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Triassic-Jurassic evolution of the Pomeranian segment of the Mid-Polish Trough — basement tectonics and subsidence patterns

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Based on reflection seismic data, a regional tectonic model was constructed for the sub-Zechstein basement of the Pomeranian (NW) segment of the Mid-Polish Trough (MPT). This model is based on the concept that the thick Zechstein salts acted on a basin-wide scale as a mechanical decoupling layer during the Mesozoic evolution of the MPT. Due to this regional decoupling effect, Mesozoic extensional faulting was mostly restricted to the sub-Zechstein salt basement whilst normal faulting played a subordinate role in the Mesozoic syn-extensional sedimentary series characterized by gradual lateral thickness changes. Locally, normal faulting affecting Mesozoic series triggered the development of salt diapirs. Mechanical decoupling of Mesozoic series from their pre-Zechstein substratum played also an important role during the Late Cretaceous-Paleogene inversion of the Mid-Polish Trough. Taking into account: 1— the location of Mesozoic thickness gradients, 2 — the structural configuration of the sub-Zechstein basement, and 3 — the location of salt structures, a tectonic map was constructed showing the inferred sub-salt fault zones that were active during the subsidence and inversion of the Pomeranian part of the MPT. A high degree of correlation was achieved between the seismically mapped regional sub-salt structural patterns and magnetic and gravity features, as well as the main inversion structures. Moreover, a very good correlation was established between the inferred basement fault zones and the gross thickness patterns of the Triassic-Jurassic successions. The NE boundary of the MPT was generally controlled by the SW margin of the East European Craton, whilst its SW boundary coincides with a system of fault zones most probably inherited from earlier tectonic phases. Contrary to previous hypotheses, there is no evidence for important strike-slip faulting transverse to the main axis of the Pomeranian segment of the MPT.

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INTRODUCTION

In the Mid-Polish Trough (MPT), Mesozoic series accumulated in depositional continuity with the Late Permian Zechstein evaporites that in turn overlay early Late Permian continental Rotliegend clastics. These rest unconformably on Early Permian volcanics and Carboniferous and older sediments.

Comparably to other sedimentary basins that contain thick salt layers, the Zechstein salts exerted a strong control on the structural and sedimentary architecture of the Mid-Polish Trough during its tensional Mesozoic subsidence as well as during its Late Cretaceous-Paleocene inversion by acting as a mechanical decoupling layer between the sub-salt "basement" and the supra-salt sedimentary sequences (e.g. Brun and Nalpas, 1996).

Depending on the thickness of the decoupling salt layer, the thickness of its overburden and the magnitude and rate of "basement" faulting during extensional basin subsidence, various structures can form in the supra-salt sequences. These include various scales of forced folds, *i.e.* forced folds that develop above deep-seated normal faults, and systems of planar or listric normal faults that are restricted to the supra-salt series and sole out in the salt layer (*cf.* Withjack *et al.*, 1990; Bishop *et al.*, 1995; Stewart, 1999; Withjack and Callaway, 2000). Such supra-salt fault systems can be considerably offset with respect to the deep-seated master fault zones that controlled the extensional basin subsidence. Correspondingly, they can be regarded as so-called peripheral structures that are located outside the main subsidence axis of the basin. Moreover, such peripheral fault systems can also be reactivated during compressional basin inversion (Brun and Nalpas, 1996).

During the extensional basin subsidence, salt layers underlying a thick sedimentary overburden can start to flow, giving rise to the development of a variety of halotectonic structures, such as salt diapirs, salt pillows and salt walls. Salt flow can be triggered by extensional faulting of the sub-salt "basement" (e.g. Koyi *et al.*, 1993; Jackson and Vendeville, 1994; Dooley *et al.*, 2005), as well as by thin-skinned extension of the post-salt sedimentary cover (Vendeville and Jackson, 1992*a*, *b*), and differential sedimentary loading of the salt layer (Worrall and Snelson, 1989). In intracontinental settings, salt structures are particularly often related to sub-salt fault zones as in such basins localized extension and subsidence is associated with significant faulting within the pre-salt basement (e.g.; Koyi and Petersen, 1993; Koyi *et al.*, 1993; Christensen and Korstgard, 1994; Amor, 1999; Al-Zoubi and ten Brink, 2001; Larsen *et al.*, 2002).

Halotectonic structures are particularly well developed in the Southern Permian Basin of Europe that extends from the southern North Sea to Poland and that has undergone a polyphase Mesozoic and Cenozoic evolution (Fig. 1; Ziegler, 1990; Stewart and Coward, 1995; Kockel, 1998; Scheck *et al.*, 2003).

The presence of a thick salt layer at the base of the sedimentary infill of a basin often results in poor seismic resolution at sub-salt basement levels, as evaporites attenuate seismic energy. Therefore, analyses of the basement tectonic style often rely partly on indirect information, such as gross sedimentary patterns of the supra-salt cover and the style of the salt and cover tectonics.

This paper summarizes the results of a regional analysis of industrial seismic reflection data from the NW Pomeranian segment of the Mid-Polish Trough with emphasis on the identification of potential sub-salt (sub-Zechstein) basement fault zones that were active during the extensional subsidence and subsequent inversion-related uplift of this basin (*cf.* Krzywiec and Wybraniec, 2003; Krzywiec, 2004*a*; Krzywiec *et al.*, 2006). The inferred regional basement fault system will be compared with regional Triassic and Jurassic thickness maps and potential field maps. In order to clarify the pre-inversion Triassic-Jurassic evolution of the Mid-Polish Trough, selected topics on the Late Cretaceous-Paleogene inversion tectonics will be addressed (see also Krzywiec, 2006).

GEOLOGICAL SETTING

The Mid-Polish Trough (MPT) formed the axis of the Polish Basin that forms part of the Permian-Mesozoic system of West- and Central-European epicontinental basins (Ziegler, 1990). During the Permian, the MPT formed the easternmost part of the Southern Permian Basin (Kiersnowski *et al.*, 1995; Van Wees *et al.*, 2000). Prior to its Late Cretaceous-Paleocene inversion, the MPT was filled with several kilometres of Permian and Mesozoic sediments, including thick Zechstein salts (Marek and Pajchlowa, 1997; Dadlez *et al.*, 1998). The presence of these Zechstein salts gave rise to the development of a complex system of salt structures in the central and north-west segments of the MPT. In this basin, various aspects of salt tectonics have been analysed by numerous authors, including e.g. Sokołowski (1966), Dadlez and Marek (1969, 1974), Burliga, (1996) (for summaries and further references see e.g. Pożaryski, 1977; Tarka, 1992 and Krzywiec, 2004*b*, *c*).

