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Triassic evolution of the Kłodawa salt structure: basement-controlled salt tectonics within the Mid-Polish Trough (Central Poland)

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The Mid-Polish Trough formed the axial part of the Polish Basin belonging to a system of the Permian-Mesozoic epicontinental basins of Western and Central Europe. It was filled by several kilometres of siliciclastics and carbonates, including thick Zechstein (approximately Upper Permian) evaporites. The Mid-Polish Trough was inverted in the Late Cretaceous–Paleocene times, when it was strongly uplifted and eroded. The presence of thick salt significantly influenced Triassic evolution of the central (Kuiavian) part of the Mid-Polish Trough where the Kłodawa salt structure is located. Analysis of seismic data calibrated by several deep wells point to three main stages of the Triassic evolution of this structure. During Early and Middle Triassic Kłodawa salt pillow grew above the basement extensional fault zone, during early Late Triassic (approx. time of deposition of the Lower Gypsum Beds) Kłodawa salt structure reached diapiric stage and salt eventually extruded onto the basin floor. Last stage was characterised by rather uniform sedimentation and lack of major salt movements. Wojszyce salt pillow located north-east of the Kłodawa salt structure grew until the Late Triassic (approx. time of deposition of the Upper Gypsum Beds) when basement fault zone located below it was probably inverted. This inversion triggered formation of the salt-cored Wojszyce Anticline and was followed by localised erosion and rather uniform Norian–Rhaetian (Lower Kłodawa Beds) sedimentation above the anticline. Local tectonic activity below the anticline might have additionally enhanced growth of the Kłodawa salt diapir. The presented tectono-sedimentary model of the relationship between basement and salt tectonics and their influence on the Triassic depositional systems is compatible with results of analogue modelling of linked basement-salt tectonics, and with a model based on mesostructural studies completed for the Kłodawa salt mine.

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INTRODUCTION

Rock salt, due to its specific bulk properties, is one of the most important components of the sedimentary infill influencing the structure and stratigraphic architecture of sedimentary basins. Consequently, formation of salt structures has long been a subject of detailed studies. Salt structures often form and evolve in extensional settings, during subsidence of sedimentary basins. In such settings, salt tectonics could be triggered by a thin-skinned extension of the post-salt sedimentary cover (Vendeville and Jackson, 1992*a*, *b*) and/or by extension within the sub-salt basement (e.g. Koyi *et al*., 1993; Jackson and Vendeville, 1994). Extensionally induced salt flow within sedimentary basins results in a formation of various structures like salt pillows, diapirs, walls, *etc*.

Depending on various parameters, e.g., the amount and rate of basement faulting, the thickness of the ductile salt layer, the thickness of overburden, *etc*., two basic groups of structures could form during basement extension. The first group comprises various systems of structures developed within the post-salt sedimentary succession, including extensionally forced folds, i.e., forced folds that form above normal faults (Withjack *et al*., 1990). Due to the presence of a ductile salt layer, the development of a master normal fault within the basement could also lead to a development of systems of planar or listric normal faults detached within the salt layer (e.g. Stewart, 1999; Withjack and Callaway, 2000; *cf*. Krzywiec, 2002*b*).

The second group consists of salt structures formed directly above or in relatively close vicinity of the basement extensional fault zones (Koyi *et al*., 1993). Such salt structures are particularly numerous in intracontinental settings as in such basins localised extension and subsidence is associated with significant faulting within the pre-salt basement (e.g. Koyi and Petersen, 1993; Christensen and Korstgard, 1994; Stewart and Coward, 1995; Amor, 1999; Al-Zoubi and ten Brink, 2001; Larsen *et al*., 2002).

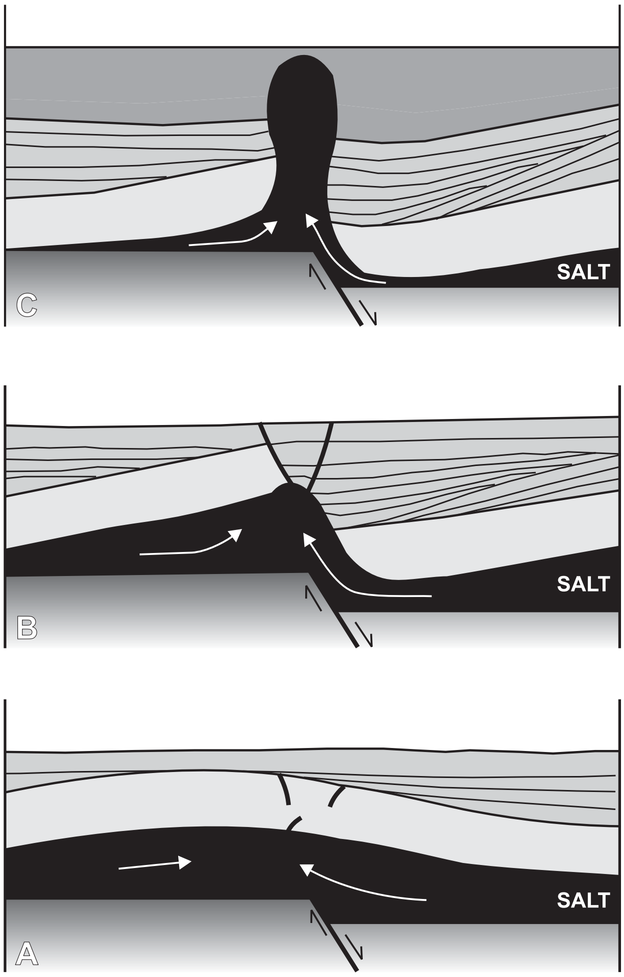

Fig. 1. Schematic diagram (based on results of analogue modelling) showing different stages of salt structure evolution above faulted basement (from Koyi *et al*., 1993, slightly modified)

A — pillow stage: basement faulting, pillow growth, flexure of the overburden, differential sedimentation; B — diapiric stage: further basement faulting, faulting of the overburden, vertical salt flow into the salt diapir, C — late/post diapiric stage: further regional subsidence, faulting of overburden units and piercement of diapir

For both groups of structures mentioned above, basement tectonics and related cover tectonics result in significant modifications of syn-extensional depositional systems. Faults detached within the salt layer often focus sedimentation and are associated with locally thicker syn-kinematic deposits of the post-salt sedimentary sequence (Withjack and Callaway, 2000). Growing salt pillows and diapirs are associated with lateral and vertical salt flow, and influence formation of local sub-basins and barriers for sedimentation — processes studied for many years.

Classical halokinetic theory is based on an assumption that the primary mechanism necessary for initiation of salt movements is change in density equilibrium, whereas sub-salt faulting plays only secondary role or is not necessary at all (Trusheim, 1960). Trusheim (1960) described two major stages of salt structure development, pillow stage and diapiric stage, each related to a different thickness distribution of syn-kinematic sedimentary cover. Similar stages could be also distinguished for salt structures evolving above the basement normal fault, although scenario of their formation could be much more complex then in classical halokinetic scenario. They are shown on a schematic diagram (Fig. 1) based on the results of analogue modelling (from Koyi *et al*., 1993). On this diagram, internal depositional architecture of syn-kinematic deposits related to the pillow and diapiric stages is also shown. Syn-kinematic deposits formed during basement faulting and associated growth of a salt pillow are characterised by a significantly reduced thickness of overlying sediments towards the pillow (Fig. 1A). Increased basement faulting results in faulting of the overburden and increased vertical salt flow into the diapir. During such an early diapiric stage, syn-kinematic deposits formed above the hangingwall show prominent internal divergent geometries related both to a basement faulting as well as to a salt withdrawal (Fig. 1B). Further subsidence and faulting of the overburden result in piercement of the diapir and deposition of younger sedimentary successions of less variable thickness (Fig. 1C).

