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

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In my recent papers (Krzywiec, 2006*a*, *b*; see also Krzywiec *et al*., 2006) I proposed a new sub-Zechstein fault system, connected to Mesozoic subsidence and subsequent Late Cretaceous–Paleogene inversion of the Mid-Polish Trough (MPT). This fault pattern is considerably different from the MPT tectonic models developed by Dadlez (e.g. Dadlez, 1994, 1997, 2003, 2005). In his welcomed discussion (Dadlez, 2006) he has reiterated some of his opinions in an attempt to question my model. In this context, a summary of the arguments and models of Dadlez gave me a better opportunity to sustain my new tectonic model, and to discuss both models in the following text in more detail. The discussion by Dadlez (2006) consists of 12 points; for the sake of clarity I follow his points in my reply.

1. In his quotation Dadlez (2006) omitted one important word that played a central role in this sentence — I stressed that there is a lack of direct seismic information regarding sub-Zechstein tectonics, not a lack of any information. In my paper I presented several other arguments in order to justify my new tectonic model of the sub-Zechstein fault pattern (base Zechstein regional morphology, MPT present-day (i.e. post-inversion) sub-Cenozoic geology, distribution of salt structures, regional Mesozoic thickness pattern, gravity and magnetic data) which formed the basis for my reasoning regarding the location and nature (inclination and kinematics) of these inferred fault zones.

2. I used gravity and magnetic data to determine the main crustal blocks that subsided and were consequently uplifted during the development and inversion of the MPT. Consequently, fault zones delineating these crustal blocks were proposed, and they coincide with fault zones derived from analysis of other independent data. In the case of magnetic data certainly only first-order anomalies could be analysed and compared to other geological data, as they would be caused by sources located primarily in the crystalline basement, deeply buried in this area. However, a wedge-shaped West Pomerania magnetic anomaly (*cf*. Królikowski, 2006) seems to be directly related to the sub-Zechstein fault pattern I proposed (Krzywiec, 2006*a*, fig. 8). Gravity data provided more precise information on the location and extent of upper crustal blocks Boundaries of observed gravity anomalies could be, taking into account the overall resolution of the Bouguer gravity data, correlated with inferred tectonic boundaries (Krzywiec, 2006*a*, fig. 7). Certainly, Bouguer gravity map does, as stressed by Dadlez, correspond to the cumulative effect of all subsurface layers, but considering the size of the crustal blocks analysed and the wavelengths of associated gravity anomalies we are discussing comparable features. A more comprehensive analysis of this particular problem, together with examples of various processed gravity and magnetic maps and their precise correlation with the inferred sub-Zechstein fault pattern, is given in Krzywiec *et al*. (2006).

3. Dadlez (2006) stated that the present-day configuration of the MPT, in particular the top of the pre-Zechstein basement, could not be used in analysis of the Triassic-Jurassic evolution since it was shaped during inversion of this sedimentary basin. Although I certainly agree that the Late Cretaceous–Paleogene inversion significantly changed the basin-scale crustal geome-

try of the study area, I emphatically reiterate my suggestion that fault zones delineating crustal blocks after inversion most probably coincide with fault zones active also during earlier stages of basin evolution (although differently during different geological time intervals). Basement fault zones responsible for basin subsidence form basement weakness zones, and during basin inversion are prime sites of renewed tectonic activity, generally changing from normal to reverse faulting. I paid a good deal of attention to this problem in my paper, including also the role of salt in extensional and inversion tectonics. I approached this problem using some theoretical considerations backed up by previously published results of analogue modelling (*cf.* Krzywiec, 2006*a*, fig. 2 and accompanying text). Of course, under certain conditions, during basin inversion basement fault zones different from those active during basin subsidence could also have been (re)activated. Such a scenario should be however regarded as rather exceptional and requiring thorough analysis. Dadlez seems to assume that fault zones — no matter where located — active during Triassic–Jurassic phases of evolution of the MPT were left intact during inversion, and that during this process a completely new tectonic grain was activated. I disagree with such an assumption. It is also worth noting that Dadlez, disregarding the possible role of inversion-related reverse faulting in shaping the present-day sub-Zechstein basement, has not offered any alternative explanation of how this morphology, clearly visible on various maps and seismic profiles, has been formed. The depth map of the base Zechstein (Krzywiec, 2006, fig. 5) prepared by Papiernik *et al*. (2000) was based on the map of Dadlez (1998), but it was not only smoothed but also refined using newer seismic data. It was also cross-checked using fairly dense seismic coverage (including in the area north of Poznań, mentioned by Dadlez) available in digital form at the Department of Geophysics, Polish Geological Institute. It should also be noted that my analysis was focused on basin-scale phenomena and as such regarded only the main crustal blocks and their sedimentary cover. Such a geometry is clearly visible on my figure 5 and would not be even marginally changed should all presently available seismic data be used for creation of an even more refined base Zechstein map. Consequently, all my concluding remarks would remain unchanged.

