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Geological section through the lower Paleozoic strata of the Polish part of the Baltic region

Jędrzej POKORSKI

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The present-day structural pattern of the Baltic Depression developed due to superimposition of three main deformation phases: syn-Caledonian (after the Silurian), syn-Variscan (at the end of Carboniferous and beginning of Permian) and syn-Alpine (latest Mesozoic or earliest Cenozoic). The major restructuring of the area occurred as a result of syn-Variscan deformation that took place in latest Carboniferous and earliest Permian times. Most of the faults developed or became reactivated probably at that time. Syn-Alpine deformation manifested itself relatively weakly, mainly by reactivation of some pre-existing faults.

Jędrzej Pokorski, Polish Geological Institute – National Research Institute, Rakowiecka 4, PL-00-975 Warszawa, Poland, e-mail: jędrzej.pokorski@pgi.gov.pl *(received: February 02, 2010; accepted: May 24, 2010).*

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INTRODUCTION

The tectonic setting of the Polish Exclusive Economic Zone of the Baltic Sea has been described based on geological data derived from boreholes and interpretation of reflection seismic profiles. The eastern part of the East European Craton (named also the Precambrian platform) has been well explored by numerous boreholes and seismic surveys (Łeba, Courland and Gdańsk blocks), which enable detailed interpretation of the geological structure of the area. The western part of the East European Craton (Darłowo and Słupsk blocks) has been poorly explored by only two boreholes and a low-density network of seismic profiles. The West European Platform (named also the Paleozoic platform; Wolin, Gryfice and Kołobrzeg blocks) has been surveyed by a dense network of seismic profiles (over 2000 km) and by three boreholes.

The sketch-map (Fig. 1) illustrates the subdivision of the Polish Exclusive Economic Zone of the Baltic Sea into tectonic blocks.

In all the discussed schemes (Dadlez, 1995; Pokorski and Modliński, 2007; Jaworowski *et al*., 2010) the western part of the Polish Economic Zone on the West European Platform area is subdivided into three tectonic blocks: Wolin Block in the west (referred to as block H), Gryfice Block in the middle (referred to as block K) and Kołobrzeg Block in the east (also called block L).

The part located on the East European Craton is subdivided into 5 or 10 tectonic blocks. (Dadlez, 1995; Pokorski and Modliński, 2007; Jaworowski *et al*., 2010). They are determined (Fig. 1) based on the mapped system of faults and fault zones. In all the reports discussed, the system of faults and fault zones is the same and the differences in the number of blocks result from the analysis of their tectonic activity and the degree of generalization.

The scheme adopted in this work is based on the *Geological Map of the Western and Central Part of the Baltic Depression…* (Pokorski and Modliński, 2007), and refers to large blocks characterized by similar geological structure of the crystalline basement and its sedimentary cover, and by the faults deeply rooted in the Proterozoic crystalline basement. Therefore, the central zone consists of two blocks referred to as M (Darłowo Block) and A (Słupsk Block) after Dadlez (1995).

The eastern part of the basin consists of Block B (also referred to as the Łeba Block), comprising also the relatively small Rozewie and Żarnowiec blocks *sensu* Dadlez (1995) and two eastern blocks: D (Courland Block) and C (Gdańsk Block), which are analogously defined in the other works discussed.

In the oldest scheme of Dadlez (1995), the central part of the Polish Exclusive Economic Zone is subdivided into two blocks: the Darłowo Block (block M) and Słupsk Block (A). The eastern part of the basin was subdivided by Dadlez (1995)

