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SEISMO-GEOLOGICAL MODEL OF THE BALTIC BASIN (POLAND)

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Abstract: The aim of this study is to construct a seismo-geological model of the western part of the Baltic Syneclise. This model enables reconstruction of the tectonic processes taking place in this area, which had a significant impact on the formation of prospective zones for the occurrence of unconventional hydrocarbon accumulations. The two seismic surveys Opalino 3D and Kościerzyna–Gdańsk 2D, together with borehole data available in the vicinity, were used for the research. Well data were used not only for the seismic-to-well tie, but also for the construction of well cross-sections (including balanced ones). The structural interpretation of seismic boundaries enabled the separation of four structural stages: Precambrian, Caledonian, Permian–Mesozoic and Cenozoic. The seismic interpretation of the Opalino 3D survey indicates the presence of block-style tectonics in this area. This system is considered to be a part of a large block system, also extending throughout the area of the 2D survey. The Caledonian interval shows the greatest degree of structural complexity. Most of the large Palaeozoic dislocations already had been formed in the Cambrian. They underwent reactivation and/or inversion in the Silurian, or in the final stages of the Caledonian and/or Variscan Orogeny, at the latest. The current shape and structure of the Baltic Syneclise and the development of the Palaeozoic sedimentary cover were significantly influenced by the processes taking place in the Teisseyre-Tornquist Zone (TTZ). The dislocations of the Lower Palaeozoic stage are characterized by general NW–SE and NE–SW trends, although the first of these seems to be dominant.

Key words: Baltic Basin, East European Platform, Palaeozoic, lithostratigraphy, tectonics, seismic interpretation.

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INTRODUCTION

The Baltic Syneclise is one of main tectonic units of the East European Platform. In Poland, it is filled with the Lower Palaeozoic sediments. The Syneclise is bounded from the southeast by the Mazury-Suwałki High, from the east by the Latvian saddle, and from the north by the Baltic Shield. The southwestern border is defined by the Teisseyre-Tornquist Zone (TTZ; Pożaryski and Witkowski, 1990). The area of the Baltic Basin chosen for the research covers two seismic surveys: Opalino 3D and Kościerzyna–Gdańsk 2D (Fig. 1). This area is in the western part of the Baltic Syneclise; however, it does not extend to the southwestern margin. Unconventional hydrocarbon accumulations occur in fine-grained deposits (shales, clays and mudstones), often in the layers of minor thickness and large lateral extent. The research carried out by Dziadzio *et al*. (2017), which included facies and stratigraphic analyses, demonstrated the possibility of unconventional hydrocarbon occurrence in the Ordovician (Sasino Formation) and Silurian (Jantar Formation) mudstones. These formations may be considered to be prospective, if they are characterized by high total organic carbon (TOC), thermal maturity of the organic matter and the appropriate genetic type of kerogen (Jarvie *et al*., 2006). Botor *et al*. (2017) wrote that zones with increased shale gas potential may occur only in the narrow strip of the Precambrian platform, parallel to the edge of the TTZ. The most prospective areas of the Baltic Basin are characterized by Late Ordovician and Silurian deposits, which occur near the Lębork IG-1 – Kościerzyna IG-1 wells.

The thin beds of the Sasino Formation (Ordovician) and the Jantar Formation (Silurian) make the location of sweet spots possible only with use of high-resolution (both vertical and horizontal) seismic data. The results of the research presented by Cichostępski *et al*. (2017) show that the Kościerzyna–Gdańsk 2D seismic survey cannot be used to locate sweet spots. This is due to their low horizontal and vertical resolution. The high-resolution Opalino 3D seismic survey creates such possibilities and therefore most of the research has been focused on this area. In this paper, following a previous account published in Polish (Kasperska *et al*., 2017), the authors present an attempt to reconstruct the tectonic processes taking place in this area, which had a significant impact on the formation of intervals that are prospective for unconventional hydrocarbon accumulations.

