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Structural inversion of the Pomeranian and Kuiavian segments of the Mid-Polish Trough — lateral variations in timing and structural style

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Seven high-quality reflection-seismic lines, calibrated by wells, were interpreted in an effort to assess the timing of inversion and the structural configuration of the Pomeranian and Kuiavian segments of the Mid-Polish Trough. Seismostratigraphic analyses of the Upper Cretaceous successions imaged by these seismic lines in the NE and SW marginal troughs of the Mid-Polish Swell document important along-strike stratigraphic and structural changes. Thickness variations of the Upper Cretaceous series, combined with the development of erosional unconformities and associated tectonic deformations indicate that inversion movements commenced during the late Turonian and intermittently persisted into the Maastrichtian and Paleocene. Earliest inversion movements were focused on the margins of the Mid-Polish Trough where Mesozoic sequences are decoupled from the sub-Zechstein series by Zechstein salts. Whereas the NE margin of the Mid-Polish Trough is devoid of compressionally reactivated salt structures, its SW margin is characterized by strong inversion-related salt tectonics. Progressive inversion of the axial parts of the Mid-Polish Trough was accompanied by uplift of its pre-Zechstein floor to and above the level of flanking, non-inverted areas, and by deep truncation of Mesozoic series across the culmination of the evolving Mid-Polish Swell. Inversion movements ceased towards the end of the Paleocene, as evidenced by the burial of the Mid-Polish Swell beneath essentially flat lying Eocene and younger series. Turonian-Paleocene inversion of the Mid-Polish Trough is coeval with the inversion of the Bohemian Massif, the North German Basin and the Sorgenfrei-Tornquist Zone. Inversion of the Mid-Polish Trough is considered to have been controlled mainly by compressional intraplate stresses that built up in the Carpathian foreland during the collision of the Inner Carpathian orogenic wedge with the European passive margin, attesting to their increasing mechanical coupling, commencing during the Turonian. These stresses relaxed, however, with the end-Paleocene onset of imbrication of the Outer Carpathian domain, reflecting decoupling of the Carpathian orogenic wedge from its foreland.

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INTRODUCTION

Inversion of sedimentary basins has been the subject of increasing research since the early 1980's. The kinematics of basin inversion, as well as the relationship between the development of underlying compressional intraplate stresses and plate boundary processes (orogenic belts and sea-floor spreading axes), have been addressed by numerous papers (e.g. Ziegler, 1982, 1988, 1990; Cooper and Williams, 1989; Letouzey, 1990; Coward, 1994; Buchanan and Buchanan, 1995; Ziegler *et al*., 1995, 1998, 2002; Brun and Nalpas, 1996; Dèzes *et al*., 2004). Intraplate compressional phenomena, occurring often at considerable distance from plate margins, include the inversion of extensional basins (e.g. Mid-Polish Trough), upthrusting of basement blocks (e.g. Bohemian Massif, Rocky Mts.) and broad-scale lithospheric folding (e.g. down-warping of North Sea Basin, uplift of Fennoscandian Shield) (Ziegler *et al*., 1998). Inversion of extensional sedimentary basins involves compressional/transpressional reactivation of their fault systems as reverse fault zones (Brun and Nalpas, 1996), uplift of the basin floor and folding of the basin fill, reflecting a commensurate reduction of the basin volume. Additional mechanism inducing inversion of sedimentary basins, especially during its late phases, could be plate-wide stress relaxation as recently proposed by Nielsen *et al*. (2005). Depending on the degree of basin inversion (partial, total), erosional truncation of the uplifted sediments can lead to partial or even to complete destruction of a pre-existing basin (Hayward and Graham, 1989). Particularly during the early phases of basin inversion, intra-basinal reverse faulting, causing localized uplift and erosion, is often associated with the deposition of wedge-shaped sedimentary series, characterized by local dispersal patterns and unconformities, in adjacent depressions (Cartwright, 1989).

A very important aspect of basin inversion is the dating of its onset and its main phases. Basin inversion, and related uplift and erosion, is a destructive process during which large amounts of sediments can be eroded and re-deposited. Inversion-induced erosion can affect sediments deposited during the syn- and post rift stages, as well as sediments deposited during early stages of basin inversion. After a significant amount of inversion and uplift of the axial parts of a basin, the only remaining sedimentary record of its inversion history can often be found only in the so-called marginal troughs, representing remnants of depocentres that had developed on the flanks of the uplifted axial parts of the basin.

The presence of a thick salt layer at the base of syn-rift sedimentary series significantly influences the structural style of extension- as well as inversion-related deformation of the post-salt series by decoupling them from the pre-salt “basement” (e.g. Withjack and Callaway, 2000; *cf.* Krzywiec, 2002*a*, *b*, 2004*a*, *b*). The flanks of extensional sedimentary basins that contain a thick basal salt layer and display a well-developed axial subsidence centre that is delimited by major fault zones, are often characterized by an array of peripheral extensional detachment structures (e.g. Stewart, 1999; Withjack and Callaway, 2000; Dooley *et al.*, 2005). During basin inversion, the presence of a thick salt layer causes stress partitioning between the sub-salt basement (thick-skinned inversion tectonics) and the supra-salt sedimentary succession (thin-skinned or cover inversion tectonics) (e.g. Nalpas *et al.*, 1995).

Such basin scale geometries are shown schematically in Figure 1. In this simple model, subsidence of the axial parts of the basin was accommodated by two major sub-salt basement faults. Due to the basin-scale mechanical decoupling effect of the salt layer, syn-rift series are thicker in the basin centre and thin without faulting towards its flanks. The peripheral simple grabens or half-grabens, as shown on Figure 1 on both flanks of the basin, developed either in response to thin-skinned extension and/or by salt flow (pillows or diapirs; Vendeville and Jackson, 1992*a*, *b*; Koyi *et al.*, 1993; *cf.* also Krzywiec *et al.*, 2006; Krzywiec, 2006), depending on the complex interaction of such parameters as the rate and amount of thick- *vs.* thin-skinned extension and the thickness of the salt layer and its overburden. During the earliest inversion phases such peripheral salt-related structures may focus compressional stresses. This can be attributed to the fact that during early inversion phases, subsidence of the basin centre slows down and gradually reverses in response to slow reverse movements along its basement faults, while the detached and salt-cored peripheral structures, forming important weakness zones within the supra-salt cover, focus compressional stresses and become progressively inverted. Therefore, analysis of the post-salt internal geometry of such peripheral structures may provide information on the onset and the early phases of basin inversion, whilst the sedimentary record of these processes may be not preserved in the axial part of the basin that were subsequently strongly uplifted and eroded.

The Late Cretaceous-Paleocene intraplate compressional deformations play an important role in the tectonic framework of Western and Central Europe. They include an array of inverted Mesozoic basins as well as upthrusted blocks of the pre-Permian basement (Fig. 2; e.g. Dadlez, 1980; Liboriussen *et al*., 1987; Schröder, 1987; Norling and Bergström, 1987; Vejbæk and Andersen, 1987; *cf.* Ziegler, 1987, 1988, 1990; Stackenbrandt and Franzke, 1989; Dronkers and Mrozek, 1991; Michelsen and Nielsen, 1993; Mogensen and Jensen, 1994; Ziegler *et al*., 1995, 2002; Michelsen, 1997; Erlström *et al*., 1997; Gras and Geluk, 1999; Kossow and Krawczyk, 2002; Krzywiec, 2002*a*; De Lugt *et al*., 2003; Kockel, 2003; Otto, 2003; Mazur *et al*., 2005). It is generally accepted that the compressional/transpressional stresses which induced these intraplate deformations are related to successive collisional phases in the Alps and the Carpathians, and that these stresses were transmitted over large distances from the collision zones into the foreland, with ridge-push forces exerted by the N Atlantic sea-floor spreading axes playing a contributing role (e.g. Vejbæk and Andersen, 1987, 2002; Ziegler 1987; Golonka *et al*., 2000; Ziegler *et al*., 2002). Partly alternative model for the inversion tectonics of the sedimentary basins within the interior of the European continent has been recently proposed by Nielsen *et al.* (2005). In this model, early (Late Cretaceous) phase of inversion is related to increased in-plane compressional stresses induced at the continental collision zones, but late (Paleocene) phase could be attributed to a plate-wide relaxation of in-plate compressional stresses instead of their continued build-up.

In this paper seismic examples of Late Cretaceous inversion tectonics, syn-kinematic sedimentation and erosion are presented from the NE and SW flanks of the strongly inverted and uplifted axial part of the Polish Basin. The main goal of this study was to analyze the timing and lateral variations in structural style of inversion tectonics of the NW (Pomeranian) and central (Kuiavian) segments of the Mid-Polish Trough.

GEOLOGICAL SETTING

The Mid-Polish Trough (MPT) corresponds to the axial part of the Polish Basin that formed part of the of Permian-Mesozoic system of epicontinental basins of Western and Central

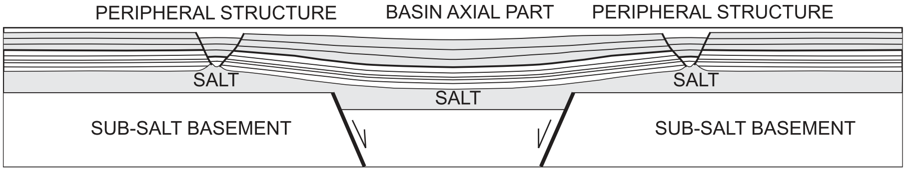

Fig. 1. Schematic model of a sedimentary basin that evolved above salt layer during thick-skinned extension (modified after Withjack and Callaway, 2000)