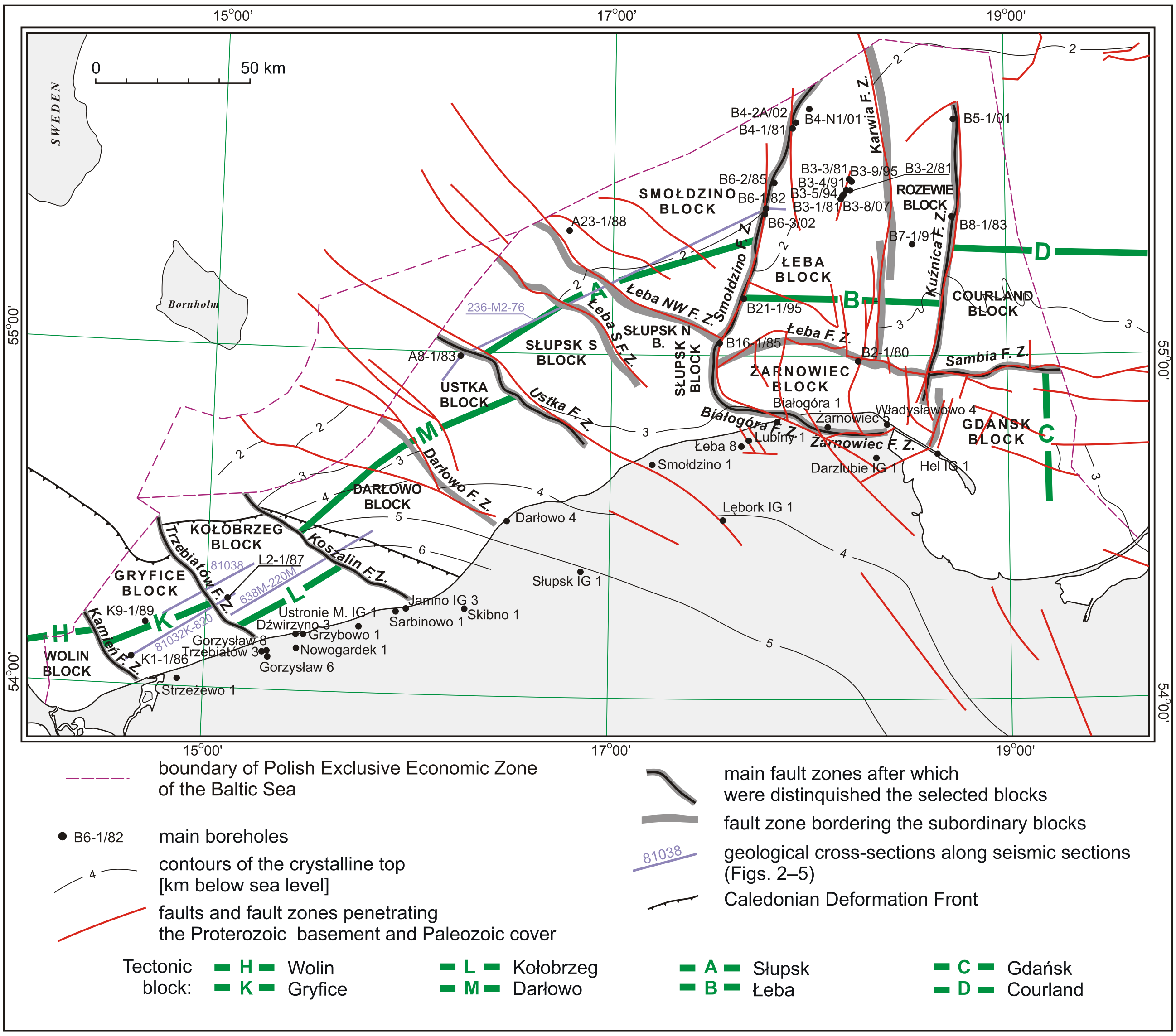

Fig. 1. Structural-tectonic sketch map of the Polish Exclusive Economic Zone of the Baltic Sea (partly after Anolik and Karczewska, 2008) and adjacent onshore area

into three northern blocks (Łeba, Rozewie and Courland blocks) and two southern blocks (Żarnowiec and Gdańsk) situated south of the Sambia Fault Zone.