The MPT evolved along the NW–SE trending Teisseyre-Tornquist Zone (TTZ) that is one of the most important crustal-scale boundaries in Europe (Kutek and Głazek, 1972; Pożaryski and Brochwicz-Lewiński, 1978; Dadlez *et al.*, 1995; Dadlez, 1997*a*, *b*, 1998; Kutek, 2001). This zone is characterized by a very complex crustal structure, as recently imaged by high-quality deep refraction data (Grad *et al.*, 2002; Grad and Guterch, 2006; Guterch and Grad, 2006). The NE boundary of the TTZ generally coincides with the SW boundary of the East European Craton (Królikowski and Petecki, 1997, 2002; Grabowska *et al.*, 1998; Pożaryski and Nawrocki, 2000; Grabowska and Bojdys, 2001; Grad *et al.*, 2002; Grad and Guterch, 2006) whilst its SW boundary lies within the Trans-European Suture Zone, which covers the Caledonian and Variscan deformation fronts and includes a number of partly hypothetical terranes (e.g. Pharaoh, 1999; for recent summaries see Grad *et al.*, 2002; Mazur and Jarosiński, 2006).

One of the major problems concerning the evolution of the MPT, and particularly of those its parts that contain thick Zechstein salts, is the relationship between regional subsidence during the deposition of the Mesozoic succession, and possible extensional faulting in the pre-Zechstein "basement". Tectonic subsidence curves reveal three major pulses

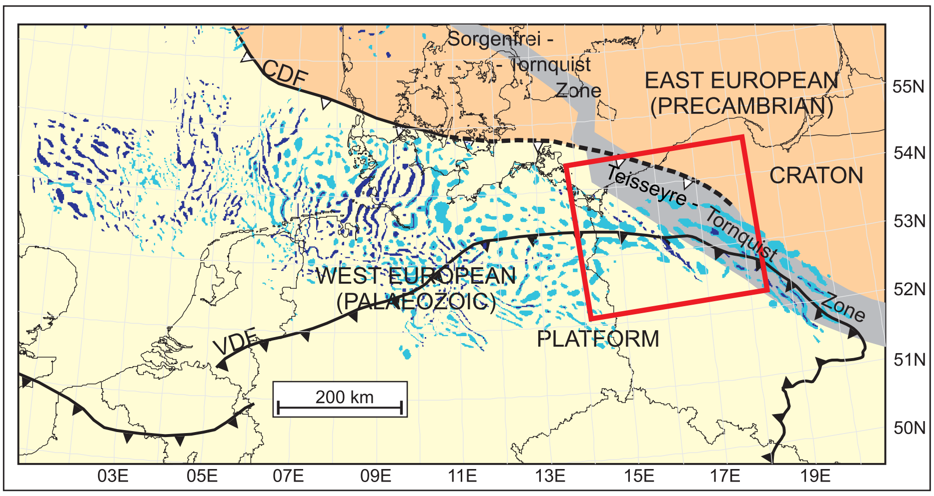

Fig. 1. Distribution of salt structures (light blue — salt pillows, dark blue — salt diapirs) related to the Southern Permian Basin (simplified after Lockhorst, 1998; Dadlez and Marek, 1998) on the background of the main basement provinces of Europe, showing the traces of the Sorgenfrei-Tornquist Zone and the Teisseyre-Tornquist Zone

VDF — Variscan deformation front, CDF — Caledonian deformation front (mainly after Pharaoh, 1999, generalized and partly hypothetical); rectangle — outline of study area shown in Figures 5–10 of increased subsidence rates during the Zechstein–Scythian, Oxfordian–Kimmeridgian and early Cenomanian, all of which are superimposed on an exponential thermal subsidence trend (Dadlez *et al*., 1995; Karnkowski, 1999; Stephenson *et al*., 2003). However, in the north-west and central segments of the MPT, that contain thick evaporites, there is no evidence for major, basin-scale extensional deformation within the Mesozoic sedimentary sequences that could be related to these pulses of accelerated basin subsidence. Instead, Mesozoic series are characterized by gradual thickness changes and by rather gentle regional depositional patterns that are not disturbed by major normal faults (*cf.* Dadlez, 2001, 2003; Wagner *et al*., 2002). Recently, this apparent contradiction has been resolved by implying a tectono-sedimentary model that involves regional mechanical decoupling of the sub-Zechstein "basement" from the supra-Zechstein Mesozoic series at the level of the Zechstein salts (Krzywiec, 2002*a*–*c*, 2004*a*–*c*). Under such a model, localized fault-related extensional strain at sub-Zechstein levels is regionally dissipated in the Mesozoic series. Moreover, localized Mesozoic subsidence anomalies may be attributed to salt withdrawal and/or dissolution, as seen e.g. in the North Sea (Clark *et al*., 1999; Cartwright *et al*., 2001). Nevertheless, pulses of extension-induced subsidence apparently overprinted the long-term regional thermal subsidence of the MPT, as evident elsewhere in Europe (see Ziegler *et al*., 2004).

During the Late Cretaceous–Paleocene partial to total inversion (*cf.* Bally, 1984) of the MPT, its uplifted axial part was subjected to deep erosion (Fig. 3; Dadlez and Marek, 1969; Pożaryski and Brochwicz-Lewiński, 1978; Dadlez, 1997*a*, *b*; Krzywiec, 2002*b*; Mazur *et al*., 2005; Scheck-Wenderoth and Krzywiec, in press). During inversion of the Baltic and Pomeranian segments of the MPT, the basement was uplifted above regional levels, whereas in the central, Kuiavian segment of the MPT, the top of the basement, although significantly uplifted as well, is still located below the regional level (Fig. 4; Dadlez, 2001). By contrast, the SE segment of the MPT is characterized by the largest uplift, as evidenced by the exposure of the pre-Permian basement in the Holy Cross Mts.

Detailed information on various aspects of the tectonic and sedimentary evolution of the Pomeranian segment of the MPT can be found in Pożaryski (1977), Jaskowiak-Schoeneich (1979), Dadlez (1980), Raczyńska (1987), Marek and Pajchlowa (1997) and Narkiewicz (1998).

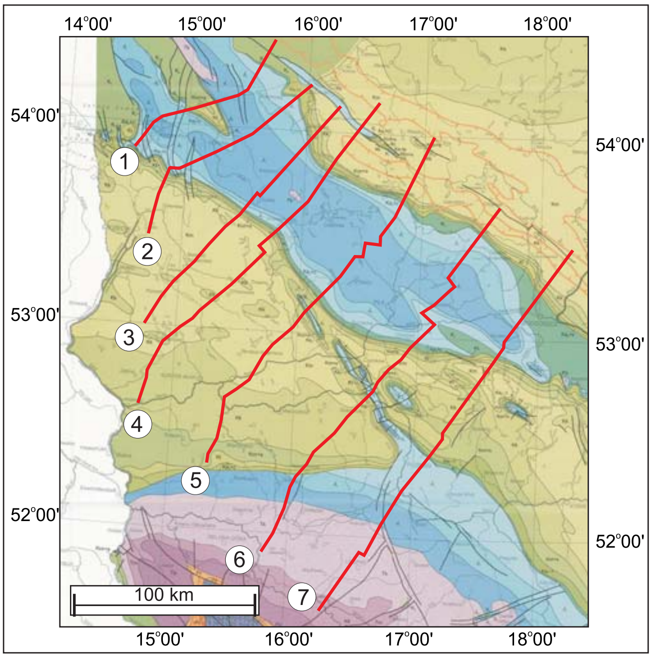

Fig. 3. Location of regional seismic reflection data (red lines) on the background of the geological map of Poland without Cenozoic cover (Dadlez *et al*., 2000)

This map covers slightly larger area than that from Figures 1 and 5–10 in order to show location of all regional seismic profiles from Figure 4; green colours — Cretaceous, blue colours — Jurassic, pink colours — Triassic (for more details see Dadlez *et al.*, 2000)

ROLE OF SALT DURING BASIN SUBSIDENCE AND INVERSION — BASIN-SCALE DECOUPLING EFFECTS ON DEPOSITIONAL PATTERNS

In the entire MPT, apart from very few exceptions (e.g. Antonowicz *et al*., 1994), there is a virtual lack of reliable seismic information on its structural configuration at sub-Zechstein levels. Therefore, only indirect information can be used to infer modes of basement tectonic activity responsible for the subsidence and inversion of this basin. Reference points for such indirect analysis were provided by the results of analogue modelling of subsidence and inversion processes.

