiavian basin.

Similar tendencies can be observed in the southernmost cross-section 5 (Fig. 7). Maximum subsidence zones developed on both sides of the Jeżów Salt-pillow. Keuper-Lower Cretaceous deposits attained or slightly exceeded 3000 m in thickness. However, salt movements were much weaker than observed in cross-section 4. At the end of phase II the base of the Zechstein had subsided in cross-section 5 to a maximum depth of about 6000 m.

PHASE III — LATE CRETACEOUS

Phase III in the evolution of the Mid-Polish Trough defines the position of the base of the Zechstein at the end of the Late Cretaceous. Reconstruction of the subsidence history and of tectonic processes that occurred at that time is difficult and controversial. Our knowledge about the processes in the area of the Mid-Polish Trough is poor due to complete erosion of all Upper Cretaceous deposits over the culmination of the Pomeranian and Kuiavian swells (Figs. 3–7). Also in other areas, in particular along anticlines, the uppermost parts of the Upper Cretaceous succession were removed (mainly Maastrichtian, locally older deposits). Therefore, reconstruction of this phase required the analysis of the original thickness of Upper Cretaceous deposits. This procedure is subject error, arising from our personal interpretation and the methods used.

Interpreting the original thicknesses of the Upper Cretaceous we assumed that salt movements were intense during that time (observed through all of the Late Cretaceous) and even intensified from the Coniacian onwards (Cieśliński and Jaskowiak, 1973; Leszczyński, 2000*a*, *b*). This increase in activity may be related to the inversion of local tectonic structures, particularly in major tectonic zones such as Koszalin-Chojnice, Drawno-Człopa-Szamotuły (Leszczyński, 2002, this volume), Gopło-Ponętów-Wartkowice, and Izbica-Kłodawa (Leszczyński, 2000*a*, *b*), and to the incipient phase of regional inversion of the entire Mid-Polish Trough. In the present interpretation, it was assumed that inversion of the Mid-Polish Trough commenced during the Coniacian, and that it was a complex, pulsatory and multi-phase process (e.g. Dadlez, 1976, 1980; Jaskowiak-Schoeneichowa, 1981; Dadlez and Marek, 1997; Dadlez *et al.*, 1997; Krassowska, 1997; Leszczyński, 1997; Leszczyński and Dadlez, 1999; Leszczyński, 2000*b*). Basin inversion culminated at the Maastrichtian/Paleocene transition, and resulted in the final uplift of the Mid-Polish Swell. However, it should be noted that there are other opinions concerning the age of inversion, suggesting that the process began after the Santonian (e.g. Hakenberg and Świdrowska, 1998; Świdrowska and Hakenberg, 1999) or even at the Cretaceous/Tertiary transition (e.g. Kutek and Głazek, 1972).

Anticlines and synclines continued to form throughout phase III of the evolution of the Mid-Polish Trough. This is seen in decreasing thicknesses of the Upper Cretaceous strata

