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Tectonostratigraphic model of the Late Cretaceous inversion along the Nowe Miasto–Zawichost Fault Zone, SE Mid-Polish Trough

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The Nowe Miasto–Zawichost Fault Zone is located within the Teisseyre-Tornquist Zone that separates the East European Craton from the Palaeozoic Platform and forms one of the most fundamental lithospheric boudaries in Europe. High-quality seismic reflection profiles, calibrated by several deep wells, were interpreted in an effort to assess the timing and structural style of inversion tectonics within the SE segment of the Mid-Polish Trough. Thickness variations of the Upper Cretaceous series indicate that inversion movements commenced during the late Turonian?–Coniacian and intermittently persisted into the Maastrichtian and Paleocene. Structural features detected on seismic data include steep reverse faults, upthrusted basement blocks and positive flower structures. Inversion-related structure imaged on seismic data could be explained by deeper basement normal and reverse faulting and associate fold-propagation folding at shallower depths. The geometry of the identified inversion-related structures and the *en-echelon* pattern of the Nowe Miasto–Zawichost Fault Zone described using processed gravity data strongly suggest that inversion along the NE boundary of the SE segment of the Mid-Polish Trough was associated with strike-slip movements.

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INTRODUCTION

The inversion of sedimentary basins has been the subject of intensive research for at least the last two decades. Different aspects of basin inversion regarding both various-scale tectonic processes operating within the basins as well as causal relationships between inverted basins and surrounding tectonic domains (orogenic zones, spreading centres) have been presented in numerous publications (e.g., Cooper and Williams, 1989; Coward, 1994; Buchanan and Buchanan, 1995; Ziegler *et al*., 2002). Basin inversion is often genetically linked to processes active within the zones of continental collision or zones of active sea-floor spreading. For example, the Late Cretaceous–Tertiary inversion within the European foreland is generally attributed to Alpine collision and Atlantic spreading (Dadlez, 1980*a*; Schröder, 1987; Ziegler, 1988, 1990; Stackenbrandt and Franzke, 1989; Dronkers and Mrozek, 1991; Erlström *et al*., 1997; Kockel, 2003; Nielsen *et al*., 2005, 2007).

Inversion of sedimentary basins is related to the compressive reactivation of extensional fault zones and their subsequent activity as reverse fault zones. Due to the obliquity of the compressive stress field and older extensional/transtensional faults, basin inversion can often be related to important strike-slip (transpressive) movements (Harding, 1985; Woodcock and Schubert, 1994; Lihou and Allen, 1996; Dubois *et al*., 2002; Panien *et al*., 2005). Reverse faulting causes gradual upward movement of basement blocks, which ultimately can lead to the complete destruction of the basin, followed by uplift and erosion of its axial part (Hayward and Graham, 1989).

A very important aspect of basin inversion is the problem of dating its onset and main phases. Inversion, being related to uplift and erosion, should be regarded as a generally destructive process, during which large amount of deposits can be eroded and re-deposited. Such erosion can involve sediments deposited during basin extension/subsidence as well as sediments deposited during the early stages of the basin inversion. After a significant amount of inversion and uplift of the axial part of the basin, the only remaining sedimentary record of the inversion might only be detected within the so-called marginal troughs, i.e. remnant sedimentary depocentres developed along the sides of uplifted axial part of the basin (*cf*., Voigt *et al*., 2008).

In this paper the results of the analysis of high-quality seismic data acquired along the NE edge of the Holy Cross Mts. (SE) segment of the inverted Mid-Polish Trough (Fig. 1) are presented. The interpretation of seismic data was combined with a re-evaluation of the Upper Cretaceous biostratigraphy and integrated with the analysis of gravity data. Such an integrated approach has provided new insights regarding the structural grain of the inversion, its exact timing and the relationship between tectonic and sedimentary processes during basin inversion.

Fig. 1. Location of the study area (black rectangle) on a schematic map showing main tectonic units of Poland: NW–SE — trending inverted Mid-Polish Trough delineated by subcrops of the Jurassic and older rock, the Carpathians and the Carpathian Foredeep Basin

MID-POLISH TROUGH — REGIONAL GEOLOGICAL SETTING

The Polish Basin formed the easternmost part of the Central European Basin System (CEBS), a continental basin system related to the Permo-Mesozoic break up of Pangea (Ziegler, 1990; Scheck-Wenderoth *et al*., 2008). It is defined as a rather broad area covering large part of Poland that was subjected to the regional Permo-Mesozoic subsidence and sedimentation. The axial part of the Polish Basin is called the Mid-Polish Trough and it underwent much stronger localized subsidence (Pożaryski and Brochwicz-Lewiński, 1978, 1979; Krzywiec, 2006*a*). Similarly, the Mid-Polish Trough was the site of the most intense Late Cretaceous–Paleocene inversion observed within the Polish Basin (Ziegler, 1990; see e.g., Dadlez *et al*., 1998; Kutek, 2001; Krzywiec, 2002*a*, 2006*b*; Stephenson *et al*., 2003 for recent summaries and further references).

Subsidence and inversion within the Mid-Polish Trough was controlled by the NW–SE oriented Teisseyre-Tornquist Zone which marks regional crustal-scale boundary between the East European Craton and the Palaeozoic Platform (e.g., Dadlez, 1997 for summary and further references; Fig. 1). The gradual regional Permo-Mesozoic thermal subsidence pattern was punctuated by three major pulses of accelerated tectonic subsidence in Zechstein–Scythian, Oxfordian–Kimmeridgian, and early Cenomanian (Dadlez *et al*., 1995; Stephenson *et al*., 2003).

Since the Permian, the Polish Basin has been filled with several kilometres of siliciclastics and carbonates, including thick Zechstein evaporites in its NW (Pomeranian) and central (Kuiavian) segments (*cf*., Dadlez *et al*., 1998). Towards the SE, the Mid-Polish Trough extended into the transition zone between the Peritethyan and Tethyan domains, with limited Permian and Triassic sedimentation. Since the Jurassic, the thickness and depositional pattern in this part of the basin was strongly influenced by tectonic processes operating within the Mid-Polish Trough as well as by increased regional subsidence in the Tethyan domain (e.g., Kutek and Głazek, 1972; Pożaryski and Żytko, 1981; Feldman-Olszewska, 1997; Leszczyński, 1997*a*; Marek and Pajchlowa, 1997; Dadlez *et al*., 1998; Kutek, 2001; Gutowski *et al*., 2005*a*, *b*; Gutowski and Koyi, 2007).

Late Cretaceous–Paleocene intraplate compressional deformation resulted in regional-scale inversion tectonics within the European plate (e.g., Dadlez, 1980*a*, *b*; Norling and Bergström, 1987; Liboriussen *et al*., 1987; Schröder, 1987; Vejbæk and Andersen, 1987; Ziegler, 1987, 1989, 1990; Stackenbrandt and Franzke, 1989; Dronkers and Mrozek, 1991; Michelsen and Nielsen, 1993; Mogensen and Jensen, 1994; Ziegler *et al*., 1995, 2002; Erlström *et al*., 1997; Michelsen, 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; Scheck-Wenderoth *et al*., 2008 for recent summary and further references). This compressive event led to the complete inversion of the Polish Basin, resulting in significant uplift and erosion of its axial part (i.e. the Mid-Polish Trough), which was transformed into the so-called Mid-Polish Swell (e.g., Pożaryski and Brochwicz-Lewiński, 1978, 1979; comp. Fig. 1). The regional trend of the inversion was, similarly to the regional subsidence trend, controlled by the NW–SE — trending Teisseyre-Tornquist Zone. In the SE segment of the Mid-Polish Trough, Palaeozoic and Precambrian basement was exposed as a result of this inversion and at present forms the core of the Holy Cross Mts. (*cf*. Fig. 1).

Numerous contributions have been published that deal with various aspects of the inversion of the Mid-Polish Trough (e.g., Dadlez and Marek, 1969; Pożaryski and Brochwicz-Lewiński, 1978, 1979; Kutek, 1994; Dadlez, 1997; Pożaryski, 1997; Karnkowski, 1999; Resak *et al*., 2007; Jarosiński *et al*., 2009). Field structural evidences of inversion tectonics are scarce and are available only within the SE (Holy Cross Mts.) segment of the Mid-Polish Trough (see below). Many papers have dealt mainly with deep crustal processes responsible for basin inversion, and vertical uplift of the axial part of the basin has been attributed to phase changes and the transition of eclogite into gabbro, and related vertical crustal isostatic movements; the role of regional compressional stresses in this process has also been discussed (Znosko, 1979; Dadlez, 1980*a*; Dadlez *et al*., 1995). Recently published models based on seismic reflection data suggest that, similarly to the extensional/subsidence phase of the development of the Mid-Polish Trough, regional pre-Permian basement fault zones also controlled basement block movements during its inversion (Krzywiec, 2000, 2002*a*, *b*, 2004*a*, *b*, 2006*b*; Krzywiec *et al*., 2003). In the central (Kuiavian) and the northwestern (Pomeranian) segments of the basin both subsidence-related basement normal faulting as well as inversion-related reverse basement faulting were significantly filtered by thick Zechstein evaporites, and this process led to regional basin-scale mechanical decoupling between the sub-Zechstein basement and the supra-Zechstein (Mesozoic) sedimentary cover. In the SE segment of the Mid-Polish Trough described in this paper, due to a small thickness or lack of the Zechstein evaporites developed in marginal facies (*cf*., Dadlez *et al*., 1998), basement faulting has much more directly controlled thicknesses and facies distribution during both extension/subsidence as well as during compression/inversion (Pożaryski, 1948, 1997; Krzywiec, 2000, 2002*a*; Gutowski *et al*., 2003). Aspects of Mid-Polish Trough inversion including amount of eroded material and timing of inversion tectonics have also been discussed by Dadlez *et al*. (1995), Dadlez (2003) and Stephenson *et al*. (2003).

Along the strike of the inverted Mid-Polish Trough, regional and local variations of the amount of total subsidence as well as subsequent inversion and uplift can be observed. At present, the top of the pre-Zechstein basement is in net subsidence in the central (Kuiavian) part of the basin, while both its NW (Pomeranian) and SE (Holy Cross Mts.) segments show uplift of their axial parts above the regional level (*cf*., Krzywiec, 2002*a*, *b*; Wagner *et al*., 2002; Dadlez, 2003; Lamarche *et al*., 2003; Krzywiec, 2004*a*, *b*; Mazur *et al*., 2005).

A very important issue related to the inversion of the Mid-Polish Trough is the timing of its onset (*cf*., Dadlez *et al*., 1995; Leszczyński and Dadlez, 1999; Świdrowska and Hakenberg, 1999, 2000; Hakenberg and Świdrowska, 2001; Świdrowska *et al*., 2008). Estimates of both the amount and exact timing of the inversion according to different authors varies because of the significant amount of axial uplift and related erosion of the Mesozoic cover, also partly removing syn-inversion Upper Cretaceous–Lower Tertiary sediments. Estimates of erosion based on compaction analysis suggest that within the Pomeranian segment of the MPT inversion started in Turonian and was associated with total erosion of up to 2 km (Dadlez *et al*., 1997). Other authors criticized these estimates, partly neglecting details of the methodology of Dadlez *et al*. (1997), and suggested — using regional reconstructed thickness and lithofacies maps based on well data — that in the Turonian the entire basin underwent increased subsidence rather then uplift and inversion, and that later (Turonian–Maastrichtian) regional basin-scale thickness/facies variations visible on reconstructed maps should be attributed to relative movements of various parts of the East European Craton rather than the inversion of the Mid-Polish Trough (Świdrowska and Hakenberg, 1999). Świdrowska and Hakenberg (1999) also suggested that, within the NW (Pomeranian) segment of the Mid-Polish Trough, inversion started in the Campanian, and that the earliest evidence of inversion of the SE (Holy Cross Mts.) segment of the Mid-Polish Trough could be observed only in the Maastrichtian. Recent studies based on subsidence and 1D thermal modelling point to the late Turonian/Coniacian–Maastrichtian/Paleogene inversion of the Polish Basin (Resak *et al*., 2007).