4. Dadlez stated that "... the most important evidence for the activity of sub-Zechstein faults are thickness gradients in the Mesozoic ... redrawn ... from my paper (Dadlez, 2003)". I reiterate my opinion that other geological and geophysical maps were equally important in my analysis, and consequently I disagree that the thickness maps I used in my analysis (Krzywiec, 2006*a*, fig. 9), redrawn from Dadlez (2003), formed the most important evidence for the inferred sub-Zechstein fault pattern. Similar thickness changes, well known for many years, could be observed on numerous seismic profiles acquired along the flanks of the inverted MPT. Thickness maps formed just one element in my analysis, providing an additional and independent test for the basement fault grain I constructed using other data including seismic profiles, a map of the Zechstein base, and gravity and magnetic maps.

5. As Dadlez (2006) has stated, and as I have also made clear in my paper (Krzywiec, 2006*a*, page 143–144), my fault zones A and B are equivalents of the long known Kamień–Adler Fault and the Trzebiatów Fault, respectively. I gave a more thorough description of these fault zones backed up by good quality seismic data and with numerous references to older literature in other recently published papers (Krzywiec *et al*., 2003; Mazur *et al*., 2005). Dadlez (2006) suggested that these faults are separated by a WSW–ENE fault from the Pomeranian segment of the MPT. In his discussion he did not provide any additional backup for such a tectonic model, while arguments presented in his earlier papers (Dadlez, 1994, 1997) are still unconvincing to me (see below).

6. Dadlez (2006) seemingly missed my statement that I recognized a spatial coincidence and genetic relationship between my fault zone C and the Koszalin–Chojnice Fault Zone though I did not treat them as the same tectonic feature. As I stated on page 144 of my paper (Krzywiec, 2006*a*), in my analysis fault zone C is restricted only to that part of the basin where we observe hard linkage between sub-Zechstein basement and supra-Zechstein sedimentary cover, while the zone of deformation that is almost entirely limited to the Mesozoic cover in fact extends much further to the SE, towards the Bodzanów structure. This zone, interpreted by me as a peripheral fault zone basically detached within the Zechstein evaporites, is shown within the NE parts of regional seismic profiles 5, 6 and 7 (Krzywiec, 2006*a*, fig. 4). Moreover, the same zone was very precisely imaged — also as a tectonic zone detached with the Zechstein succession — on high quality seismic profiles in my accompanying paper (Krzywiec, 2006*b*, figs. 3, 8–10). This zone is characterized by localized Triassic–Jurassic thickness changes, as pointed out by Dadlez and shown on my interpreted profiles from both papers (Krzywiec, 2006*a*, *b*), but these thickness changes are in my opinion not related to any important basement faulting directly beneath the Koszalin–Chojnice/Bodzanów structure and are related to peripheral thin-skinned faulting almost entirely restricted to supra-salt Mesozoic cover (*cf.* model shown on fig. 1 in my accompanying paper, Krzywiec, 2006*b*). Finally, Dadlez stated that "Krzywiec (2006*a*) marks the fault C as active during pre-Zechstein times ..."and followed it with some further considerations on pre-Mesozoic tectonic activity. In fact, the problem of pre-Zechstein tectonic activity on any of the faults I analysed in my paper was entirely of the scope of my paper and I did not discuss this issue at all.