DATA AND METHODS

The 2D and 3D seismic data chosen for this study are shown in Figure 1. The Opalino 3D seismic survey was acquired and processed in 2013 by Geofizyka Kraków S.A. It covers 181.66 km^2. The acquisition was carried out mostly by applying a vibrator source with the following parameters: 6–90 Hz sweep, recording 4s with a maximum offset of 4285 m, and the bin size of 20x20 m. Additionally, air-gun and dynamite methods were used where necessary. The seismic dataset acquired has a high signal to noise ratio (SNR) and relatively high vertical and horizontal resolution. The average dominant frequency of the signal within the Lower Palaeozoic is about 30 Hz. All these parameters allowed a detailed interpretation of the geological structure in the entire area of the 3D seismic data set. The Kościerzyna–Gdańsk 2D seismic data was acquired and processed in 2003 by Geofizyka Kraków S.A. In 2009, the whole data set was reprocessed by Geofizyka Toruń S.A. It was the first seismic survey to give any information about the sub-Permian strata in this area. Seismic acquisition was carried out using mainly vibrators as the source (9–96 sweep) and a dynamite source was supplementary. Other acquisition parameters were a bin size of 12.5 m and maximum offsets of 5012.5 m. The Kościerzyna–Gdańsk 2D seismic survey may be characterized as a grid of regional profiles with large distances between them and a very low SNR. This is especially noticeable in the sub-Permian complex, where the correlation of seismic horizons and resolution decreases with depth. In addition, the orientation of profiles is oblique in relation to the regional fault strike. All these factors make the fault zones and the traces of seismic boundaries an approximation of the actual structural image (interpolation between cross-sections). The average dominant frequency of the signal within the Lower Palaeozoic region for the Kościerzyna–Gdańsk 2D survey is about 25 Hz. In this research, the authors used data from 9 wells: O2, O3, O4, L1, Darżlubie-IG1, Ko1, Bo1, Wy1 and Kościerzyna-IG1 (Fig. 1). In most wells, the following logs and their interpretations were available: sonic logs (DT), bulk density logs (RHOB), lithologic logs, gamma-ray logs (GR) and vertical seismic profiling (VSP). In the Darżlubie-IG1 and Kościerzyna-IG1 wells, only fragmentary and synthetic logs of acoustic slowness and bulk density were available.