The third scheme referred to in this work (Jaworowski *et al.*, 2010) is based on a very detailed segmentation proposed by the "Petrobaltic" Company (Anolik and Karczewska, 2008). In that subdivision, the Darłowo Block (M) includes two smaller units: Darłowo Block in the west and the Ustka Block in the east. The Słupsk Block (A) is subdivided into three smaller blocks of Słupsk South, Słupsk North and Smołdzino.

The eastern part of the basin is subdivided after Dadlez (1995) in that cited work.

LOWER PALEOZOIC SUCCESSION OF THE EAST EUROPEAN CRATON

The eastern part of the Polish Exclusive Economic Zone of the Baltic Sea is situated on the East European Craton (Precambrian platform) and spans the central part of a large regional structural-tectonic unit called the Baltic Depression (Pokorski and Modliński, 2007). The lower Paleozoic strata of the East European Craton were deposited in a multistage, polygenetic sedimentary basin. Its development was initiated by late Neoproterozoic to Early Cambrian rifting related to break-up of the Precambrian supercontinent, followed by Cambrian to Middle Ordovician post-rift thermal sag of the passive margin (Poprawa *et al.*, 1999). Since the Late Ordovician until the end of Silurian the Baltic Basin constituted a flexural foredeep basin of the Caledonian collision zone (Poprawa *et al.*, 1999).

The lower Paleozoic succession overlies Paleoproterozoic crystalline rocks. Numerous deep boreholes and reflection seismic profiles have provided data on the structure of the top of the crystalline basement in the coastal area of the Baltic Depression between Smołdzino and Hel, as well as in the adjacent Baltic Sea area within the Łeba, Gdańsk and Courland tectonic blocks in the Polish Exclusive Economic Zone. The depth to the top of the crystalline basement in the northern part of the Łeba and Słupsk blocks is approximately 1.5–3 km and it increases towards the south to about 3.2 km in the southern part of the blocks i.e. just off the Polish Baltic Sea coast, and towards the south-east to about 3.2–3.5 km in the Gdańsk Block.

In the offshore area, there is a system of approximately N–S-trending faults (Smołdzino and Kuźnica faults) and the E–W-trending Sambia Fault rooted in the crystalline basement. These faults controlled the Paleozoic evolution of the cratonic sedimentary cover (Pokorski and Modliński, 2007).

The Baltic Depression has a typical platformal structure. The geological structure of the sedimentary cover is simple: the strata usually lie almost horizontally, dipping at shallow angles (Fig. 2). The most important structural elements are faults and fault zones, especially regional ones, which are the basis for identification of lower order tectonic units (Dadlez, 1990; Dadlez and Pokorski, 1995) referred to as tectonic blocks. The major regional fault zones of the eastern part of the Baltic Depression are the Smołdzino, and Kuźnica zones (trending NW–SE and almost N–S) and the nearly longitudinal Sambia Fault Zone. These zones mark the boundaries of individual tectonic units (Fig. 1).

The faults and fault zones are commonly reverse; some are normal faults. Most of them are dip-slip faults of steep or vertical fault planes. The faults locally pass into flexural bends. Displacements of the regional faults vary from tens to hundreds of metres. Minor local faults commonly die out over a short distance, so that they are shorter and the displacements are smaller.

The lower Paleozoic sedimentary cover was penetrated by numerous deep boreholes, and its structural pattern was imaged by a number of reflection and refraction seismic profiles. In total, the onshore area of Latvia, Lithuania, the Kaliningrad region of Russia and Poland has been explored by a few hundred boreholes, in which the sedimentary cover and the top of the crystalline basement was penetrated. In the offshore area, these rocks were penetrated by several tens of boreholes.

The amount of drilling reconnaissance and seismic data reliability between the individual areas of the Baltic Depression are variable.