7. Dadlez (2003), describing the methodology he applied during construction of his thickness maps, stated that "Short dashed lines indicate areas of erosion"(Dadlez, 2003, p. 228). For the Muschelkalk–Keuper thickness map he did not show such area(s). For this succession, which, according to mapping methodology employed by Dadlez, includes also Norian and Rhaetian strata (*cf.* Dadlez, 2003, page 229) important intraformational unconformities are observed that clearly point to Late Triassic tectonic activity, similar to tectonic movements observed in eg. the more central (Kuiavian) segment of the MPT (see Krzywiec, 2004 for more detailed description), as also mentioned by Dadlez (2006). An example of a seismic line showing the thickness distribution of the Triassic succession, developed along the NE margin of the MPT, is shown on Figure 1. This line, precisely calibrated by the Połczyn IG 1 borehole, shows that the upper Keuper deposits have been eroded and unconformably covered by the Norian deposits. This

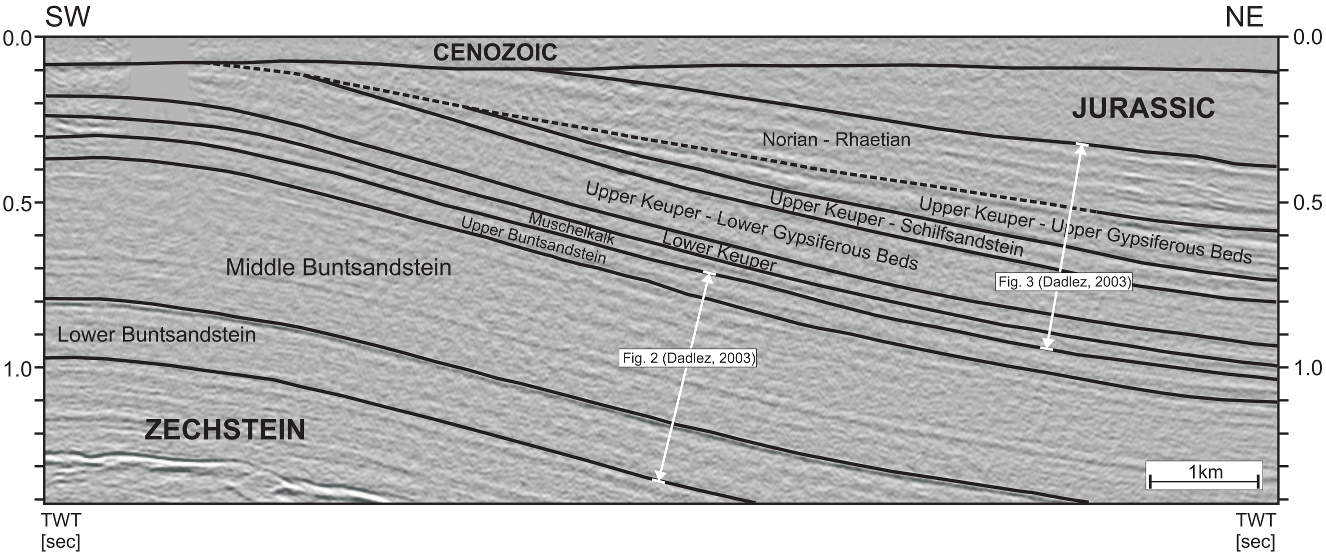

Fig. 1. Seismic example of intra-Upper Triassic unconformity and related thickness variations along the NE border of the Mid-Polish Trough

White bars refer to thickness maps shown on respective figures of Dadlez (2003)

intra-Triassic unconformity was also schematically shown on profile 4 from figure 4 in my paper (Krzywiec, 2006*a*). Even more complex, although more localized, thickness variations and intra-Upper Triassic unconformities are observed along the SW edge of the Pomeranian segment of the MPT (i.e. generally in the vicinity of fault zone E), where narrow grabens bounded by faults mostly detached in Zechstein evaporites evolved in Triassic times. Therefore, in order to use the Upper Triassic thickness map as an indicator of tectonic activity one should correct it for erosion-related thickness reductions. Consequently, the map of the present-day Muschelkalk-Keuper thickness (Dadlez, 2003), which included also Norian–Rhaetian deposits, has rather limited applicability as a basin-scale indicator of subsidence pattern.