Figure 2 shows a conceptual model for extensional subsidence and compressional inversion of a sedimentary basin that is defined by a single basement fault, with a salt layer covering the pre-kinematic sedimentary succession. This model is based on the original analogue model of Mitra and Islam (1994) that did not contain a salt layer and was focused on inversion processes. By introducing a salt layer and some changes in the supra-salt sedimentary cover, their model was modified in order to

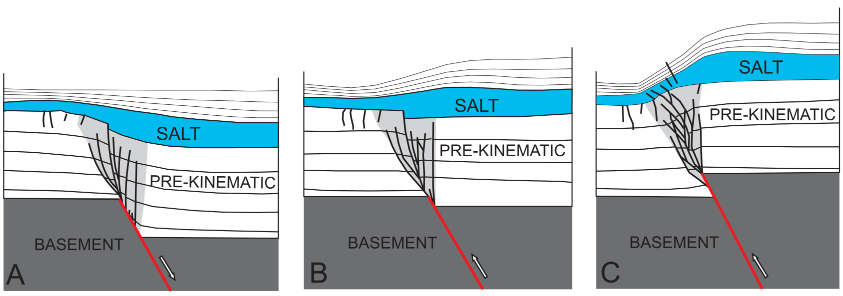

Fig. 2. Conceptual model for mechanical decoupling of pre-rift and syn-rift sediments separated by a thick salt layer, based on results of analogue modelling (modified after Mitra and Islam, 1994)

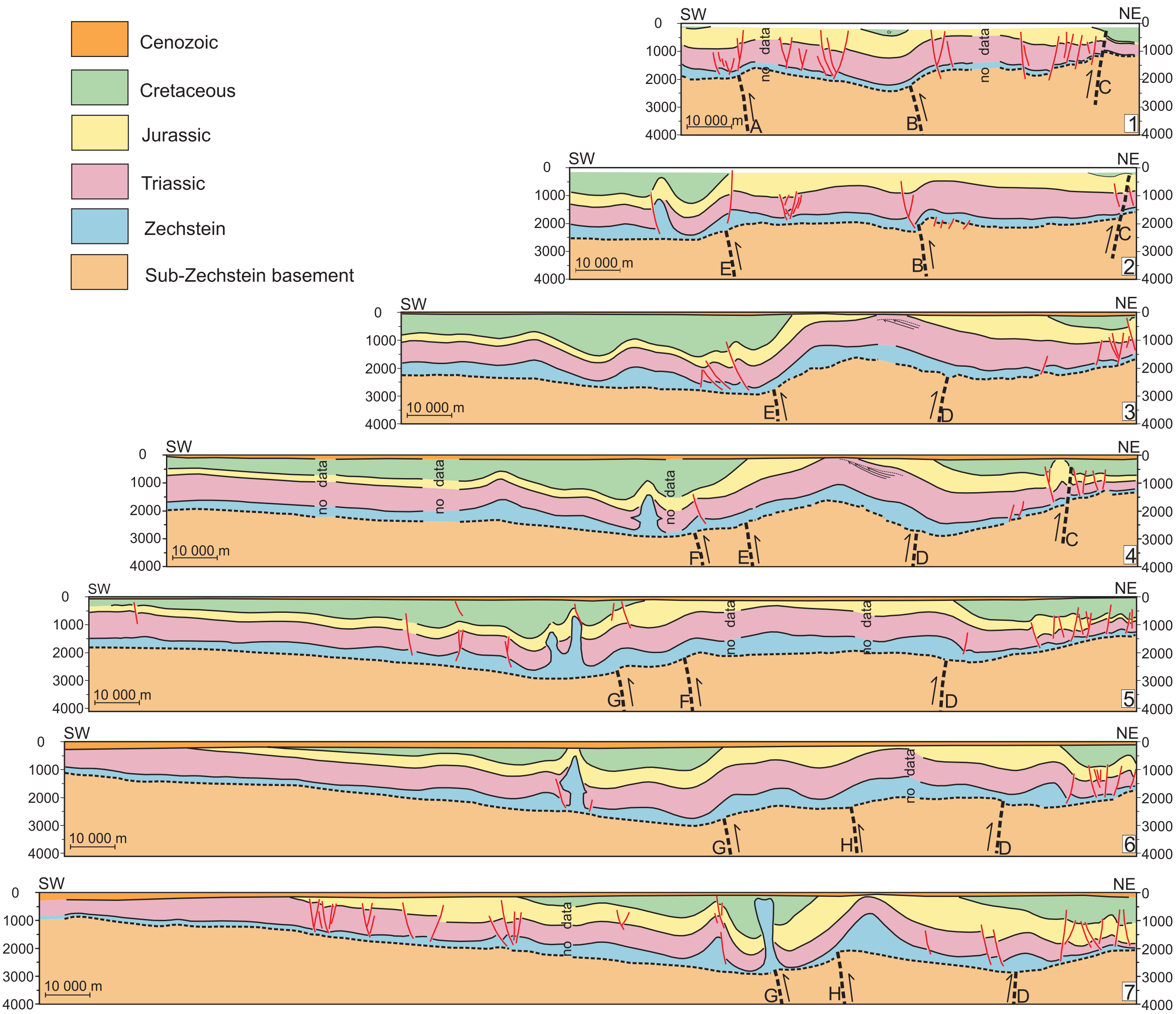

Fig. 4. Interpreted regional reflection-seismic profiles crossing the Pomeranian segment of the Mid-Polish Trough, illustrating structural relationship between sub-salt "basement", Zechstein salt and post-salt sedimentary series

The top of the sub-salt "basement" (black hatched line) has been simplified and does not show numerous small-scale faults; basement fault zones labelled A to H correspond to those shown in Figures 5–10; local intra-Upper Triassic unconformities are shown by thin black lines (profiles 3 and 4); vertical scale in miliseconds; for location see Figure 2

highlight concepts that find application in the indirect analysis of MPT basement tectonics.