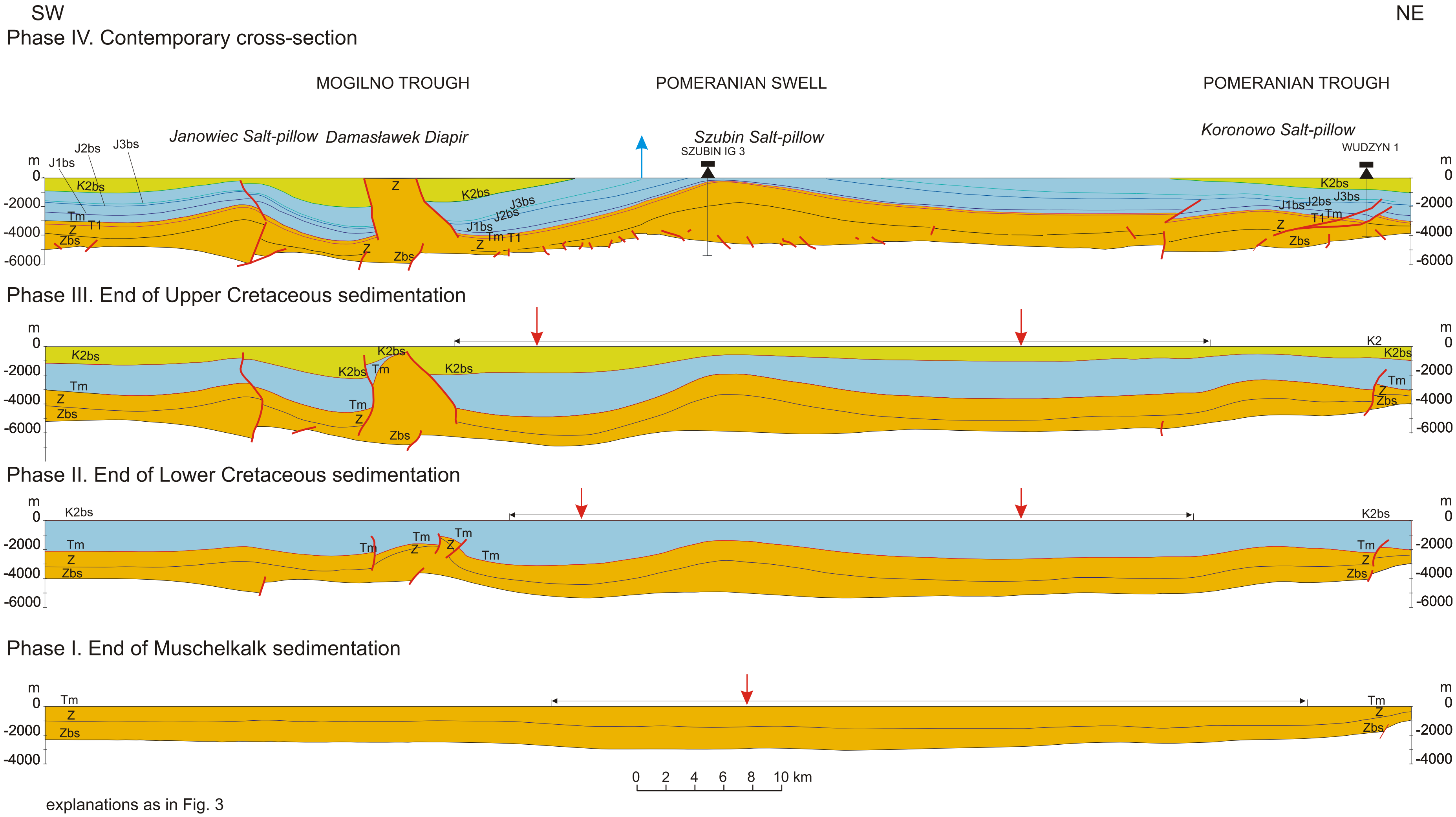


Fig. 5. Palaeotectonic cross-section 3

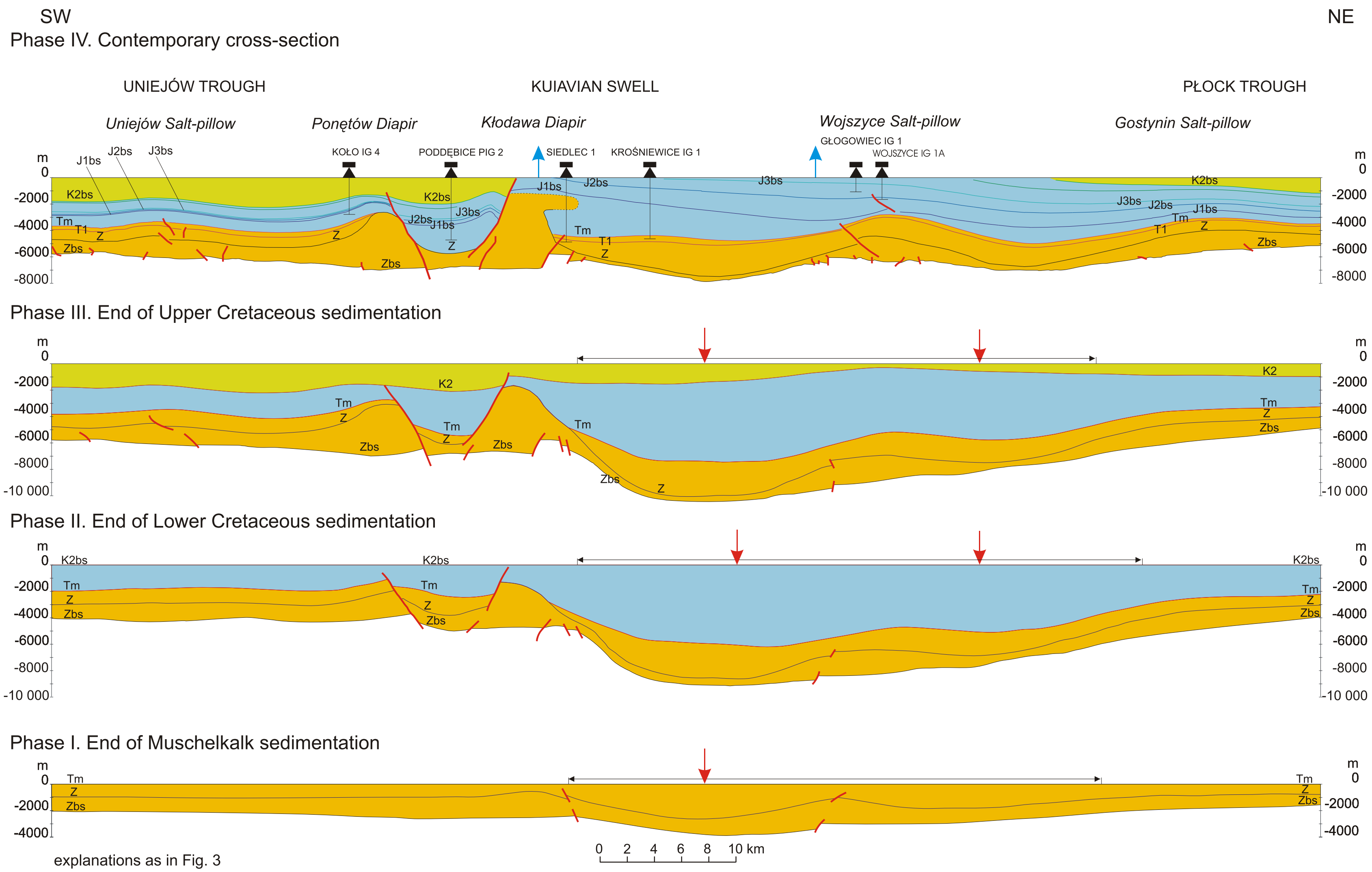


Fig. 6. Palaeotectonic cross-section 4

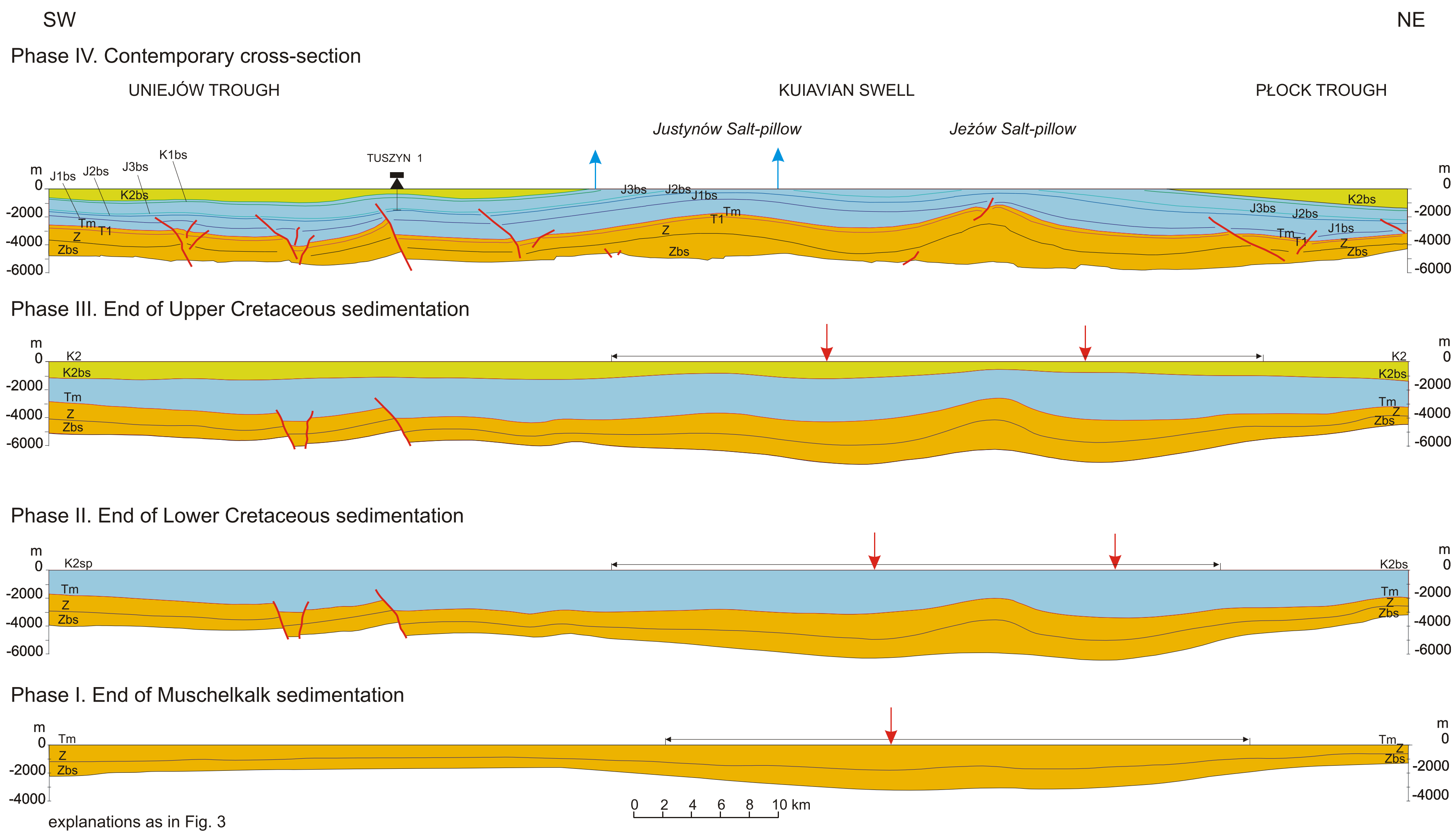


Fig. 7. Palaeotectonic cross-section 5

towards anticlinal axes (Jaskowiak-Schoeneichowa, 1981; Jaskowiak-Schoeneichowa and Krassowska, 1988). Salt structures (Ińsko Diapir — Fig. 3; Człopa Diapir — Fig. 4; Janowiec Salt-pillow, Damasławek Diapir — Fig. 5; Uniejów Salt-pillow, Ponętów Diapir, Kłodawa Diapir, Gostynin Salt-pillow — Fig. 6) were active throughout the Late Cretaceous, and particularly during Coniacian-Campanian times (Cieśliński and Jaskowiak, 1973; Leszczyński, 2000*a*, *b*). Activity of anticlines which are not salt-induced, such as the Koszalin-Chojnice Zone (Figs. 3 and 4), started in the Coniacian (Leszczyński, 2002, this volume). Synsedimentary faults may have been active in the areas of inversion and