See text for further explanations

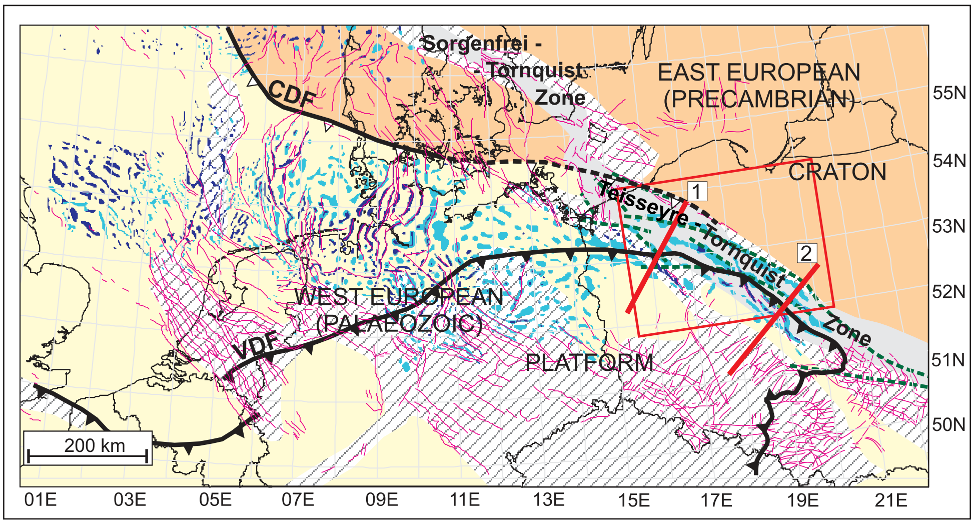

Fig. 2. Schematic extent of the Alpine foreland inversion in Western and Central Europe (patterned area; after Ziegler, 1990; Ziegler *et al.*, 2002, modified), showing salt structures related to Permian Basins (in blue; simplified after Lockhorst, 1998; Dadlez and Marek, 1998), and main faults (in dark pink; after Mazur *et al.*, 2005)

VDF — Variscan Deformation Front, CDF — Caledonian Deformation Front (mainly after Pharaoh, 1999, generalized and partly hypothetical); dark blue — salt diapirs, light blue — salt pillows; red rectangle — study area (*cf.* Figs. 4 and 5), red lines — two regional seismic profiles from Figure 3; green hatched lines — basement tectonic zones (partly inferred) active during Mesozoic subsidence and inversion of the Mid-Polish Trough (after Krzywiec *et al.*, 2006; Krzywiec, 2006); note that in Central Europe foreland inversion was focused on the Sorgenfrei-Tornquist Zone and the Teisseyre-Tornquist Zone (grey area)

Europe (Ziegler, 1990). The MPT evolved along the NW–SE trending Teisseyre-Tornquist Zone (TTZ; *cf.* Kutek and Głazek, 1972; Pożaryski and Brochwicz-Lewiński, 1978; Dadlez *et al.*, 1995; Dadlez, 1997*a*, *b*, 1998; Kutek, 2001) that is one of the most fundamental lithospheric boundaries in Europe and extends from the Baltic Sea to the Black Sea (*cf.* Thybo *et al.*, 2002). It is characterized by a very complex internal structure, imaged recently on high-quality deep refraction data (Grad *et al.*, 2002; Dadlez *et al.*, 2005; Guterch and Grad, 2006*a*, *b*). The Sorgenfrei-Tornquist Zone forms the NW prolongation of the TTZ (Pegrum, 1984; Michelsen, 1997).

The NE boundary of the TTZ generally coincides with the SW boundary of the East European Craton (*cf.* 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 so-called Trans-European Suture Zone (Królikowski, 2006). This is a wide zone entraining the fronts of the Caledonian and the Variscan orogens and various — sometimes only hypothetical — terranes (for details see Grad *et al.*, 2002; Mazur and Jarosiński, 2006; Nawrocki and Poprawa, 2006).

During the Permian stage of its evolution, the MPT formed the easternmost part of the Southern Permian Basin (Kiersnowski *et al.*, 1995; Van Wees *et al.*, 2000). The MPT was filled with several kilometres of Permian-Mesozoic sediments, including a thick Zechstein salt layer (Marek and Pajchlowa, 1997; Dadlez *et al.*, 1998). Zechstein salts account for the development of a complex system of salt structures in the central and northwestern segments of the Mid-Polish Trough (Fig. 2; for details see e.g. Pożaryski, 1977; Tarka, 1992; Krzywiec, 2004*a*, *b*). Salt movements were initiated during the Early Triassic, locally significantly modifying subsidence patterns (*cf.* Krzywiec, 2004*a*, *b*, 2006).

The Polish Basin experienced long-term thermal subsidence, commencing in the Permian and lasting until the Late Cretaceous, that was punctuated by three major pulses of extension-related accelerated tectonic subsidence during Zechstein to Scythian times, in the Oxfordian to Kimmeridgian, and in the early Cenomanian (Dadlez *et al.*, 1995; Stephenson *et al.*, 2003). Throughout the Mesozoic, regional subsidence patterns of the Polish Basin were dominated by the development of the NW–SE trending MPT, with only minor modifications imposed mainly by lateral salt movements. In the axial parts of the MPT, the observed depositional architecture and thickness patterns preserve the record of its extensional and inversion-related evolution.

For the entire MPT, apart from very few exceptions (e.g. Antonowicz *et al.*, 1994), there is a general lack of reliable seismic information on its internal structure at the sub-Zechstein levels. Therefore, only indirect information can be used to infer modes of basement tectonic activities responsible for its subsidence and inversion. A recently developed model for sub-Zechstein basement tectonics shows complex array of NW–SE and WNW–ESE striking fault zones (Fig. 2; *cf.* Krzywiec *et al.*, 2006; Krzywiec, 2006) that played an important role during the Mesozoic subsidence and subsequent inversion and uplift of the MPT. Inferred sub-Zechstein fault zones are shown on the regional seismic profiles given in Figure 3 (for detailed explanations see Krzywiec, 2006).

The Polish Basin was inverted during the Late Cretaceous and Paleocene, resulting in the uplift and erosion of its axial part, which presently forms a regional antiform structure, referred to as the Mid-Polish Swell (Fig. 3), that is outlined by the Cenozoic subcrop of Cretaceous and older rocks (Fig. 4). The NW Pomeranian segment of the MPT underwent full inversion, as evidenced by uplift of the sub-salt "basement" above the surrounding flanking areas (Fig. 3, profile 1), whilst the central Kuiavian segment underwent only partial inversion since in its axial part top of the pre-salt series is still located at a lower level than in the adjacent flanking areas (Fig. 3, profile 2). A more detailed discussion on mechanisms and amounts of subsidence and inversion in different segments of the MPT with an extensive reference list is given in Krzywiec (2002*a*, *b*), Mazur *et al.* (2005), Krzywiec *et al.* (2006) and Krzywiec (2006).

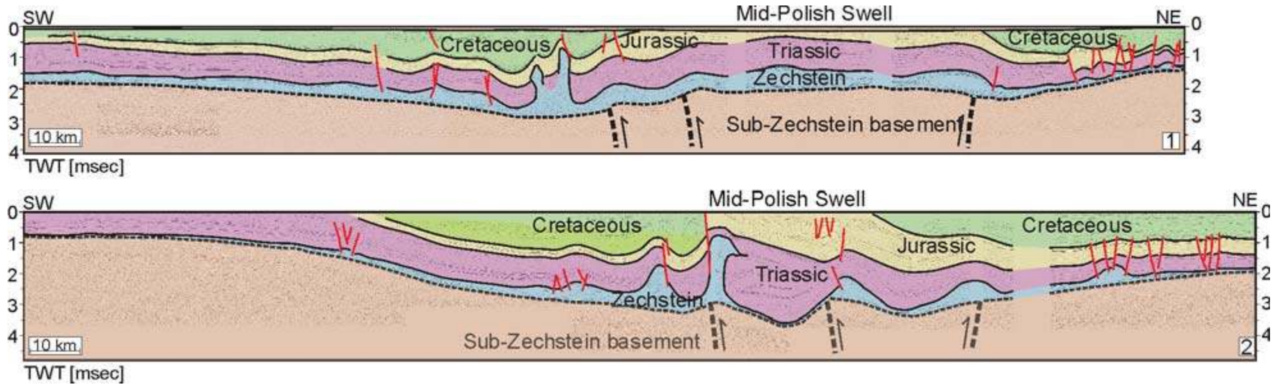

Fig. 3. Regional seismic profiles across the Pomeranian (1) and the Kuiavian (2) segments of the inverted Mid-Polish Trough (after Krzywiec, 2004*a*, 2006; Krzywiec *et al.*, 2006)

Black hatched lines — inferred basement fault zones responsible for subsidence and subsequent inversion of the Mid-Polish Trough; for location of the profiles see Figure 2

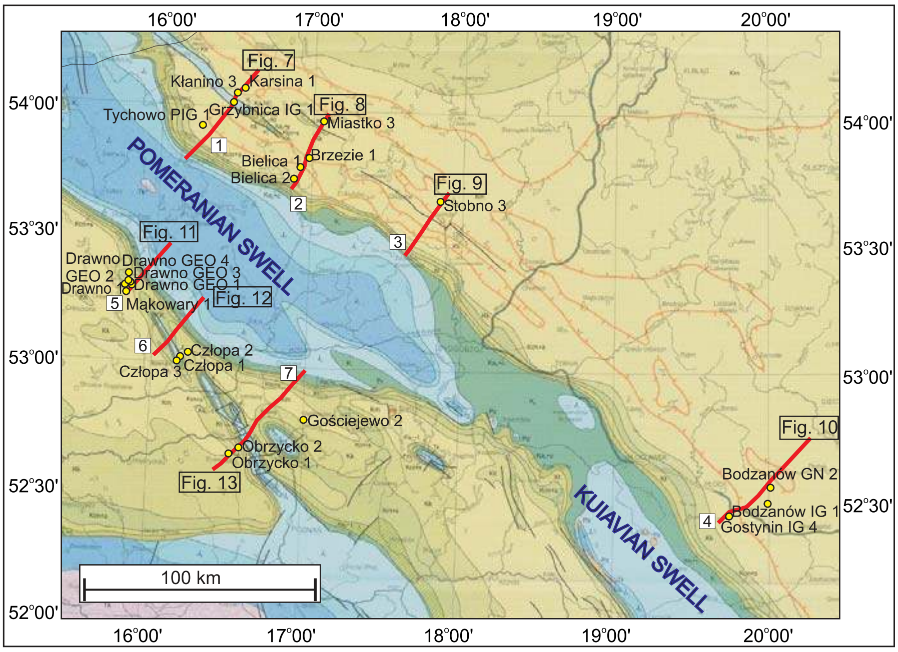

Fig. 4. Geological map of Poland without Cenozoic cover (Dadlez *et al.*, 2000)

Red lines (1–7) — location of interpreted seismic profiles with corresponding figure numbers; yellow dots — calibration wells, green colours — Cretaceous, blue colours — Jurassic, pink colours — Triassic, see Dadlez *et al.* (2000) for further explanations

Estimates on both the magnitude and exact timing of inversion differ due to the significant amount of axial uplift and related erosion of Mesozoic series, including syn-inversion Upper Cretaceous sediments. These estimates are indirectly constrained by well data and reconstructed palaeothickness maps (e.g. Dadlez *et al.*, 1995, 1997; Hakenberg and Świdrowska 1998, 2001; Świdrowska and Hakenberg, 1999, 2000; Leszczyński, 2000, 2002; *cf.* Stephenson *et al.*, 2003). Surface geological evidence of inversion tectonics is only available from the SE segment of the MPT, namely from the area of the Holy Cross Mts. and their surroundings. For this area, tectonic analyses indicate a complex Late Cretaceous-Paleocene compressional to partly strike-slip reactivation of Mesozoic and/or Palaeozoic fault zones under a NE–SW directed compressional stress regime, that was accompanied by the formation of uplift-related extensional fractures and conjugate normal faults within the axial part of the MPT (e.g. Jaroszewski, 1972; Lamarche *et al.*, 1998, 2002, 2003*a*; Konon, 2004).