The model presented in Figure 2 includes four building blocks, namely the deep ("crystalline") basement, its sub-salt pre-kinematic sedimentary cover, the ductile salt layer, and the supra-salt sedimentary succession that was deposited during basement extension and basin subsidence. The deep basement together with its sub-salt sedimentary cover can be regarded as the sub-salt "basement". In the MPT, the sub-Zechstein "basement" consists of the Rotliegend clastics which rest on an up to 20 km thick succession of low velocity sediments and meta-sediments that are underlain by a high velocity crust (Grad *et al.*, 2002; Grad and Guterch, 2006; Guterch and Grad, 2006). The Zechstein salt layer is overlain by the Triassic-Cretaceous sedimentary succession that can be regarded as the syn-kinematic supra-salt cover.

The stage shown in Figure 2A reflects subsidence of the post-salt basin that was controlled by localized extensional faulting of the basement and distributed faulting in its pre-salt sedimentary cover (*cf.* Hardy and McClay, 1999). Basement faulting triggered some salt movements and the localized growth of a salt pillow over the crest of which the supra-salt sedimentary cover is characterized by localized thinning. On a more regional scale, the supra-salt succession thickens gradually towards the basin centre and displays a grossly divergent pattern.

During partial basin inversion (Fig. 2B) the deep-seated basement fault is reactivated in a reverse mode, causing uplift of the entire hanging-wall block. Although only part of the extensional strain along this fault was recovered during its reverse reactivation, as evidenced by a remaining normal offset at top-basement level, the post-salt series are already uplifted above the regional level. Reverse reactivation of the discrete basement fault was accompanied by complex deformation along the distributed fault zone in the sub-salt sediments.

During total inversion of the basement fault (Fig. 2C) the top-basement of the hanging-wall block was uplifted above the level of the footwall block. Similarly, the distributed fault zone in the sub-salt sediments was also fully inverted whilst the supra-salt series were significantly uplifted.

As the analyzed model does not include syn- and post-inversion erosion, the thickness of the supra-salt cover is fully preserved. However, erosion of the elevated parts of the post-salt sediments, which were thickest in the axial parts of the now inverted basin, causes a significant reduction of their thickness. Furthermore, the small salt pillow that had developed near the sub-salt fault zone during basin extension is still preserved in its original position; the same applies to the high thickness gradients in the supra-salt succession (Fig. 2). Based on the model described above, these criteria can be used as proxies for the identification of potential sub-salt fault zones that were active during the entire basin evolution cycle. Such indirect indicators are often the only available tools for the analysis of the sub-salt "basement" tectonics as seismic data provide very little information on its configuration. In the MPT, the deepest reliably correlative seismic horizon is almost always the base-Zechstein reflector (top of the sub-salt "basement"). This only partly continuous reflector permits, however, to define at a regional scale the gross configuration of the sub-salt "basement" top. Main criteria for the identification of sub-salt fault zones that were active during the subsidence and inversion of the MPT are:

— in supra-salt series, the location of zones of high thickness gradients increasing towards the basin centre;

— structure of the top sub-salt "basement" as derived from the base-Zechstein reflector;

— location of early formed salt structures.

Implication for the identification of basement fault systems derived from the model described above (Fig. 2) can be directly applied to the analysis of the MPT, and more specifically to its NW Pomeranian and central Kuiavian segments that are characterized by thick Zechstein salts. Although various salt structures developed during the subsidence of the MPT, locally modifying sedimentation patterns, the entire basin is characterized on a regional scale by the gradual thickening of its Mesozoic series towards the basin centre (*cf.* Dadlez, 2003), except for the Upper Cretaceous and younger successions that were deposited during and after the inversion of the basin (*cf.* Krzywiec, 2002*b*, *c*, 2004*c*, *d*, 2006). The top of the sub-salt "basement" is characterized by significant structural variations that are closely related to salt structures and zones of high thickness gradients in the Mesozoic series.

SUB-SALT FAULT ZONES — INTERPRETATION OF SEISMIC DATA

The base-Zechstein structure of the Pomeranian segment of the MPT was mapped on the basis of regional seismic profiles that cross its axial parts that underwent maximum uplift and erosion, as evidenced by the subcrops of Jurassic and Triassic strata beneath Cenozoic deposits (Fig. 3). A selection of interpreted regional profiles, showing base-Zechstein, top-Zechstein, top-Triassic, top-Jurassic and base-Cenozoic, is given in Figure 4. Dadlez (2001) and Krzywiec *et al*. (2006) give more detailed descriptions of these profiles.

A key element of the interpretation was to identify potential sub-Zechstein fault zones that were active during the subsidence and subsequent inversion of the MPT, applying the above described three criteria. It must be stressed that fault zones shown on Figure 4 should be regarded only as a first-order approximation of potential fault zones occurring beneath the Zechstein salts. According to the model of Figure 2, the faults shown on Figure 4 immediately beneath the base-Zechstein are in fact distributed fault zones that are related to more focused faulting at deeper levels. The sub-Zechstein fault zones identified on seismic profiles were laterally correlated with the aide of the regional base-Zechstein map that was prepared by Papiernik *et al*. (2000). This way, a rather consistent picture of the sub-Zechstein fault zones, delimiting blocks that underwent differential inversion-related uplift, was achieved (Fig. 5; *cf.* Krzywiec *et al*., 2006). Considering the map view of these first-order approximation fault zones, it should be stressed that they presumably correspond to wider fault zones consisting of overlapping fault segments and intervening ramps. However, for the purpose of the regional analysis presented in this paper, such a simplification is justifiable, particularly in the face of the poor resolving power of available seismic data at pre-Zechstein levels.

In the analyzed Pomeranian segment of the MPT, eight fault zones, labelled A to H, were identified and correlated, three of which are well known from the literature. Fault zone A is the Adler-Kamień Fault Zone, fault zone B — the Trzebiatów Fault Zone, and fault zone C partly corresponds to the Koszalin-Chojnice Fault Zone. Zones A and B are related to the SW margin of the offshore part of the MPT located within the SW Baltic Sea (Kiersnowski and Buniak, 2006). As in this area Zechstein series are developed in a thin marginal facies,

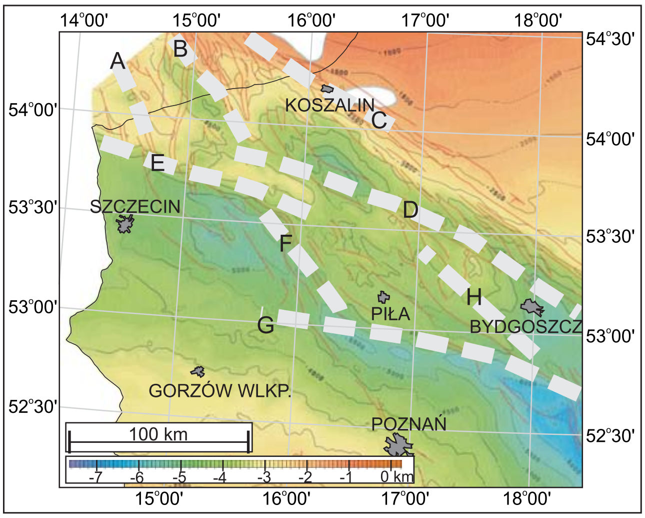

Fig. 5. Inferred basement fault zones A–H shown on the background of present-day base Zechstein salt depth map (from Papiernik *et al*., 2000)