strong salt movements (Człopa Diapir — Fig. 4; Janowiec Salt-pillow, Damasławek Diapir — Fig. 5; Kłodawa Diapir — Fig. 6), resulting in thickness differences of the individual Upper Cretaceous phases.

During the Cenomanian, tectonic subsidence was still low. It rapidly increased during the Turonian, culminating during the Turonian-Santonian. Subsequently, subsidence rates gradually decreased until the end of the Late Cretaceous (Leszczyński, 2000*b*). After the Coniacian, subsidence rates varied from area to area. They were higher in the Szczecin-Mogilno-Uniejów and Pomeranian-Płock troughs, and lower across the area of the present-day Mid-Polish Swell, with possible areas of local and periodic uplifts. Prior to the Coniacian, the zone of maximum subsidence coincided with the central part of the Mid-Polish Trough. From the Coniacian onwards the subsidence axis probably shifted towards the troughs flanking the present-day Mid-Polish Swell to the NE and SW (Figs. 3–7). The greatest thicknesses of Upper Cretaceous deposits (over 2000 m) are observed in the synclines of the Mogilno-Uniejów Trough (near the Damasławek Diapir — Fig. 5; on both sides of the Ponętów Diapir — Fig. 6) and Szczecin Trough (on both sides of the Ińsko Diapir — Fig. 3; SW of the Człopa Zone — Fig. 4), near salt structures. The interpreted thickness of Upper Cretaceous deposits in the area of the present-day Mid-Polish Swell probably did not exceed 2000 m.

During the Late Cretaceous the base of Zechstein had subsided to its maximum depth and reached in the Pomeranian segment a depth of approximately 6500 m, and in the Kuiavian segment depths in the range of 7000 to 10 000 m. In Figure 5, showing a cross-section situated in the transition zone between the Pomeranian and Kuiavian segments, the base of Zechstein reached depths typical of the Pomeranian segment of the order of 6000 m.