Three evolutionary stages have been described for a development of salt diapirs formed during thin-skinned extension (i.e. extension affecting post-salt overburden): reactive, active and passive (Vendeville and Jackson, 1992*a*). During the first stage, diapir moves upward through thick post-salt sedimentary cover in response to its faulting. When diapir becomes tall enough and its overburden thin enough, it could actively pierce due to fluid pressure, forming true intrusive body. This process is regarded as being rather rapid in geological terms. During the third stage — passive growth — emergent diapir continues to grow by sediment downbuilding due to a continued sedimentation, and its crest is located close to or at the depositional surface (basin floor). A model of a salt diapir development during purely thin-skinned extension can be directly applied to e.g. passive margins, as in such post-rift settings regional basement (thick-skinned) faulting is negligible. For intracratonic settings however, during syn-rift extension, a complex interaction of sub-salt (basement) faulting and supra-salt (cover) faulting/folding is observed, that trigger lateral and vertical salt movements (Nalpas and Brunn, 1993; Jackson and Vendeville, 1994).

If the sedimentation rate is small and/or diapir's growth rate is high, salt could form extrusion, related to its lateral spreading onto the depositional surface. This process could be active both in sub-marine (Fletcher *et al*., 1995) and sub-aerial (Talbot, 1998) environments. During passive growth of a diapir, such extrusion could be covered by sediments. Repeated pulses of sedimentation, diapiric passive growth and erosion could result in a very complex structural and stratigraphic relationship within the near-salt sedimentary complexes, highlighted by local unconformities and thickness variations (Giles and Lawton, 2002; Rowan *et al*., 2003; Schulz-Ela, 2003).

Salt very effectively attenuates seismic energy, and often seismic information regarding the structure of the sub-salt basement is sparse, if available at all. Hence, direct analysis of the location of the basement fault zones and their interaction with the overlying salt layer and post-salt sedimentary cover may not be possible. Therefore, often the only available way to construct a model of basement tectonic activity is by analysis of shape and distribution of salt structures, and by analysis of thickness variations and internal depositional architecture of the post-salt cover.

In this paper, a problem of mutual interaction between supposed sub-Zechstein basement activity and salt tectonics and their influence on the Triassic sedimentary systems of the

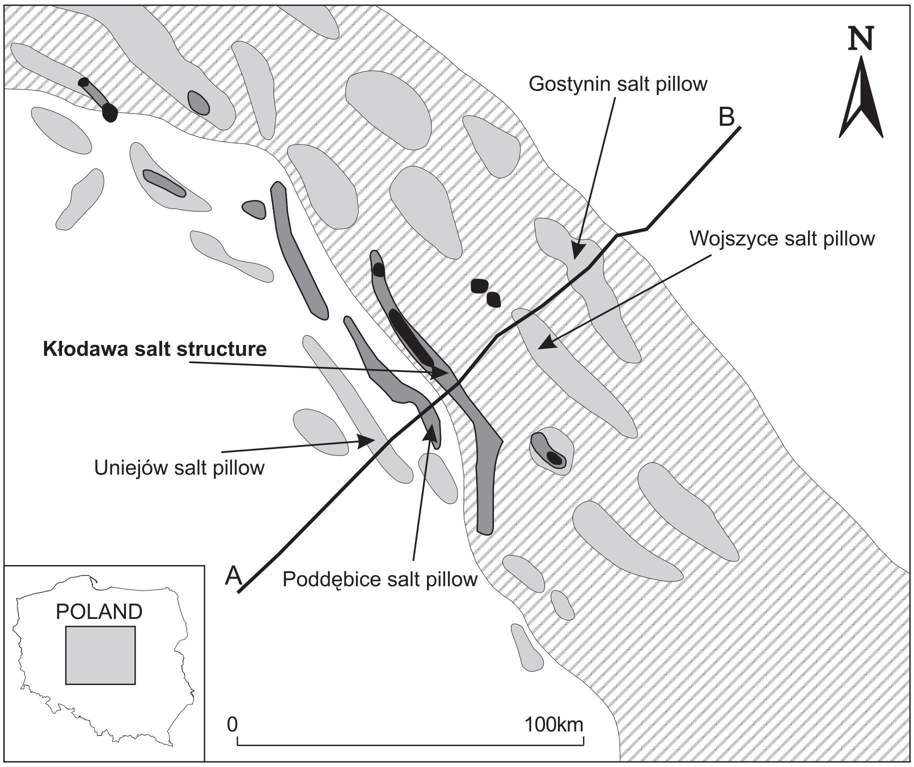

Fig. 2. Distribution of salt structures within the central (Kuiavian) part of the Mid-Polish Trough (from Dadlez and Marek, 1998, simplified)

Black — salt diapirs; dark grey — partly pierced salt diapirs; light grey — salt pillows; patterned area — sub-Cenozoic subcrops of Jurassic and older deposits along the inverted axis of the Mid-Polish Trough; A–B — regional seismic profile shown on Figure 4; names are given for the salt structures crossed by this regional profile

Mid-Polish Trough (MPT) is discussed. The main focus is on structural and seismostratigraphic interpretation of such linked Triassic tectono-stratigraphic phenomena described for the central part of the MPT, from the vicinity of the Kłodawa salt structure (Fig. 2). In order to visualise various aspects of the complex interaction between basement and salt tectonics, and between the salt and the surrounding depositional system, interpreted seismic data and palaeotectonic reconstructions are presented. These are simplified geometrical reconstructions derived from the seismic profiles flattened along selected stratigraphic tops. In particular, these reconstructions are neither balanced, nor do they include decompaction of thick Mesozoic successions. Restoration of a salt thickness and its distribution during early stages of the Mid-Polish Trough subsidence should be regarded as a first approximation only. Additional possible effects that could have modified depositional architecture such as salt dissolution (e. g., Cartwright *et al.*, 2001) also have not been taken into account. However, despite these limitations, the results obtained clearly portray the main aspects of the decoupled Triassic MPT evolution in its central (Kuiavian) segment, especially showing how basement and salt tectonics have interacted in this region, and how such complex tectonic activity has shaped Triassic depositional systems. The constructed model of such complex tectono-sedimentary evolution of the central MPT follows the idea of a regional tectonic decoupling between the sub-Zechstein basement and the post-Zechstein Mesozoic sedimentary infill proposed earlier (Krzywiec, 2002*a*–*c*; *cf*. Dadlez and Marek, 1974).