Previously completed analyses of seismic data, illustrating examples of different modes of inversion within the Polish Basin (Krzywiec 2002*a*, *b*; 2004*b*, Krzywiec *et al.*, 2003), point to the reactivation of generally NW–SE trending fault zones and to a certain importance of both NW–SE and SW–NE directed strike-slip movements. Earlier results based on seismic data indicate, in agreement with estimates derived from the analysis of well data (e.g. Leszczyński, 2000, 2002), that inversion may have locally commenced during the Late Turonian and reached a climax during Campanian–Maastrichtian and post-Maastrichtian times.

In the Mid-Polish Trough, upper time limit of inversion tectonics is defined by the oldest Cenozoic series that seal the erosionally truncated Upper Cretaceous succession. Paleocene deposits occur almost exclusively along the NE flank of the Mid-Polish Swell, while Eocene deposits are present on both of its flanks (Piwocki, 2004). This suggests that by Paleocene times inversion movements had ended on the SW flank of the Mid-Polish Swell that formed an uplifted area with sedimentation continuing on its NE flank. Eocene is characterized by sedimentation along both flanks of the already inverted MPT, and

Oligocene is sealing the eroded inversion structures, including its axial part (Piwocki, 2004).

Detailed information on various aspects of the tectonic and sedimentary evolution of the Pomeranian and Kuiavian segments of the MPT, analyzed in this paper, can be found in e.g. Pożaryski (1977), Marek (1977), Jaskowiak-Schoeneich (1979), Dadlez (1980), Raczyńska (1987), Marek and Pajchlowa (1997). Regional analyses dealing specifically with the Late Cretaceous evolution of the MPT or its particular segments with focus on sedimentary patterns and facies evolution are given by Jaskowiak-Schoeneich (1981), Jaskowiak-Schoeneich and Krassowska (1988), Leszczyński (1997, 2000, 2002), with elements of regional tectonic analyses being provided e.g. by Wagner *et al*. (2002) and Dadlez (2003).

INTERPRETATION OF SEISMIC DATA

Previous seismic analyses of Late Cretaceous inversion structures clearly indicated that there are significant lateral variations in the structural style and syn-kinematic sedimentation along the axis of the MPT (Krzywiec, 2002*a*, *b*; Krzywiec, 2004*b*, *c*). In order to better understand these aspects of inversion processes in the Pomeranian and Kuiavian segments of the MTP selected high-quality seismic profiles from these areas were interpreted with focus on detailed analysis of the Upper Cretaceous succession. These profiles, the location of which is shown in Figures 4–6, were selected to visualize the present-day structure of the marginal troughs that are characterized by local increase in the thickness of Upper Cretaceous series

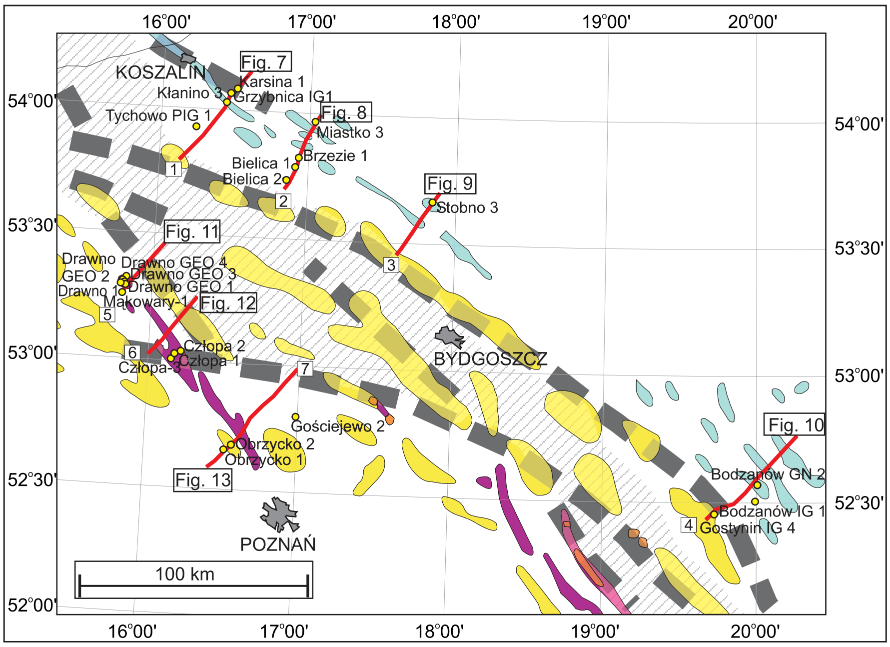

Fig. 5. Distribution of salt structures (yellow — pillows; pink — partly pierced diapirs; orange — fully pierced diapirs) and other anticlinal structures (blue) of the Mid-Polish Trough (after Dadlez and Marek, 1998)

Grey broad blocky lines — sub-Zechstein fault systems (after Krzywiec *et al*., 2006, Krzywiec, 2006); patterned area — axial part of inverted Mid-Polish Trough (i.e. the Mid-Polish Swell); for other expanations see Figure 4

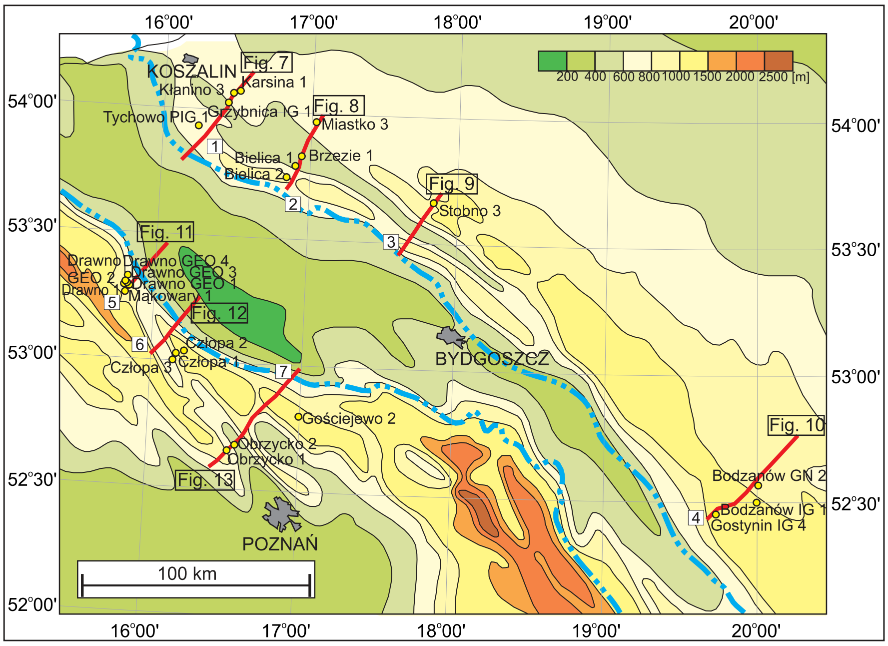

Fig. 6. Restored isopach map of Upper Cretaceous successions (redrawn from Leszczyński, 1998)

Blue hatched line — erosional limit of Upper Cretaceous successions (see Fig. 5); for other expanations see Figure 4

(Fig. 6). Six of these profiles are located in the Pomeranian segment of the MPT, and only one profile comes from its Kuiavian segment. This distribution reflects the availability of good quality seismic data and the observed regional variations in the gross structure in these segments of the MPT.

The Pomeranian segment is characterized by an overall symmetric structure of the Upper Cretaceous deposits being preserved on both flanks of its inverted axial part. By contrast, the Kuiavian part is strongly asymmetric with inversion being centered on the basement fault zone in the central part of the regional seismic profile 2, located beneath the Kłodawa salt structure (Fig. 3; Krzywiec, 2004*a*). Upper Cretaceous deposits are preserved only immediately to the SW of this structure, but available seismic data are of too low quality to image details of their internal structure (*cf.* Leszczyński, 2000).

Analyzed seismic lines were calibrated by deep wells penetrating the entire Upper Cretaceous interval (Figs. 4–6). Some of these wells are located on or very close to the investigated lines, whilst others were correlated with these seismic lines by means of connecting lines. For most of these wells velocity data are available permitting a precise correlation of the borehole stratigraphy with the two-way-travel time seismic data. Wells, for which no velocity data are available, were tied to the seismic data using time-depth tables derived from neighbouring wells, resulting in some uncertainties in the stratigraphic calibration of the seismic lines. Stratigraphic data were derived mostly from the SADOG database constructed by the Polish Oil and Gas Company and from well reports available for deep research wells drilled by the Polish Geological Institute. In some cases information on stratigraphic tops was modified using other available sources. In a relatively large number of analyzed wells only a composite Campanian-Santonian succession was distinguished and as such interpreted on the seismic data (*cf.* Leszczyński, 2002).

It should be stressed that the Upper Cretaceous stratigraphy available in various databases must be regarded as partly tentative, owing to several factors (for details see Leszczyński, 2002). In almost all wells drilled in the MPT, the Upper Cretaceous succession was only partly cored, and for newer wells, drilled during exploration for hydrocarbon (entirely focused on the Zechstein and older deposits), only cuttings and well logs are available for the interpretation of this interval. Moreover, the well-log signatures of the Upper Cretaceous do not allow for unequivocal correlation of particular stratigraphic boundaries. Finally, as recently shown for the SE segment of the MPT, analysis of core material from deep research wells drilled by the Polish Geological Institute, applying modern stratigraphic principles, can results in a significant revision of the stratigraphic zonation and architecture of Upper Cretaceous successions (Gutowski *et al*., 2003). Although the results of seismic data interpretation presented in this paper give a reliable representation of the inversion-related depositional and tectonic architecture of Upper Cretaceous series, certain error bars remain regarding the dating of key seismic horizons.