PHASE IV — PRESENT CONFIGURATION, AFTER INVERSION

Phase IV defines the present-day configuration of the Polish Trough, resulting from its inversion and the formation of the Mid-Polish Swell. Inversion caused uplift of this area and intense erosion of Cretaceous and Jurassic strata, locally in the Pomeranian segment even of Triassic deposits (Dadlez *et al*., 2000). The magnitude of uplift has been estimated to amount to 1000–2000 m in the Pomeranian segment and up to 3000 m in the Kuiavian segment where inversion movements were the strongest (Dadlez *et al*., 1997; Dadlez ed., 1998). Our palaeotectonic analyses indicate that these values could be greater by up to 1000 m in both segments. Maximum uplift zones are observed near Czaplinek (Fig. 3), around the Szubin Salt-pillow (Fig. 5), close to the Kłodawa Diapir (Fig. 6) and near the Justynów and Jeżów salt-pillows (Fig. 7). In the Kuiavian segment, and locally also in Pomerania, the maximum uplift zone is observed close to the SW edge of the Mid-Polish Trough (Figs. 5 and 6). The troughs, occurring on either side of the Mid-Polish Swell, were ultimately shaped after the Maastrichtian. North-east of the Mid-Polish Swell the troughs are less downwarped and structurally less complicated as compared to the troughs which developed to the SW of the swell. Moreover, Lower Paleocene deposits occur at the top of the Zechstein-Mesozoic succession in the northeastern troughs (Jaskowiak-Schoeneichowa and Krassowska, 1988; Dadlez *et al*., 2000). The northeastern slope of the Mid-Polish Swell is also more gentle. All these facts indicate an asymmetry of inversion (Dadlez ed., 1998). As a result of inversion, the base of the Zechstein beneath the Mid-Polish Swell was uplifted to depths more or less equal to that in the flanking Szczecin and Mogilno-Uniejów troughs, and locally distinctly shallower (Figs. 3–7).

After the Maastrichtian, salt structures acquired their ultimate shape (Krzywiec, 2000). Salt-pillows were formed in the Pomeranian segment (cross-section 1 — Fig. 3; cross-section 2 — Fig. 4). In the Szczecin Trough, Zechstein salts pierced through almost all of the Mesozoic succession (Człopa Diapir, cross-section 2 — Fig. 4). The salt structures evolved most rapidly not in the Pomeranian Swell but in the Szczecin Trough, adjacent to the Mid-Polish Swell. In the transitional area between the Pomeranian and Kuiavian segments (cross-section 3 — Fig. 5), the Szubin Salt-pillow was ultimately formed. In the neighbouring troughs the development of salt structures was completed at this time (final piercing of Damasławek Diapir and formation of Koronowo Salt-pillow). In terms of salt structure evolution, this area resembles more the Kuiavian than the Pomeranian segment. In the former area the intensity of salt movements was strong within both the Kuiavian Swell and the Mogilno-Uniejów Trough (Kłodawa and Ponętów diapirs, cross-section 4 — Fig. 6; Justynów and Jeżów salt-pillows, cross-section 5 — Fig. 7).

Inversion caused the reactivation of pre-existing faults as well as the development of new ones, particularly along zones of strong tectonic activity. The faults cut different successions of the Permian-Mesozoic cover (Dadlez ed., 1998; Krzywiec, 2000). These can be faults observed within the lower portion of the cover or cutting it from bottom to top, often rooted within deeper fault zones. Distinct faults also bound salt structures (Figs. 3–7). Both normal and reverse faults are observed (Dadlez, 2001). The occurrence of substantial number of reverse faults (40%) may be indicative of regional compression within the sedimentary cover of the Mid-Polish Swell (Krzywiec, 2000). Dadlez (2001) rejects such a hypothesis, explaining the faulting by inverse vertical movements during inversion. Nevertheless, apart from the presence of reverse faults, the images of some salt structures (e.g. Wojszyce Salt-pillow, cross-section 4 — Fig. 6; Koronowo Salt-pillow, cross-section 3 — Fig. 5) indicate a contribution from a compressional component.