8. I disagree with the statement of Dadlez that the SW boundary of the MPT should be correlated with an inferred fault zone located beneath the Drawno (Grzęzno)–Człopa salt structures instead of with fault zone F as I proposed in my paper (Krzywiec, 2006). The Drawno-Człopa Fault Zone, which I considered as of secondary importance for basin evolution, did not form a hinge zone related to major thickness changes in the Mesozoic strata, as suggested by Dadlez; such a hinge is located in closer vicinity to fault zone F (*cf.* also Krzywiec, 2006*b*, figs. 11 and 12). A basement fault zone possibly located beneath the Drawno-Człopa salt structure extends to the SE, directly beneath the Szamotuły salt structure towards the "Poznań–Kalisz graben structure" (*cf.* Kwolek, 2000). and eventually reaches the Bełchatów graben (Fig. 2). This basement fault zone progressively migrated away from the axial part of the basin, losing any connection with the basinal border faults. It is mostly of strike-slip character (Kwolek, 2000) with a very limited dip-slip component, and played a minor role regarding the regional thickness distribution of the Mesozoic cover apart from very localized thickness changes within tectonic grabens. Basement strike-slip movements along this fault zone have co-triggered thin-skinned cover deformations that, closer to the basin axis, were associated with salt diapirism (Drawno–Człopa–Szamotuły Zone), while further away from the basin axis they were mostly restricted to listric faulting and graben formation.

9. As I stressed above, the thickness maps of Dadlez (2003) were just one of several lines of evidences that I used to infer the location of basement faults. Considering that (1) Mesozoic cover evolved above a thick salt layer and, as an effect of this, the imprint of basement tectonics on the Mesozoic thickness distribution was significantly filtered and smoothed, and that (2) particular basement fault zones could have been active in different times with variable intensity, I think that the correlation between the sub-Zechstein fault pattern and the thickness maps of Dadlez (2003) is quite good. An independent basis for their identification was provided by other geophysical and geological maps (see above). Additionally, exactly along the NW segment of the fault zone D several salt pillows are aligned — a feature stressed in my paper (Krzywiec, 2006*a*) but not commented on by Dadlez (2006) — which provides in my opinion a good proxy for location of the basement faults (*cf.* Krzywiec, 2004, figure 1 together with accompanying description). Finally, on a regional scale the fault zones E and G are concordant with the tectonic grain defined by the Holy Cross Fault Zone (Krzywiec, 2006*a*, fig. 11), which is another feature omitted by Dadlez in his discussion (2006).

10. I sustain my statement that the Upper Jurassic map is poorly constrained because of the wide large extent of inversion-related erosion. Seismic data acquired along the edges of the Mid-Polish Swell often provide enough information to interpolate thickness changes of Middle Jurassic and older strata towards the basin axis, while Upper Jurassic shows only a just divergent pattern giving considerable room for extrapolation (*cf.* e.g. Dadlez, 2005 and his figs. 6 and 7 or Krzywiec, 2006*b*, figs. 11 and 12).