Numerous seismic examples illustrating different modes and timing of inversion tectonics from the entire Mid-Polish Trough have been recently presented by Krzywiec (2000; 2002*a*, *b*, 2004*b*, *c*, 2007, 2009), Krzywiec *et al*. (2003, 2004, 2006), Gutowski *et al*. (2003), Mazur *et al*. (2005) and Scheck-Wenderoth *et al*. (2008). Regional analysis of seismic data indicates a Late Cretaceous–Early Tertiary reactivation of the generally NW–SE trending fault zones and to a certain importance of both NW–SE and SW–NE directed strike-slip movements. Analysis of seismic data from different parts of the basin shows that various factors influenced inversion of the Mid-Polish Trough:

1. Location of older fault zones in respect to the regional stress field generated at plate boundaries;

2. Presence or lack of the Zechstein evaporites causing mechanical decoupling (*cf*., Krzywiec, 2002*a*, *b*, 2004*a*, *b*, 2006*a*, *b*; Scheck-Wenderoth *et al*., 2008).

For example, Mesozoic normal fault zones located beneath the present-day Carpathians have not been inverted (Krzywiec *et al*., 2004); inversion of the major fault zones within the Nida Trough took place in the Maastrichtian or Early Tertiary (Krzywiec, 2004*c*; Scheck-Wenderoth *et al*., 2008); inversion of the Nowe Miasto–Zawichost Fault Zone began as early as late Turonian(?)–Coniacian times and continued until the Maastrichtian–Early Tertiary (Krzywiec, 2000, 2002*a*, 2007; Gutowski *et al*., 2003; Gutowski and Koyi, 2007; see also below); inversion of the Koszalin–Chojnice Fault Zone was complex and multi-stage with the onset of inversion-related uplift after the Turonian (Krzywiec, 2002*a*, 2004*b*); inversion of the Oświno–Drawno–Człopy salt structure was also multi-stage with its onset in Turonian–Coniacian times (Krzywiec, 2002*a*, *b*; 2004*b*, 2006*b*). In the case of the last two structures time estimates of the inversion based on seismic data are in good agreement with those based on detailed sedimentological–stratigraphic well studies (Leszczyński, 2002). Sedimentological and stratigraphic analysis from wells in the central (Kuiavian) part of the Mid-Polish Trough indicates that inversion started in Santonian–Campanian times (Leszczyński, 2000). All these results suggest that inversion of the Mid-Polish Trough was a rather heterogeneous process. In particular, inversion in certain areas of the Mid-Polish Trough began earlier than in other areas probably because the influence of regional compressional stresses was enhanced by the presence of the ductile Zechstein evaporites and/or by preferred location and orientation of older fault zones.

Regional analysis of seismic data from the central and NW Mid-Polish Trough allowed reconstruction of the regional sub-Zechstein fault pattern possibly responsible for subsidence and inversion of this basin (Fig. 2; Krzywiec, 2004*c*; Krzywiec *et al*., 2006). Inversion along the NE edge of the Mid-Polish

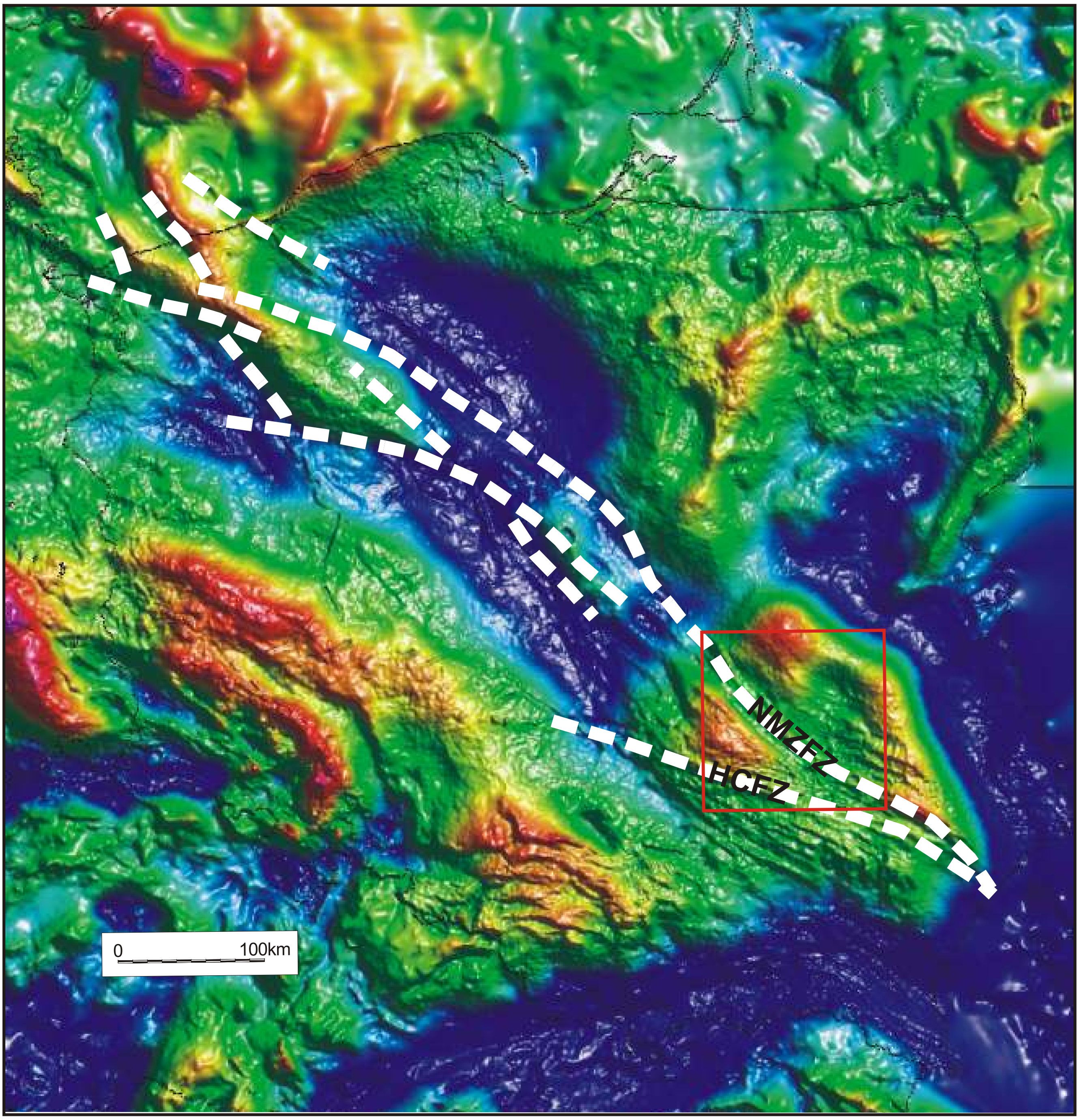

Fig. 2. Regional inferred fault pattern within the pre-Zechstein basement on the gravity map of Poland and surrounding areas (after Krzywiec *et al.*, 2006)

HCFZ — Holy Cross Fault Zone, NMZFZ — Nowe Miasto–Zawichost Fault Zone; red rectangle — area shown on Figures 3 and 13

Trough was generally controlled by the SW edge of the East European Craton (*cf.*, Dadlez, 1997); in the off-shore (S Baltic) and partly in the Pomeranian segment it coincided with the so-called Koszalin–Chojnice Fault Zone. Towards the SE it extends into the Nowe Miasto–Zawichost Fault Zone. The inversion pattern along the SW edge of the Mid-Polish Trough was less focused and was controlled by a system of regional *en-echelon* fault zones, generally concordant — on a regional scale — with the Holy Cross Fault Zone. (Krzywiec, 2004*c*; Krzywiec *et al*., 2006). Apart from the major basement fault zones mentioned above, including the Holy Cross and the Nowe Miasto–Zawichost Fault zones located within the study area described in this paper, numerous other fault zones were active during Mid-Polish Trough subsidence and inversion and many of these faults can be observed on magnetic and — especially gravity (Fig. 2) maps. Therefore, fault zones shown on Figure 2 should be regarded as only a sketch of regional basement fault patterns and not as a detailed tectonic map.

SE (HOLY CROSS MTS.) SEGMENT OF THE MID-POLISH TROUGH — AN OVERVIEW

The study area (Fig. 3) has been the focus of intense geological and geophysical studies for many decades. These studies, that included refraction and reflection seismic surveying, and gravity and magnetic surveys, were motivated by discoveries of hydrocarbons, hard coal deposits and various building stones of economic importance. In this region, two main structural complexes can be distinguished that are imaged on the seismic data analysed in this paper: the Palaeozoic (excluding Permian) complex and the Permo-Mesozoic complex. The Palaeozoic (Carboniferous–Devonian and older) complex that forms the basement of the Permo-Mesozoic sedimentary cover includes two main units: the Radom–Kraśnik High and the Lublin Basin (see Narkiewicz, 2007; Krzywiec, 2007, 2009, for a recent summary and further references).

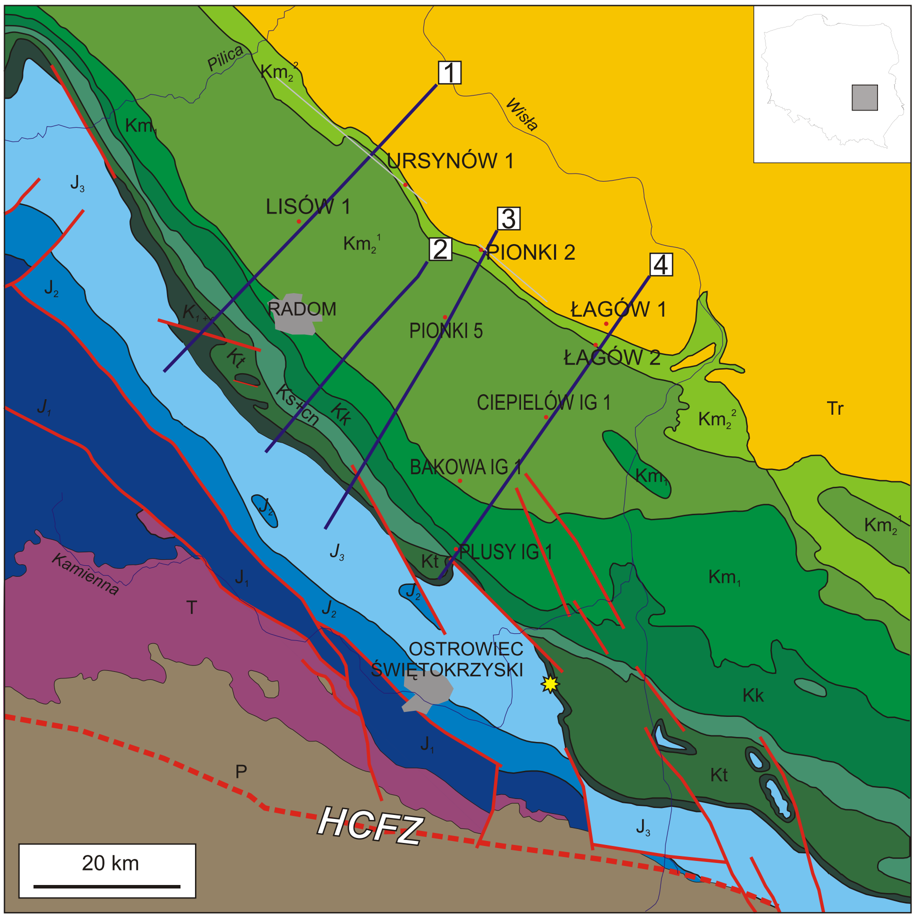

Fig. 3. Location of interpreted seismic profiles and selected wells on a geological map (without post-Paleocene cover) of the study area (based on Pożaryski, 1997)

1–4 — seismic profiles shown on Figures 9 and 10; HCFZ — Holy Cross Fault Zone, P — Palaeozoic, J_1 — Lower Jurassic, J_2 — Middle Jurassic, J_3 — Upper Jurassic, K_{1+c} — Lower Cretaceous + Cenomanian, Kt — Turonian, Ks+cn — Santonian + Coniacian, Kk — Campanian, Km_1 — lower Maastrichtian, Km_2^1 — upper Maastrichtian (lower part), Km_2^2 — upper Maastrichtian (upper part), Tr — Tertiary; yellow asterisk — location of the Ożarów quarry (*cf.* Fig. 8)

DEPOSITIONAL SYSTEMS OF THE SE SEGMENT OF THE MID-POLISH TROUGH

Permo-Mesozoic sedimentary cover analysed in this paper was formed within the SE (Holy Cross) segment of the Mid-Polish Trough (Fig. 3), that was situated within the transitional zone between the Peritethyan domain (i.e. a system of epicontinental basins that developed in western and central Europe) and the Tethyan rift basins to the south (e.g., Ziegler *et al.*, 1995; Golonka *et al.*, 2000; Kutek, 2001). Sedimentary and tectonic processes that acted within the Holy Cross Mts. area during the time from the Callovian–Oxfordian boundary (135 Ma) to the end of the Cretaceous (65 Ma) reflect a transition from extension and subsidence to compression and basin inversion.