faults active during the extensional subsidence of the basin, as well as during its inversion, extend from the basement upward into Mesozoic series (*cf*. Vejbæk *et al*., 1994; Schlüter *et al*., 1997; Krzywiec, 2002*b*; Mazur *et al*., 2005; Scheck-Wenderoth and Krzywiec, in press). Fault zone C forms part of the Koszalin-Chojnice Fault Zone that is defined as a rather wide deformation zone primarily in Mesozoic series that extends much further towards SE than fault zone C, as shown in Figure 5. Only close to the Baltic coast, the Koszalin-Chojnice Fault Zone is characterized by relatively small amounts of hard-linked sub- and supra-salt faulting, both normal and — later — reverse (Antonowicz *et al*., 1994; Strzetelski *et al*., 1995). For the purpose of this analysis, fault zone C was defined as a fault zone rooted within the sub-Zechstein basement, whereas the Koszalin–Chojnice Fault Zone includes also peripheral thin-skinned deformations that are detached within the Zechstein layer. Fault zones D–H are defined at the base-Zechstein level and do not extend upward into the Mesozoic series.

From Figure 5 it is clearly evident that the Pomeranian segment of the MPT is characterized by two intersecting fault systems. Fault zones D (in its NW segment), E and G define complex structure of the SW margin of the East European Craton, fault zones A, B, C, F and H are oriented NW–SE and follow the main trend of the Teisseyre-Tornquist Zone.

Although the fault zones A–H should be regarded as major basement discontinuities, they are not the only faults that affected pre-Zechstein levels during the evolution of the MPT. Good examples of smaller-scale fault systems are the faults that occur on the Fore-Sudetic Monocline to S and SE of Poznań (Kwolek, 2000) where they underlay Triassic graben structures (Fig. 4, SW part of profile 7). These faults that at sub-Zechstein level are characterized by significant strike-slip and only limited dip-slip displacements (Kwolek, 2000), are not shown in profile 7, owing to their negligible effect on basin-scale subsidence and inversion. Similarly, there are probably minor basement faults associated with the Drawno–Człopa salt structure, that apparently played also a subordinate role during basin subsidence and inversion (Krzywiec, 2004*d*, 2006).

SUB-SALT FAULT ZONES AND UPPER CRUSTAL STRUCTURE

The regional fault zones described above were compared with structural, gravity and magnetic maps in order to assess whether they coincide with the boundaries of major crustal blocks (see Krzywiec *et al*., 2006 for more comprehensive analysis and additional details).

In Figure 6 these fault zones are compared with the distribution of salt-related and other structures that were mapped in Mesozoic series (after: Dadlez and Marek, 1998; Lockhorst, 1998). From this figure it is clearly evident that salt structures are closely associated with the trend of the fault zones D–H and their intersections. This geometrical relationship suggests that faulting of the sub-Zechstein "basement" controlled the localization and development of salt-related structures.

From Figure 7, that shows the inferred basement fault zones superimposed on the Bouguer gravity map, it is apparent that major gravity anomalies occurring in the axial part of the MPT are roughly outlined by these fault systems. Basement blocks that were uplifted during basin inversion correspond to gravity highs whereas gravity lows denote blocks that did not undergo significant uplift. Detailed analyses of processed gravity data confirmed that these fault zones indeed coincide with zones of gravity gradients (*cf*. Krzywiec *et al*., 2006).

Similarly, there is good correlation between the inferred basement fault system and magnetic anomalies (Fig. 8). Of particular importance is the correlation of the West Pomeranian

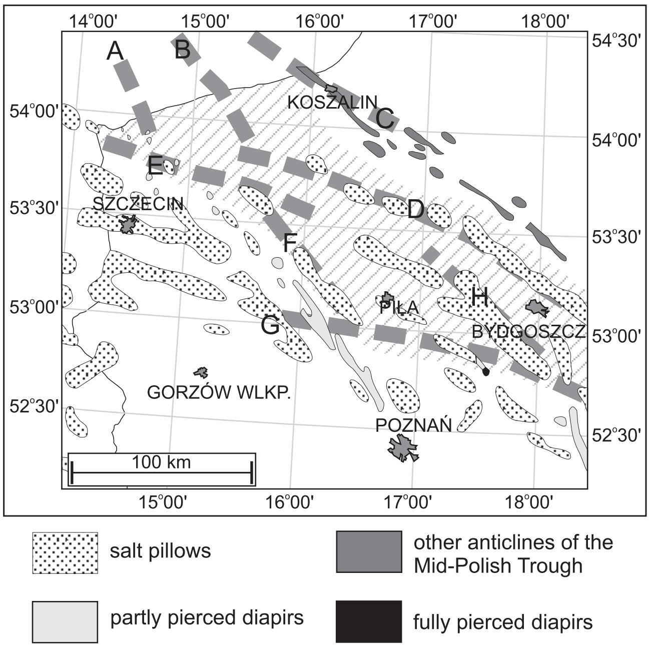

Fig. 6. Inferred basement fault zones A–H superimposed on a map showing the location of Zechstein salt structures (slightly modified after Dadlez and Marek, 1998; Lockhorst, 1998)

Patterned area — axial part of the Mid-Polish Trough that underwent maximum uplift and erosion and presently is devoid of the Upper Cretaceous cover

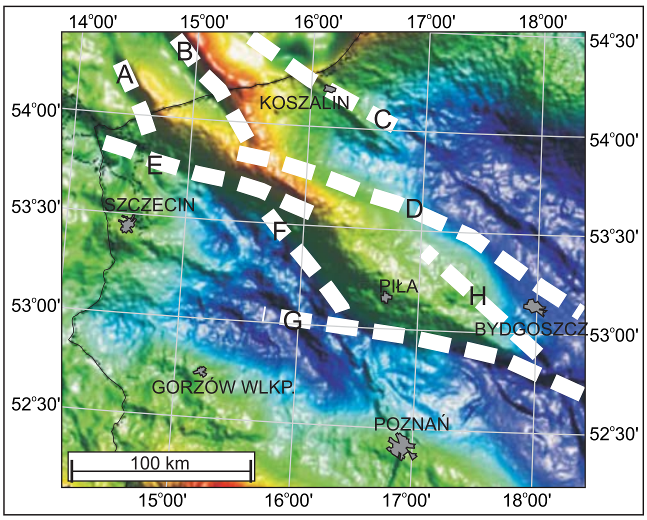

Fig. 7. Inferred basement fault zones A–H superimposed on the Bouguer gravity map of Poland (after Krzywiec *et al*., 2006)