GEOLOGICAL SETTING

The Mid-Polish Trough formed the axial part of the Polish Basin belonging to a system of Permian-Mesozoic epicontinental basins of Western and Central Europe (Ziegler, 1990). The MPT evolved during Permian to Cretaceous times along the NW–SE trending Tornquist-Teisseyre Zone (Pożaryski and Brochwicz-Lewiński, 1978; Ziegler, 1990; Dadlez, 1997; Kutek, 2001). During the Permian stage of its evolution, the MPT belonged to the Southern Permian Basin (Kiersnowski *et al.*, 1995; van Wees *et al.*, 2000). The MPT was filled with several kilometres of Permian–Mesozoic sediments (Marek and Pajchlowa, 1997; Dadlez *et al.*, 1998).

A complex system of salt structures formed during the Mesozoic within the central and north-west segments of the Mid-Polish Trough characterised by the presence of the thick Zechstein evaporites (Wagner, 1998). Various aspects of salt tectonics within the MPT have been analysed by numerous authors, including e.g. Sokołowski (1966), Dadlez and Marek (1969, 1974), Burliga (1996; see e.g. Pożaryski, 1977; Tarka, 1992 for summary and further references). Distribution of various salt structures from the central (Kuiavian) part of the MPT is shown on Figure 2. System of salt structures of the MPT is a direct counterpart of an analogous system of salt structures from the North German Basin (e.g. Trusheim, 1960; Kockel, 1996, 2003; Kossow *et al*., 2000; Scheck *et al*., 2003), from the Danish North Sea (e.g. Geil, 1993; Koyi and Petersen, 1993) and the Southern North Sea (e.g. Stewart and Coward, 1995; Krzywiec and Trudgill, 2003), i.e. systems of salt structures genetically linked to the evaporites deposited within the Southern Permian Basin.

One of the major problems concerning the evolution of the MPT, especially its part characterised by thick Zechstein deposits, is the relationship between regional depositional and tectonic pattern of the Mesozoic succession, and tectonic activity within the pre-Zechstein basement. Analysis of tectonic subsidence curves reveals that three major pulses of increased subsidence can be distinguished (Zechstein–Scythian, Oxfordian–Kimmeridgian, and early Cenomanian), each superimposed on a more gradual thermal subsidence pattern (Dadlez *et al*., 1995). However, the north-west and central parts of the MPT containing thick evaporites are characterised by a lack of major, basin-scale extensional deformations within the Mesozoic sedimentary cover related to the above tectonic phases and are characterised by gradual thickness changes and by a rather gentle (i.e. not disturbed by major normal fault zones) regional depositional pattern (Dadlez, 2001, 2003; Dziewińska *et al*., 2001; Wagner *et al*., 2002). Stephenson *et al*. (2003) explicitly stressed the deficit of observable extensional features responsible for the Permian-Mesozoic subsidence. This apparent contradiction can be explained by a regional decoupling between the sub-Zechstein basement and the Mesozoic sedimentary infill (Krzywiec, 2002*a*–*c*).

The MPT was inverted during the Late Cretaceous–Paleocene, and this inversion was associated with significant uplift and erosion of its axial part (e.g. Dadlez and Marek, 1969; Pożaryski and Brochwicz-Lewiński, 1978; Dadlez, 1997; Krzywiec, 2002*a*).

An important problem related to the evolution of the central and NW part of the MPT is the origin of salt tectonics and the relationship between basement tectonic processes and the development of salt structures. Some authors followed classical idea of halokinesis (Trusheim, 1960), according to which salt movements are triggered by differential loading caused by overburden (e.g. Sokołowski, 1966). Others addressed the issue of potential role of basement tectonic activity as a trigger for salt tectonics. Numerous published cross-sections contain inferred sub-Zechstein basement faults and fault zones, some of them located directly below or in a close vicinity of salt structures. In most cases, however, these are rather wide and vertical fault zones for which only a general link between the inferred basement tectonic activity (often of an unspecified nature) and salt movements was suggested (e.g. Dadlez and Marek, 1969; Marek and Znosko, 1972*a*, *b*; Marek, 1977). In his analysis of the Triassic and Jurassic sedimentary cover in the area of the Kłodawa salt structure Znosko (1957) suggested that tectonic activity was responsible for initiation of salt movements. Selected publications presented more detailed tectonic interpretations, for the Kuiavian part of the MPT reverse faults located below the Kłodawa salt structures have been proposed by, for example, Pożaryski (1957, 1977) and Dadlez and Marek (1974). Dadlez and Marek (1974) proposed also a Mesozoic faults activity restricted to the sub-Zechstein basement (see their fig. 14), i.e. suggesting mechanical decoupling between the sub-Zechstein basement and the post-Zechstein sedimentary cover. Some papers presented genetic models inferring modes of activity within the sub-Zechstein basement: for example extension/inversion during the Mesozoic subsidence and subsequent uplift of the MPT (Pożaryski, 1977) or extension during its Triassic evolution (Burliga, 1996). Recently published regional cross-sections across the MPT show a rather gentle top of the sub-Zechstein basement, with a very minor faulting restricted to its uppermost interval (Dadlez, 2001, 2003; Wagner *et al*., 2002). In particular, no major basement tectonic zones were proposed in order to explain the basin-scale subsidence pattern of the Mesozoic in palaeotectonic reconstructions based on these regional cross-sections (Wagner *et al*., 2002).

Salt movements within the MPT started in the Triassic and led to a formation of numerous intraformational unconformities and thickness variations (e.g. Sokołowski, 1966; Marek and Znosko, 1972*a*, *b*; Pożaryski, 1977). In his recent publication Dadlez (2001) stressed that in the vicinity of the Kłodawa salt structure salt movements might have started already in the Early Triassic; he also stressed that lithostatic pressure of the Buntsandstein cover was high enough to initiate salt movements, suggesting halokinetic (i.e. mostly unrelated to the basement tectonic activity) origin of salt tectonics.

The Kłodawa structure, located in the Kuiavian segment of the MPT (Dadlez and Marek, 1998; Fig. 2), is one of the largest salt structures developed within the Mid-Polish Trough, being almost 30 km long and 6 km tall. Within the central part of the MPT the Triassic succession attains its maximum thickness directly north-east of the Kłodawa salt structure. A rather complete stratigraphic profile comprises the Lower Triassic (lower–middle Buntsandstein), Middle Triassic (upper Buntsandstein, Muschelkalk and lower Keuper) and Upper Triassic (upper Keuper, Norian and Rhaetian). A summary of the Triassic stratigraphy for the MPT with detailed information on relationship between chronostratigraphic and lithostratigraphic subdivisions has been recently given by Gajewska (in: Marek and Pajchlowa, 1997). Relationship between standard, regional and local lithostratigraphic Triassic subdivisions together with the thickness distribution in the deep borehole Krośniewice IG 1 is shown on Figure 3.

INTERPRETATION OF SEISMIC DATA

During tens of years of exploration for hydrocarbons, vast amounts of seismic reflection data have been acquired, and hundreds of deep research and exploration wells have been drilled within the area of the MPT. Recently, many seismic datasets and well logs data from old, deep research wells have been reprocessed. Together with newly acquired data, such an extensive regional geophysical-geological database offers a unique opportunity to study various regional aspects of the Mesozoic evolution of the MPT, including salt tectonics and its influence on depositional systems.