In the Polish zone of the Baltic Sea of the East European Craton, the geological structure of the lower Paleozoic sedimentary cover is well explored owing mainly to both high-quality offshore reflection seismic surveys and numerous boreholes. Reflection seismic investigations are focussed on the three major seismic boundaries: the top of the Proterozoic (Pre), within the Ordovician (Arenigian–Llanvirnian, Or) and within the Silurian (Gorstian–Ludfordian, S). The first one is related to the top of the crystalline basement. The Or boundary probably coincides with the Kopalino Limestones Formation (Modliński and Szymański, 1997) corresponding to the lower part of the Ordovician section (upper Arenigian–Llanvirnian). The S boundary is associated with Ludlow deposits, maybe with calcareous mudstones of the Reda Member (Modliński *et al.*, 2006). The investigations enabled the construction of time and depth maps and, in some regions, detailed maps of local structures. The most characteristic feature of the geological structure of the area is the orthogonal fault system.

The relatively poorly penetrated onshore area of the Baltic Depression is located between Darłowo and Łeba, where few reflection seismic profiles have been acquired to image the lower Paleozoic geological structure. In this region, upper Ludlow deposits subcrop at the sub-Permian surface. Cambrian and Ordovician deposits are deeply buried. The position of the Or (?) horizon suggests that the region is composed of tectonic blocks of large amplitudes.

A much better explored area is situated between Łeba and Władysławowo. A number of local structures and fault zones of displacements of up to approximately 50 m are observed here. Some of them are extensions of objects recognized by offshore surveys. The major reflection horizon Or is related to the Kopalino Limestones Formation. Reflection horizons associated with the Cambrian quartzitic sandstones are also observed.

Thickness analysis of the lower Paleozoic deposits shows the occurrence of differently oriented separate depocentres during the latest Vendian and Cambrian of the present-day Baltic Depression (Modliński *et al*., 1999). In Ordovician times, the dominant palaeotectonic element was the extensive, longitudinal Jelgava Depression. The formation of the NE–SW-trending Baltic Depression, in a structural pattern resembling the present-day one, was controlled by strong Silurian downward movements in the marginal zone of the craton, manifested by, e.g. large thicknesses of Wenlock and Ludlow deposits in the Słupsk and Darłowo regions. During the Pridoli, the depocentre shifted towards the north-east to the Gdańsk Gulf.

The present-day structural pattern of the Baltic Depression developed due to superimposition of three main deformation phases: syn-Caledonian (after the Silurian), syn-Variscan (before the Permian) and syn-Alpine (latest Mesozoic or earliest Cenozoic).

Syn-Caledonian deformation relied on reactivation of faults cutting the Paleoproterozoic crystalline basement. Late Neoproterozoic to Early Cambrian faults developed in an extensional regime, related to rifting (Poprawa *et al*., 1999). Extensional faults of that age have been documented from seismic data in the Swedish offshore area (Floden, 1980), and in the southwestern Baltic Sea (Lassen *et al.*, 2001). The majority of faults developed in the Polish part of the Baltic region cut through the entire lower Paleozoic section and terminate at a major unconformity, covered by upper Permian strata, therefore the time of their development cannot be constrained in details. However in the Lithuanian and Latvian part of the East European Craton continuous section from the lower Paleozoic to the Devonian and lower Carboniferous is preserved. In that area, a system of compressional to transpressional faults developed in the latest Silurian and Lochkovian (earliest Devonian), related to compression sourced in the Scandinavian Caledonides (Poprawa *et al*., 2006). The offset on a single fault zone is usually 50–200 m. In most cases late tectonic activity reactivated older faults (Poprawa *et al.,* 2006).

The major restructuring of the area occurred as a result of syn-Variscan deformation that took place in latest Carboniferous and earliest Permian times. Most of the faults became reactivated probably at that time. Also further east in the Lithuanian and Lat-