CONCLUSIONS

The palaeotectonic analysis of regional seismic sections permit to reconstruction of the evolution of the Mid-Polish Trough at the major phases of its tectonic development. This allows to evaluate subsidence history of the base Zechstein during the Late Permian and Mesozoic, and to determine depth to which the base of Zechstein deposits had subsided, as well as the timing and intensity of the formation of salt structures. Reconstruction of the evolution of the Zechstein and Mesozoic basins has provided further means of understanding some details of the geological structure of this area during its Late Cretaceous and Tertiary inversion, as well as differences between the Pomeranian and Kuiavian segments.

1. The analysis of the palaeotectonic evolution of the Mid-Polish Trough confirms that the Pomeranian and Kuiavian segments (Dadlez, 2001) differ in many aspects of their geological evolution.

2. Compared to the Kuiavian segment, the Pomeranian segment was characterised by lower subsidence during Late Permian-Mesozoic times. The maximum original thickness of the Zechstein-Mesozoic succession attained about 6000–6500 m in the Pomeranian segment, and about 10000 m in the Kuiavian segment.

3. Correspondingly, the maximum depth to which the base of the Zechstein had subsided prior to basin inversion differs between these two segments by about 3500–4000 m.

4. Both segments differ in the configuration of the sedimentary basins which developed during successive evolutionary phases. In the Pomeranian segment these basins were only slightly asymmetric and were characterised by only one depocentre, the axial zone of which shifted somewhat through time. In the Kuiavian segment the sedimentary basins were characterised by several depocentres which were separated by gradually rising salt-cored zones.

5. In the Pomeranian segment, flow-induced salt structures are developed more weakly and were probably formed relatively late, during the latest Cretaceous or during basin inversion. In Kujawy, salt structures began to rise at the end of the Muschelkalk and remained active throughout Mesozoic times, forming salt pillows and diapirs, controlling lateral thickness and facies changes.

6. The magnitude of syn-inversion uplift of the base of Zechstein is estimated at 2000–3000 m in the Pomeranian segment, and at 3000–4000 m in the Kuiavian segment.

7. The transition zone between the Pomeranian and Kuiavian segments, displays mixed features in its structural evolution during the successive phases.

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REFERENCES

ANTONOWICZ L., IWANOWSKA E. and RENDAK A. (1994) — Tensional tectonics in the Pomeranian section of the T-T zone and the implictions for the hydrocarbon exploration. Geol. Quart., **38** (2): 289–306.

BERTHELSEN A. (1992) — Mobile Europe. In: A Continent Revealed: the European Geotraverse: 11–32.

CIEŚLIŃSKI S. and JASKOWIAK M. (1973) — Kreda górna. Niecka mogileńsko-łódzka. In: Budowa geologiczna Polski. Stratygrafia, Mezozoik: 580–586. Warszawa.

DADLEZ R. (1976) — Rozwój sedymentacyjno-paleotektoniczny. In: Permian and Mesozoic of the Pomeranian Trough (in Polish with English summary). Pr. Inst. Geol.,**79**: 105–112.

DADLEZ R. (1980) — Tectonics of the Pomeranian Swell (NW Poland) (in Polish with English summary). Kwart. Geol., **24** (4): 741–767.

DADLEZ R. (1997) — Seismic profile LT-7 (northwest Poland): geological implications. Geol. Mag., **134** (5): 653–659.

DADLEZ R. (1998) — Devonian to Cretaceous epicontinental basins in Poland: relationship between their development and structure of the crystalline crust. In: Sedimentary basin analysis of the Polish Lowlands (in Polish with English summary). Pr. Państ. Inst. Geol. **165**: 17–30.

DADLEZ R. ed. (1998) — Tectonic Map of the Zechstein-Mesozoic Complex in the Polish Lowlands, 1:500 000, II ed. Państw. Inst. Geol. Warszawa.

DADLEZ R. (2000) — Pomeranian Caledonides (NW Poland), fifty years of controversies: a review and new concept. Geol. Quart., **44** (5): 221–236.

DADLEZ R. (2001) — Mid-Polish Trough — geological cross-section, 1:200 000. Państw. Inst. Geol. Warszawa

DADLEZ R., JÓŹWIAK W. and MŁYNARSKI S. (1997) — Subsidence and inversion in the western part of Polish Basin — data from seismic velocities. Geol. Quart., **41** (2): 197–208.

DADLEZ R. and MAREK S. (1997) — General tectonic framework of the Midlle Polish Trough. In: The epicontinental Permian and Mesozoic in Poland (eds. S. Marek and M. Pajchlowa) (in Polish with English summary). Pr. Państw. Inst. Geol., **153**: 403–414.