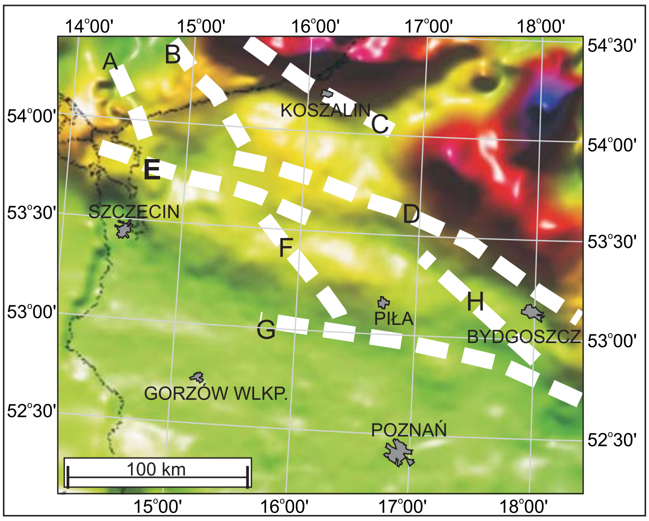

Fig. 8. Inferred basement fault zones A–H superimposed on the magnetic map of Poland (after Krzywiec *et al.*, 2006)

magnetic anomaly (Petecki, 2001, 2002; Królikowski, 2006*a*, *b*) with the basement fault zones, and specifically fault zone G that parallels the SW edge of this magnetic anomaly and, at the same time, the SW margin of the MPT. This suggests that this anomaly is related to a basement block whose boundary faults (especially fault zone G) were crucial in the localisation and evolution of this part of the MPT (Krzywiec *et al.*, 2006).

COMPARISON OF SUB-SALT FAULT SYSTEM WITH REGIONAL TRIASSIC AND JURASSIC ISOPACH MAPS

In order to further test whether the inferred sub-Zechstein basement fault system was indeed active during the subsidence of the MPT, it was compared with regional isopach maps of Triassic and Jurassic series (Fig. 9; Dadlez, 2003).

The thickness of the Bunter series characteristically increases in successive steps towards the basin centre (Fig. 9A)

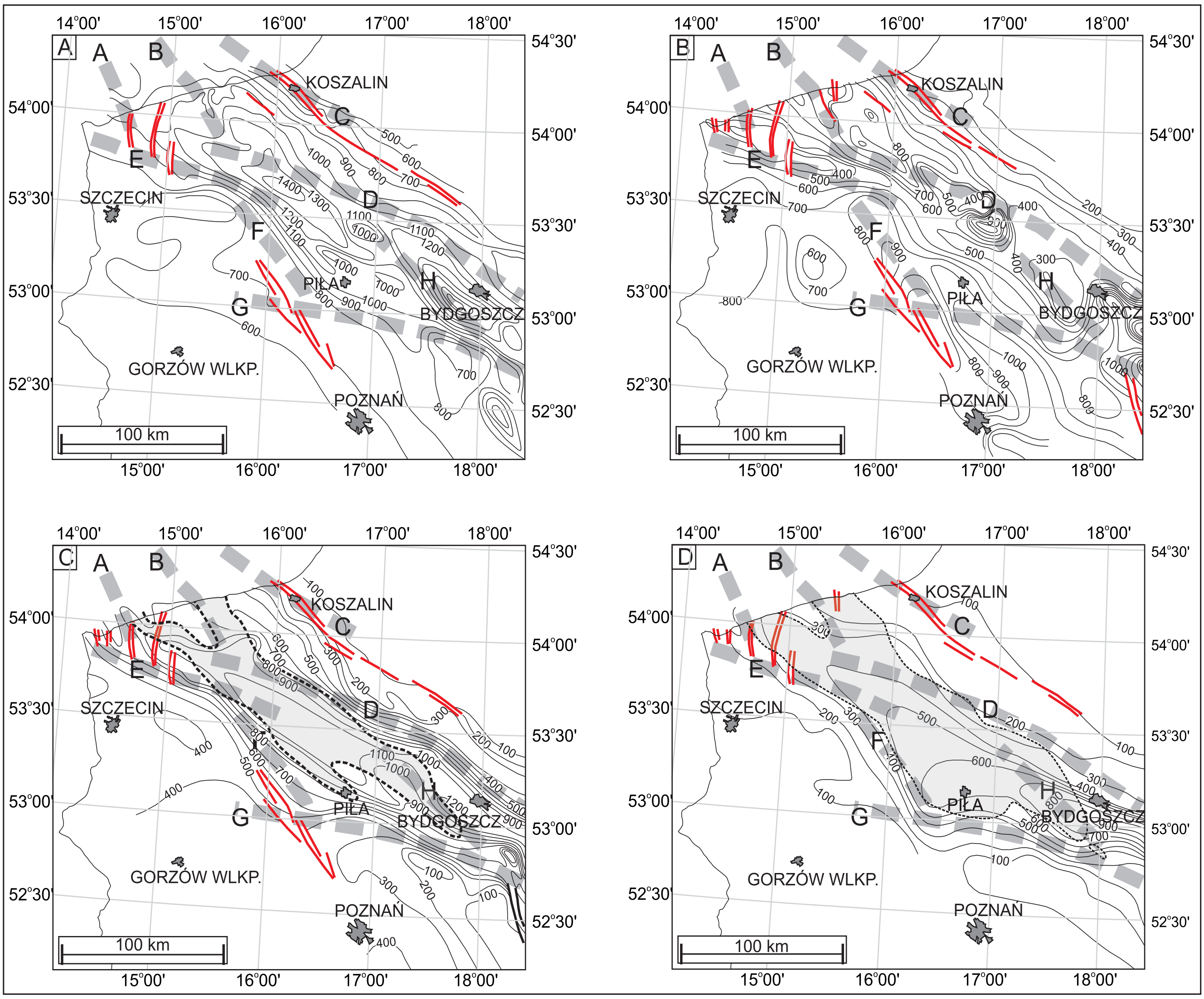

Fig. 9. Inferred basement fault zones A–H superimposed on regional isopach maps of Triassic and Jurassic series (redrawn from Dadlez, 2003)

Contour intervals in metres: A — Bunter thickness, B — Muschelkalk and Keuper thickness, C — Lower Jurassic thickness, D — Middle Jurassic thickness; grey areas denote erosion of the mapping interval across the inversion axis of the Mid-Polish Trough that is clearly outlined by the inferred sub-salt basement fault zones. Zones of maximum thickness gradients coincide in many cases with the inferred basement fault zones D, F, G and H whereas smaller-scale thickness variations (Dadlez, 2003) may be attributed to early salt movements, known from various parts of the basin (e.g. Sokołowski, 1966; Burliga, 1996; Krzywiec, 2004*b*, *c*).

Similarly, the thickness distribution of the Muschelkalk-Keuper succession appears to be controlled by the inferred basement fault system, with fault zones E, F and G playing a primary role (Fig. 9B). Muschelkalk-Keuper series thin towards the axial parts of the MPT with respect to its flanks. This thinning, however, is the result of the intra-Triassic erosion that apparently was not corrected for in this thickness map, and as a result could not be used as a basin-scale indicator of overall Middle–Late Triassic subsidence pattern. This erosional event is attributed to an important intra-Keuper unconformity, clearly evident on seismic lines, that is probably related to early salt movements in the axial parts of the basin. Corresponding thickness changes of the Upper Triassic series are mainly observed along the NE flank of the basin, and are schematically shown on profiles 3 and 4 in Figure 4. Basement faulting presumably triggered the underlying salt movements (*cf.* Krzywiec, 2004*b*, *c*).