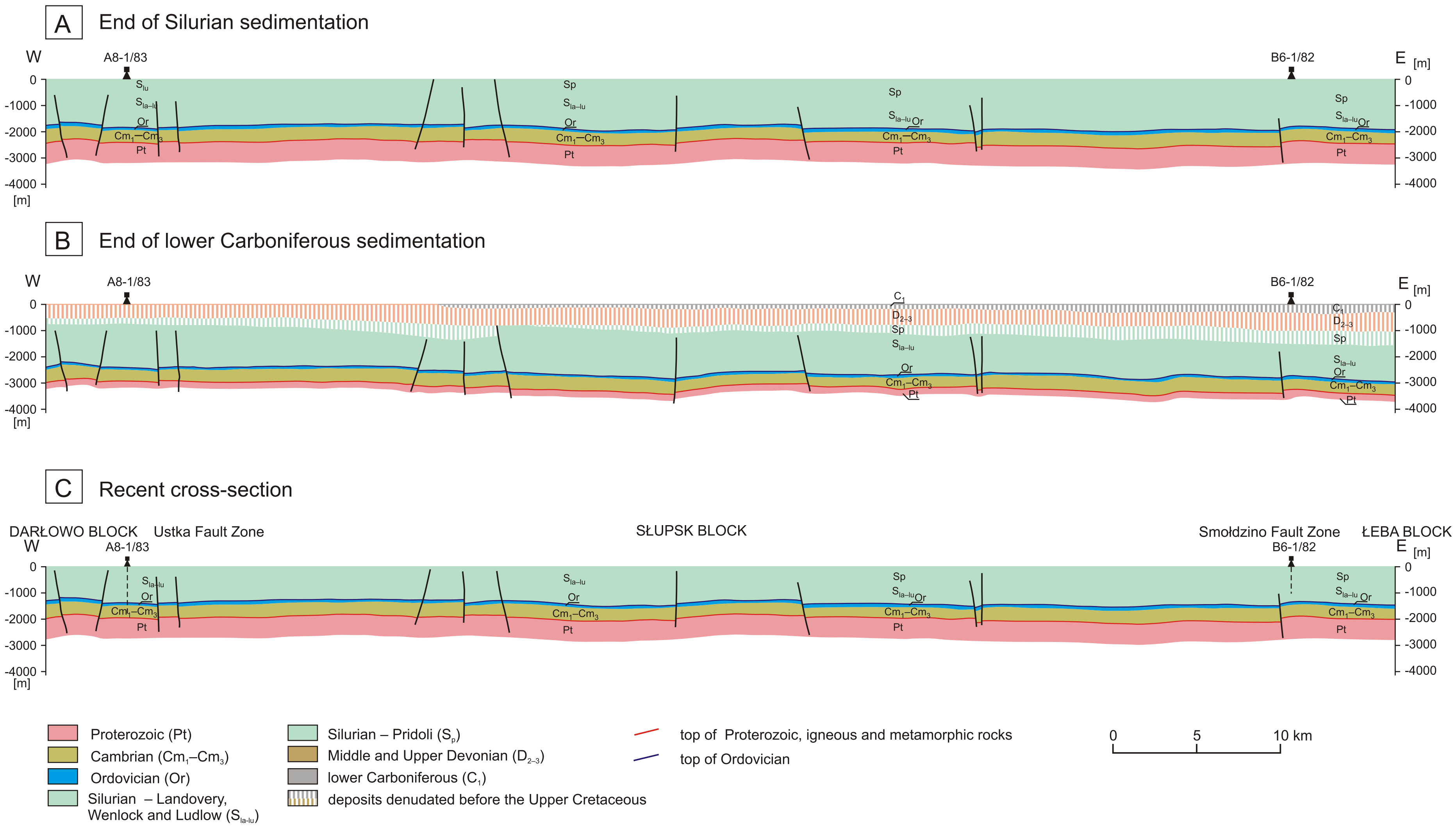

Fig. 2. Palaeotectonic cross–section along seismic cross-section 236-M2-76 (location see Fig. 1)