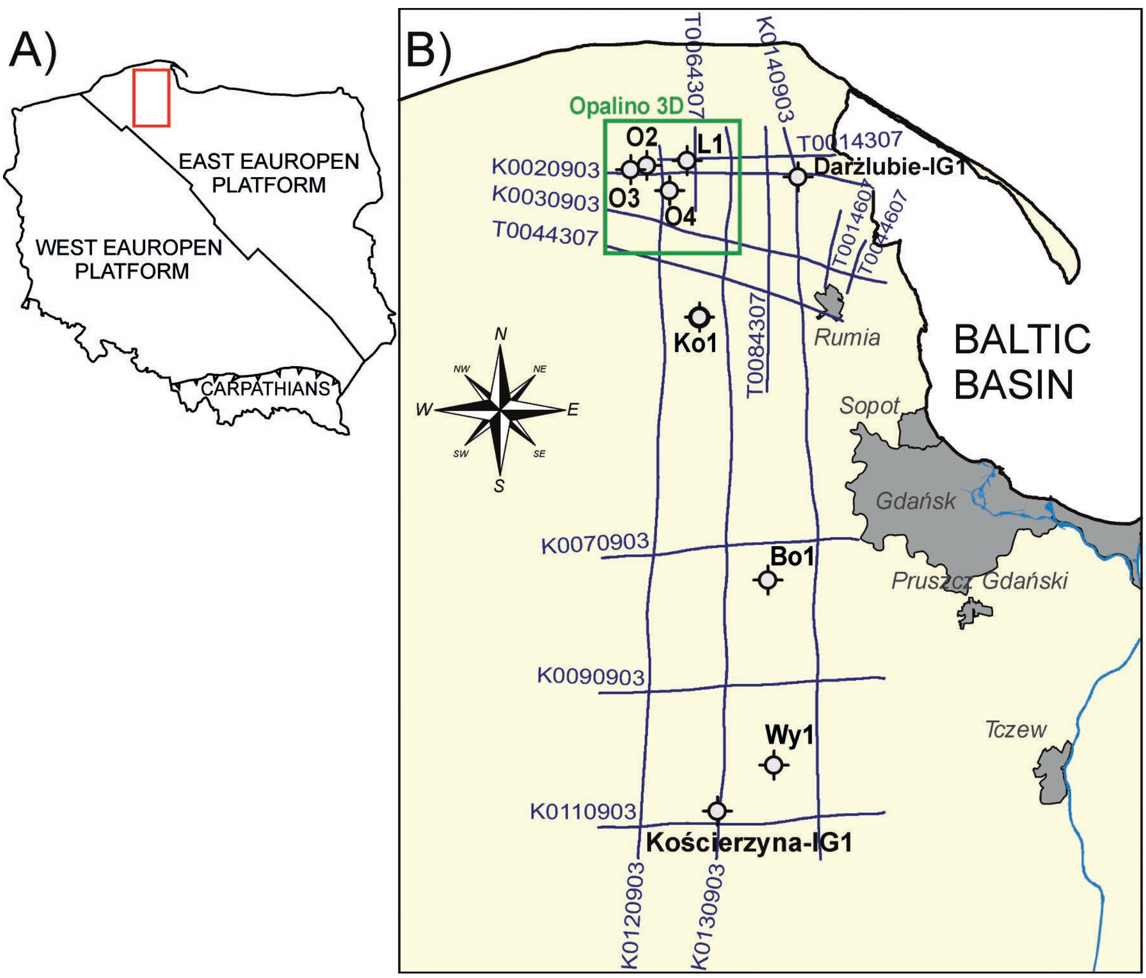

Fig. 1. Location and seismic surveys. **A.** Location of the study area (red rectangle) against main tectonic units in Poland (according to Żelaźniewicz *et al.*, 2011). **B.** The seismic surveys and wells. Blue lines – Kościerzyna–Gdańsk 2D seismic survey, green line – Opalino 3D seismic survey (Kasperska *et al.*, 2017).

GEOLOGICAL INTERPRETATION OF SEISMIC PROFILES

In the study area, four main structural stages can be distinguished: (1) the Precambrian, (2) the Caledonian, (3) the Permian–Mesozoic and (4) the Cenozoic, which covers all the others. The Precambrian complex is made of crystalline or metamorphic rocks of the Archean and Proterozoic. Locally, there are deposits of the Żarnowiec Formation, the age of which is estimated as being Vendian – lowermost Cambrian (Areń and Lendzion, 1978). The Caledonian structural complex (Lower Palaeozoic) includes the deposits from the Cambrian to the Silurian and the Permian–Mesozoic complex from the Permian to the Cretaceous. These two stages are separated by the Variscan gap, which is related to the elevation of the Baltic Syneclise in the Late Palaeozoic and strong denudation, including the removal of the Upper Silurian, Carboniferous, Devonian and Rotliegend deposits (Witkowski, 1989). The thickness of the sedimentary cover in the eastern part of the Syneclise is several hundred metres, and in the western reaches up to 5 km.

Seismic-to-well tie

The seismic-to-well tie is an indispensable step before the correlation of seismic horizons along seismic profiles. It was made using synthetic seismograms (1D modelling). , created in the Petrel Program. The input data for the calculation of seismograms were: (1) acoustic slowness calibrated with mean velocities and (2) density logs that were used to calculate the acoustic impedance and the distribution of reflection coefficients.

Synthetic seismograms were calculated for all wells available in the research area. The O2, O3, O4 and L1 boreholes were used for the seismic-to-well tie of the Opalino 3D survey, and the Ko1, Bo1, Wy1, Kościerzyna-IG1 and Darżlubie-IG1 for the Kościerzyna–Gdańsk 2D survey (Fig. 1). The following section presents only synthetic seismograms calculated for two typical wells in this region, O4 (Fig. 2) and Wy1 (Fig. 3). Comparison of the calculated seismograms with the recorded wave field demonstrates their similarities. The synthetic seismograms were compiled with fragments of seismic sections located in the immediate vicinity of the wells. The O4 well was tied to the Opalino 3D seismic survey (Fig. 2), using a statistical signal variable in time and extracted from two time intervals: from the Cretaceous to the Permian (100 ms–850 ms) and from the Silurian to the Cambrian top (850 ms–1800 ms). The Wy1 well lies in the vicinity of the Kościerzyna–Gdańsk 2D seismic survey (Fig. 3). This 2D survey is characterized by a much larger share of random noise than the analyzed 3D survey, especially in the Lower Palaeozoic part. Additionally, there is a noticeable decrease in resolution with depth increase. As a result, the quality and precision of the seismic well tie of the Lower Palaeozoic horizons are weaker than in the Opalino 3D survey. In the Wy1 well tie, a zero-phase signal with a dominant frequency of approx. 30 Hz was used. The following lithostratigraphic boundaries were identified in all wells: J – the seismic horizon associated with a positive reflection in the Upper Jurassic top (J3), T – the seismic boundary connected with a strong positive reflection forming below the level of the Bunter Sandstone (Tp2), P – the seismic boundary associated with the positive reflection from the anhydrite–dolomite package (A3 / Ca3) in the top of the Zechstein sediment, S – the seismic boundary associated with the negative reflection at the bottom of the Werra cycle, at the same time it is the Silurian top, Sb – the seismic boundary linked to the level of the Reda Member, O – the seismic boundary connected with the top of the Prabuty Formation (Ordovician top), Cm – the Cambrian top (the seismic boundary connected with the middle Cambrian sandstone top, tied to a negative reflection formed below the strong Ordovician horizon), Pr – the seismic boundary associated with a positive reflection from the top of the crystalline Proterozoic basement. This boundary was drilled only in the Kościerzyna-IG1 and Darżlubie-IG1 wells and on this basis extrapolated throughout the entire research area.