The isopach map of Lower Jurassic series shows again a distinct thickness increase towards the axial parts of the MPT where they were partly eroded in response to inversion movements (grey area in Fig. 9C). Correspondingly, reconstructed thickness values given for this part of the basin must be regarded as approximate. Nevertheless, from Figure 9C it is evident that sub-salt basement faulting exerted a strong control on the thickness development of Lower Jurassic series. Fault zones E, F and G controlled the SW margin of the MPT, while fault zones C and D controlled its NE margin.

In the Pomeranian segment of the MPT, Middle Jurassic series have been deeply truncated and partly even totally eroded due to the inversion-related uplift of its axial part (Fig. 3). Consequently, for these areas, the isopach map given in Figure 9D shows tentative values only, with observed thickness values being restricted to the marginal and SE axial parts of the basin. Nevertheless, the gross thickness distribution is compatible with the concept of activity along inferred sub-salt basement fault zones controlling basin subsidence, especially along the SW basin margin that coincides with fault zones E, F and G. The axial part of the basin is clearly delimited by these three fault zones and by fault zone D marking its NE flank.

The isopach map of the Upper Jurassic series (Dadlez, 2003) is very poorly constrained as inversion-induced erosional truncation and total removal of these deposits is rather widespread, particularly within the Pomeranian segment of the MPT. Therefore, this map was not analysed in this paper.

DISCUSSION

Results presented in this paper differ in several aspects from previous tectono-sedimentary models of the Triassic–Jurassic evolution of this part of the MPT that stressed the dominant control of NW–SE oriented fault zones on subsidence patterns (Dadlez, 1997; Dadlez *et al*., 1998). As it was shown above, tectonic activity along a more complex sub-Zechstein fault system, consisting of NW–SE and WNW–ESE striking elements, presumably controlled the Triassic–Jurassic subsidence pattern of the Pomeranian segment of the MPT.

Concluding from his analysis of Mesozoic sedimentary thicknesses, Dadlez (2003) stated that no fault zones bordering the MPT were active during its Triassic and Jurassic subsidence. By contrast, results presented in this paper show that the Triassic and Jurassic subsidence patterns of the MPT were controlled by extensional tectonics along discrete sub-Zechstein fault zones, displacements along which were dissipated in the thick Zechstein salts, thus giving rise to gradual thickness changes in the Mesozoic series. This is fully compatible with the model of extensional basins in which pulses of tectonic subsidence are directly related to basement faulting whilst the basement is decoupled from the syn-rift sediments by a ductile evaporite layer (*cf.* Brun and Nalpas, 1996). Therefore, the absence of faulting in the supra-salt cover cannot be regarded as a proof that the evolution of such a basin was not related to ongoing crustal extension (rifting). Indeed, Dadlez (2003), noting the absence of major extensional faults in the Mesozoic series of the MPT, accepted the model of a decoupled basin in which active extensional faulting in the sub-salt basement is upwards attenuated in the thick Zechstein evaporites. In fact, the presence of the regional sub-salt basement fault zones A–H, described in this paper, together with a decoupled model for the Mesozoic evolution of the MPT, satisfies active basement extension, the existence of bordering faults, and flexure-induced (forced folding) un-faulted thickness changes in the Mesozoic syn-extensional series. A similar interaction between basement faulting, a thick salt layer and its supra-salt sedimentary cover was documented in many other basins, with good example provided by the Dead Sea Basin. In this basin, which is presently undergoing active transtensional rifting, the presence of thick Pliocene salt and active Quaternary basement normal faulting resulted in the development of numerous salt structures and in different degrees of decoupling between thick-skinned basement tectonics and thin-skinned cover tectonics (*cf.* Al-Zoubi and Ten Brink, 2001; Al-Zoubi *et al*., 2001; Larsen *et al*., 2002).

Moreover, the regional analysis of the sub-Zechstein fault pattern does not support the concept that the MPT is segmented by a system of SW–NE striking transverse strike-slip faults that were active during its Triassic-Jurassic subsidence, as proposed by Dadlez (1994, 1997) and shown in Figure 10 for the Pomeranian segment. This concept is largely based on the assumption that during the Late Cretaceous inversion of the MPT, reactivation of these strike-slip faults may have caused lateral displacement of some salt structures (*cf.* Dadlez, 1994, his figs. 1 and 2). Whilst in the Pomeranian segment of the MPT there is no reflection seismic evidence for wrench movements along such SW–NE striking fault zones during basin inversion, the Grójec Fault Zone, separating the Kuiavian and the Holy Cross segments, is the only notable exception (Krzywiec, 2002*b*). Indeed, the sub-salt basement fault system proposed in this paper for the Pomeranian segment of the MPT fully explains its Triassic and

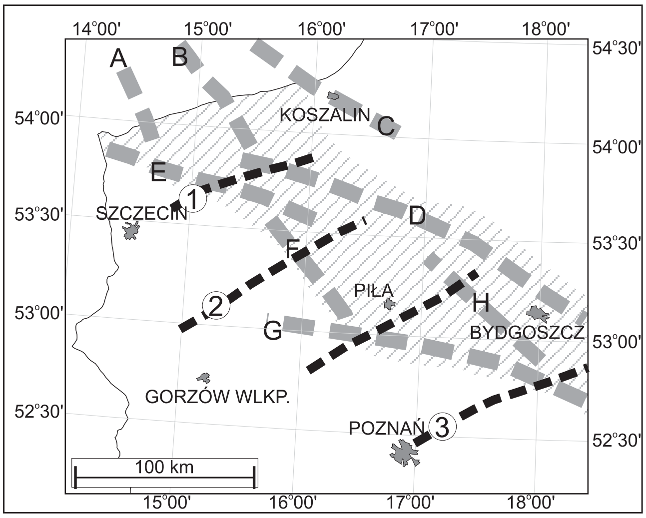

Fig. 10. Inferred basement fault zones A–H compared to transverse major strike-slip fault zones (black bars) proposed by Dadlez (1994, 1997*b*)

1 — Szczecin-Miastko Fault Zone, 2 — Choszczno-Szczecinek Fault Zone, 3 — Poznań-Toruń Fault Zone; patterned area — axial part of the Mid-Polish Trough that underwent maximum uplift and erosion (after Dadlez and Marek, 1998)

Jurassic subsidence patterns and present-day structural configuration and does not require invoking transverse strike-slip zones for which there is no evidence on available seismic data.