The main focus of the present study was the seismostratigraphic analysis of Upper Cretaceous series in terms of syn-kinematic sedimentation, including the detection of local unconformities, thickness variations and underlying deformations (*cf.* Cartwright, 1989). As a working hypothesis, it was assumed that during the Late Cretaceous locally modified sedimentation patterns, particularly in vicinity of compressionally triggered structures (including compressionally reactivated salt structures), are related to first phases of basin inversion (*cf.* Fig. 1).

NE FLANK OF THE MID-POLISH SWELL

Along the NE flank of the inverted Mid-Polish Trough four profiles were selected in order to visualize along-strike variations in structural style and timing of inversion-related processes.

Seismic line 1 (Fig. 7) crosses the SE tip of a basement fault zone, that is partly equivalent to the so-called Koszalin-Chojnice Fault Zone. For a detailed discussion on the location of the sub-Zechstein fault zones and their role during evolution of the Mid-Polish Trough the reader is referred to Krzywiec *et al*. (2006) and Krzywiec (2006). The Koszalin-Chojnice Fault Zone formed the true border fault zone of the MPT only in its Baltic (offshore) segment, both during basin subsidence and inversion (Vejbæk *et al*., 1994; Schlüter *et al*., 1997; Krzywiec, 2002*a*; see also fig. 7 in Mazur *et al*., 2005). Onshore, this fault zone is generally defined as a deformation zone that is confined to Mesozoic series, and that continues much further to the SE than the basement fault zone, as shown in profiles 2, 3 and 4 (Figs. 8–10). Only close to the Baltic coast, the Koszalin-Chojnice Fault Zone is characterized by some hard-linked sub-salt and supra-salt faulting (Antonowicz *et al*., 1994; Strzetelski *et al*., 1995). Along this tectonic zone some Late Cretaceous NW–SE strike-slip movements were postulated (*cf.* Krzywiec, 2002*a*).

Seismic line 1 (Fig. 7) is calibrated by the wells Karsina 1, Kłanino 3, Grzybnica IG 1 and Tychowo PIG 1 (Figs. 4–6) for all of which check-shot data are available to construct time-depth tables. The Tychowo PIG 1 well was correlated with line 1 with the aid of an intersecting line, while other wells are located at small distances from line 1. According to SADOG database, the Tychowo PIG 1 well did not encounter Coniacian deposits, whereas reinterpretation of its stratigraphic profile by Leszczyński (2002) shows the presence of a 22 m thick Coniacian sequence. The Grzybnica IG 1 well is located on the crest of the strongly inverted Koszalin-Chojnice Zone that is devoid of the Upper Cretaceous deposits. The Kłanino 3 and Karsina 1 wells, located on the NE flank of this fault zone, penetrated complete Upper Cretaceous successions. On seismic line 1, the Upper Cretaceous series maintains a fairly constant thickness towards the axial part of the inverted and uplifted Mid-Polish Swell. Some subtle thickness changes towards the SW cannot be excluded, although the resolution of seismic data at shallowest levels, where such thickness changes may occur, is too low to detect them. Along the NE flank of the Koszalin-Chojnice structure individual Upper Cretaceous units maintain fairly constant thicknesses, suggesting continuous sedimentation and the absence of localized tectonic activity.

There are, however, important seismostratigraphic features along the SW margin of the Koszalin-Chojnice structure indicative of its late to post-Turonian uplift and erosion (Fig. 7). In this area, the Cenomanian interval displays a constant thickness and parallel seismic reflectors, whilst the Turonian interval is also characterized by parallel seismic reflectors that are progressively truncated by an unconformity towards the

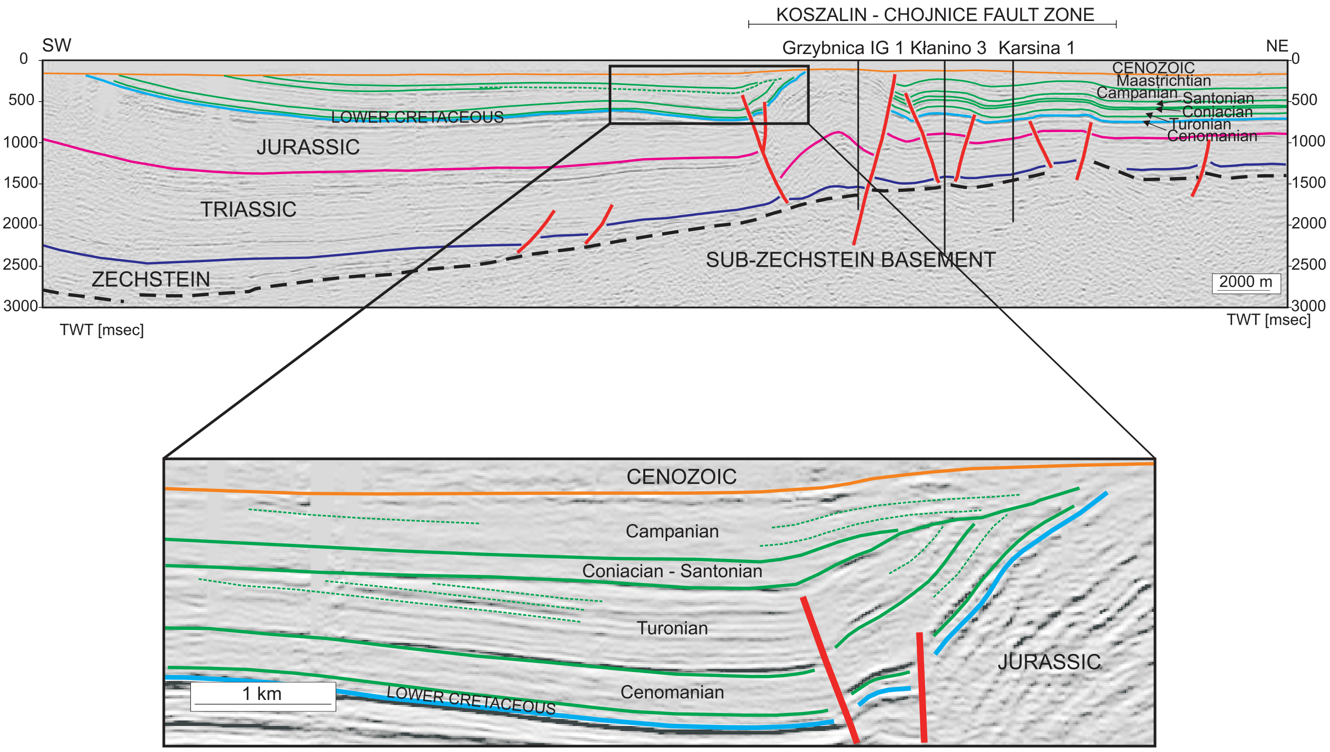

Fig. 7. Interpreted seismic profile 1, NE flank of Mid-Polish Swell

For location see Figures 4–6

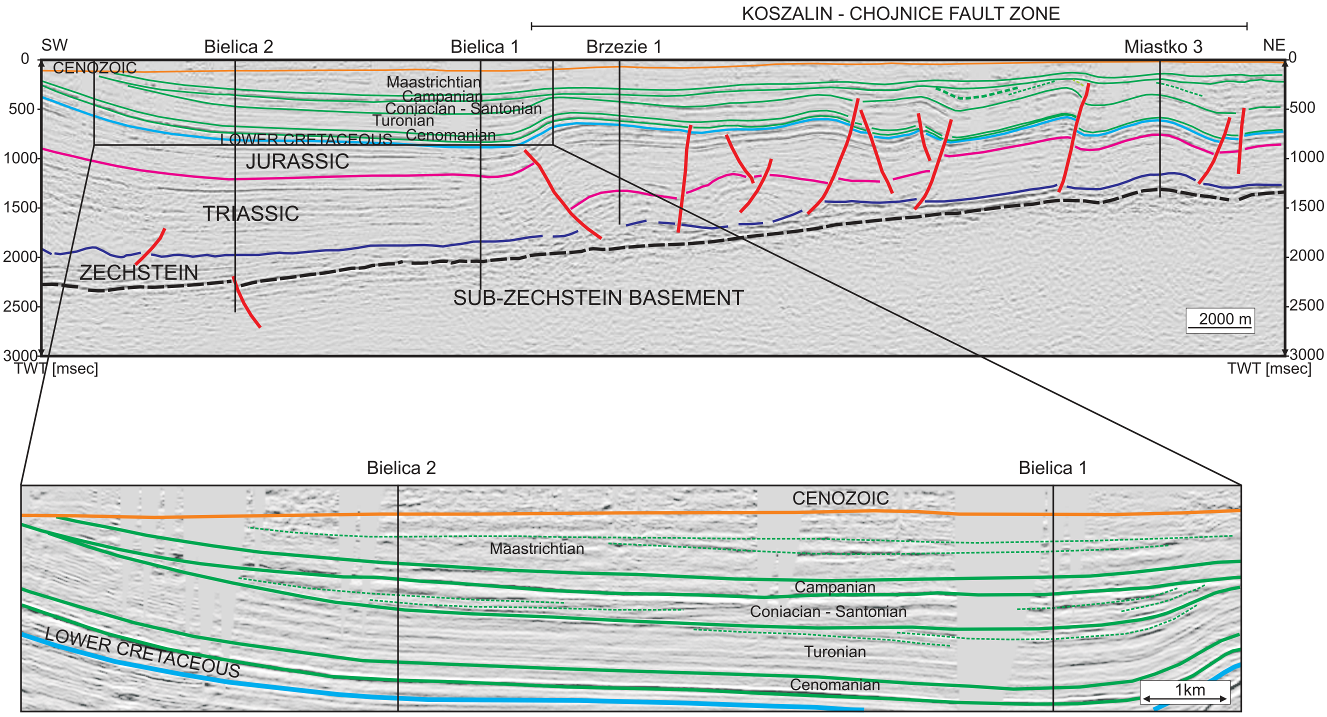

Fig. 8. Interpreted seismic profile 2, NE flank of Mid-Polish Swell

This profile is the enlarged NE part of the regional seismic profile 1 given in Figure 3; for location see Figures 4–6