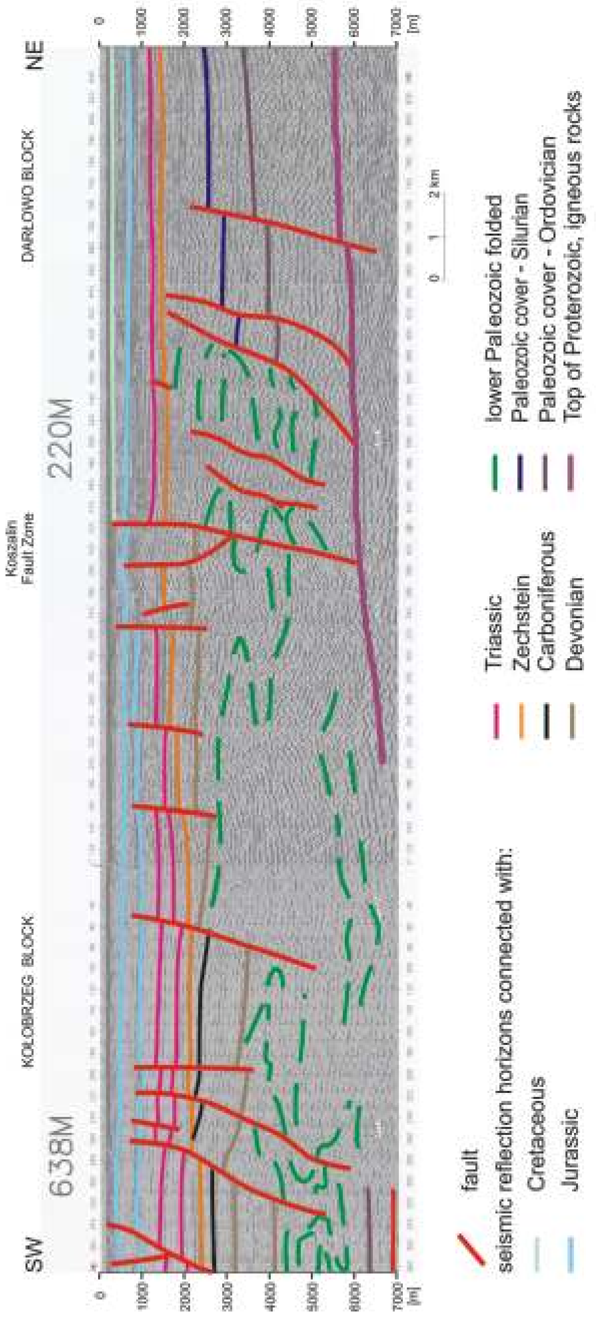

Fig. 3. Seismic cross-section (638M-220M, for location see Fig. 1) along the Kołobrzeg Block and the western part of the Darłowo Block

vian part of the basin transpressional reactivation of older structures is documented from seismic data (Poprawa *et al.*, 2006). Syn-Alpine deformation manifested itself relatively weakly, mainly by reactivation of some pre-existing faults. Development of faults in the Darłowo, Słupsk and Łeba blocks from the end of Silurian through to the end of the early Carboniferous to recent are presented on Figure 2.

In the central part of the Baltic Depression, the Smołdzino and Kuźnica major fault zones run meridionally and, in the south and east, also longitudinally (Sambia and Liepaja–Riga fault zones; Pokorski and Modliński, 2007). In the western part of the craton [Darłowo (M) and Słupsk (A) blocks], NW–SE-trending faults are dominant, i.e. parallel to both the craton edge and to fault zones of the West European Platform (Pokorski and Modliński, 2007; Figs. 1 and 2).

LOWER PALEOZOIC COMPLEX OF THE WEST EUROPEAN PLATFORM

The relief of the crystalline basement in the Paleozoic platform area is unknown. In the area situated to the west of the Koszalin Fault Zone and the Caledonian deformation front, there is no borehole penetrating the crystalline basement. The depth to the basement can be inferred from both interpretation of reflection seismic profiles acquired in the Polish Exclusive Economic Zone of the Baltic Sea (Pokorski and Modliński, 2007) and the regional dipping trend of the basement in the adjacent areas.