Stratigraphy and facies development of the Mesozoic deposits of the Holy Cross Mts. and their margins are well recognized and synthesised in several papers based on outcrop and well data (e.g., Kutek 1968, 1994; Cieśliński and Pożaryski, 1970; Daniec, 1970; Senkowiczowa, 1970; Karaszewski and Kopik, 1970; Kopik, 1970; Malinowska, 1970; Matyja, 1977; Matyja *et al.*, 1989; Marcinowski and Radwański, 1983; Gutowski, 1992*a*, *b*, 1998, 2004*a*, *b*; Walaszczyk, 1992; Ogg and Gutowski, 1996; Hakenberg and Świdrowska 1997, 1998*a*, 2001; Gutowski *et al.*, 2005*a*, *b*). In this paper we focused on depositional architecture of the Mesozoic (mainly Upper Cretaceous) succession NE from the Nowe Miasto–Zawichost Fault Zone, i.e. within the footwall of this inverted fault zone. It is characterized by almost exclusively Jurassic–Cretaceous deposits, with a very limited thickness of the Zechstein–Triassic cover. The hanging wall of this inverted fault zone is, on the other hand, characterized by a thicker Zechstein, Triassic and partly — Jurassic succession while Cretaceous cover is rather thin or absent due to inversion-related erosion (see below). A summary of the Jurassic–Cretaceous depositional systems within the study area (i.e. generally towards the NE from the Nowe Miasto–Zawichost Fault Zone) is given in Figure 4.

PERMIAN AND TRIASSIC

The Permian–Lower Triassic (Buntsandstein) continental evaporitic-siliciclastic series are widely developed in the Holy Cross Mountains, as well as carbonate marine sediments regarded as Muschelkalk and fine clastic Keuper series (Mid-

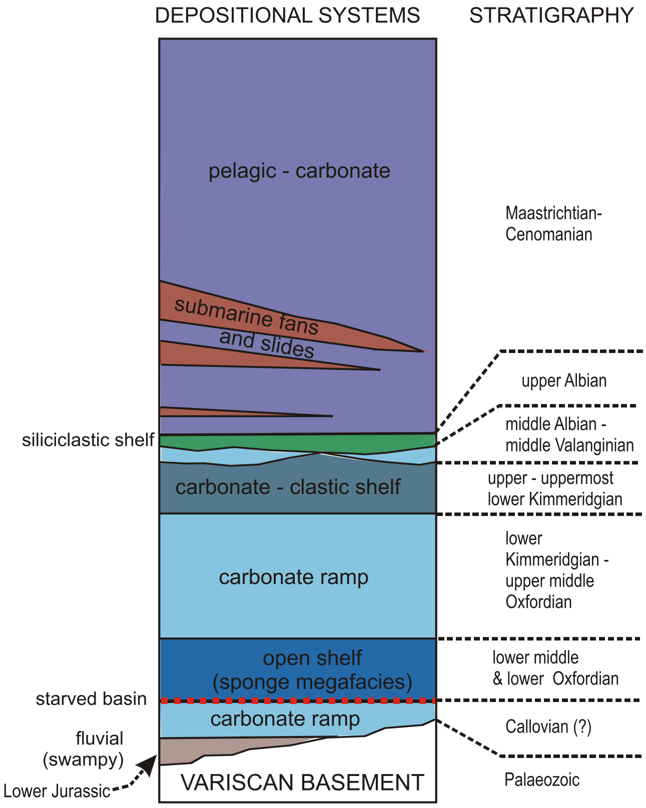

Fig. 4. Summary of the Upper Jurassic–Cretaceous depositional systems of the SE Mid-Polish Trough, area located towards the NE from the Nowe Miasto–Zawichost Fault Zone

dle–Upper Triassic). All these sediments are absent in the Bąkowa IG 1, Ciepielów IG 1 and Płusy IG 1 wells, i.e. are not present towards the NE from the inverted and uplifted axial part of the Mid-Polish Trough. In general, the study area is located in the marginal parts of the Permian–Triassic basin, and towards the N and NW this succession is characterized by a significantly increased thickness (*cf*., Dadlez *et al*., 1998).

LOWER JURASSIC

The Lower Jurassic sediments are rather thin NE from the Nowe Miasto–Zawichost Fault Zone. They are absent in the Ciepielów IG 1 well but a few metres thick clastic unit without marine fauna was identified just above the Palaeozoic basement in the Płusy IG 1 well. These sediments are possibly of Lower Jurassic age and can be related to clastic fluvial/swampy systems (most likely the Hettangian–Sinemurian Zagaje Formation) developed in the NE margin of the Holy Cross Mts. (Pieńkowski, 1984, 1991, 1997). The thickness of relevant deposits very likely increases towards the SW, within the hanging wall of the Nowe Miasto–Zawichost Fault Zone (i.e. towards the axial part of the inverted Mid-Polish Trough).

MIDDLE JURASSIC

The transgressive succession of base conglomerate passing upward into crinoidal limestones and dolomites, that appears above the Palaeozoic basement in the Ciepielów IG 1 well, may be attributed to the Middle Jurassic, most likely Callovian carbonate ramp system (*cf*., Niemczycka, 1974; Feldman-Olszewska, 1997). Relevant sediments are absent in the Płusy IG 1 well. The topmost part of this sequence is developed as a condensed layer (“nodular bed”) and represents a starved basin system widely developed in Central and Southern Poland in the Callovian/Oxfrodian transition beds (e.g., Matyja and Wierzbowski, 1996; Dembicz and Praszkier, 2003) and also in the NE margin of the Holy Cross Mts. (Gutowski, 1992*a*, 1998).

UPPER JURASSIC

The Late Jurassic depositional systems and sequence stratigraphy were recently summarized on a regional scale by Gutowski *et al*. (2005*a*, *b*). The early Oxfordian sedimentation started with carbonates of the open shelf system (sponge megafacies) (Matyja, 1977; Matyja and Pisera, 1991; Matyja and Wierzbowski, 1995; Gutowski, 1998). The system is characterized by denivelations of the sea bottom ranging up to 200 metres caused by growth of the cyanobacteria-sponge bioherm buildups (Matyja *et al*., 1992) The system was widely distributed along the northern Tethyan shelf in Europe and is commonly interpreted as deposited during exceptional highstands of sea level, which resulted in water depths up to about 400 metres within the shelf (Matyja and Wierzbowski, 1996). A shallow water carbonate ramp prograded onto the NE margin of the Holy Cross Mts. in the latest Transversarium Chron of the middle Oxfordian (Gutowski, 1998, 2004*a*). The carbonate ramp was submerged at the turn of Hypselocyclum and Divisum Chrones of the early Kimmeridgian (Gutowski, 1992*a*, 1998; Kutek, 1994) and overlain by oyster shellbeds and marls deposited in open marine conditions and ranging up to the Eudoxus Zone of the upper Kimmeridgian. These deposits are categorized as a carbonate-clastic shelf system. The top of the Kimmeridgian strata in both of the mentioned wells clearly has an erosional nature.

LOWER CRETACEOUS (NEOCOMIAN)

Neocomian strata have been drilled both in the Płusy IG 1 and in the Ciepielów IG 1 wells. They include upper Valanginian–middle Albian and middle–upper Valanginian intervals respectively (Marek, 1974). They represent a carbonate–clastic shelf system (*cf*., Leszczyński, 1997*a*).

UPPER ALBIAN AND UPPER CRETACEOUS

The Upper Cretaceous succession, due to its relationship with the inversion of the Mid-Polish Trough, is of prime interest for this paper. The late Albian worldwide marine transgression is recorded by the siliciclastic shelf system (*cf*., Leszczyński, 1997*b*). Rapid expansion of the sea in the early Cenomanian (Walaszczyk, 1987) resulted in shifting the clastic facies belt landwards and sedimentation of pelagic carbonate system sediments (*cf*., Leszczyński, 1997*b*), which persisted in the investigated area until the end of the Maastrichtian (Walaszczyk, 1992). The stratigraphy of Turonian through Santonian strata in both reference well sections is based on inoceramids and has been slightly revised in comparison to the former scheme of Krassowska (1974). The upper Albian siliciclastic shelf system is represented by glauconitic marly sandstones, often containing phosphatic nodules (e.g., Cieśliński, 1976; Walaszczyk, 1987). The Cenomanian–Maastrichtian pelagic carbonate system is represented by limestone-opoka facies (Walaszczyk, 1992; Leszczyński, 1997*b*) and consists of a monotonous succession of rhythmically bedded mudstones, skeletal wackestones and, rarely, packstones which often contain cherts and flints or are silified. The sediments are rich in fauna, mainly of inoceramids, belemnites, ammonites sponges, brachiopods foraminifers, radiolarians and calcareous nannoplankton. The system is believed to have been deposited in relatively deep water of an open marine shelf at depths up to 200 m and perhaps even 500 m (Leszczyński, 1997*b* and literature cited therein). Within this rather monotonous chalk succession there is some evidence for localized progradation and redeposition towards the NE. Close to the Nowe Miasto–Zawichost Fault Zone a lithostratigraphic unit — the Janików Limestones (upper Turonian) has been described that is composed of grainstones in which the main components are crinoids and bryozoan fragments (*cf*., Pożaryski, 1948; Walaszczyk, 1992). The Janików Limestones have been interpreted by Pożaryski (1948) as a talus of an organic reef developed to the S, i.e., in the Holy Cross area and at least partly abraded due to the uplift of that area by "Sub-Hercynian movements". Walaszczyk (1992) indicated their progradational, NE oriented patterns and transport of the bioclastic material to NE. The Maastrichtian opoka beds are conformably overlain by sandy gaizes with limestone intercalations of Danian age (Hansen *et al*., 1989), which start the Paleogene succession comprising marine clastic sediments, mainly glauconitic sands, gravels and clays of the Lower Paleocene, Upper Eocene and Oligocene.