Well correlation

An important step in the structural interpretation of seismic data, apart from the seismic-to-well tie, was well correlation. Figures 4–8 present two main cross-sections connecting the wells: Kościerzyna-IG1, Wy1, Bo1, Ko1, O3 and O3, L1 and Darżlubie-IG1. To construct the lithostratigraphic sections, the authors used stratigraphic markers, well-logging data, synthetic seismograms and a VSP corridor stack in the depth domain. This enabled (1) determination with some accuracy of the depth of the Precambrian top in the wells, in which drilling was completed before reaching this level (Figs 2, 4) and (2) determination of the nature of the changes in the seismic signature of the waves reflected from the individual lithostratigraphic boundaries. Well cross-correlation provided a framework for seismic interpretation for seismic sections located near or crossing the well correlation profiles.

On the depth cross-sections, a simplified balancing procedure was performed by flattening the selected lithostratigraphic horizon and showing the relative depth and thickness relationships. The analysis of such data allowed the authors to predefine the probability of a fault or a fault zone occurrence between wells. If the seismic data confirmed it, balancing enabled the dating of faults by analyzing the thickness relations. Figures 5 and 6 show examples of correlation of the Kościerzyna IG-1–O3 and O3–Darżlubie-IG1 cross-sections flattened to the level of the Middle Ordovician. The observed changes in the thickness of lithostratigraphic levels within the Ordovician and Upper Cambrian formations are small. This proves that the Kościerzyna fault, located between the wells Kościerzyna-IG1 and Wy1 (Fig. 4), was not active in the Ordovician and perhaps it was formed in the Silurian. Only between the wells Ko1 and O3 (Fig. 5) the authors observed a significant increase in the thickness of the sediments from the Upper Cambrian to the Middle Ordovician. This may indicate the presence of a ramp with the thickness of sediments increasing towards the north or (more likely) the presence of faults active in the Cambrian and dying out in the Ordovician. On the seismic section K0130903 (Fig. 4), several faults are visible to the north of the Ko1 well, each of which may show this effect.