Several seismic profiles acquired within the MPT's Kuiavian segment in late '70 have been recently reprocessed by the Polish Oil and Gas Company and Apache Poland pe-

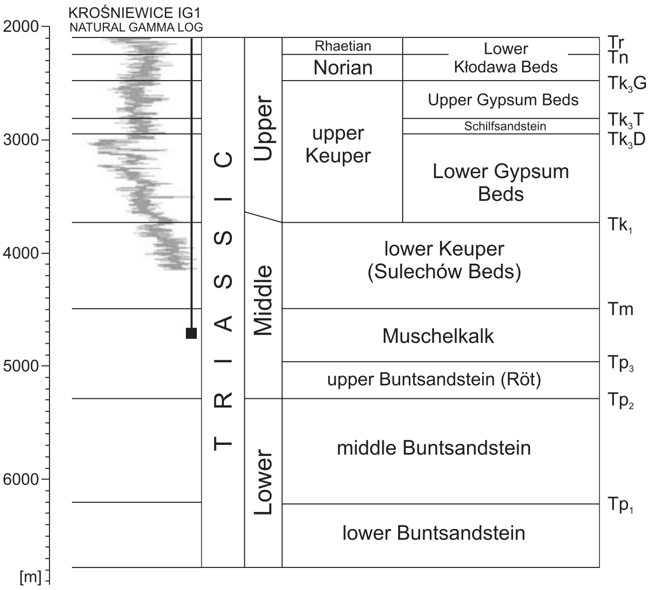

Fig. 3. Triassic lithostratigraphy (after Gajewska in: Marek and Pajchlowa, 1997, simplified) and the Triassic thickness distribution along and below the Krośniewice IG 1 borehole

The well reached Muschelkalk, but natural gamma log was measured only down to the lower Keuper; thickness of the undrilled Triassic complexes is based on depth seismic line (see Fig. 4); symbols along the right margin of the stratigraphic table are the same as on interpreted seismic line (Fig. 5)

troleum company. Some of these profiles have been merged into the single regional profile crossing the entire central Mid-Polish Trough (*cf.* Dadlez, 2001; Fig. 4). Along this profile several deep wells are located, often with velocity data available which is necessary for a correlation of depth well data with time seismic data. All seismic and well (stratigraphy, time-depth tables, well logs) data was available in a digital form and was loaded into the *Landmark Graphics* interpretation software and database.

The regional seismic profile (Fig. 4) clearly shows that the total Triassic thickness north-east of the Kłodawa structure is 2–3 times larger than the average thickness of this successions in this part of the MPT. Triassic succession is also characterised by significant thickness variations of particular stratigraphic complexes. South-west of the Kłodawa structure, Mesozoic cover was drilled by four deep boreholes: Koło IG 4, Wartkowice 1, Poddębice IG 1 and Poddębice IG 2 (*cf.* Dadlez, 2001). All these boreholes ended no deeper than within the Upper Triassic, hence location of lower stratigraphic boundaries in this part of the regional profile (Fig. 4) was based on a long-distance seismic correlation and thus should be regarded as approximate although fairly reliable. North-east of the Kłodawa structure, Mesozoic cover was drilled, among others, by Siedlec 1 and Krośniewice IG 1 boreholes located in immediate proximity of the structure, within the area characterised by a significantly thicker Triassic cover (*cf.* Marek, 1973; Dadlez, 2001). Both boreholes provided crucial information on the stratigraphy of the Triassic in this area. Krośniewice IG 1 borehole ended in the Muschelkalk and Siedlec 1 borehole ended in Buntsandstein; lower horizons were interpreted using available seismic and well data from this part of the basin.

Liszkowski and Topulos (1996, 1997), using results of well log correlation, suggested that the Triassic cover has very different thickness and internal structure than shown on Figure 4. Both regional analysis of seismic and well data (Dadlez *et al.*, 1997; Krzywiec *et al.*, 2001), and detailed biostratigraphic studies of the Muschelkalk drilled by the Krośniewice IG 1 borehole (Narkiewicz, 1999) proved, however, that such interpretation is incorrect.

STRATAL PATTERNS OF THE TRIASSIC SUCCESSION

The Triassic succession north-east of the Kłodawa structure is characterised by three main types of stratal geometry (Fig. 5):
— thinning towards the diapir,
— thickening towards the diapir,
— onlapping the diapir.

The Buntsandstein, Muschelkalk and lower Keuper (Sulechów Beds; *cf.* Gajewska in: Marek and Pajchlowa, 1997; Fig. 3) complexes show thinning towards the Kłodawa structure (Fig. 5). Such stratal pattern could be interpreted as related to the early (pillow) stage of the Kłodawa structure, i.e. lateral and limited vertical movement of the salt towards a footwall without major faulting of the overburden (*cf.* Fig. 1). Close to the Kłodawa structure a local unconformity can be observed between the middle (Tp_2) and upper (Tp_3–Röt) part of the Buntsandstein (Fig. 5). This suggests that lower–middle Buntsandstein was passively uplifted and forms local sheath-like structure adjacent to the diapir (*cf.* Schulz-Ela, 2003).

The lower part of the upper Keuper (approx. Lower Gypsum Beds — *cf.* Gajewska in: Marek and Pajchlowa, 1997; *cf.* Fig. 3) is characterised by a prominent divergent seismic pattern with a maximum thickness along the northeastern flank of the structure (Fig. 5). Such internal architecture can be related to the diapiric stage (*cf.* Marek, 1973). At the end of this stage, salt formed a characteristic overhang, (i.e. extrusion onto the basin floor), during deposition of the uppermost part of the Lower Gypsum Beds.

Extruded salt body was later covered by the uppermost Lower Gypsum Beds, Schilfsandstein, Upper Gypsum Beds, Norian and Rhaetian. These units are characterised by the third type of a stratal configuration with a rather uniform thickness, reduced only above the salt overhang (Fig. 5). This reduction is related to an onlapping pattern of the uppermost Triassic against extruded salt, indicating relatively passive infill and burial of the mostly inactive salt body. Some small-scale local thickness variations in proximity to the Kłodawa diapir could be related to the passive growth of the structure, its localised uplift and erosion. Observed uplift and folding of the Triassic and Jurassic complexes above the salt overhang are most probably related also to the Late Cretaceous inversion of the MPT (*cf.* Krzywiec *et al.*, 2003).

BASEMENT VERSUS SALT TECTONICS

Thickness variations and stratal patterns of the Triassic succession in the vicinity of the Kłodawa salt structure strongly suggest that a Triassic tectonic activity played important role in this part of the basin. Two tectonic mechanisms, operating si-

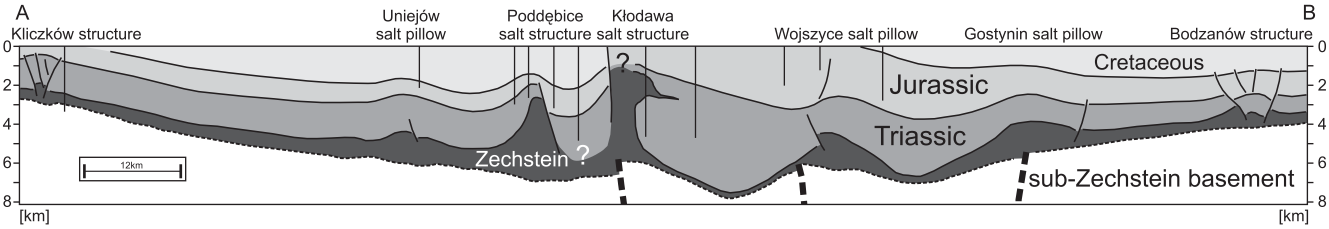

Fig. 4. Interpreted regional seismic profile from the central part of the Mid-Polish Trough, crossing the Kłodawa salt structure

Note significant thickness variations of the Triassic and Jurassic deposits in vicinity of the Kłodawa salt structure; for a location see Figure 2

multaneously, could have been responsible for the internal architecture of the Triassic successions:

— extension and normal faulting within the sub-Zechstein basement;

— salt withdrawal and formation of the rim syncline.