DADLEZ R., MAREK S. and POKORSKI J. eds. (1998) — Palaeogeographical Atlas of the Epicontinental Permian and Mesozoic in Poland, 1:2 500 000. Państw. Inst. Geol. Warszawa.

DADLEZ R., MAREK S. and POKORSKI J. (2000) — Geological Map of Poland without Cainozoic Deposits, 1:1 000 000. Państw. Inst. Geol. Warszawa.

DADLEZ R., NARKIEWICZ M., STEPHENSON R. A., VISSER M. T. M. and VAN WEES J.-D. (1995) — Tectonic evolution of the Mid-Polish Trough: modelling implications and significance for central European geology. Tectonophysics, **252** (1–4): 179–195.

DADLEZ R., NARKIEWICZ M., POKORSKI J. and WAGNER R. (1998) — Subsidence history and tectonic controls on the Late Permian and Mesozoic development of the Mid-Polish Trough. In: Sedimentary basin analysis of the Polish Lowlands (in Polish with English summary). Pr. Państw. Inst. Geol., **165**: 47–56.

DZIEWIŃSKA L., MAREK S. and JÓŹWIAK W. (2001) — Seismic-geological cross-sections across the Kujawy and Gielniew Swell (scale 1:100 000) (in Polish with English summary). Biul. Państw. Inst. Geol., **398**: 5–22.

GRAD M., JANIK T., YLINIEMIl J., GUTERH A., LUOSTO U., TIIRA T., KOMMINAHO K., ŚRODA P., HOING K., MAKRIS J. and LUND C.-E. (1999) — Crustal structure of the Mid-Polish Trough beneath the Teisseyre-Tornquist Zone seismic profile. Tectonophysics, **314**:145–160.

GUTERCH A., GRAD M., JANIK T., MATERZOK R., LUOSTO U., YLINIEMI J., LÜCK E., SCHULTZE A. and FÖRSTE K. (1994) — Crustal structure of the transition zone between Precambrian and Variscan Europe from new seismic data along LT-7 profile (NW Poland and eastern Germany). Geophysique/Geophysics, C. R. Acad. Sci., **319** (2): 1489–1496.

GUTERCH A., GRAD M., THYBO H., KELLER G. R. and POLONAISE WORKING GROUP (1999) — POLONAISE'97 — International seismic experiment between Precambrian and Variscan Europe in Poland. Tectonophysics, **314**:101–121.

HAKENBERG M. and ŚWIDROWSKA J. (1998) — Evolution of the Holy Cross segment of the Mid-Polish Trough during the Cretaceous. Geol. Quart., **42** (3): 239–262.

JASKOWIAK-SCHOENEICHOWA M. (1981) — Upper Cretaceous sedimentation and stratigraphy in north-western Polish (in Polish with English summary). Pr. Inst. Geol., **98**.

JASKOWIAK-SCHOENEICHOWA M. and KRASSOWSKA A. (1988) — Palaeothickness, lithofacies and palaeotectonic of epicontinental Upper Cretaceous in Poland (in Polish with English summary). Kwart. Geol., **32** (1): 177–198.

KARNKOWSKI P. H. (1999) — Origin and evolution of the Polish Rotliegend Basin. Spec. Papers, Państw. Inst. Geol., **3**: 1–93.

KIERSNOWSKI H. (1991) — Lithostratigraphy of the Permian north-west of the Upper Silesia Coal Basin — a new proposal (in Polish with English summary). Prz. Geol., **39** (4): 198–203.

KRASSOWSKA A. (1997) — Kreda górna. Sedymentacja, paleogeografia i paleotektonika. In: The epicontinental Permian and Mesozoic in Poland (in Polish with English summary) (eds. S. Marek and M. Pajchlowa). Pr. Inst. Geol., **153**: 386–402.

KRZYWIEC P. (2000) — On mechanisms of the Mid-Polish Trough inversion — results of seismic data interpretation (in Polish with English summary). Biul. Państ. Inst. Geol., **393**: 135–166.

KUTEK J. (2001) — The Polish Permo-Mesozoic rift basin. In: Peri-Tethys Memoir, 6: Peri-Tethyan Rift/Wrench Basin and Passve Margis (eds. P. A. Ziegler, W. Cavazza, A. H. F. Robertson and S. Crasquin-Soleau). Mem. Mus. Nat. Hist. Nat., **186**: 213–236. Paris.