TECTONICS OF THE SE SEGMENT OF THE MID-POLISH TROUGH

The NE edge of this segment of the Mid-Polish Trough was controlled by a fault system collectively referred to as the Nowe Miasto–Ostrowiec Świętokrzyski–Zawichost (Pożaryski, 1948, 1997) or the Nowe Miasto–Iłża Fault Zone (Hakenberg and Świdrowska, 1997, 1998*a*, *b*; Świdrowska and Hakenberg, 2000). In this paper, this fault zone is referred to as the Nowe Miasto–Zawichost Fault Zone (*cf*., Krzywiec, 2007, 2009). This fault zone was active during the Permian–Mesozoic evolution of this segment of the MPT and directly influenced facies and thickness pattern in this part of the basin (e.g., Hakenberg and Świdrowska, 1997, 1998*a*, *b*, 2001; Gutowski 1998, 2004*a*; Gutowski *et al*., 2003, 2005*a*, *b*). For instance, a Late Jurassic major extension and subsidence stage was recorded by the Oxfordian (Bathonian?)–Kimmeridgian sedimentary sequences, especially by the relatively thick middle Oxfordian–lower Kimmeridgian highstand systems tract, the thickness of which rapidly increases within the SW limb of the marginal fault zone. The overall extension/subsidence was interrupted in the Early Cretaceous by several uplifts recorded by stratigraphic gaps and/or subtle angular unconformity between the upper Kimmeridgian and the upper Valanginian successions. Major, regional uplift resulted in sedimentary discontinuity and a correlative erosional gap which underlie the upper Albian transgressive sediments. Erosion locally removed the Lower Cretaceous deposits and even cut the Kimmeridgian sequence down to the Divisum Zone oolites (e.g., in the Ożarów quarry).

In his seminal paper, Pożaryski (1948) provided a detailed account of the Jurassic–Cretaceous history of the Holy Cross segment of the Mid-Polish Trough. His paper, published well before modern concepts of inversion of sedimentary basins were established, presented a conceptual geological cross-section based on detailed field mapping and shallow cartographic wells that shows a system of reverse (i.e. inversion-related) faults dissecting both the Palaeozoic basement as well as the Mesozoic sedimentary cover (Fig. 5). Later interpretations, based on deep research wells and analogue seismic reflection data, introduced very significant modifications — instead of reverse faulting normal faulting towards the NE was proposed (Żelichowski, in: Niemczycka, 1974, 1975). No suitable geological explanation was, however, given justifying such a modification; in particular, it was not explained how the footwall of such an extensional system, belonging to the axial part of the inverted sedimentary basin, could be characterized by an increased thickness of Mesozoic sediments. Seismic examples illustrating different modes of inversion within this part of the Mid-Polish Trough were recently analysed by Krzywiec (2000, 2002*a*, 2007, 2009), Krzywiec *et al*. (2003, 2004) and Gutowski *et al*. (2003) and point to the reactivation of the generally NW–SE trending fault zones. The obtained results fully confirm the concepts of the in-

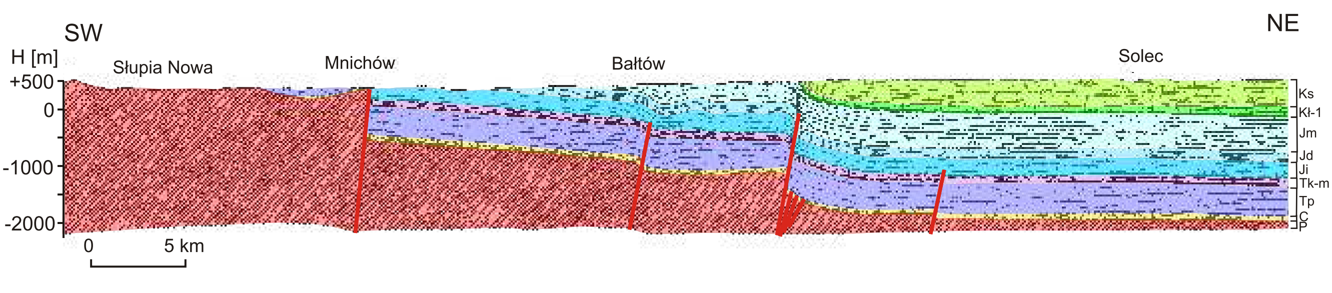

Fig. 5. Synthetic geological cross-section across the NE boundary of the Holy Cross segment of the Mid-Polish Trough based on shallow wells and outcrops only (Pożaryski, 1948)

Note system of reverse faults, clearly indicating late–post-Cretaceous inversion tectonics in this area; P — Old Paleozoicum, C — Zechstein, Tp — Trias-Bunter, Tk-m — Trias-Keuper and Muschelkalk, Jl — Lower Jurassic, Jd — Middle Jurassic, Jm — Upper Jurassic, Kt-1 — Cretaceous-Turonian-Albian, Ks — Cretaceous-Senonian (original explanations of Pożaryski, 1948) version-related reverse faulting proposed by Pożaryski (1948, 1997). Field studies indicate that Late Cretaceous tectonic reactivation of the fault zone bounding to the NE Holy Cross segment of the Mid-Polish Trough included strike-slip component, and resulted in the development of a series of small-scale *en-echelon* faults (Jaroszewski, 1972; Lamarche *et al*., 1999, 2002; Świdrowska and Hakenberg, 2000).

Within the SE (Holy Cross) segment of the Mid-Polish Trough some field structural evidence of inversion tectonics are available. They indicate a complex compressional Late Cretaceous reactivation of older Mesozoic or/and Palaeozoic fault zones, partly in a strike-slip (transpressional) regime, accompanied by the formation of uplift-related extensional fractures and conjugate normal faults within the axial part of the Mid-Polish Swell (e.g., Stupnicka, 1971, 1972; Jaroszewski, 1972; Lamarche *et al*., 1998, 2002, 2003; Konon, 2004).

The majority of the models of inversion of the SE segment of the Mid-Polish Trough was constructed using data from wells located along both flanks of the inverted Mid-Polish Trough (Kutek and Głazek, 1972; Hakenberg and Świdrowska, 1998*b*, 2001; Świdrowska and Hakenberg, 2000). According to these models the basin was inverted not earlier than during Maastrichtian–Paleogene times because constructed maps and regional geological cross-sections show an increasing thickness of these particular isochronic stratigraphic units towards the reconstructed axis of the basin. Recent results based on seismic and well data suggest that inversion had started significantly earlier, most probably already in the late Turonian and continued during Coniacian–Maastrichtian and post-Maastrichtian times (Krzywiec, 2000, 2002*a*, 2007, 2009; Gutowski *et al*., 2003). Problems related to the dating of inversion of this part of the Mid-Polish Trough are thoroughly discussed below.

REVISED UPPER CRETACEOUS STRATIGRAPHY FROM THE CIEPIELÓW IG 1 WELL

Stratigraphy of the Turonian through Santonian strata in Ciepielów IG 1 reference well sections is based on inoceramids and has been revised in comparison to former scheme (Krassowska, 1974). The rich palaeontological record, particularly in the lower part of the Upper Cretaceous, up to the middle Santonian, enabled the revision of its bio- and chronostratigraphical subdivisions.

The base of the Cenomanian is well marked by the stratigraphically oldest record of *Inoceramus crippsi* at depth 831.0 m. Up to 824.0 m inoceramids characteristic for the lower Cenomanian occur, and already at depth 807.0 m the first representative of *Inoceramus* ex gr. *lamarcki* Parkinson appears, indicating at least the middle Turonian. It means that this 17 m thick interval between 807 and 824 comprises the middle–upper Cenomanian, lower Turonian and possibly also a basal part of the middle Turonian, suggesting a strong condensation and/or stratigraphic gaps in this part of the Late Cretaceous, this situation well known from surface exposures in the area (see e.g., Cieśliński, 1959; Marcinowski, 1980; Walaszczyk, 1987). Although no complete *Mytiloides* ex gr. *labiatus* (Schlotheim), a very good marker of the base of the Turonian, was found, the occurrence of a limestone bed, rich in inoceramid prisms, at depth 815.3 to 814.7 m is taken here as the base of the stage, closely corresponding to the conclusion by Krassowska (1974). The inoceramid rich limestone bed at the base of the Turonian is a very charactersitic feature in the area (e.g., Pożaryski, 1948; Walaszczyk, 1992).

The Turonian ranges between depths 815 and 726.1 m. The latter value accepted herein as the base of the Coniacian is precisely documented by the first occurrence of *Cremnoceramus deformis erectus* (Meek, 1877), the inoceramid marker of the base of the Coniacian (see e.g., Walaszczyk and Wood, 1999). The inoceramid record also enables a further substage subdivision of the Turonian. As mentioned above, the base of the middle Turonian should be placed not higher than 807 m, and the base of the upper Turonian is marked by the co-appearance of first, small *Inoceramus perplexus* Whitfield, 1877, and *Mytiloides* sp., at depth 793.5 m.

The base of the middle Coniacian marks the lowest occurrence of *Volviceramus koeneni* (Müller), at depth 668.2 m. Moreover, 50 cm higher was noted first *Platyceramus* ex gr. *mantelli*. The record of *Inoceramus percostatus* or *Inoceramus annulatus*, at depth 686.0 m, is interpreted herein as a marker of the *Inoceramus gibbosus* Zone, the topmost zone of the lower Coniacian (see Walaszczyk and Wood, 1999). *Mytiloides subquadratus*, the inoceramid marker of the base of the upper Coniacian, is noted at depth 654.1 m.

The base of the Santonian cannot be precisely located, as the marker of the stage, *Cladoceramus undulatoplicatus*, was not found in the Ciepielów section. However, the first *Sphenoceramus pachti*/*cardissoides*, noted at depth 635.0 m, suggests this boundary to be located only slightly deeper, as demonstrated in other Central European areas (Seitz, 1965; Remin, 2004). Sphenoceramids are quite common up to depth 621.6 m, indicating a relatively lower portion of the stage.

The faunal remains higher in the section are too sparse to allow reliable statigraphic checking. However, based on a comparison with the classic exposures of the Vistula section (Pożaryski, 1938, 1948; Błaszkiewicz, 1980; Walaszczyk, 2004), the thickness of the Santonian in the Ciepielów well as assumed in the original description of this borehole (Krassowska, 1974), is highly overestimated, and most probably does not exceed 100 m.

INTERPRETATION OF SEISMIC DATA

Several deep wells located within the study area (Fig. 3) provided key stratigraphic and lithological information for calibration of seismic data. Reinterpreted Upper Cretaceous biostratigraphy in the Ciepielów IG 1 well (see above) was regarded as the reference point for the entire study area. For this well, sonic log and check shot data were available together with natural gamma and electrical logs, and allowed for very detailed correlation of the well with seismic data. In order to tie depth well data to time seismic data, a synthetic seismogram was calculated for this well, using sonic and density data (Fig. 6). Several wavelets were tested and the best results were obtained for a zero-phase 35 Hz Ricker wavelet. The final fit between synthetic and measured wavefields was achieved after relevant corrections were applied to the sonic log (vertical shift and stretch-squeeze). As a result, the following stratigraphic boundaries from the Ciepielów IG 1 well were precisely tied to the seismic wavefield and interpreted on seismic data — top of: Campanian, Santonian, Coniacian, Turonian, Cenomanian, Kimmeridgian, Oxfordian, Lower Jurassic and top of the Palaeozoic (pre-Zechstein) basement (Fig. 6). On Figure 7 Jurassic–Cretaceous stratigraphy and depositional systems are integrated with seismic data. This figure also shows Jurassic–Cretaceous boundary underlined by subtle angular unconformity. This boundary is related to an important stratigraphic gap (see above), well known from numerous outcrops located along the NE margin of the Holy Cross Mts. (Fig. 8; e.g., Gutowski, 1998).