A general qualitative model of such linked basement and salt tectonic activity in the central MPT is shown on Figure 6. Because of the presence of the Zechstein evaporitic complex, the quality of seismic data for the sub-Zechstein basement is very poor and the interpreted basement fault zones should be regarded as tentative. In the surroundings of the Kłodawa structure, the subsidence was presumably controlled by two major normal faults, or fault zones. One of them is located at the northeastern boundary of the MPT, approximately below the Gostynin salt pillow. It extends along large part of the Trough and coincides with the southwestern boundary of the East European Craton; its Mesozoic activity and relationship to gravity and magnetic data was demonstrated by palaeotectonic reconstructions based on regional seismic data (*cf.* Krzywiec and Wybraniec, 2003). It directly continues towards the south-east as the Radom–Kraśnik fault zone (Krzywiec, 2002*a*; Krzywiec and Wybraniec, 2003). The second fault zone is located below the Kłodawa structure. Between them, an intra-basinal fault zone is assumed below the Wojszyce salt pillow. Its exact geometry is difficult to define. Both major tectonic zones might have acted as normal fault zones during the Zechstein to Jurassic times (*cf.* also Dadlez, 2001). The intra-basinal Wojszyce basement fault zone was most probably active as a normal fault zone partly during the Triassic, and in the latest Triassic it might have been inverted (see below).

Basement faulting was associated with a lateral and vertical salt flow and formation of the Kłodawa, Wojszyce, and Gostynin salt structures. The largest amount of extension along the Kłodawa basement fault zone, together with a significant salt withdrawal into the growing Kłodawa structure (first into the salt pillow, then into the salt diapir), and into the Wojszyce salt pillow resulted in a strongly asymmetric thickness pattern of the Triassic succession (Fig. 6B). Additionally, in the north-easternmost part of this profile, the peripheral salt-related Bodzanów structure detached within the Zechstein ductile complex was formed.

A qualitative model of the Triassic evolution of the major basement fault zones, salt structures, and the depositional systems in the vicinity of the Kłodawa structure is shown in Figure 7. During the Early to Middle Triassic (Fig. 7A) basement faulting triggered salt flow towards both the hangingwall and the footwall, resulting in the formation of the Kłodawa and Wojszyce salt pillows. Interaction between salt flow and basement faulting resulted in the displacement of the local depocenter during the pillow stage. Its migration towards the Kłodawa salt pillow suggests that within the area of the subsequent Kłodawa salt diapir, salt flow was most active suggesting a continuous process of transition from the pillow to diapiric stage. During the Late Triassic, during deposition of the Lower Gypsum Beds (i.e. lower part of the upper Keuper — *cf.* Fig. 3) salt extruded onto the basin floor and salt overhang formed most probably due to increased basement faulting and/or slow sedimentation (see also below). Late Triassic reconstruction (Fig. 7B) shows salt overhang passively onlapped by the youngest Triassic deposits including the uppermost Lower Gypsum Beds, Schilfsandstein, Upper Gypsum Beds and Lower Kłodawa Beds (Fig. 5).

Increased Late Triassic basement tectonic activity might have resulted in the inversion of the Wojszyce basement fault zone which in turn led to the uplift of the salt-cored Wojszyce Anticline. This possible intra-basinal inversion was a rather unique tectonic event as within the entire MPT subsidence prevailed in the Triassic and no basin-scale compression and related inversion took place. Such inversion could be a strictly local feature of the Kuiavian part of the MPT, triggered by e.g. intense subsidence between its major bordering (i.e. Kłodawa and Gościno) basement fault zones. Inversion of the Wojszyce fault zone could have been associated with a formation of the inversion-related basement shortcut (McClay and Buchanan, 1992). Late Triassic localised tectonic activity within the Wojszyce area, apart from the enhanced basement and cover faulting and sediment accumulation, could have additionally triggered diapirism within the Kłodawa region.

Uppermost Triassic deposits unconformably covered the Wojszyce salt-cored anticline as well as the salt overhang attached to the Kłodawa structure (Fig. 7B; *cf.* Krzywiec *et al.*, 2003). Crestal part of the Wojszyce Anticline is covered by the Upper Triassic (approx. Lower Kłodawa Beds; *cf.* Gajewska in: Marek and Pajchlowa, 1997; Fig. 3) deposits. Lower Gypsum Beds show thinning above the Wojszyce salt pillow (Fig. 5). This indicates that during diapiric stage of the evolution of the Kłodawa structure the Wojszyce salt pillow was still growing, and the Wojszyce Anticline was formed after deposition of the Upper Gypsum Beds (*cf.* Figs. 6 and 7).

Presented kinematic interpretation of the Wojszyce basement structure should be regarded only as one of several possibilities, as lack of reliable data regarding sub-Zechstein basement does not allow for unequivocal interpretation of the exact structural pattern below the Zechstein salt layer and evolution of the Wojszyce intra-basinal basement fault zone. It must be stressed, however, that even opposite dip of the Wojszyce basement zone (i.e. south-west instead of north-east) would not

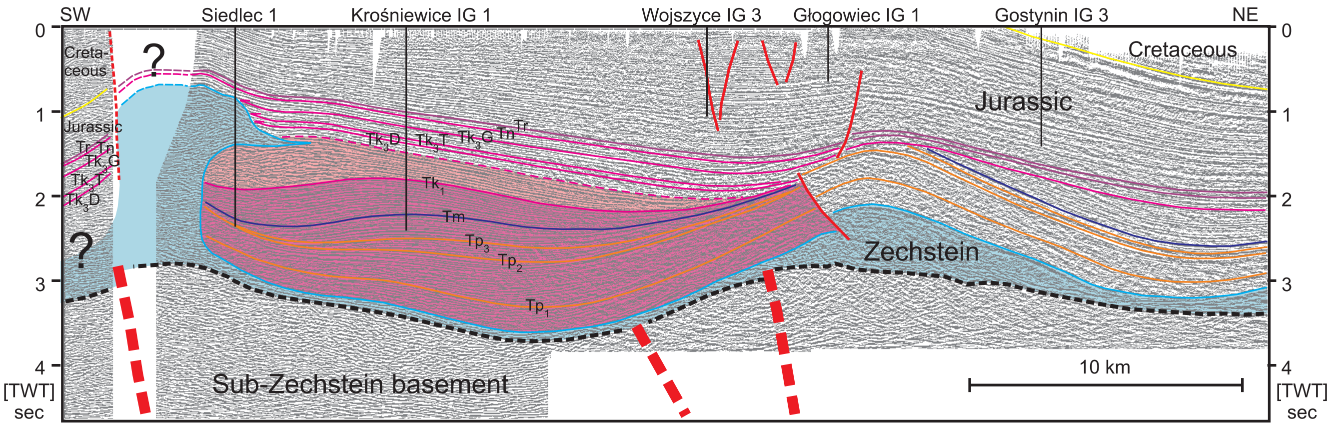

Fig. 5. Interpreted part of regional seismic profile crossing the Kłodawa salt structure