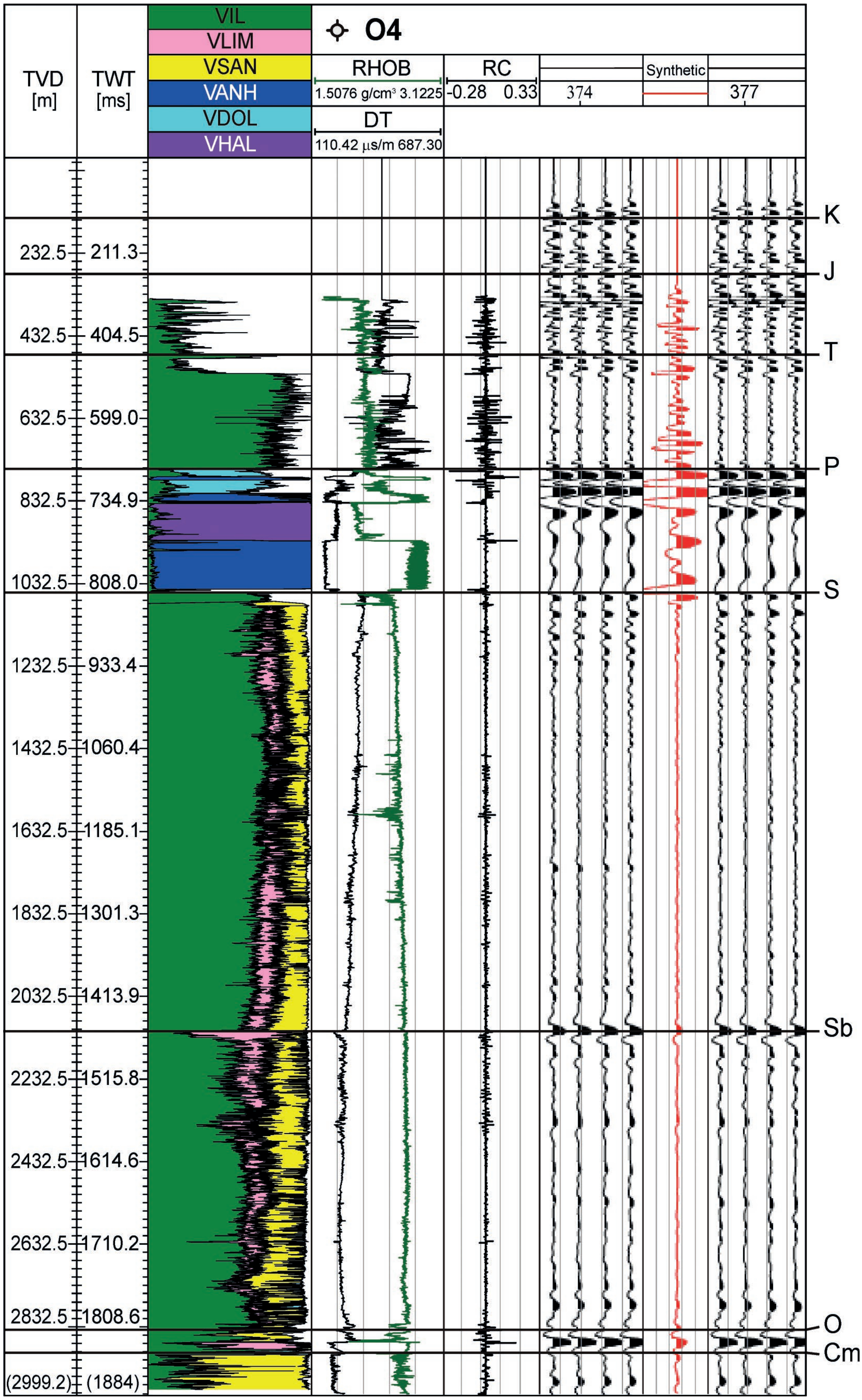

Fig. 2. Well-to-seismic tie for the O4 well. From left: depth (TVD), two-way time (TWT), lithology, P-wave velocity (DTP), bulk density (RHOB), reflectivity (RC), synthetic seismogram (red) on seismic data. Abbreviations in Figs 2–3, 9–21: K – Cretaceous top, J – upper Jurassic top, T – positive reflection forming below the level of Bunter Sandstone (Tp2), P – top of Zechstein deposits, S – Silurian top, Sb – Reda Member, O – Ordovician top, Cm – Cambrian top, Pr – top of the crystalline Proterozoic basement (Kasperska *et al.*, 2017).