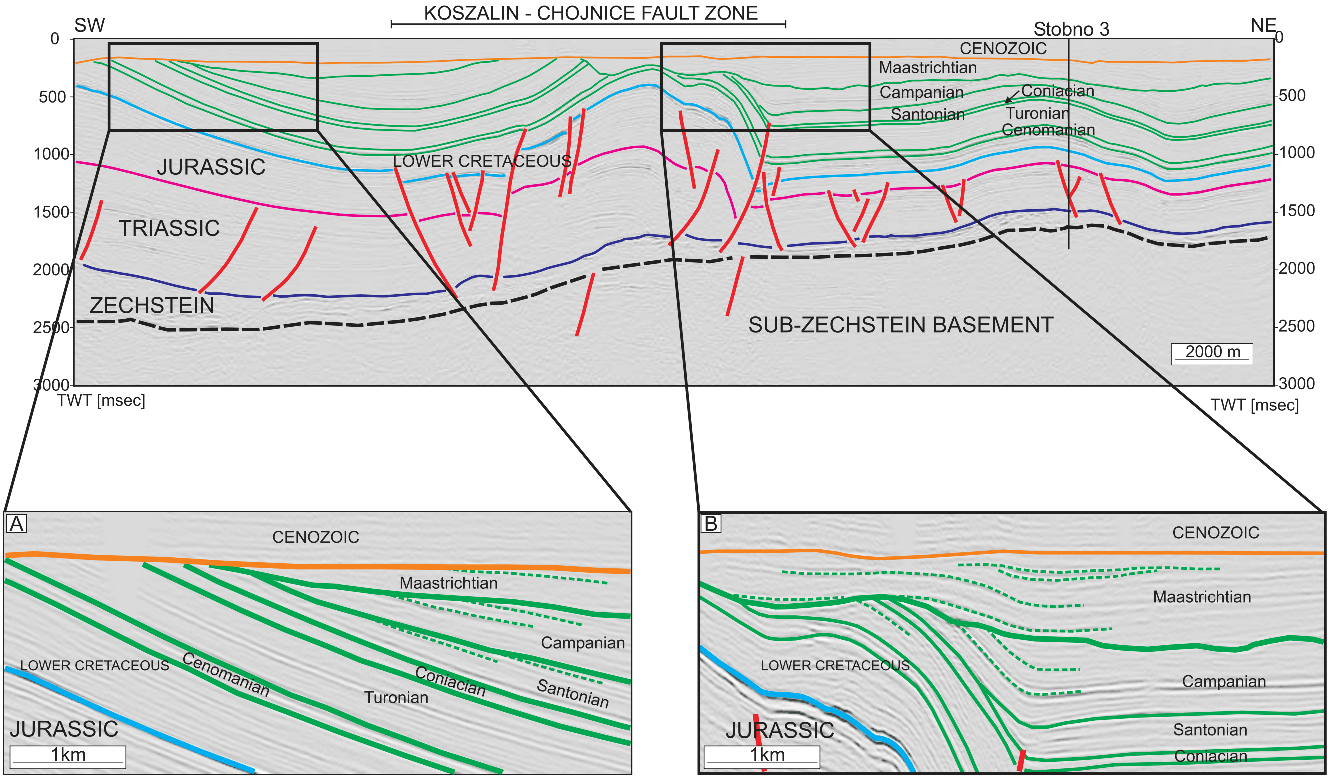

Fig. 9. Interpreted seismic profile 3, NE flank of Mid-Polish Swell

For location see Figures 4–6

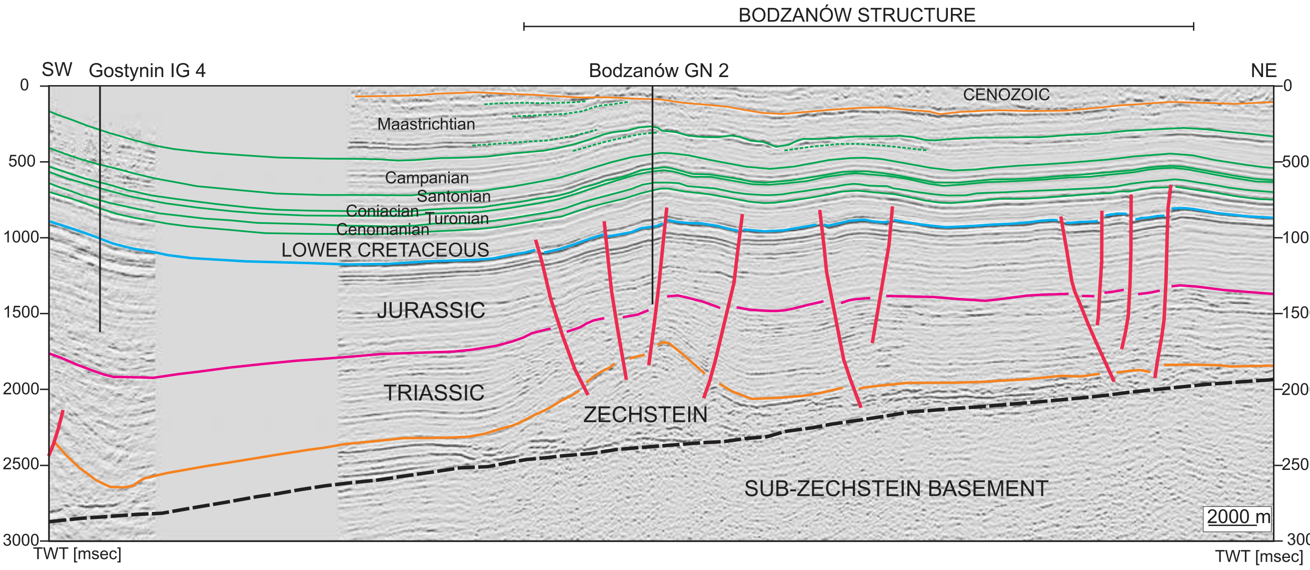

Fig. 10. Interpreted seismic profile 4, NE flank of Mid-Polish Swell

This profile is the enlarged NE part of the regional seismic profile 2 given in Figure 3; for location see Figures 4–6

Koszalin-Chojnice structure in the NE, as well as towards the SW. This late to post-Turonian tectonic activity can be regarded as reflecting a potential first pulse of inversion-related tectonic activity in the peripheral NE zone of the MPT. Coniacian-Campanian deposits cover and onlap folded and truncated Cenomanian-Turonian series, and in turn are slightly folded, suggestive of a late Campanian or younger inversion phase. The Campanian is unconformably covered by Cenozoic successions, which may be Oligocene-Miocene in age, as indicated by stratigraphic data from the well Tychowo PIG 1. However, a recently published summary of the Paleogene evolution of the Polish Lowlands suggests that in this area also Paleocene deposits are preserved on the NE flank of Mid-Polish Swell (Piwocki, 2004). Considering that on the NE flank of the Koszalin-Chojnice structure the Maastrichtian and older Upper Cretaceous succession is preserved and characterized by fairly parallel seismic horizons, and that in this area the entire Upper Cretaceous sequence is gently folded, it is likely that a final inversion pulse affected the Koszalin-Chojnice structure during late to post-Maastrichtian times, at the Maastrichtian/Paleocene boundary.

Seismic line 2 (Fig. 8) is calibrated by the wells Brzezie 1 and Miastko 3, located on this line, and by the projected wells Bielica 1 and Bielica 2. For Brzezie 1 no velocity information is available and time-depth tables derived from other wells were used, whereas the other three wells contained check-shot data. On line 2, which forms the NE-most part of the regional seismic profile 1 (Fig. 3), numerous thickness variations and unconformities related to syn-kinematic sedimentation during basin inversion are evident. The Cenomanian is characterized by a fairly uniform thickness distribution, gradually decreasing towards the NE basin margin, and by generally parallel seismic reflectors. Similarly, the Turonian is also characterized by parallel horizons, whilst its topmost part is eroded and unconformably covered by Coniacian-Santonian deposits along the SW margin of the Koszalin-Chojnice structure. This reflects an initial late Turonian/early Coniacian inversion-related pulse of compressional uplift of this structure that is located peripheral to the main axis of the Mid-Polish Swell (*cf.* Figs. 3 and 4). Towards the SW, the Turonian maintains a constant thickness up to its erosional truncation at the end of line 2.

The Coniacian–Santonian is only partly preserved in the Bielica marginal trough and has a complex internal structure. Towards the SW the Coniacian–Santonian subtly onlaps the Turonian, whereas towards the NE (i.e. towards the Koszalin-Chojnice structure) it is folded, eroded and unconformably covered by Campanian deposits. This suggests that after the Turonian the axial part of the MPT was already slightly uplifted, as evidenced by the subtle onlap of Coniacian-Santonian strata towards the SW. The late Santonian/early Campanian marks the main phase of inversion and uplift of the Koszalin-Chojnice structure, as documented by prominent angular unconformities. At the same time the axial part of the MPT was also uplifted, as evidenced by progressively deeper erosion of the Turonian and Coniacian-Santonian towards the SW. Campanian deposits, characterized by a uniform thickness and internal geometry, overstep this unconformity. Campanian and overlying Maastrichtian series, which are only mildly folded on the Koszalin-Chojnice structure, were significantly uplifted towards the SW, i.e. towards the axial part of the MPT during its final late/post-Maastrichtian inversion phase. A localized unconformity visible within the Maastrichtian could be related to minor inversion-induced tectonic activity both within the Koszalin-Chojnice structure as well as within the axial part of the basin. On the Koszalin-Chojnice structure the Maastrichtian is covered with a very minor angular unconformity by Cenozoic deposits, suggesting that it was not severely reactivated during the final and main inversion phase of the MPT. Wells used for calibration of this seismic line do not contain detailed stratigraphic data on the Cenozoic succession. Considering a recent regional synthesis of the Paleogene-Neogene evolution of the Polish Lowland (Piwocki, 2004) it is likely that final inversion pulse occurred during Paleocene and prior to the Eocene.

Seismic line 3 (Fig. 9) comes from a very high-quality survey and images in great detail the Upper Cretaceous multi-stage inversion history of the Pomeranian NE flank of the Mid-Polish Swell. This line is calibrated only by the well Stobno 3, for which check-shot data are available. This well, which penetrated a complete Upper Cretaceous succession, is located on the NE flank of the Koszalin-Chojnice Fault Zone, and therefore provides only indirect calibration of the marginal trough located between this structure and the uplifted axial parts of the MPT. However, owing to the very high quality of the seismic data, a very reliable reflection character correlation could be established between Upper Cretaceous series occurring on the conjugate sides of the Koszalin-Chojnice structure.