Tp_1 — lower Buntsandstein, Tp_2 — middle Buntsandstein, Tp_3 — upper Buntsandstein (Röt), Tm — Muschelkalk, Tk_1 — lower Keuper, Tk_3D — Lower Gypsum Beds, Tk_3T — Schilfsandstein, Tk_3G — Upper Gypsum Beds, Tn — Norian, Tr — Rhaetian (*cf*. Fig. 3); dark pink area — part of the Triassic succession (Buntsandstein, Muschelkalk and lower Keuper) deposited during pillow stage, light pink area — part of the Triassic succession (approx. lower Keuper–Lower Gypsum Beds) deposited during diapiric stage; note that salt overhang is onlapped by the uppermost Lower Gypsum Beds, Schilfsandstein, Upper Gypsum Beds, Norian and Rhaetian, and this entire succession retains fairly equal thickness further towards the north-east; vertical scale in seconds; see the text for further explanations

change neither presented conclusions on timing of formation of the Wojszyce Anticline nor large-scale model of the Triassic evolution of the Kuiavian part of the MPT, as these interpretations are entirely based on analysis of the Triassic sedimentary cover precisely imaged on seismic data.

DISCUSSION

Scenario of the Triassic development of the Kłodawa salt structure presented in this paper includes complex interplay between faulting within the sub-Zechstein basement and development of salt structures. It is compatible with an earlier published model based on mesostructural studies in the Kłodawa salt mine (Burliga, 1996). According to this author, Zechstein and Early Triassic subsidence in the central MPT was related to the normal faulting of the sub-Zechstein basement. Early salt movements included lateral flow and displacement and/or folding of more competent evaporitic layers, well visible in numerous outcrops in the salt mine (Burliga 1996; *cf*. Krzywiec *et al*., 2003), whereas during the Late Triassic vertical salt flow dominated (Burliga, 1996).

Recently, Wagner *et al*. (2002) presented palaeotectonic reconstructions of the central MPT, in many respects similar to the reconstructions described in this paper. They selected different time slices, but overall approach was very similar to the approach adapted in this paper. The palaeotectonic reconstructions of the Kłodawa region by Wagner *et al*. (2002) are based on the same regional seismic profile flattened on certain stratigraphic tops, they are neither balanced nor do they account for decompaction of the Mesozoic sediments. Their reconstruction also suggests significant localised Triassic subsidence. There are, however, very important differences between the conclusions presented in this paper and those of Wagner *et al*. (2002). They concern: development of the Wojszyce structure, importance of the sub-Zechstein basement faulting and formation of the salt overhang attached to the Kłodawa salt diapir.

Development of the Wojszyce salt-cored anticline is here attributed to the Late Triassic (*cf*. Figs. 6 and 7). Such timing is different from conclusions presented by Wagner *et al*. (2002) who correlated formation of the Wojszyce structure with the inversion of the MPT. On their figure 6 the Wojszyce salt pillow is still not fully developed by the end of Cretaceous (their Phase III), e.g. it lacks important reverse fault cutting salt overburden. Only their contemporary cross-section (Phase IV) shows fully developed Wojszyce structure. This implies that significant Cenozoic compressional event influenced sedimentary infill of the MPT. Such interpretation however, implied by the palaeotectonic reconstruction of Wagner *et al*. (2002), has not been substantiated in their text. In particular, no arguments for regional mechanisms of a Cenozoic compression have been presented. During both Jurassic and Early Cretaceous subsidence as well as Late Cretaceous inversion of MPT some re-shaping of the Wojszyce structure most probably have taken place, but clearly the main episode of its formation occurred in the Late Triassic, as described in this paper.

Reconstructions by Wagner *et al*. (2002) show a rather gentle top of the sub-Zechstein basement, with very minor faulting restricted to its uppermost interval, similarly to interpretations by Dadlez (2001, 2003). In particular, no major basement tectonic zones were inferred in order to explain the basin-scale subsidence pattern of the post-Zechstein sedimentary cover. On the cross-sections of Wagner *et al*. (2002) there are minor faults within the topmost part of the sub-Zechstein basement. Apart of their very small throw incompatible with observed thickness variations of the Mesozoic sedimentary cover, there are also problems with their kinematic characteristic that could be inferred from cross-sections and palaeotectonic reconstructions by Wagner *et al*. (2002). For example, small faults beneath the northeastern boundary of the Kłodawa structure during MPT subsidence are dipping towards north-east (Phases I, II and III; fig. 6 of Wagner *et al*., 2002), while on their contemporary cross-section (Phase IV) the same faults are dipping in opposite direction. Such reorientation, requiring major rotation of the basement blocks, would be very difficult to explain. Additionally, flexed, non-faulted basement top and its short-wavelength undulations (Wagner *et al*., 2002), would imply unrealistic rheological properties of a weak sub-Zechstein basement.