The analysed seismic profiles, acquired in 1997 and 1998, are located within the NE border zone of the Holy Cross Mts. segment of the Mid-Polish Trough and partly cross its inverted axial part (Fig. 3). This is a high-quality, high-resolution dataset, that allowed for a very precise interpretation of the entire Mesozoic succession, especially for the thick Upper Cretaceous interval. Seismic horizons are usually high amplitude continuous events that could be traced over long distances. Seismic stratigraphy based on selected seismic horizons is of at least one order higher resolution than well-based biostratigraphy, in particular for the Campanian and the Maastrichtian, as within these complexes at least 15–20 continuous seismic horizons could be distinguished and correlated (Figs. 6 and 7). Such good quality and resolution of seismic data allowed for precise analysis of thickness variations of the Upper Cretaceous deposits in immediate vicinity of the Nowe Miasto–Zawichost Fault Zone that defines the present-day NE boundary of the inverted Mid-Polish Trough in Holy Cross Mts. region (Figs. 2 and 3).

Four profiles were selected to illustrate the present-day structure of the Nowe Miasto–Zawichost Fault Zone and surrounding areas and its tectono-sedimentary evolution (Figs. 9 and 10; *cf*. Krzywiec, 2002*a*, 2007, 2009; Scheck-Wenderoth *et al*., 2008).

All the four seismic profiles show the major inversion-related tectonic structure of the border zone between the uplifted (inverted) axial part of the Mid-Polish Zone (that includes the Holy Cross Mts.) and its NE flank (Figs. 9 and 10). In this re-

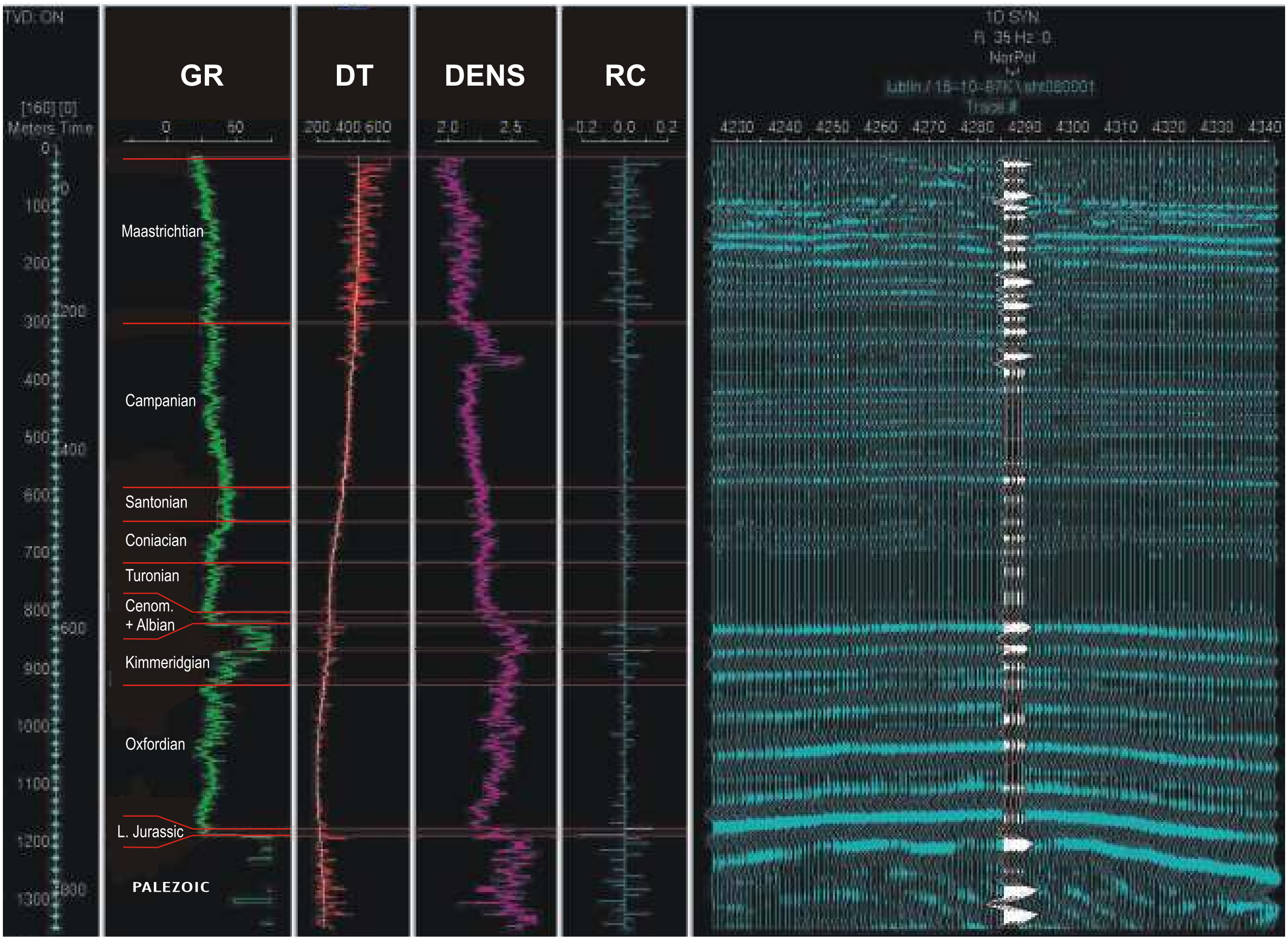

Fig. 6. Synthetic seismogram and its correlation with seismic data — well Ciepielów IG 1

GR — natural gamma-ray log, DT — acoustic log (with superimposed check-shot data, white curve), DENS — density log, RC — reflection coefficients; synthetic seismogram was constructed using 35Hz zero-phase Ricker wavelet

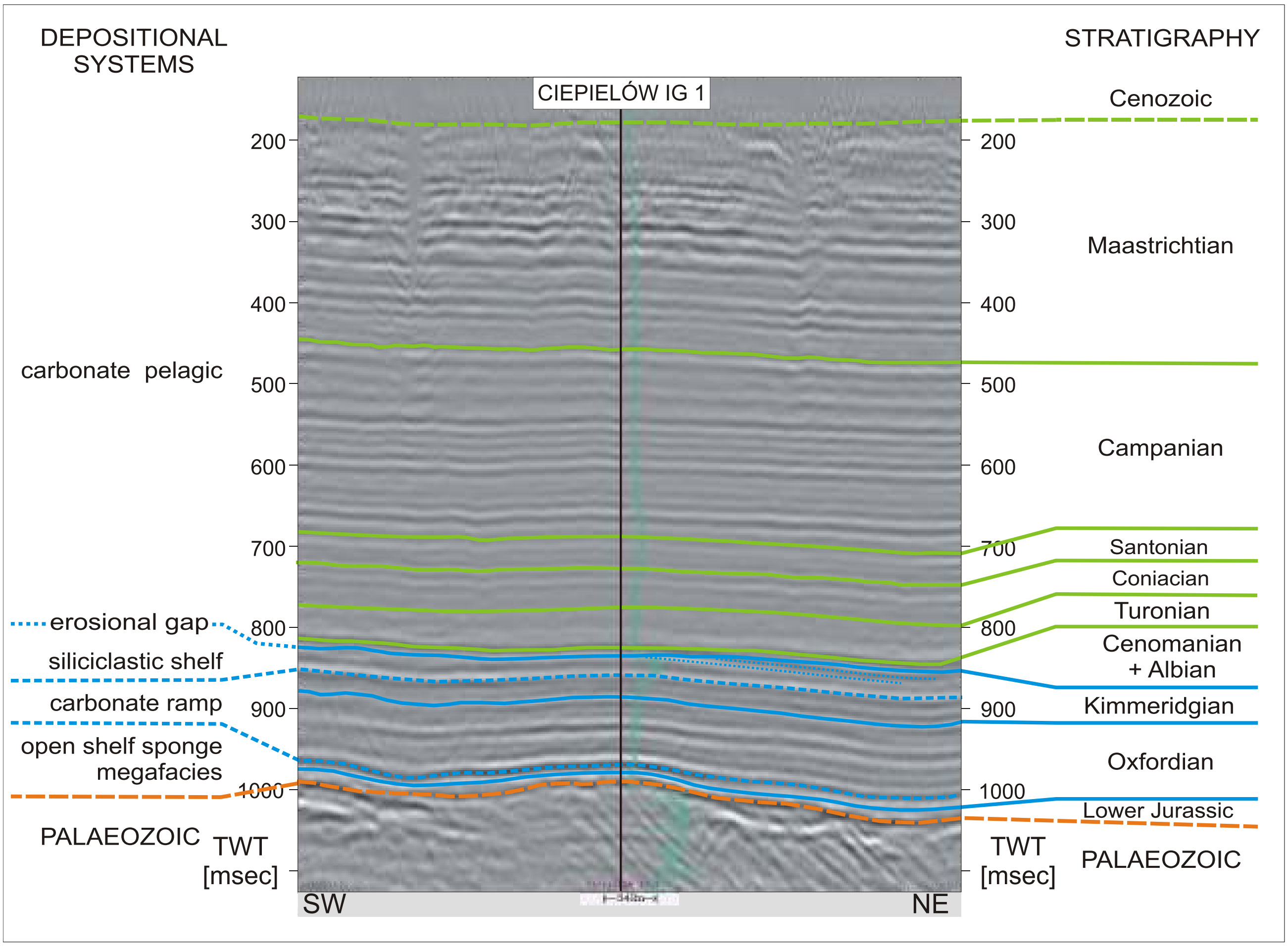

Fig. 7. Correlation of Ciepielów IG 1 well with seismic profile showing relationship between the seismic wave field, lithology (represented by the natural gamma log), stratigraphy and depositional systems

Dotted lines highlight unconformity at the Jurassic–Cretaceous boundary (*cf*., Fig. 8)

gion, Permo-Mesozoic deposits within the uplifted hanging wall have not been drilled and, consequently, stratigraphic/thickness relationships shown on seismic profiles should be regarded at least in part as approximate, although fairly reliable. The Zechstein/Triassic boundary was not drilled and is based on regional thickness relationships known from other wells in this region as well as on general characteristics of the seismic wavefield — it was correlated with a strong seismic horizon possibly related to the boundary between Zechstein evaporites and Triassic clastics. The Triassic/Jurassic boundary was drilled by several wells, but within the hangingwall it is also partly approximate. The Jurassic/Cretaceous boundary is calibrated by numerous wells in the region and is related to the high-amplitude high-continuity seismic horizon that could be traced over long distances. This seismic event is related to the sharp lithological contrast between Jurassic carbonates and marls and Cretaceous siliciclastics. The Jurassic/Cretaceous boundary could be fairly reliably correlated across the Nowe Miasto–Zawichost Fault Zone.