In this area, Cenomanian strata display a constant thickness whilst the Turonian is characterized by very minor and local thickness reduction at the NE margin of the Koszalin-Chojnice structure (Fig. 9B). This thickness reduction can be attributed to the first, late Turonian pulse of inversion tectonics. The Coniacian and Santonian intervals maintain over considerable distances rather constant thicknesses and are characterized by parallel seismic reflectors. Towards the SW, on the flank of the uplifted axial part of the MPT, as well as on the NE margin of the Koszalin-Chojnice structure, the top of the Santonian is eroded and unconformably covered by Campanian deposits (Fig. 9), thus testifying to a second mild inversion phase. Campanian sediments, characterized by parallel bedding, were deposited during a tectonically quiescent period. Towards the end of the Campanian the Koszalin-Chojnice structure was strongly folded, resulting in the development of an erosional unconformity that cuts down across its culmination into the Cenomanian (Fig. 9). At the same time also the axial parts of the MPT were uplifted and subjected to erosion. This end-Campanian deformation reflects a further, albeit major inversion phase that is constrained by the transgression of Maastrichtian series which onlap and overstep a complex palaeotopographic surface. Local erosional unconformities within the Maastrichtian series speak for mild ongoing syn-depositional deformation (Fig. 9B). A final pulse of inversion occurred during late/post-Maastrichtian times, resulting in the development of a regional erosional unconformity that was overstepped by transgressive Paleogene series (Paleocene–Eocene?; Piwocki, 2004) (Fig. 9).

Seismic line 4 (Fig. 10), forming the NE-most part of regional seismic profile 2 (Fig. 3), is calibrated by the on-line wells Gostynin IG 1 and Bodzanów GN 2 and the projected well Bodzanów IG 1 that could be tied into the line by means of additional seismic data. For these wells, all of which penetrated a full Upper Cretaceous succession, check-shot data are available. In this part of the MPT, the Upper Cretaceous succession maintains its thickness towards the SW axial part of the basin that underwent very prominent asymmetric inversion-related uplift (*cf.* Fig. 3). Over the crest of this structure, Upper Cretaceous series were removed by erosion, including also potential syn-kinematic deposits (Fig. 4). Therefore, only indirect information on the inversion history of the Kuiavian part of the MPT could be derived from the analysis of the peripheral Bodzanów structure (Fig. 10) that forms the SE, albeit subdued continuation of the Koszalin-Chojnice Fault Zone. Across the Bodzanów structure that is detached within the Zechstein evaporites, the Cenomanian-Santonian succession maintains a constant thickness and is characterized by parallel reflectors, indicating that is was deposited during a tectonically quiescent period. Whilst the Campanian interval is also characterized by fairly parallel bedding, its top is marked by a clear erosional unconformity that is covered by Maastrichtian series. The entire Upper Cretaceous sequence was mildly folded, resulting in the development of a top-Maastrichtian erosional unconformity that was transgressed by Paleogene (Paleocene–Eocene?; Piwocki, 2004) flat laying series. This geometry indicates that the Bodzanów structure was active during late Campanian and late/post-Maastrichtian (Paleocene) times, but that the overall degree of tectonic complexity is rather low due to its limited inversion and uplift.

SW MARGIN OF THE MID-POLISH SWELL

Subsidence and inversion along the SW margin of the Pomeranian segment of the MPT was controlled by complex tectonic activity along sub-salt fault zones (Fig. 5; Krzywiec *et al.*, 2006; Krzywiec, 2006). To the SW of these fault zones, a complex system of peripheral salt structures developed that is commonly referred to as the Drawno–Człopa–Szamotuły salt structure. Segments of this structure are shown on Figures 11–13, respectively. Along this border zone numerous wells were drilled, however, almost all of them were located above or very close to salt structures, with relatively few wells located in the marginal trough adjacent to the uplifted axial part of the MPT.

Seismic line 5 (Fig. 11) is calibrated by the wells Drawno 1, Drawno GEO 1, Drawno GEO 2, Drawno GEO 3, Drawno GEO 4 and Mąkowary 1 (Figs. 4–6), for all of which velocity data are available. The first five wells, located at some distance from seismic line 5, were drilled in a very complex zone of highly deformed Mesozoic series above the axial part of the Drawno salt structure, and therefore provided only limited stratigraphic calibration for seismic line 5. Only the Mąkowary 1 well that was drilled in a syncline between two elements of the Drawno salt structure provided information on the stratigraphy of the Upper Cretaceous succession. Whereas the SADOG database shows for this well an incomplete Upper Cretaceous stratigraphic record, other data indicate the presence of a complete Upper Cretaceous succession (Wróbel, 1970; Jaskowiak-Schoeneich, 1981). Calibration for the marginal trough located between this salt structure and the uplifted axial part of the MPT was provided by a long-distance correlation with well Człopa 2 (see below).

Along seismic line 5, the Turonian-Campanian succession thins towards the Drawno salt structure. This is interpreted as being related to syn-kinematic sedimentation above and adjacent to this compressionally reactivated salt diapir. As this thinning is rather regular (only less evident for the partly eroded topmost part of Campanian) and is not related to the development of significant intra-Upper Cretaceous unconformities, it suggests rather continuous Turonian-Campanian growth of this segment of the Drawno–Człopa–Szamotuły salt structure. In the only locally preserved Maastrichtian no such thinning is observed although it cannot be ruled out due to strong erosional truncation of this interval. The entire Upper Cretaceous is folded and truncated across the Drawno salt structure, as well as the inverted axial part of the Pomeranian segment of the MPT, and is unconformably covered by Cenozoic deposits (Fig. 11), suggestive of an end Maastrichtian major inversion pulse. According to stratigraphic data from the wells Drawno GEO 1, 2, 3 and 4 the oldest Cenozoic deposits are of Oligocene age. However, recently published Paleogene palaeogeographic maps (Piwocki, 2004) suggest that within the entire Pomeranian segment of the MPT, apart from its axial parts, Eocene sediments are present. Therefore, it is postulated that the final inversion pulse occurred during the

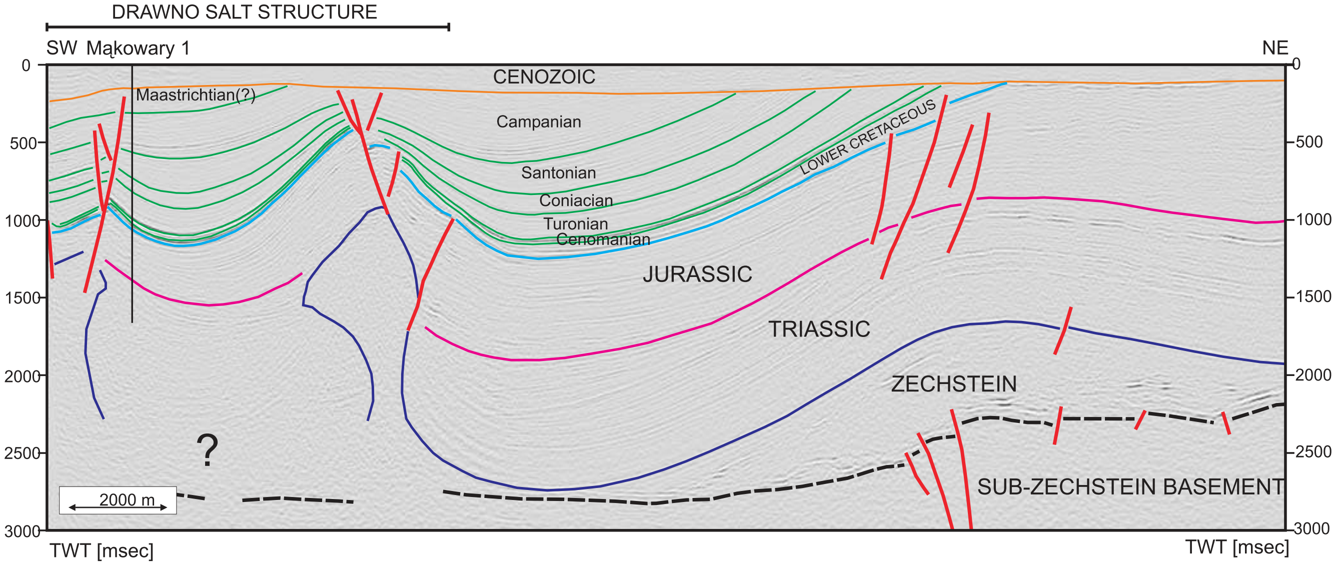

Fig. 11. Interpreted seismic profile 5, SW flank of Mid-Polish Swell

For location see Figures 4–6

Paleocene, with Eocene deposits forming the basal part of the post-tectonic succession.

Seismic line 6 (Fig. 12) crosses the Człopa salt structure that, similarly to the Drawno structure, consists of two main elements (Człopa and Dzwonowo salt diapirs), and extends NE-ward onto the flank the inverted axial parts of the MPT. This seismic line was calibrated by wells Człopa 1, Człopa 2 and Człopa 3 (Figs. 4–6) that were correlated using tie lines of the same survey. For all these wells check-shot data are available facilitating good well-to-seismic ties. Only the Człopa 2 well was drilled on the flank of the marginal trough that is located between the Człopa salt structure, and the inverted and uplifted axial part of the MPT, thus provided stratigraphic calibration of its Upper Cretaceous succession. Although the SADOG database claims that this well did not penetrate Campanian strata, this is at odds with the findings of Binder (1971) and Jaskowiak-Schoeneich (1981).

The complex Człopa salt structure, as imaged by seismic line 6, is characterized by an overall geometry that clearly points to its Late Cretaceous compressional reactivation. Its Late Cretaceous compression-driven growth was multi-stage. The Turonian-Santonian succession thins towards this structure, is erosionally truncated across its culmination and unconformably covered by Campanian deposits. This angular unconformity is itself gently folded, reflecting a further stage of diapir growth. The entire preserved Upper Cretaceous sequence (*cf.* Fig. 4) is progressively eroded towards the axial parts of the Mid-Polish Swell and unconformably covered by flat lying Cenozoic strata. Calibration wells from this area do not provide detailed stratigraphic information on Cenozoic series. Nevertheless, taking into account recently published maps for the Paleogene from the Polish Lowland (Piwocki, 2004), it appears that Eocene deposits form the basal part of post-inversion sequences, thus documenting that the final inversion phase occurred during the Paleocene.