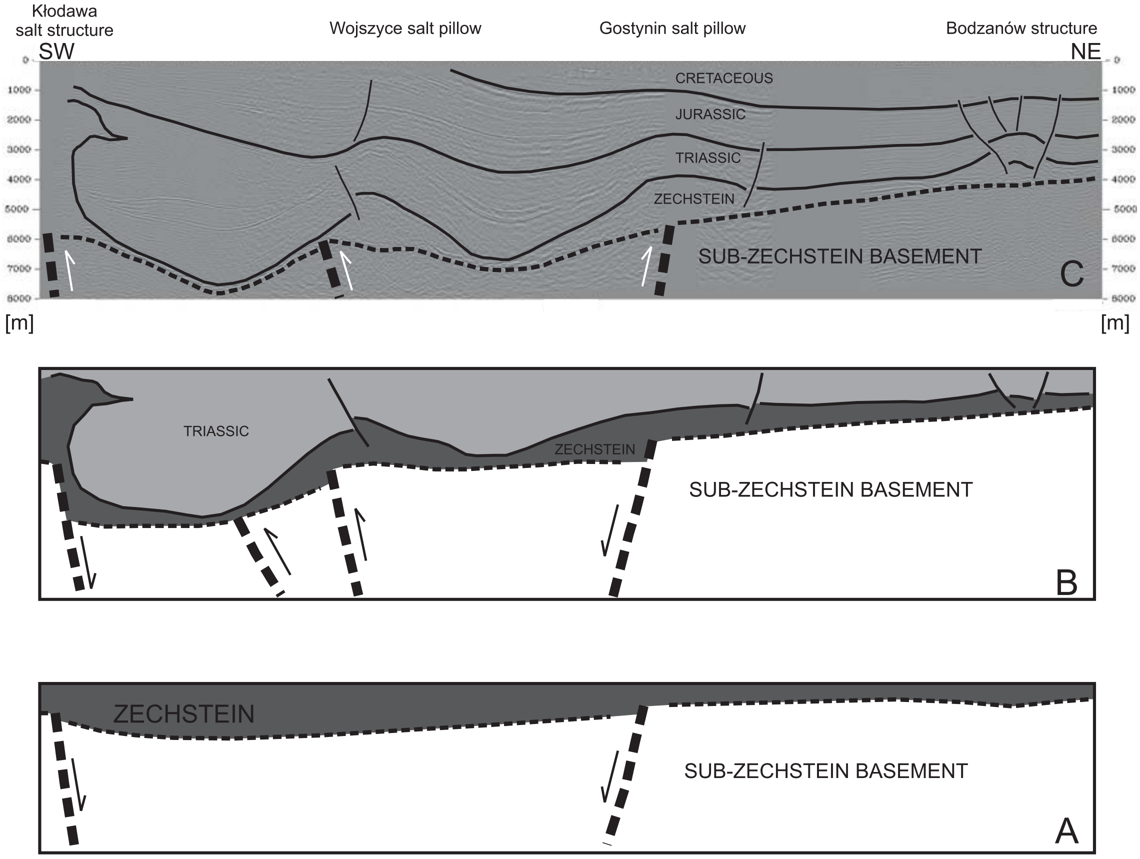

Fig. 6. Late Permian (A) and Late Triassic (B) qualitative (not balanced, without decompaction) reconstructions, and present-day (C) upper crustal configuration along the central part of the regional seismic profile from Figure 4

All these problems and contradictions are avoided in the simpler model based on existence of the major sub-Zechstein fault zones, as described above.

According to Wagner *et al*. (2002), the overhang attached to the Kłodawa salt structure formed in Cenozoic as on their palaeotectonic reconstruction for the end of Upper Cretaceous sedimentation this overhang is not shown and it is present on their contemporary cross-section. This implies that the overhang formed in Cenozoic, and consequently, as in the case of the Wojszyce salt structure described above, that important tectonic activity took place during Cenozoic within the MPT, a feature not previously indicated for this sedimentary basin. According to Wagner *et al*. (2002), during this young tectonic phase salt would intrude Triassic sedimentary succession. Such hypothesis — apart from the problems with timing of this tectonic phase — can be rejected using two arguments.

Firstly, intrusion into the Triassic succession during late stages of the MPT development would imply that salt moved laterally instead of moving upward towards the free surface. Mechanically, lateral salt intrusion into the surrounding rocks during compression and inversion of a sedimentary basin is much less favourable for the following reasons:

— compressional stress field would counteract the lateral salt movement;

— lithostatic pressure of the overburden at the level of the future overhang was much higher then lithostatic pressure of the overburden above the diapir itself.

During compression of the diapirs, vertical and not lateral salt movements dominate (*cf*. Koyi, 1998), hence formation of the intrusive overhang seems to be a rather rare phenomenon.

Secondly, lateral salt intrusion would imply that overlying layers would be uplifted above the overhang, thus not influencing the primary thickness of the layers both above and away from the overhang (*cf*. Kockel, 2003; Fig. 8A). On the other hand, salt extrusion developed during late diapiric stage implies onlap of the younger (i.e. post-extrusive) sediments onto the extruded salt and their local thickness reduction above the salt overhang (Fig. 8B). The described overhang attached to the Kłodawa salt structure is clearly onlapped by the Upper Triassic (uppermost Keuper, Norian and Rhaetian) deposits with reduced thickness above the overhang (Fig. 5). Such relationship implies that the Kłodawa overhang developed in the Late Triassic, not in Cenozoic, contrary to the suggestion by Wagner *et al*. (2002).

The Upper Triassic is represented by shallow marine to terrestrial deposits (Marek and Znosko, 1972*b*; Krzywiec *et al*., 2001). Within the Keuper (Lower Gypsum Beds) rock salt is present with its maximum (up to 260 m) thickness recorded in Krośniewice IG 1 borehole in vicinity of the Kłodawa structure (Gajewska, 1978). Therefore, as already suggested by Gajewska (1978), such thick salt layers could have formed at least partly due to a dissolution and localised concentration of recycled Zechstein salt transported to the surface. Such a depositional scenario would be compatible with a model pre-

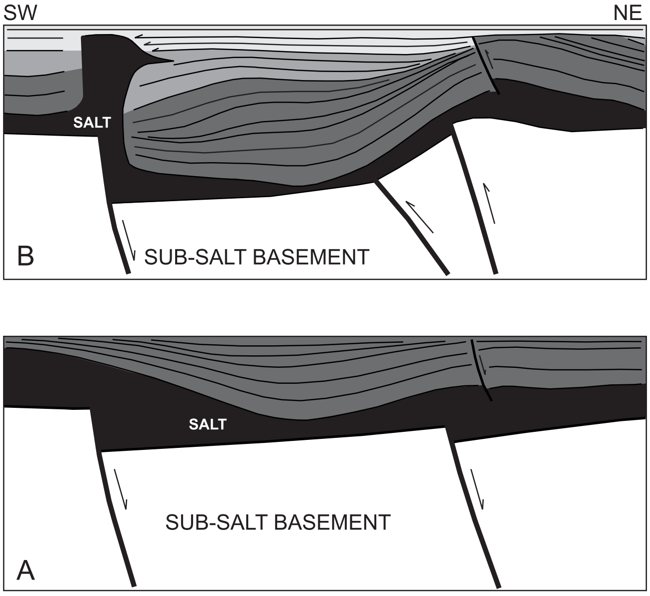

Fig. 7. A qualitative model of the Triassic development of the Kłodawa salt structure and surrounding depositional systems

A — pillow stage (approx. end of Muschelkalk sedimentation) — decoupled basement faulting, salt flow towards the footwall and towards rotated part of hanging wall; secondary basement and cover faulting within the Wojszyce area; B — post-diapiric stage (end of Triassic); dark grey — deposits of pillow stage, grey — deposits of the (active) diapiric stage, light grey — late (passive)/post-diapiric deposits; see text for further explanations

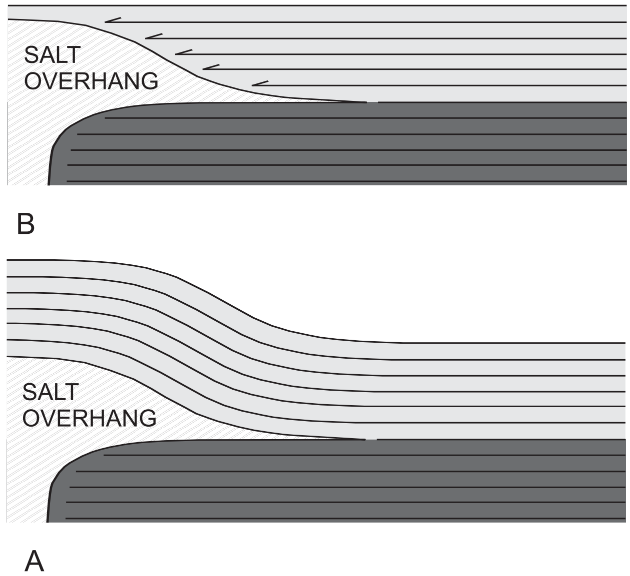

Fig. 8. Alternative models of a relationship between the salt overhang and overlying deposits

A — intrusive salt overhang and related wedge-shaped structure of the pre-intrusive sedimentary layers (light grey); B — extrusive salt overhang onlapped and covered by the post-extrusive sedimentary layers (light grey); see the text for further explanations

sented above which assumes that during deposition of the Lower Gypsum Beds Kłodawa salt structure reached diapiric stage, Zechstein salt was relatively close to the surface and eventually was extruded onto the basin floor. Later geochemical studies of the bromine content within the Keuper salts shoved however that most probably Zechstein salt was not a source for the Keuper salts (Gajewska *et al*., 1985). These results, precluding dissolution of the Zechstein salt during Late Triassic, are not however contradictory to the hypothesis of the Late Triassic salt extrusion, as the Late Triassic sedimentary basin in Central Poland was characterised by primarily hypersaline conditions and therefore large-scale dissolution of the emergent salt could not occur.