Similarly, the regional structural model developed for the Polish Basin by Lamarche and Scheck-Wenderoth (2005) is not fully compatible with the sub-salt basements structure of the Pomeranian segment of the MPT as presented in this paper. Whilst the geo-seismic profiles given in Figure 4 clearly illustrate that in the axial parts of the MPT the sub-salt basements was uplifted to variable degrees during basin inversion, the cross-sections given by Lamarche and Scheck-Wenderoth (2005, their fig. 5 profiles 1–4) suggest that it was not affected by inversion tectonics. Moreover, they postulate that the Pomeranian and Kuiavian segments of the MPT were separated by a transverse fault that was active during their subsidence as well as during their inversion. As shown in this paper, the structural configuration of the sub-salt basements and the gross Triassic-Jurassic subsidence patterns in the transitional area between the Pomeranian and Kuiavian segments of the MPT can be readily explained by tectonic activity along the proposed basement fault zones D, F, G and H (see Figs. 5–10) without invoking important transversal faulting. In this context, it should be stressed again that interpretation of a large number of good quality seismic profiles available for this area precludes the presence of important SW–NE striking transverse wrench faults, comparable to the Grójec fault (Krzywiec, 2002*b*).

Finally, it should be noted that the inferred basement fault system of the Pomeranian segment of the MPT is compatible with the gross basement tectonics of the Holy Cross Mts. segment of the MPT (Fig. 11; *cf*. Krzywiec *et al*., 2006). The Holy Cross Fault Zone (HCFZ) that is well defined by field studies, strikes in the same WNW direction as the fault zones E, D (in its NW segment) and G of the Pomeranian segment. The HCFZ played a prominent role during the Triassic-Jurassic evolution of the SE part of the MPT by controlling, together with the Nowe Miasto-Iłża Fault Zone, the development of a subsidence centre (Hakenberg and Świdrowska, 1997; Krzywiec *et al*., 2005; Gutowski *et al*., 2005; Gutowski and Koyi, submitted). The Nowe Miasto-Iłża Fault Zone coincides with the SW margin of the East European Craton and forms the continuation of fault zone D of the Pomeranian segment of the MPT. The HCFZ underwent a complex Palaeozoic tectonic history and was reactivated during Mesozoic times, first during subsidence of the MPT and later during its inversion (see Krzywiec *et al*., 2006 for detailed description and further references). Therefore, by analogy, and taking into account the very similar orientation of fault zones of the Pomeranian and Holy Cross segments of the MPT, it is likely that the inferred basement fault zones mapped in the NW part of the basin controlled its Triassic–Jurassic subsidence. A main difference is the "decoup-

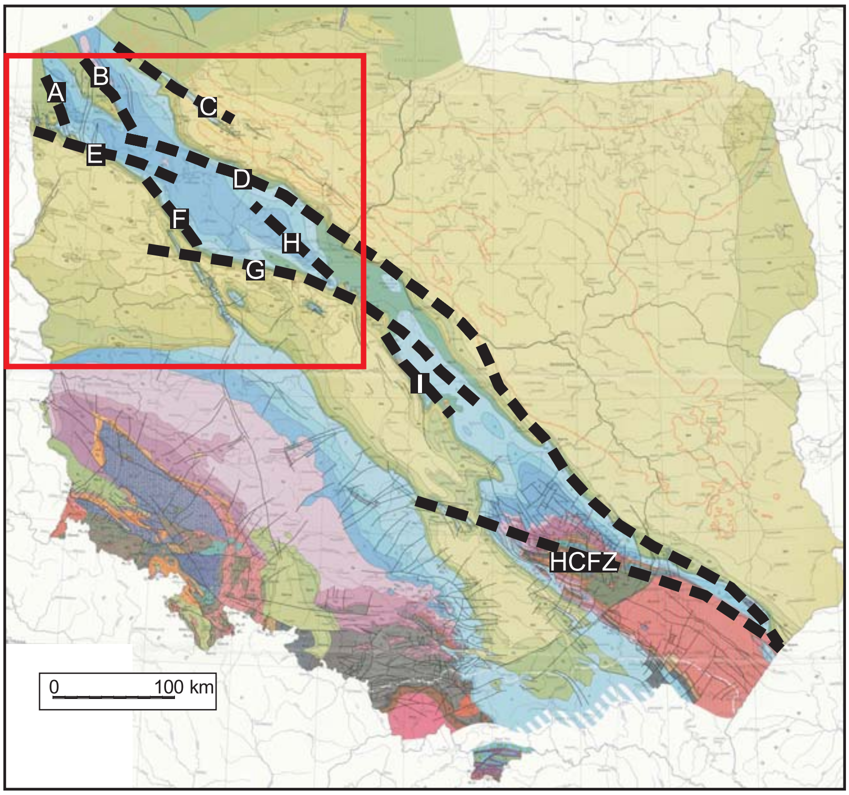

Fig. 11. Inferred major basement fault zones for the entire Mid-Polish Trough (after Krzywiec *et al*., 2006) superimposed on the geological map of Poland without Cenozoic deposits (Dadlez *et al*., 2000)

HCFZ — Holy Cross Fault Zone; red rectangle — area shown in Figures 5–10; green colours – Cretaceous, blue colours — Jurassic, pink colours — Triassic (for more details see Dadlez *et al.,* 2000) ling"effect of the thick Zechstein evaporites, both during subsidence and thin-skinned inversion tectonics that is restricted to the NW parts of the basin. Otherwise, basement tectonic processes operating at a basin scale appear to be consistent between the different basin segments.

CONCLUSIONS

Based on the interpretation of regional reflection-seismic lines and geological and potential-field maps, a new model was developed for the sub-Zechstein fault system that was active during evolution of the Pomeranian segment of the MPT. This model differs in many aspects from previously published models and concepts. The following criteria were used to identify the location of the different basement fault zones:

— thickness variations of the Triassic and Jurassic post-salt sediments;

— structural configuration of the sub-Zechstein salt "basement";

— location of salt structures;

— gravity data;

— magnetic data.

The NE boundary of the MPT was generally controlled by the SW margin of the East European Craton, whilst its SW boundary coincides with a system of fault zones probably inherited from earlier tectonic phases. Identified sub-Zechstein fault zones coincide closely with boundaries of magnetic and gravity features observed in the Pomeranian segment of the Mid-Polish Trough, as well as with main inversion structures and salt structures. They also show very good correlation with gross thickness patterns of the Triassic-Jurassic successions.

The inferred basement fault system is fully compatible with published models for extensional sedimentary basin in which the basement is decoupled from the syn-rift sediments by a thick salt layer. Moreover, this fault system is also compatible with the regional scale basement structure and basin evolution of the MPT, including its SE Holy Cross segment where some basement faults are exposed and where the absence or small thickness of Zechstein evaporites provides for linked deformation of the basement and the overlying sedimentary cover.

The results of the study presented in this paper support an extensional evolution of the MPT during Triassic and Jurassic times that was superimposed on the long-term thermal subsidence of the basin, reflecting the decay of lithospheric-scale thermal anomalies that were introduced during the latest Carboniferous-Early Permian pulse of wrench faulting and magmatic activity.

Future work should include comprehensive testing of this model, including 2D balancing and palinspastic restoration of geological cross-section to reconstruct the extensional subsidence and compressional inversion of the basin, taking into account complex salt tectonics (*cf.* Canérot *et al.*, 2005). This should be coupled with 3D analogue modelling aimed at simulating basin-scale processes (*cf.* Dooley *et al.*, 2005).

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