Seismic line 7 (Fig. 13) crosses the Szamotuły salt structure and a relatively wide marginal trough flanking the inverted axial parts of the MPT (*cf.* Fig. 4). The Upper Cretaceous succession on the SW flank of this salt structure was calibrated by the wells Obrzycko 1 and Obrzycko 2, with check-shot data available for the Obrzycko 1 well only. In this area a continuous Upper Cretaceous succession is preserved that was, however,

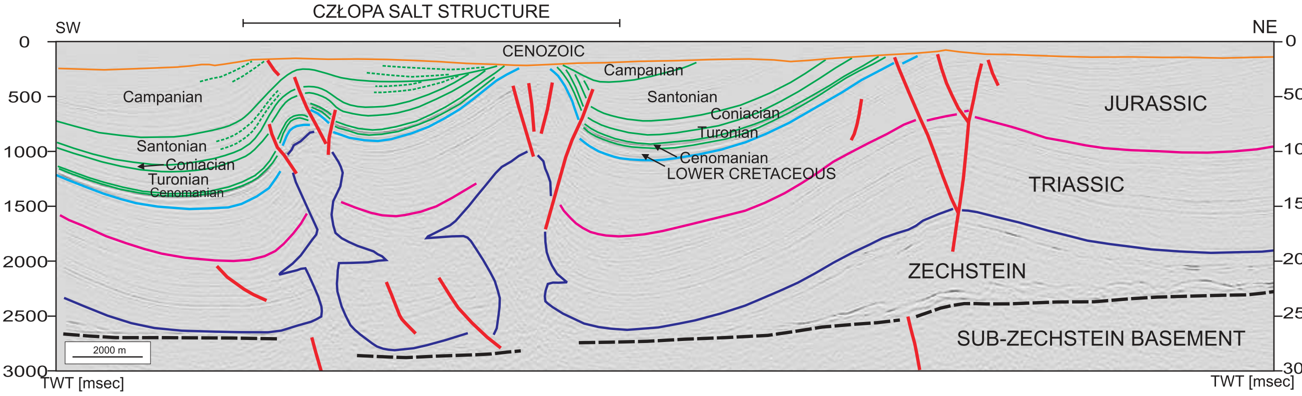

Fig. 12. Interpreted seismic profile 6, SW flank of Mid-Polish Swell; this profile lies adjacent to the SW part of regional seismic profile 1 given in Figure 3

For location see Figures 4–6

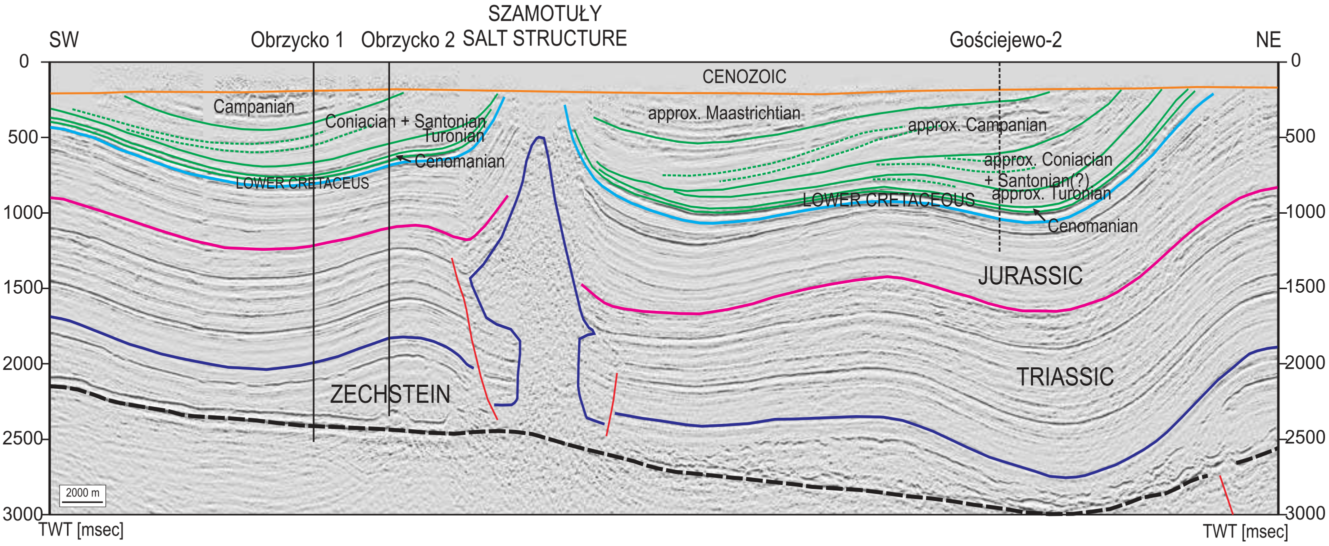

Fig. 13. Interpreted seismic profile 7, SW flank of Mid-Polish Swell

For location see Figures 4–6

strongly eroded at its top. Consequently the Campanian is only partly preserved whilst Maastrichtian deposits are missing entirely on the SW flank of the Szamotuły salt structure (*cf.* Fig. 4). In the marginal trough located to the NE of this structure, most probably the entire Upper Cretaceous succession is preserved, including the Maastrichtian (*cf.* Fig. 4). In this area, however, there are very few wells that can provide stratigraphic information for the calibration of seismic data. For instance, as for the well Gościejewo 2 located at a significant distance from seismic line 7, no velocity data are available, and the time-depth table of well Obrzycko 2 was used to establish a tie with line 7 by means of a low quality vintage seismic line. Therefore, the identified Upper Cretaceous markers shown in Figure 13 for the marginal trough located between the Szamotuły salt structure and the inverted MPT should be regarded as tentative.

Along the line 7, the Turonian strata show in the marginal trough very minor thinning towards the Szamotuły salt structure and some thickening towards the MPT axis; as its upper boundary is marked by an unconformity, these thickness variations may be attributed to erosion. By contrast, the Coniacian-Santonian interval thins progressively SW-ward towards this salt structure owing to its erosional truncation, whilst it is much thicker in the area of the Obrzycko wells where it is characterized by southwestward dipping internal clinoforms. Similarly, the lower part of the Campanian is characterized in the marginal trough by a SW-ward dipping clinoform pattern, suggesting sediment progradation from the uplifted axial parts of the MPT. Similar intra Campanian progradational geometries are also observed on seismic data from the SE part of the MPT, along the NE margin if the Holy Cross Mts. (Krzywiec, 2002*a*). On line 7, Maastrichtian sediments locally preserved in the marginal trough, appear to rest conformably on Campanian deposits and are in turn unconformably covered by flat lying Cenozoic series. The angularity of the base-Cenozoic unconformity increases rapidly NE-ward towards the axial parts of the MPT, thus evidencing its strong inversion during late/post-Maastrichtian times. Whilst in the wells Obrzycko 2 and Gościejewo 2 an Oligocene age is given for the oldest Cenozoic deposits, recently published maps for the Paleogene of the Polish Lowlands indicate that in this area also Eocene deposits are present (*cf.* Piwocki, 2004). Thus, in this part of the Mid-Polish Trough, the final inversion pulse probably occurred during the Paleocene.

DISCUSSION

Many authors have discussed problems related to the inversion of the MPT, with emphasis on its timing. All these analyses were almost exclusively based on well data. Some authors acknowledged only minor and very localized Campanian-Maastrichtian inversion movements preceding the post-Maastrichtian main inversion of the basin (e.g. Świdrowska and Hakenberg, 1999), but neglected the possibility of earlier phases, while others accepted also earlier inversion pulses (e.g. Dadlez *et al.*, 1997; Leszczyński, 2002). The interpretation of seismic lines calibrated by well data presented in this paper shows that basin inversion commenced already during the late Turonian, in agreement with estimates based on well data (e.g. Dadlez *et al.*, 1997) and earlier conclusions based on seismic data (Krzywiec, 2002*a*, *b*). So far, the available inventory of inversion movements in the different parts of the MPT suggests following general inversion phases: late Turonian–early Coniacian, late Santonian–Campanian and late Maastrichtian–Paleocene. Owing to the above-described stratigraphic uncertainties in calibration wells, these phases should for the time being still be regarded as tentative.

The analysis of lateral variations in the structural style of inversion tectonics along the NE and SW margin of the Mid-Polish Trough does not show an along-strike unequivocal systematic pattern. This can be attributed to different modes of compressional reactivation of structures that are to variable degrees detached from the pre-salt series by thick Zechstein evaporites, depending on the thickness and facies development of this evaporitic layer.

Peripheral structures along the NE and SW margins of the MPT, such as the Koszalin–Chojnice–Bodzanów and the Drawno–Człopa–Szamotuły structures, respectively, underwent in part significant inversion-related compressional reactivation during the pre-Maastrichtian inversion phases, while the final and major late/post-Maastrichtian inversion pulse was focused on the axial part of the MPT. Along the NE margin of the basin, reactivated peripheral structures appear to be mostly detached within Zechstein evaporites, though owing to their limited thickness no major salt structures developed. Within the northwestern-most offshore and onshore parts of the Koszalin-Chojnice Zone, faults within the pre-Zechstein basement directly controlled the style of inversion tectonics (Fig. 7; *cf.* Mazur *et al.*, 2005).

Along the SW basin margin, however, salt tectonics played a dominant role during the evolution of its peripheral structures due to the larger thickness of the Zechstein evaporites. During basin inversion, pre-existing salt structures (Drawno–Człopa–Szamotuły salt structure system, *cf.* Figs. 11–13) were significantly reactivated in response to the build-up of compressional stresses. Recently, Dadlez (2005) presented alternative tectonic interpretation of the Drawno–Człopa salt structure using the same seismic lines as shown in Figures 11 and 12. In his interpretation that is partly neglecting good-quality continuous reflectors, these salt structures show much less compressional reactivation as they are generally thicker at their base and thin upward, contrary to interpretation proposed in this paper (Figs. 11 and 12; *cf.* Vendeville and Nilsen, 1995). In this paper, the Drawno-Człopa structure was described as a strongly compressionally reactivated system of salt structures that, forming an important weakness zone within the Mesozoic cover, focused compressional stresses controlling inversion of the basin. A model of compressionally reactivated salt structures along the margin of the Mid-Polish Trough during its inversion is compatible with similar tectonic style observed within the North German Basin (*cf.* Kockel, 1998, 2003; Hudec, 2004; Mohr *et al.*, 2004) and the North Sea (Davison *et al.*, 1993, 2000; see also Nalpas *et al.*, 2003). Furthermore, localized lateral compressional stresses may have been exerted by the uplifted axial part of the basin that during later inversion phases was uplifted above the flanking areas (*cf.* Krzywiec, 2002*a*, *b*).