The entire Permian-Mesozoic succession is characterized by very prominent thickness changes, with the Permian, Triassic and Jurassic deposits significantly increasing their thickness

Fig. 8. Jurassic–Cretaceous boundary associated with an important stratigraphic gap, Ożarów quarry

For location see Figure 3

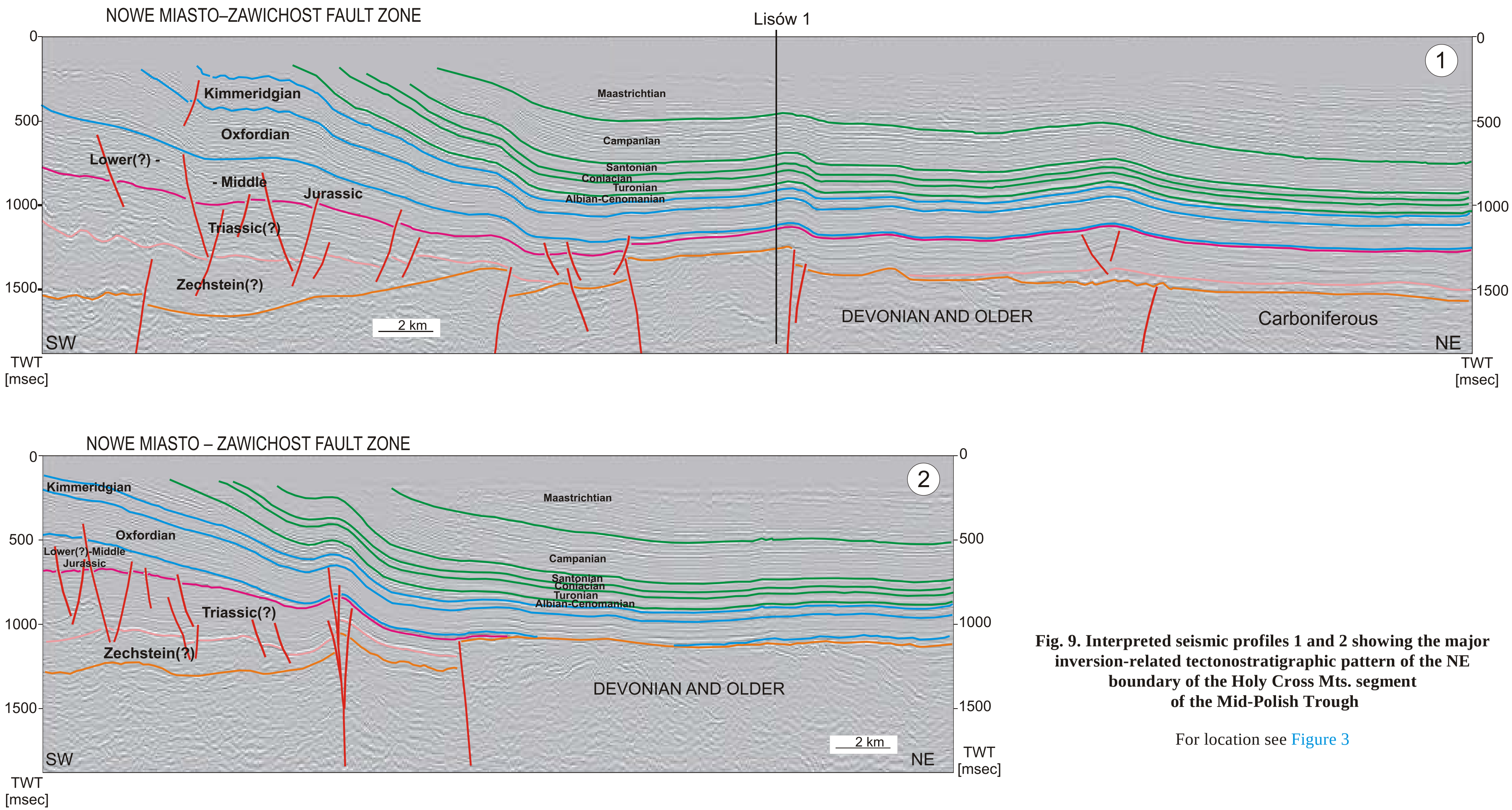

Fig. 9. Interpreted seismic profiles 1 and 2 showing the major inversion-related tectonostratigraphic pattern of the NE boundary of the Holy Cross Mts. segment of the Mid-Polish Trough

For location see Figure 3

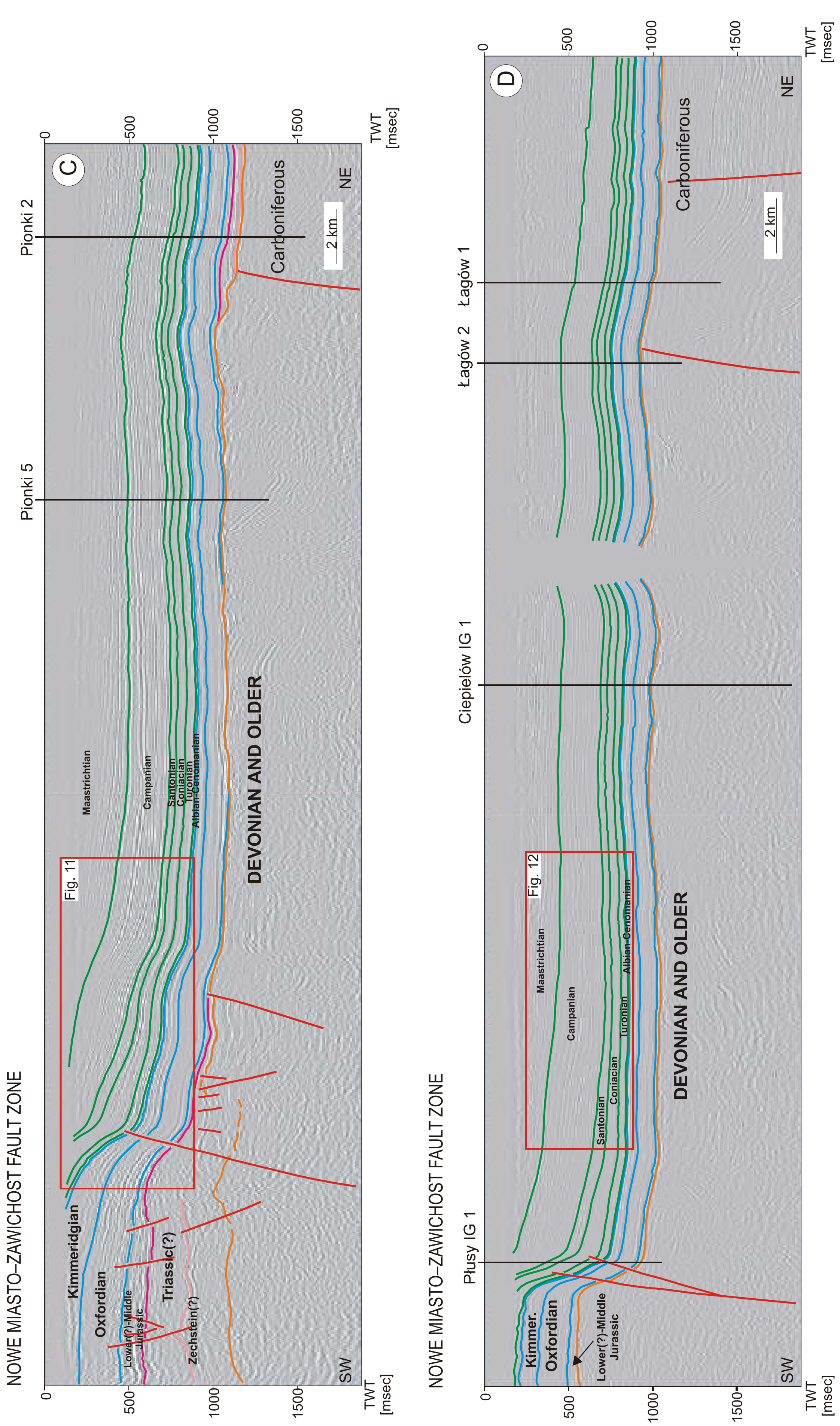

Fig. 10. Interpreted seismic profiles 3 and 4 showing the major inversion-related tectonostratigraphic pattern of the NE boundary of the Holy Cross Mts. segment of the Mid-Polish Trough

For location see Figure 3; rectangles — enlarged parts of seismic profiles 3 and 4 shown on Figures 11 and 12 towards the SW (*cf*., Pożaryski, 1948, 1997; Żelichowski in Niemczycka, 1974, 1975; Krzywiec, 2000, 2002*a*, 2007, 2009). The Cretaceous succession comprises Cenomanian–Maastrichtian deposits; its upper boundary is of clearly erosional character.

Pre-Cretaceous to Cenomanian sedimentary cover imaged on the analysed seismic profiles is characterized by increased thickness towards the SW, i.e. towards the inverted Mid-Polish Trough. This reflects a subsidence stage within the basin's axial part, accompanied by deposition of thick sedimentary cover above the hangingwall.

In contrast, almost the entire preserved Upper Cretaceous succession is characterized by a different thickness pattern — particular seismic packages thin both towards the SW as well towards the NE (Figs. 9 and 10). Seismostratigraphic interpretation of the Upper Cretaceous succession was focused on subtle thickness variations in the vicinity of the border fault zone responsible for the subsidence and subsequent inversion of the Mid-Polish Trough (i.e. the Nowe Miasto–Zawichost Fault Zone).

The overall Upper Cretaceous depositional architecture imaged on seismic data resembles a low-angle progradational complex with a general direction of sediment supply from the SW (*cf*., Krzywiec, 2000, 2007, 2009). Turonian deposits show only gentle thinning towards the SW and are characterized by a very subtle long-distance thinning towards the NE (Figs. 9–11). Coniacian–Santonian deposits more clearly show the thickness variations mentioned above — they thin towards the SW, towards the Nowe Miasto–Zawichost Fault Zone, as well as towards the NE. A local zone of maximum thickness of the Coniacian–Santonian deposits is located in the immediate vicinity of this fault zone. Campanian deposits are characterized by much thicknesses, and consequently it was possible to correlate many intra-Campanian seismic horizons and delineate several intra-Campanian packages. They all show thinning both towards the SW and the NE. Bi-directional thinning of the Campanian deposits, similar to the same feature observed within the Coniacian–Santonian interval, is rather local, and defines local zones of thickening for each mapped intra-Campanian package. The Maastrichtian was significantly eroded and it is mostly missing in the immediate vicinity of the Nowe Miasto–Zawichost Fault Zone. Nevertheless, preserved Maastrichtian deposits also are characterized by clearly visible thinning towards the SW and the NE. Identified bi-directional thinning defines a clinoformal seismic pattern related to the migation of local zone of maximum thickness combined with sediment progradation from the SW (i.e. zone of inversion-related uplift and erosion) towards the NE (i.e. towards marginal trough developed along the inverted axial part of the Mid-Polish Trough). NE-ward and upward migration of the zone of maximum thickness of the Turonian(?)–Maastrichtian succession is observed. This implies progradation and aggradation, connected to a relatively high sediment supply and relatively high (rising) sea level (Van Wagoner *et al*., 1988).

Other rather peculiar features have been identified within the Campanian–Maastrichtian succession apart from the thickness variations described above. These are small-scale (up to approx. 2 km wide) localized zones of asymmetrical thickness increase of the Upper Cretaceous packages (Fig. 12). They are visible on all seismic profiles located along the analysed inverted axial part of the Mid-Polish Trough (*cf*., Figs. 9 and 10). They could represent submarine slides (*cf*., McAdoo *et al*., 2000; Imbo *et al*., 2003) that developed along flanks of the Mid-Polish Swell during its progressive uplift. They might have been controlled by normal listric faults developed in only partly lithified Upper Cretaceous deposits. Listric faulting would have been triggered by progressive uplift of basin axis, increased morphological gradients along its flanks and gravitational instability (*cf*., Hesthammer and Fossen, 1999; Lykousis *et al*., 2002), combined with tectonic movements along basement faults and related earthquakes. An alternative — though less favourable — explanation for the seismic features detected along the inverted axial part of the Mid-Polish Trough is that they might represent deposits of contour currents (*cf*., Faugorès *et al*., 1999), that had moved along the inverted basin axis (NW–SE).