KUTEK J., GŁAZEK J. (1972) — The Holy Cross area in the Alpine cycle. Acta Geol. Pol., **22** (4): 603–652.

LESZCZYŃSKI K. (1997) — The Upper Cretaceous carbonate-dominated sequences of the Polish Lowlands. Geol. Quart., **41** (4): 521–532.

LESZCZYŃSKI K. (2000*a*) — The Late Cretaceous sedimentation and subsidence south-west of the Kłodawa Salt Diapir, central Poland. Geol. Quart., **44** (2): 167–174.

LESZCZYŃSKI K. (2000*b*) — Ewolucja geologiczna strefy Ponętów-Wartkowice w kredzie (in Polish). Ph. D. Thesis. Centr. Arch. Geol. Państw. Inst. Geol. Warszawa.

LESZCZYŃSKI K. (2002) — Late Cretaceous inversion and salt tectonics in the Koszalin-Chojnice and Drawno-Człopa-Szamotuły zones, Pomeranian sector of the Mid-Polish Trough. Geol. Quart., **46** (3): 347–367.

LESZCZYŃSKI K. and DADLEZ R. (1999) — Subsidence and the problem of incipient inversion in the Mid-Polish Trough based on thickness maps and Cretaceous lithofacies analysis — discussion (in Polish with English summary). Prz. Geol., **47** (7): 625–628.

MŁYNARSKI S., POKORSKI J., DZIEWIŃSKA L., JÓŹWIAK W. and ZIENTARA P. (2000) — Deep reflection seismic experiments in western Poland. Geol. Quart., **44** (2): 175–181.

POKORSKI J. (1997) — Perm dolny (czerwony spągowiec). In: The epicontinental Permian and Mesozoic in Poland (eds. S. Marek and M. Pajchlowa) (in Polish with English summary). Pr. Państw. Inst. Geol., **153**: 35–62.

POKORSKI J. (1998*a*) — Prospects of the occurrance of gaseous hydrocarbons in the Rotliegend deposits (in Polish with English summary). Pr. Państw. Inst. Geol., **165**: 293–298.

POKORSKI J., (1998*b*) — Late Rotliegend, Drawa subgroup — palaeogeography, Plate 2. Late Rotliegend, Noteć subgroup — palaeogeography, Plate 3. In: Palaogeographical Atlas of the Epicontinental Permian and Mesozoic in Poland, 1:2 500 000 (eds. R. Dadlez, S. Marek and J. Pokorski). Państw. Inst. Geol. Warszawa.

POKORSKI J. (2001) — Early Permian. In: The Paleotectonic Atlas of the PeriTethyan Domain (eds. G. Stampfli, G. Borel, W. Cavazza, J. Mosar and P. A. Ziegler). IGCP Project no 369. European Geophys. Soc.

ŚWIDROWSKA J. and HAKENBERG M. (1999) — Subsidence and the problem of incipient inversion in the Mid-Polish Trough based on thickness maps and Cretaceous lithofacies analysis — discussion (in Polish with English summary). Prz. Geol, **47** (1): 61–68.

WAGNER R. (1994) — Stratigraphy and evolution of the Zechstein Basin in the Polish Lowland. Pr. Państw. Inst. Geol., **146**.

WAGNER R. (1998) — Zechstein, thickness, Plate 9. In: Palaogeographical Atlas of the Epicontinental Permian and Mesozoic in Poland (eds. R. Dadlez S. Marek and J. Pokorski). Państw. Inst. Geol. Warszawa.

WOJEWODA J. and MASTALERZ K. (1989) — Climat evolution, allo- and autociclicity of sedimentation: an example from the Permo-Carboniferous continental deposits of the Sudetes, SW Poland (in Polish with English summary). Prz. Geol., **37** (4): 173–180.

VAN WEES J.-D., STEPHENSON R. A., ZIEGLER P. A., BAUER U., McCANN T., DADLEZ R., GAUPP R., NARKIEWICZ M., BITZER F. and SCHECK M. (2000) — On the origin of the Southern Permian Basin, Central Europe. Mar. Petrol. Geol., **17**: 43–59.

ZIEGLER P. A. (1990) — Geological Atlas of Western and Central Europe. Shell. Intern. Petrol. Maatschappij. B. V.