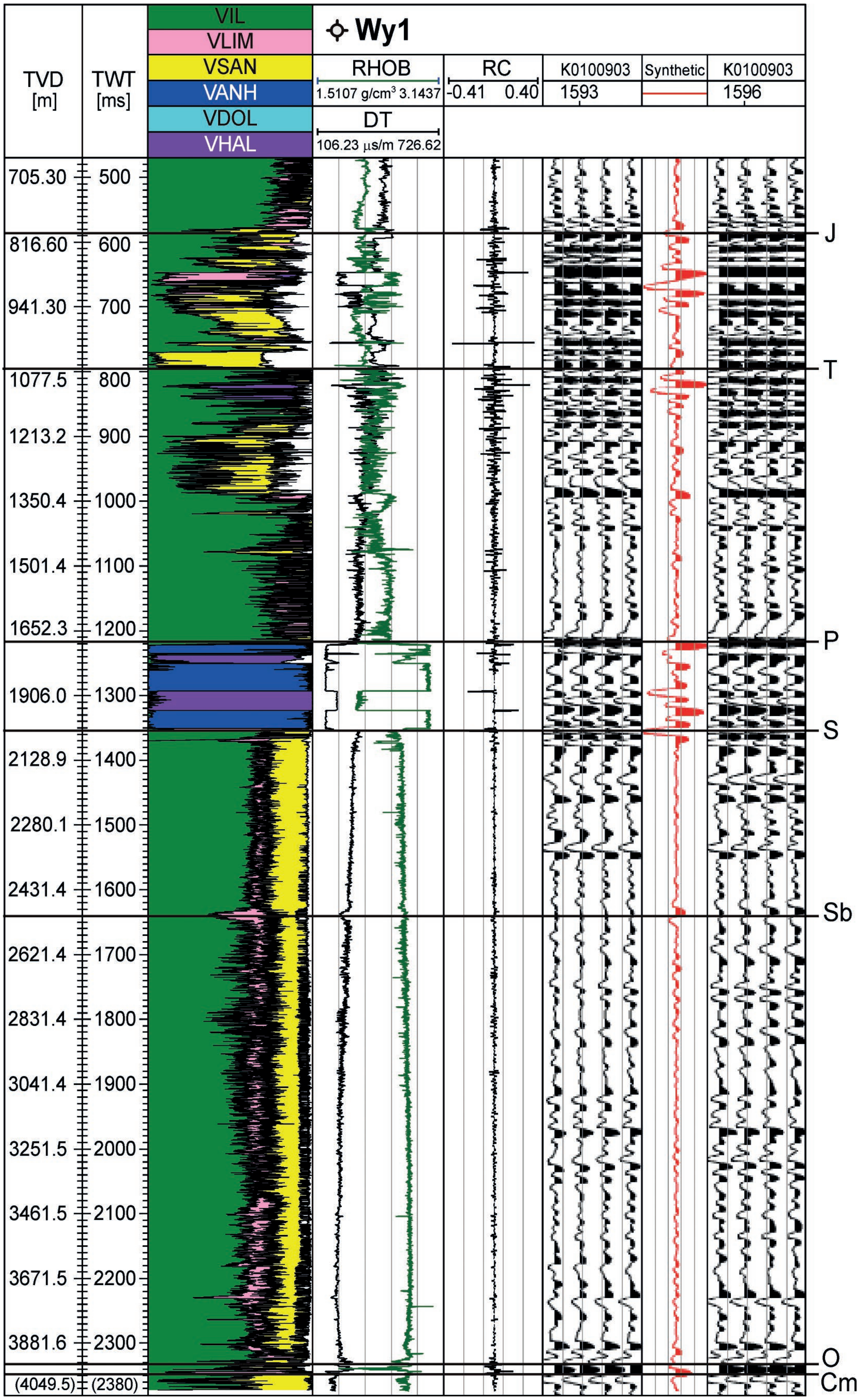

Fig. 3. Well-to-seismic tie for the Wy1 well. From left: depth (TVD), two-way time (TWT), lithology, P–wave velocity (DTP), bulk density (RHOB), reflectivity (RC), synthetic seismogram (red) on seismic data (Kasperska *et al*., 2017).