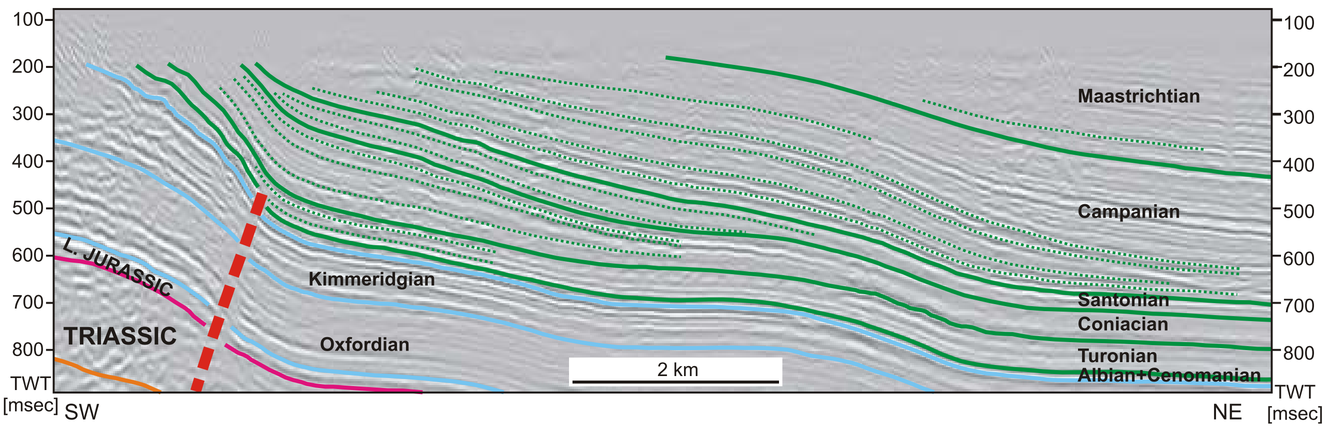

Fig. 11. Enlarged part of the seismic profile 3 from Figure 10

Observed thickness reductions within the Turonian(?)–Maastrichtian towards the SW and towards the NE are related to inversion and uplift of the Holy Cross segment of the Mid-Polish Trough (*cf*., Krzywiec, 2002, 2007, 2009)

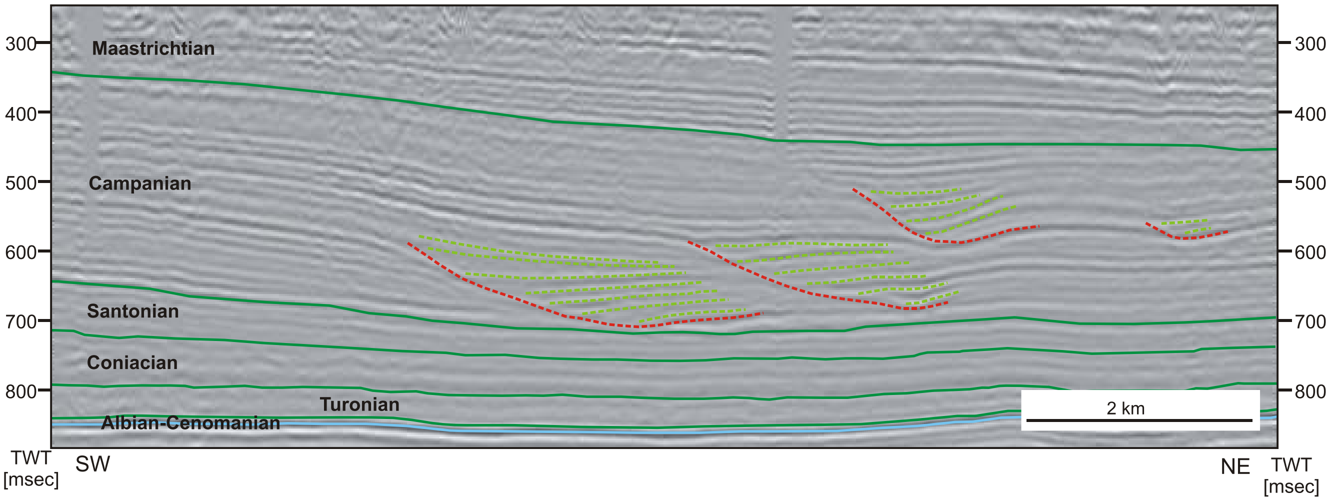

Fig. 12. Details of depositional architecture of the Campanian succession deposited along the inverted NE boundary of the Mid-Polish Trough (*cf*. Fig. 10)

DISCUSSION

Detailed interpretation of seismic data from the NE surroundings of the Holy Cross Mts., located within the axial part of the inverted Mid-Polish Trough (Figs. 1 and 3) proves that almost the entire Upper Cretaceous complex (Turonian?–Maastrichtian) was deposited during inversion of the Mid-Polish Trough. This is implied by the thickness distribution of particular seismic packages, that thin towards the SW and towards the NE, in contrast with the Permo-Jurassic succession that rapidly thickens towards the NE (i.e. towards the basin axis). Also, the presence of local features like submarine slumps/listric faulting and/or contour deposits suggest that during deposition of the Upper Cretaceous complex there was uplifted area towards the SW from the study area, which could be attributed to the inverted axial segment of the Mid-Polish Trough. Such seismically-defined depositional architecture is compatible with earlier models constructed using mostly well and outcrop data, with additional information provided by analogue seismic profiles acquire in the 1960s (Pożaryski, 1948, 1997; Fig. 5).

Such timing of inversion tectonics in the study area is considerably different from that proposed by other authors (Hakenberg and Świdrowska, 1998*b*, 2001; Świdrowska and Hakenberg, 1999, 2000; Świdrowska *et al*., 2008), all of whom assumed only a late Maastrichtian–post-Maastrichtian inversion phase. Their results were, however, based on the analysis of regional thickness and lithofacies maps, constructed using well data only. Within the relatively narrow (up to 10 km) zone of syn-inversion sedimentation, flanking the uplifted Mid-Polish Swell (Fig. 3; *cf*., Krzywiec, 2002*a*, 2007) and critical for dating of inversion tectonics, not enough well information is available to enable precise mapping of the syn-inversion sedimentary succession. In the study area, only Bąkowa IG 1 well is located within this zone (Fig. 3), while other wells are located outside the zone of identified inversion-related sedimentary features, and this does not allow for the construction of maps with sufficiently precise facies variations, required for analysis of inversion-related sedimentation. Additionally, well stratigraphic resolution for the relatively thick Upper Cretaceous interval is not precise enough to allow for delineation of subtle thickness and facies changes within the Turonian–Maastrichtian complex. This is in contrast to modern reflection seismic profiles presented here that precisely imaged this interval and have shown the Upper Cretaceous inversion-related depositional architecture.

A model depicting tectono-sedimentary evolution of the studied SE segment of the Mid-Polish Trough during its Late Cretaceous inversion is shown on Figure 13. This model was constructed using seismic profile 3 (Fig. 10) flattened on top of Jurassic (Fig. 13A), top of Cenomanian (Fig. 13B), top of Turonian (Fig. 13C), top of Coniacian (Fig. 13D), top of Santonian (Fig. 13E) and top of Campanian (Fig. 13F). Figure 13G shows present-day configuration redrawn from interpreted seismic profile (Fig. 10). Reconstruction for end of Maastrichtian is not shown as in this area top of Maastrichtian is erosional, and no reliable surface could be used to approximate depositional top of Maastrichtian. Flattened seismic profile could be regarded as reliable first-order approximation when tectonic activity is mostly restricted to vertical movements, i.e. when no significant lateral displacement takes place. This was the case during inversion of the SE Mid-Polish Trough, illustrated on Figure 13. It must be, however, kept in mind that this approach slightly underestimates displacement along boundary fault shown on this model. Flattening does not also account for possible basin floor gradient that must have existed between the uplifted axial part of inverted basin and its flank, in relatively deep waters ranging during Late Cretaceous between approx. 100–250 m. 2D cross-section balancing would be required to reconstruct exact tectono-sedimentary evolution along this profile.

For simplicity, boundary fault responsible for subsidence and inversion was shown on Figure 13 as a discrete fault plane, although most probably more complex model of discrete faulting within the deeper basement combined with drape folding

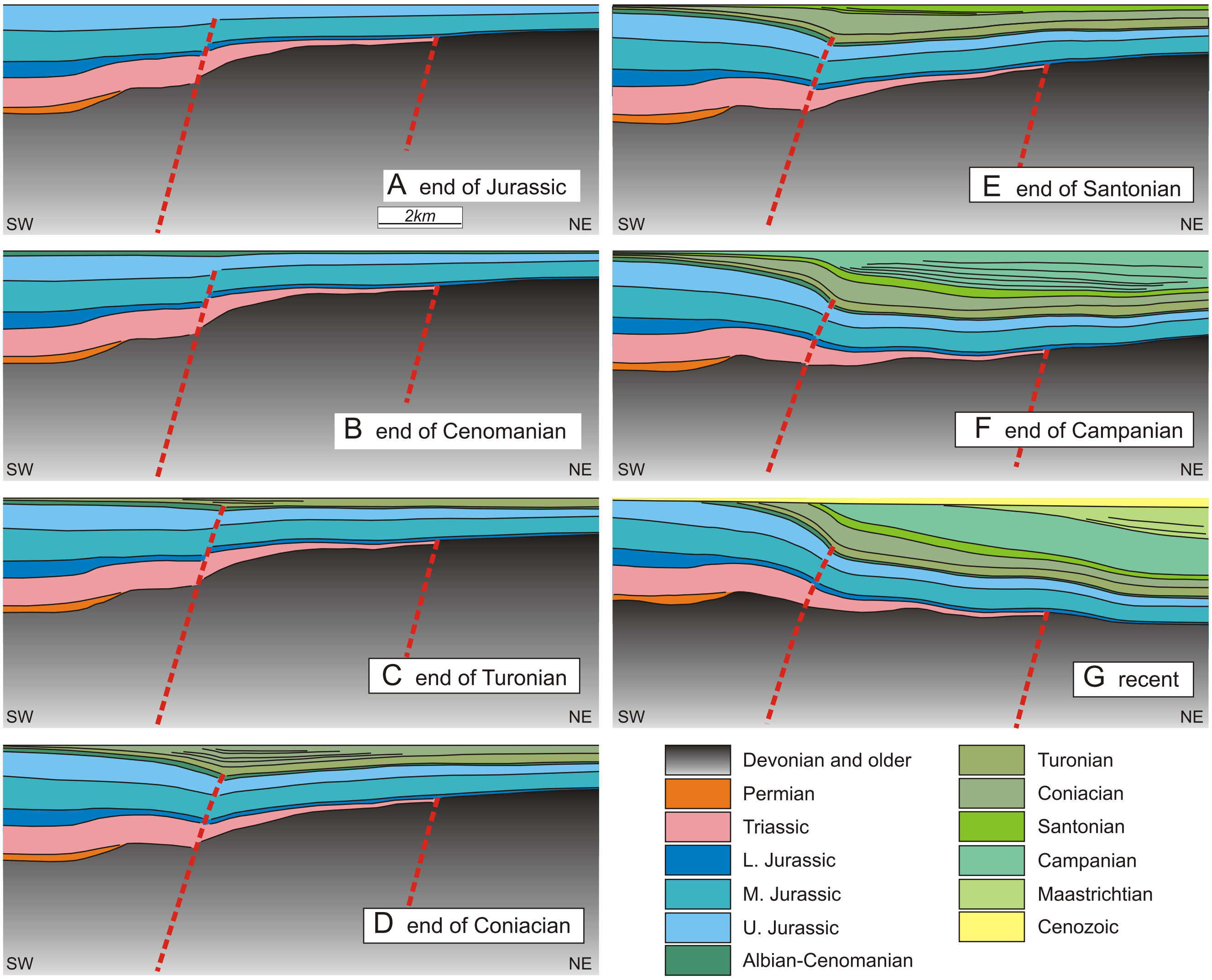

Fig. 13. Transition from Jurassic extension and subsidence to Late Cretaceous inversion and uplift along the Nowa Iłża–Zawichost Fault Zone — model based on seismic profile 3 (Fig. 10)

Vertical scale approximately equals horizontal scale; see text for further explanations

and distributed faulting at shallower levels should has been considered (see below).