A problem of the Triassic growth of the Kłodawa salt structure and its influence on sedimentary systems has been discussed also by other authors (Znosko, 1957; Różycki, 1958; Marek and Znosko, 1972*b*). In his detailed analysis based on well data Różycki (1958) suggested that already during latest Middle Triassic (lower Keuper time) cap rock of the Kłodawa salt structure was located close to the surface. He also described thick conglomerates at the base of the Lower Kłodawa Beds (Różycki, 1958), built of redeposited Keuper shales and supplied from the uplifted region of the axial part of the Kłodawa structure. Such redeposition could be clearly correlated with a stepwise uplift and erosion of the upper part of the Keuper cover that originally onlapped salt body extruded onto the basin floor (Fig. 7). During post-extrusive, passive growth of the salt diapirs, sediments onlapping a salt body could be folded, uplifted and eroded depending on interplay of various parameters like a rate of the diapir growth, rate of sedimentation, variations of bathymetry, *etc*. (Rowan *et al*., 2003; Schulz-Ela, 2003). Lack of significant drag folds above the salt overhang (Figs. 6 and 7) suggests that no significant passive growth of the salt diapir took place after extrusion. It might be speculated, however, that the post-extrusive cover built of the uppermost Lower Gypsum Beds, Schilfsandstein and Upper Gypsum Beds originally extended further above the salt extrusion, and due to a growth of the diapir was partly eroded and redeposited. It must be stressed that observed present-day geometry of the Kłodawa salt diapir and its sedimentary cover are also the result of the Late Cretaceous compression and inversion. Analysis of a relative role of the Triassic (and younger?) growth of the Kłodawa salt diapir versus its Late Cretaceous reactivation would require detailed studies of the entire Mesozoic evolution of the study area and is beyond the scope of this paper.

A proposed model for the Triassic evolution of the Kuiavian MPT segment includes a significant link between basement tectonics and the development of salt structures ultimately controlling the deposition of the syn-kinematic Triassic succession. This model conforms very well with published results of analogue modelling in which both the development of salt structures above the basement faults as well as the evolution of post-salt sedimentary cover were considered (Koyi *et al*., 1993). These models did not attempt to simulate the structural inversion of such a tectonosedimentary system. However, comparison of the qualitative palaeotectonic reconstructions and models from Figures 6 and 7 with the results of analogue modelling (Figs. 1 and 9) demonstrates that presented models for the Kłodawa area should be regarded as very probable reconstructions of the Mesozoic evolution of the central Mid-Polish Trough.

Figure 9 shows the results of centrifuge modelling of basement faulting and salt movements from Koyi *et al*. (1993). During basement extension, salt moved along the hanging wall towards a secondary salt pillow partly (equivalent of the

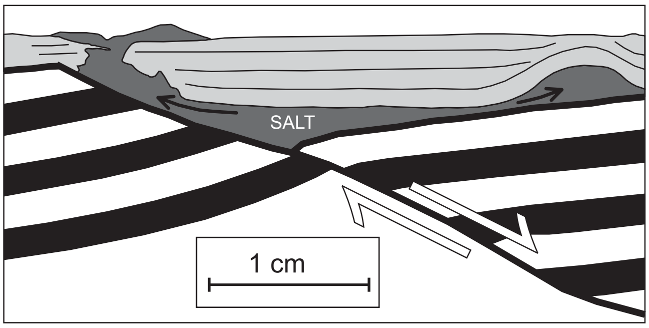

Fig. 9. Basement faulting, salt movements and deposition — results of centrifuge modelling; note movement of the salt along the hangingwall towards the salt pillow, and towards the footwall, towards the salt diapir (from Koyi *et al*., 1993); compare to the model of the Triassic evolution of the Kłodawa salt structure (Fig. 7)

Wojszyce salt pillow), and towards the footwall, as well as towards the salt diapir (equivalent of the Kłodawa salt diapir). Such a configuration closely resembles the reconstructed Late Triassic upper crustal configuration for the central MPT shown in Figures 6B and 7B.

One very thoroughly discussed aspect of the modelling by Koyi *et al*. (1993) is an overburden internal architecture related to a basement faulting and growth of salt structures. One of the important conclusions of Koyi *et al*. (1993) was that sedimentation associated with diapirs triggered by the basement faulting shows significant asymmetry on both sides of the diapir and across the sub-diapiric basement fault zone. This conclusion fully agrees with the observed thickness patterns of the Triassic and Jurassic in the vicinity of the Kłodawa diapir. Such asymmetry also results in asymmetry of the diapir itself. Diapirs, if extruded due to e.g. low sedimentation rate, would form asymmetric overhangs towards the subsiding areas (Koyi *et al*., 1993). Such subsiding areas form due to combined effects of movement and subsidence along the basement fault, and salt withdrawal, with the first mechanism being primary and dominant. In the case of the Kłodawa salt diapir, such asymmetry of the diapir itself, apart from the asymmetry of the overburden, is also observed (Figs. 4–7). Therefore, the asymmetric shape of the structure together with the asymmetry of the overburden could be used as a non-direct, but very strong, argument for the existence and Mesozoic activity of the basement fault beneath this diapir.

CONCLUSIONS

Analysis of seismic data from the central (Kuiavian) segment of the Mid-Polish Trough showed that basement extension and associated normal faulting was the principal mechanism responsible for the tectonic subsidence. Within this area, a significant link between sub-salt (sub-Zechstein) basement tectonics and salt tectonics existed. Basement faulting triggered development of salt pillows and diapirs. Strong basement faulting resulted in faulting of the post-salt cover that ultimately led to the formation of the Kłodawa diapir in the Late Triassic. Linked asymmetric basement faulting and salt flow led to the formation of a strongly asymmetric depositional pattern of the syn-kinematic Triassic deposits characterised by significant thickness variations, and local and regional unconformities.

Tectonic models based on seismic data closely resemble published results of the analogue modelling of basement faulting and salt tectonics. This is an additional argument that the proposed model of linked basement and salt tectonics, and their mutual influence on the development of sedimentary cover should be regarded as very probable. Future work should include qualitative cross-section balancing, possibly aided by analogue modelling. Ultimately, full 3D analysis of the Mid-Polish Trough development, including basement tectonics, spatial/temporal evolution of salt structures and surrounding depositional systems, should be undertaken. Available dense basin-scale coverage of high-quality seismic data calibrated by numerous deep wells would allow completion of such study, being rather unique in terms of the area covered and complexity of the geological processes studied.

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