The total thickness of the preserved Upper Cretaceous succession is characterized by elongated maxima that flank the inverted, uplifted and eroded axial parts of the Mid-Polish Trough (Fig. 6). Some authors attributed these present-day maxima to increased sedimentation in the marginal troughs that developed along the margins of the inverting the axial parts of the MPT (Lamarche *et al.*, 2003*b*; Lamarche and Scheck-Wenderoth, 2005; Nielsen *et al.*, 2005). The results of the study presented here clearly show, however, that the preserved total thickness of the Upper Cretaceous series is only to a minor degree an effect of late-/post-inversion sedimentation within the marginal troughs flanking the uplifted Mid-Polish Swell. Examples of seismic profiles across these marginal troughs show that they are characterized by a complex internal sedimentary architecture, including lateral thickness variations and erosional unconformities (*cf.* also Dadlez, 2003), that document several episodes of inversion tectonics that laterally vary in terms of timing, intensity and structural style. The Late Cretaceous succession is rarely characterized by clearly visible thickness reductions and related unconformities towards the axial part of the inverted Mid-Polish Trough (*cf.* Figs. 8 and 9). This indicates that Late Cretaceous sedimentation was much more widespread in the axial part of the basin that it could be suggested using present-day thickness distribution of the Upper Cretaceous deposits. Correspondingly, the present-day thickness distribution of the entire Upper Cretaceous succession is primarily a function of inversion-related uplift and erosion of the axial part of the basin. This study shows that the inversion history of the MPT can be, at least partly, deciphered by analyzing the internal architecture of the Upper Cretaceous succession that is preserved in the marginal troughs and the Cenozoic series that overstep the deeply truncated Mid-Polish Swell and its flanks, and not by simply analyzing thickness variations of the entire Upper Cretaceous succession (see also below).

Late Cretaceous-Paleocene inversion tectonics affected also other parts of the Central European Basin System, including those that are located adjacent to the MPT, such as the Bohemian Massif, the North German Basin and the Sorgenfrei-Tornquist Zone in Southern Sweden and Northern Denmark (Fig. 1; *cf.* Ziegler, 1987, 1990).

Up-upthrusting of basement blocks forming the Bohemian Massif commenced during the late Turonian, intensified during the Senonian and culminated during the Paleocene (Malkovsky, 1987). Related fault systems of the Bohemian Massif extend southward into the Austrian Molasse Basin where they are sealed by late Eocene clastics and marine carbonates (Nachtmann and Wagner, 1987).

Selected examples of inversion structures from the North German Basin (NGB) were recently presented by Kockel (2003). Based on the interpretation of seismic profiles and calibration wells, these structures began to develop during the late Turonian with inversion movements culminating during the Coniacian–Campanian and locally persisting until the late Paleocene. This was accompanied by significant compressional reactivation of numerous salt structures. Undeformed latest Paleocene and Eocene deposits rest unconformably on the deeply truncated Mesozoic series of these inversion structures (Betz *et al.*, 1987; Kossow and Krawczyk, 2002; Kockel, 1998, 2003; Scheck *et al.*, 2003).

The timing of inversion phases in the Bohemian Massif and the NGB closely conforms to that of the MPT. In the Bohemian Massif, including the Harz Mts. and the Flechtingen High, as well as in the Lower Saxony Basin, inversion movements affected the Variscan basement together with its sedimentary cover. However, further north the presence of thick Zechstein salts allowed for the development of thin-skinned inversion structures almost up to the shore of the Baltic Sea, with the shortening achieved in them being taken up at basement levels by the Flechtingen-Gardelegen fault system along the southern margin of the NGB (Kossow and Krawczyk, 2002; Kockel, 2003; Otto, 2003; Scheck *et al.*, 2003).

The North Danish Basin evolved above and adjacent to the Sorgenfrei-Tornquist Zone (STZ; Mogensen, 1995; *cf.* Fig. 2) that forms the NW prolongation of the Teisseyre-Tornquist Zone (TTZ). Inversion of the STZ commenced during the Santonian and ended during the Paleocene (Norling and Bergström, 1987; Liboriussen *et al.*, 1987; Michelsen, 1997) and, as such, compares readily to the timing of inversion movements in the MPT and NGB. Inversion structures associated with the STZ offshore Bornholm and in Scania involve important transpressional reverse faulting affecting the Precambrian basement and its entire Palaeozoic and Mesozoic sedimentary cover (Liboriussen *et al.*, 1987; Mogensen and Jensen, 1994; Vejbæk *et al.*, 1994; Erlström *et al.*, 1997; Michelsen, 1997). In NW Denmark, the presence of thick Zechstein salts allowed for the development of partly decoupled inversion structures at Mesozoic levels (Michelsen, 1997), similarly to the Kuiavian and Pomeranian segments of the MPT.

Nielsen *et al.* (2005) recently proposed that Palaeocene phase of inversion of both the Sorgenfrei-Tornquist Zone in Denmark as well as the Teisseyre-Tornquist Zone in Poland could be related to plate-wide relaxation of the intraplate compressional stresses instead of their build-up. Key element of this model is pronounced difference between style of sedimentation within the marginal troughs that develop during early (compression related) and late (relaxation related) phases of inversion, in this case during the Late Cretaceous and Paleocene inversion phases. In the model of Nielsen *et al.* (2005), marginal troughs formed during early inversion should be fairly narrow and located adjacent to the main inversion axis, while late inversion caused by stress relaxation is characterized by more domal uplift and consequently by shallower marginal troughs developed in more distal position. This model however seems to be only partly applicable to inversion of the Mid-Polish Trough and underlying Teisseyre-Tornquist Zone. Present-day thickness of the Upper Cretaceous succession shows very localized maxima adjacent to the inversion axis (*cf.* fig. 3 of Nielsen *et al.*, 2005), it should not be, however, identified with the original thickness of this succession, as it was shown in this paper. Therefore, key assumption of Nielsen *et al.*, (2005) in their model that the Late Cretaceous inversion along the Teisseyre-Tornquist Zone in Poland was associated with development of narrow marginal trough should be rejected. Additional fact that seems to have been not fully considered by Nielsen *et al.* (2005) in their analysis of the TTZ inversion tectonics is pronounced regional inhomogeneity of the lithosphere along the TTZ. This feature which implies that application of simple flexural models for modelling subsidence and inversion of sedimentary basins could be questionable in this particular area. Finally, both subsidence and inversion of the MPT were strongly influenced by Zechstein evaporites, and consequently evolution of marginal troughs was also overprinted by salt tectonics and basin-scale decoupling.

Compressional stresses controlling the Late Cretaceous-Paleocene inversion of the MPT are thought to have originated at the Carpathian collision zone. In this context, it is of interest to note that during the closure of the Vahic Ocean, compressional stresses began to build up during the Turonian in the Outer Carpathian domain, as evidence by the onset of inversion movements in its Silesian, Sub-Silesian and Skole sub-basins (Oszczypko, 2006). These inversion movements intensified in the course of the Senonian and reached a peak during the Maastrichtian-Paleocene when the Inner Carpathian orogenic wedge collided with the Czorsztyn Ridge that presumably formed the outer marginal high of the European passive margin. At the end of the Paleocene, foreland compressional stresses relaxed in the Outer Carpathian domain and its foreland whilst subduction of the Magura Basin commenced (Oszczypko, 2006). This relaxation of intraplate compressional stresses in the Carpathian foreland reflects mechanical decoupling of the Inner Carpathian orogenic wedge (South Magura Cordillera) from the foreland lithosphere, presumably owing to water-containing sediments entering the subduction zone (*cf.* Ziegler *et al.*, 1998, 2002).

CONCLUSIONS

Seismostratigraphic analysis of the Upper Cretaceous successions imaged by high-quality seismic lines from both flanks of the NW (Pomeranian) and central (Kuiavian) segments of the Mid-Polish Swell shows that inversion of the MPT was characterized by important along-strike structural and stratigraphic variations. Thickness variations of the different Upper Cretaceous units, combined with erosional unconformities and assessment of underlying tectonic deformations, point towards multiple inversion phases, commencing in the Late Turonian and culminating in late Maastrichtian-Paleocene times.

Initially, inversion tectonics focused on peripheral structures that had developed along the margins of the Mid-Polish Trough. As these structures were detached from the “basement” by the Zechstein evaporitic layer, they were more prone to compressional reactivation than the central parts of the basin. Along these peripheral structures, significant lateral variation in the timing and structural style of inversion tectonics is observed. The NE margin of the MPT is devoid of compressionally reactivated salt structures, whereas its SW margin is dominated by pronounced inversion-related salt tectonics. During the Campanian and Maastrichtian, and even more so during the Paleocene, inversion movements shifted towards the axial parts of the MPT that were uplifted to form the present-day Mid-Polish Swell that, after its deep erosion, is now buried beneath a veneer of essentially flat laying Eocene–Oligocene and younger sediments.

Inversion of the Mid-Polish Trough, spanning late Turonian–Paleocene times, is compatible with the timing of uptrusting of basement blocks in the Bohemian Massif, the inversion of parts of the North German Basin and also of the Sorgenfrei-Tornquist Zone. Basement — involved inversion tectonics characterizes the Mid-Polish Trough, Bohemian Massif, Lower Saxony Basin, Rønne Graben, Scania and the North Danish Basin. Owing to the presence of thick Zechstein salts, inversion of the central and NW parts of the Mid-Polish Trough, the North German Basin and the NW part of the North Danish Basin was associated with partial detachment of Mesozoic series from the basement and compressional reactivation of salt structures.

Late Turonian-Paleocene inversion of the Mid-Polish Trough, the Sorgenfrei-Tornquist Zone, the Bohemian Massif and the North German Basin could be attributed to the build-up of intraplate compressional stresses during contemporaneous collisional events in the Carpathian domain.

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