End of significant extension and subsidence is shown on Figure 13A, where Triassic–Jurassic cover is characterized by significantly increased thickness within the axial part of the basin. For Albian–Cenomanian (*cf*., Figs. 9 and 10) only very minor subsidence in this part of the basin, with no signs on inversions, could be observed (Fig. 13B). In Turonian (Fig. 13C) minor uplift within the axial part of the basin is already marked, related to minor thinning of Turonian deposits towards SW. Due to relatively small thickness of the Turonian cover and deep erosion this thinning could be observed only in a relatively narrow zone, therefore late Turonian onset of inversion tectonics should be regarded as a tentative. For Coniacian–Campanian (Fig. 13D–F) rather clear inversion-related thinning towards the SW as well as towards the NE is observed (*cf*., Figs. 9, 10 and 11). Thinning towards the SW (i.e. towards inversion axis) was caused by reverse reactivation of basin bounding faults (i.e. the Nowe Miasto–Zawichost Fault Zone) that led to significant uplift (upthrusting) of basement blocks associated with drape folding of sedimentary cover. This in turn resulted in reduced accommodation space within the axial part of the basin. Similar features related to inversion tectonics could be observed within the NW (offshore) part of the inverted Mid-Polish Trough (Deeks and Thomas, 1995; Krzywiec *et al*., 2003).

Figure 13 illustrates progressive upward and NE-directed migration of zone of local maximum thickness of particular inversion-related sedimentary packages. This defines actual, rather small size (both vertical and lateral) of the marginal trough that existed along the NE flank of inverted Mid-Polish Trough. Regional present-day thickness distribution of the entire Upper Cretaceous succession, with well defined maximum (*cf*., Nielsen *et al*., 2005) is in fact mostly geometrical effect of post-inversion erosion (Krzywiec, 2006*b*; Scheck-Wenderoth *et al*., 2008).

The seismically-imaged depositional architecture of the Upper Cretaceous syn-inversion succession is similar to what can be observed within the so-called Subhercynian Cretaceous Basin (Voigt *et al*., 2004, 2008; Von Eynatten *et al*., 2008), where progressive tilting caused by the middle Santonian–early Campanian basement reverse faulting within the Harz Anticline resulted in the development of localized thickness and facies variations, and progressive unconformities. Due to later erosion only remnants of this syn-inversion cover are now preserved. Within the Danish Central Graben, Late Cretaceous inversion took place in a relatively deepwater environment with only moderate uplift, and therefore the stratigraphic record of the inversion tectonics, detected using seismic data, is relatively complete (Cartwright, 1989).

Inversion-related structure imaged on seismic profiles located above the Nowe Miasto–Zawichost Fault Zone (Figs. 9 and 10), despite imaged thickness variations, related both to the subsidence as well as to inversion, does not show any important displacement at the top of the pre-Permian basement that could be possibly correlated with downward and upward movements of the basement blocks within the axial part of the Mid-Polish Trough. This could be explained by a model based on results of analogue modelling by Mitra and Islam (1994). Under this model, deep crystalline basement, covered by relatively thick pre-extension sedimentary cover, is deformed by discrete fault (Fig. 14). During extensional phase (Fig. 14A), such basement faulting is related to fault-propagation (drape) folding within the pre-extension cover, associated with smaller scale distributed faulting within the tri-shear deformation zone centered above the basement master fault zone (Mitra, 1993; Mitra and Islam, 1994; Hardy and McClay, 1999). Basement faulting leads to deposition of syn-extension succession. During inversion of the basement fault (Fig. 14B), pre- and syn-extension cover undergoes reverse fault-propagation folding. This results in development of relatively wide, partly folded deformation zone located above the basement fault zone (Fig. 14B). Syn-inversion succession is characterized by thinning towards the uplifted basement block.

In the study area, pre-extension cover consists of Devonian and older rocks, deformed during earlier tectonic phases, and characterized by rather homogenous seismic pattern, and to various degree uplifted, folded and locally faulted, especially within the zone that coincides with thickness gradients of the Permo-Mesozoic cover (Figs. 9 and 10). This could be explained by a fault-propagation drape folding caused by deeper basement faulting, both normal (during basin's extension and subsidence) and reverse (during basin's inversion). Within the Mid-Polish Trough, including its SE segment, basement rocks are deeply buried, as it was revealed by recently acquired high-quality deep refraction and wide-angle reflection data (Malinowski *et al*., 2005; Grad *et al*., 2006, 2007). Therefore, a model shown on Figure 14, seems to be fully applicable as an explanation of the observed inversion-related structure of the NE boundary zone of the Mid-Polish Trough and its Permo-Mesozoic evolution.

Seismic profiles provide two-dimensional information regarding fault location and orientation as well as thickness variations of the analysed Permo-Mesozoic sedimentary cover. However, the observed tectonic features suggest that inversion tectonics along the Nowe Miasto–Zawichost Fault Zone (i.e. along the NE boundary of the Mid-Polish Trough) was also associated with strike-slip movements. For example, on profile 2 (Fig. 9), a positive flower structure (basement pop-up basement block bounded by steep reverse faults and associated tight drape fold within the Triassic–Cretaceous cover) can be observed, indicating a transpressive stress regime. Such a conclusion is confirmed by the analysis of gravity data. Figure 15 shows a processed Bouguer gravity map (vertical first derivative) with superimposed main fault zones: the Nowe Miasto–Zawichost Fault Zone, analysed in this paper, the Skrzynno (Ostałów) Fault Zone, and the Holy Cross Mts. Fault Zone. The Skrzynno Fault Zone (Kowalczewski, 2002) is also a reverse fault zone related to inversion of the Mid-Polish Trough (Krzywiec, 2000). The Nowe Miasto–Zawichost Fault Zone could be correlated with an *en-echelon* pattern, visible on the gravity map. It can be observed, for example, that the flower structure visible on profile 2 (Fig. 9) is in fact branching off the main fault zone, and forms one of the *en-echelon* segments of the entire strike-slip fault system (Fig. 15). Such a fault arrangement suggests that particular fault segments forming the Nowe Miasto–Zawichost Fault Zone and imaged on seismic profiles have been finally shaped during reverse oblique-slip faulting within the Mesozoic cover due to the transpressional tectonic regime responsible for inversion of this segment of the

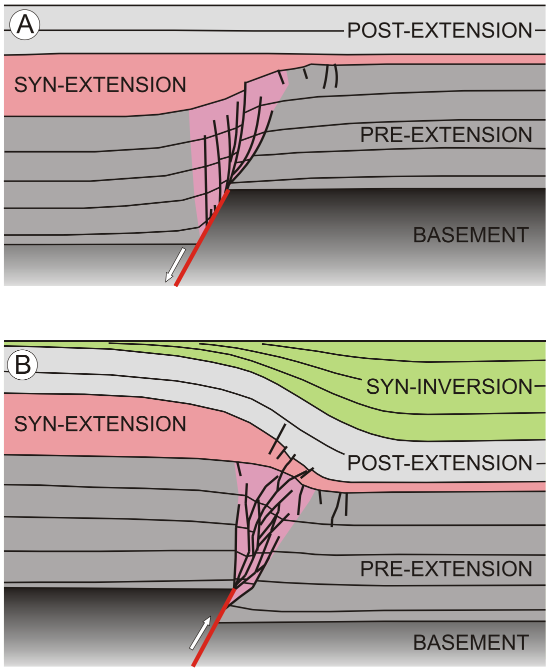

Fig. 14. Model of transition from extension to inversion, based on results of sandbox modelling (from Mitra and Islam, 1994, modified and supplemented)

Due to large thickness of pre-extension sedimentary cover, normal or reverse faulting along single fault plane within the "crystalline" basement was transferred to relatively wide zone of distributed faulting above the basement, and net displacement along the basement fault is related to folding and only very minor faulting within the topmost part of pre-extension cover. Such geometry could be compared to structure of the inverted Nowe Miasto–Zawichost Fault Zone imaged on seismic data (Figs. 9 and 10)

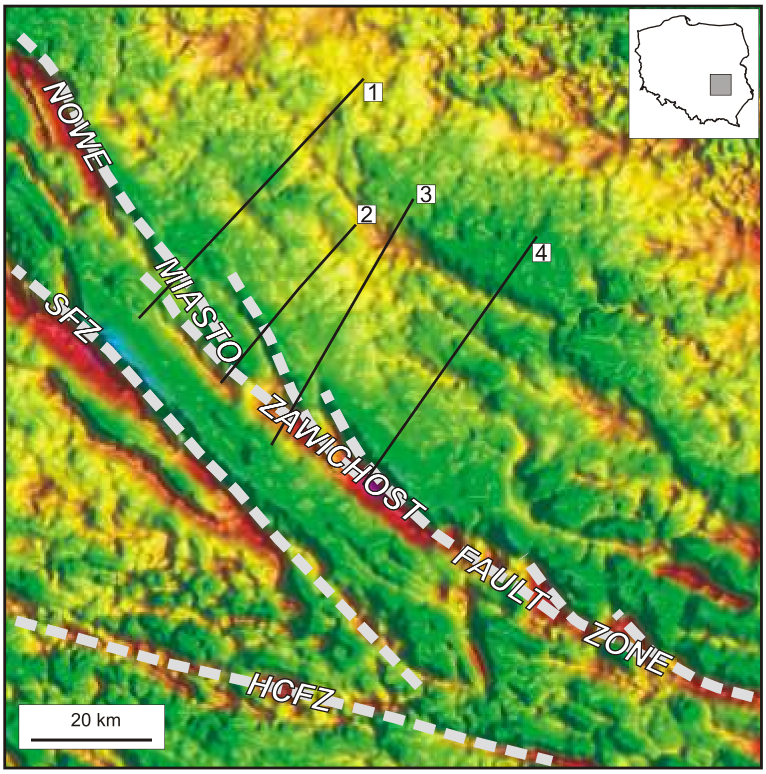

Fig. 15. Processed gravity map (first vertical derivative of Bouguer anomaly), showing the locations of the main fault zones within the study area

Note *en-echelon* pattern of the Nowe Miasto–Zawichost Fault Zone, suggesting component of strike-slip movements during inversion of this segment of the Mid-Polish Trough; SFZ — Skrzynno Fault Zone (*cf*., Krzywiec, 2000; Kowalczewski, 2002), HCFZ — Holy Cross Fault Zone

Mid-Polish Trough. This is compatible with other studies based on structural and palaeomagnetic data and sandbox modelling studies, all of which postulated some role for strike-slip movements during the Palaeozoic and Mesozoic history of this area (Lewandowski, 1994, 2003; Lamarche *et al*., 1998, 1999, 2002, 2003; Nawrocki, 2000; Konon, 2004; Gutowski and Koyi, 2007), although mode and amount of strike-slip movements proposed by these authors were different.

CONCLUSIONS

Analysis of well, seismic and gravity data provided new insights regarding the tectono-stratigraphic history of inversion tectonics along the NE boundary of the Mid-Polish Trough:

1. Inversion started in late Turonian?–Coniacian times, and lasted until Maastrichtian–post-Maastrichtian times;

2. It was associated with deposition of the Upper Cretaceous syn-tectonic complex, developed within a relatively narrow zone located to the NE from the Nowe Miasto–Zawichost Fault Zone;

3. Within this complex, characteristic thickness variations and submarine slumping/listric faulting and/or deposits of contour currents have been detected, that point to syn-tectonic inversion-related deposition;

4. Structural features detected on seismic data include steep reverse faults, upthrusted basement blocks and positive flower structures;

5. Inversion-related structure imaged on seismic data could be explained by deeper basement reverse faulting and associate fold-propagation folding at shallower depths;

6. The geometry of the identified inversion-related structures and *en-echelon* pattern of the Nowe Miasto–Zawichost Fault Zone prove that inversion along the NE boundary of the SE segment of the Mid-Polish Trough was associated with strike-slip movements.

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