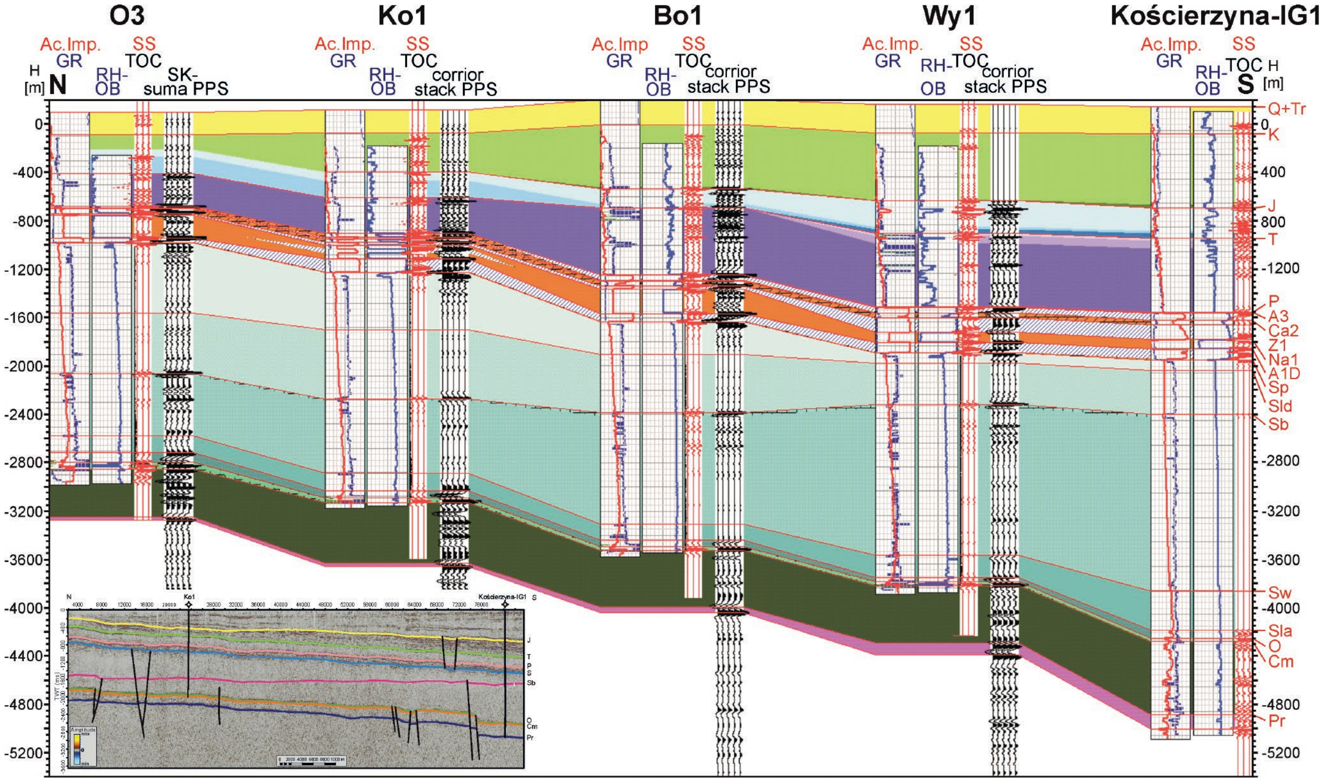

Fig. 4. Lithostratigraphic well correlation section Kościerzyna-IG1–O3 (depth domain) and matching seismic section. Abbreviations in Figures 4–8: Q+Tr – Cenozoic, K – Cretaceous top, J – upper Jurassic top (J3), T – Triassic top, P – top of Zechstein deposits, A3 – top of Cambrian, Ca2 – top of Main Dolomite, Z1 – top of first cyclothem, Na1 – top of Oldest Halite, A1D – top of Lower Anhydrite, S – Silurian top, Sp – top of Pridoli, Sld – top of Ludlow, Sb – top of Reda Member, Sw – top of Wenlock, Sla – top of Llandovery, O – Ordovician top, Om – top of Middle Ordovician, Cm – Cambrian top, Cm3 – top of upper Cambrian, Cm2 – top of middle Cambrian, Pr – top of crystalline Proterozoic basement (Kasperska *et al*., 2017).