In the southwestern part of the Kołobrzeg Block and in the Gryfice Block, the crystalline basement is deeply buried and occurs probably at depths of approximately 10–13 km, as seen from the regional dipping trend as well as from drilling and geophysical data from Rügen and the German sector of the Baltic Sea. To reconstruct the relief of the top of the crystalline basement in the northern part of the Kołobrzeg and Gryfice blocks, the results of structural investigations conducted in the Danish sector of the Baltic Sea, south-west of Bornholm, were used (Vejbæk and Britze, 1994; Vejbæk *et al.*, 1994). There is a system of NNW–SSE-trending faults in that area, which continue into the Polish sector. The top of the crystalline basement here dips towards the SSW and probably occurs at a depth of 6–10 km.

In the area located immediately to the south-west of the Koszalin Fault Zone, the top of the crystalline basement lies probably at a depth of 5.5 km, and it gradually descends to approximately 9 km, dipping towards the SSW (Pokorski and Modliński, 2007).

In the western part of the Polish sector of the Baltic Sea (Kołobrzeg, Gryfice and Wolin blocks), the lower Paleozoic deposits were penetrated only by the

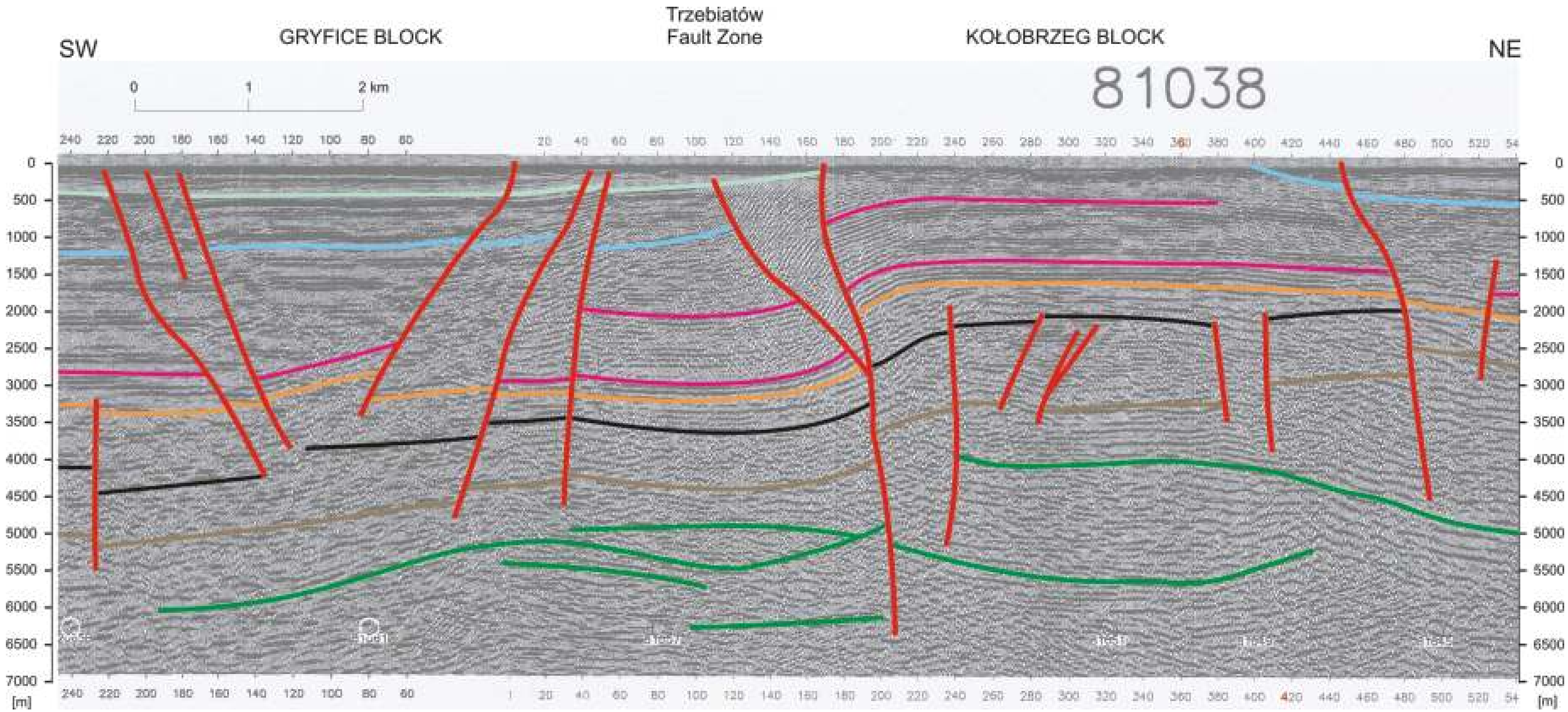

Fig. 4. Seismic cross-section (81038, for location see Fig. 1) penetrating the Trzebiatów Fault Zone

Explanations as in Figure 3

L2-1/87, K9-1/89 and K1-1/86 boreholes, where a thin section (*ca*. 100 m in thickness) of strongly tectonically deformed Ordovician (lower Caradocian) deposits were encountered (Modliński, 1968). In the lower Paleozoic succession of that area, seismic data sporadically reveal reflection horizons related to the top of the crystalline basement (Pt) and platformal Cambrian or Ordovician deposits (Cm+O). There are also numerous reflections associated with a folded Cambro-Silurian succession (Caledonides; Figs. 3 and 4).

At the end of Silurian, the western part of the offshore area underwent intense thrust-and-fold deformation. The lower Paleozoic deposits were thrust over the Wolin, the Gryfice and Kołobrzeg blocks and over the western flank of the Darłowo Block. The Caledonian deformation front is shown in the *Geological Map of the Western and Central Part of the Baltic Depression*... (Pokorski and Modliński, 2007; Fig. 1). The peneplanated surface of the Caledonian belt of the allochthonous lower Paleozoic is overlain by Paleozoic platform deposits, whose sedimentation started in Eifelian, locally Emsian times. Developed of sedimentation and faults in the Gryfice and Kołobrzeg blocks from the end of Rotliegend times through to the end of Muschelkalk and Late Cretaceous to recent time.