11. It was not my intention to suggest that Dadlez (1994, 1997) regarded his SW–NE transverse fault zones as Triassic

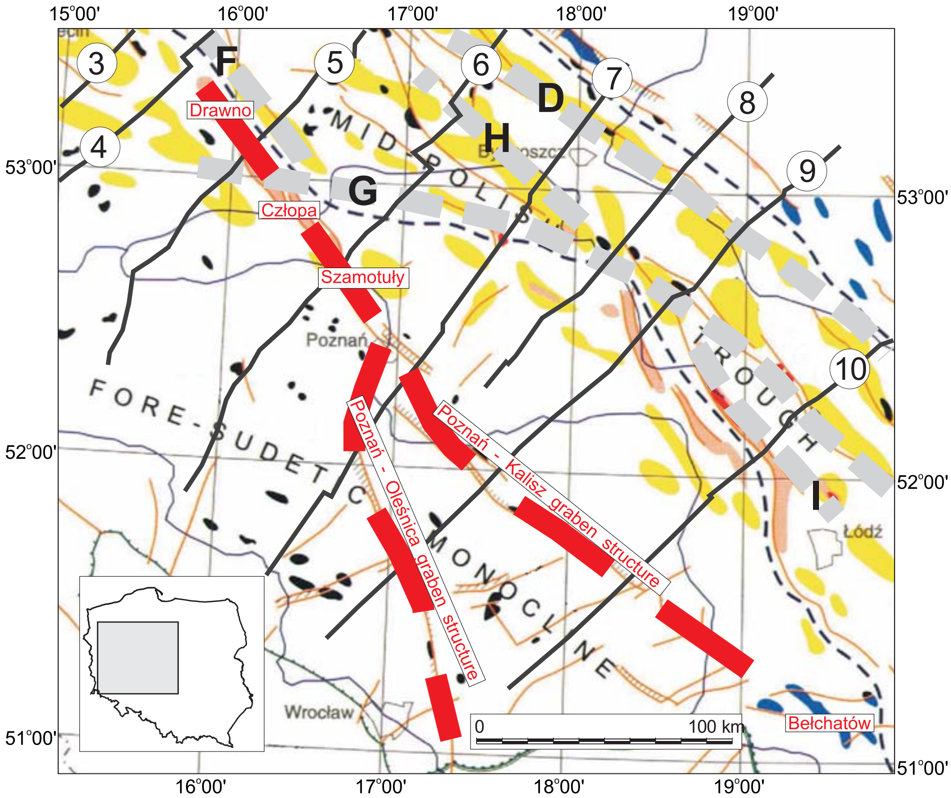

Fig. 2. Location of main sub-Zechstein basement fault zones (grey blocky lines — D, F–I, after Krzywiec, 2006*a*, *b*) and peripheral fault zones extending from the Drawno-Człopa area towards the SE (red broken lines) at the background of tectonic map of the Zechstein-Mesozoic complex (Dadlez and Marek, 1998, simplified); 3–10 — location of regional seismic profiles (Krzywiec, 2006*a*; Krzywiec *et al.*, in press), for further explanations see Dadlez and Marek, 1998)

and Jurassic strike-slip fault zones; in the sentence he has quoted my was that meaning the fault zones he linked with strike-slip movements were active during Triassic and Jurassic subsidence. I reject, however, his opinion that these faults were reactivated as strike-slip faults during the Late Cretaceous–Paleogene inversion (*cf.* e.g. Dadlez, 1994, fig. 2). For all the transverse fault zones of Dadlez (*cf.* Krzywiec, 2006*a*, fig. 10) it can be easily shown, using high-quality seismic data, that they were not associated with any inversion-related SW–NE wrenching, in contrast to what Dadlez has advocated in his papers (Dadlez, 1994, 1997). In particular, he argued that the present axes of the salt structures are displaced because of such inversion-related wrenching; in reality these salt structures have never been aligned along straight NW–SE trending lines but developed following directions determined by the basement fault zones I proposed in my paper.

12. Dadlez (2006) confirmed his acceptance of my tectonic model of decoupled evolution of the MPT during the Mesozoic which I advocated in several papers (e.g. Krzywiec, 2002, 2004, 2006*a*, *b*). However, two major issues contradict his statement. Firstly, numerous examples of interpreted seismic profiles from the MPT shown by Dadlez in his publications (eg. Dadlez, 2001, 2003, 2005) clearly show that in most cases he links faults within the Mesozoic cover with the sub-salt basement, essentially illustrating a lack of any decoupling between these two levels. A marked example of non-decoupled tectonics of the MPT was shown by Dadlez in his recent paper (2005). On several seismic profiles (figs. 5, 6–8) he not only extended faults bounding salt structures across the salt layer (indicating its brittle rather than ductile behaviour) into the sub-Zechstein basement but also showed Zechstein deposits beneath these salt structures being displaced beneath its regional base, indicating the virtually absence of any decoupling. At the same time such geometry, caused by hard-linked, non-decoupled tectonics, would require an unusual tectonic model of salt displacement beneath its regional base into the void created by localized basement extension below the salt structure, and this is highly improbable in my opinion. Secondly, I see a major problem with the statement of Dadlez (2006) regarding the regional evolution of the MPT that, in my opinion, contains a fundamental internal contradiction. Dadlez wrote that "My idea is that the deep faults Koszalin–Chojnice and Grzęzno–Człopa are fundamental features of NW–SE trend being fault induced boundaries of the northwestern segment of the MPT", clearly adhering to the idea that the MPT was bounded by deep-seated sub-Zechstein faults (although different from the ones I proposed). At the same time however he wrote "...the MPT was not a rift in the Mesozoic times since it was not bounded by regional active faults at that time". I see these two statements being completely opposite to each other. A similar contradiction is contained in his other paper (Dadlez, 2003, p. 238).

In summary, I fully sustain my new model of the sub-Zechstein tectonic fault zones of the Mid-Polish Trough, finding it superior to the model of Dadlez. These fault zones were mapped using independent data, were not concept-driven and provide a comprehensive and logical explanation regarding all major features observed within this sedimentary basin and its basement. In my opinion, Dadlez (2006) did not provide any convincing evidence that my new tectonic model should be abandoned in favour of his older model.

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