The Paleozoic platform was dismembered into the Wolin, Gryfice and Kołobrzeg blocks as a result of syn-Variscan diastrophism (in Carboniferous and early Permian times). The major fault zones (Koszalin, Trzebiatów and Kamień), marking the boundaries of the blocks, are rooted in the crystalline basement. These fault zones, reactivated as a result of syn-Variscan diastrophism, became rejuvenated during Paleogene times (syn-Alpine deformation).

CONCLUSIONS

Research better exploring the geological structure of the Polish Exclusive Economic Zone of the Baltic Sea should be directed towards studying the structural patterns of the lower Paleozoic (Ordovician and Cambrian) and Proterozoic formations, and towards creating a more complete drilling documentation of new structural objects.

The major fault zones of Kamień, Trzebiatów and Koszalin from the area of the West European Platform are deeply rooted in the Paleoproterozoic crystalline basement, as illustrated in the seismic profiles. The recent magnetotelluric investigations (MT), performed on profile D–PL running along the shoreline (Smołdzino–Szczecin), show that both the fault zones and the Ustka Fault Zone are rooted in the crystalline basement to a depth of approximately 10 km (Stefaniuk *et al*., 2008).

In the East European Craton area, the meridional, N–S-trending Smołdzino and Kuźnica fault zones and the longitudinal (E–W) Samlino Fault Zone are clearly rooted in the crystalline basement. During the syn-Caledonian deformation phase (after the Silurian), the Caledonides were thrust over the East European Craton (onto the Darłowo Block) and the general framework of the structural pattern of the central part of the Baltic Depressions was formed. Syn-Variscan (pre-Permian) deformation resulted in both rejuvenation of most of these faults and the ultimate formation of the structural pattern of the basin.

Syn-Alpine deformation was manifested by reactivation of some older faults.

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