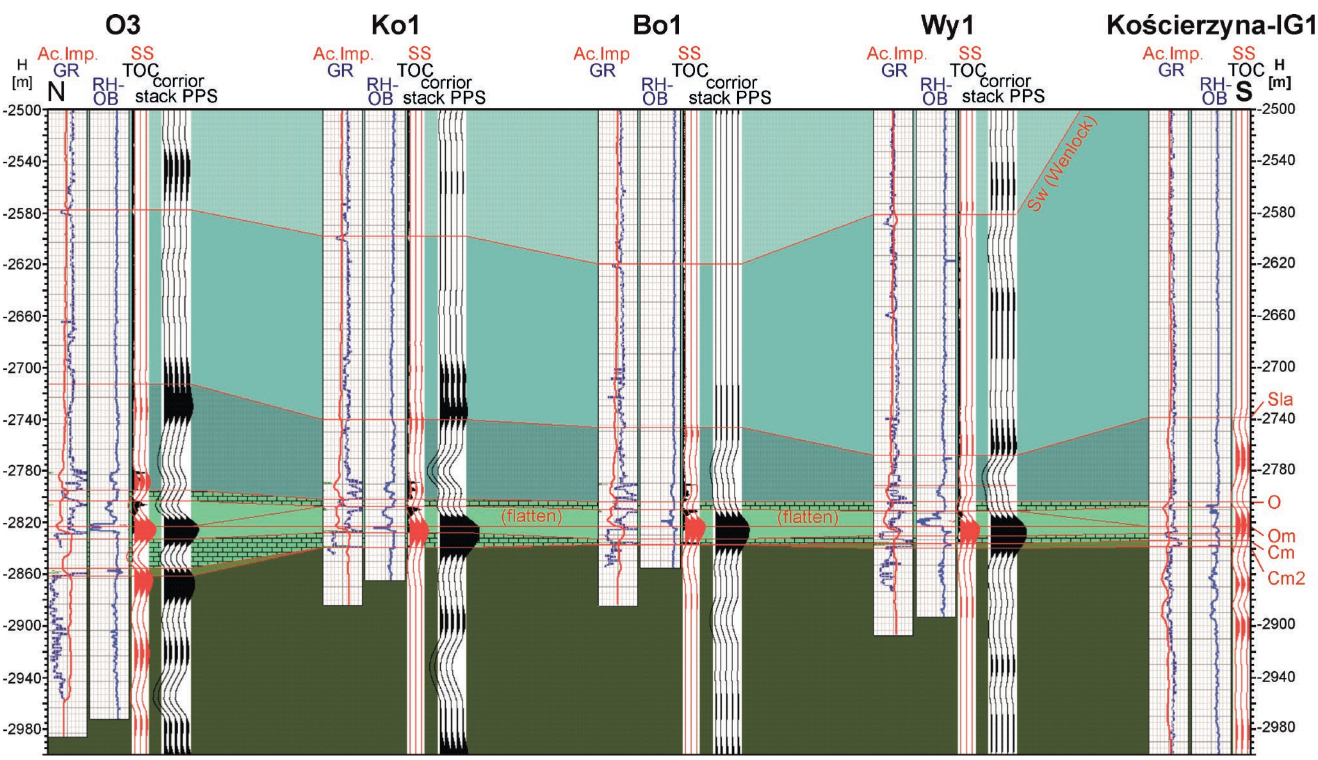

Fig. 5. Lithostratigraphic well correlation Kościerzyna-IG1–O3 (depth domain) flattening on the Middle Ordovician (Kasperska *et al*., 2017).

Because the thickness relations of the Ordovician and Cambrian formations in the O3, L1 and Darżlubie-IG1 wells are the same, a potential fault or the fault zone should have an almost N–S orientation. The final structural map of the top of the Ordovician is the confirmation of this hypothesis. Lack of any thickness change within the layers between the Wy1 and Kościerzyna-IG1 wells may indicate that a large fault zone observed on the seismic data between them (Fig. 4) was created only in the Silurian. From the analysis of the seismic waveform signature of the Ordovician and the uppermost Silurian sediments, it is noticeable that its shape and amplitude are constant (Ko1, Bo1 and Wy1 wells; Fig. 5). This correlates with the constant thickness of the Middle and Upper Ordovician deposits. A slightly different signature appears in the O2 well. The amplitude of the negative reflection, located directly above the positive reflection created on the top of the Lower and Middle Ordovician, increases. This is accompanied by a gentle increase in the thickness of the Upper Ordovician. There are also no changes in the thickness and shape of the seismic signal signature in the wells O3, L1 and Darżlubie-IG1 (Fig. 6). It can be assumed that on the northern side of the Cambrian faults (ending in the Ordovician), separating the wells O3, L1 and Darżlubie-IG1 from the well Ko1, there may be a slightly larger thickness of the Middle and Upper Ordovician deposits. Figures 7 and 8 show the cross-sections Kościerzyna-IG1–O3 and O3–Darżlubie-IG1, flattened to the level of the Silurian top. In the correlation horizons, there is a noticeable presence of a clinoform dipping to the north. It is already marked in the Wenlock, but it is best tracked in the Ludlow at the level of the Reda Member, which is a good marker and the only seismic marker in the Upper Silurian. The Kościerzyna fault is visible both in seismic (Fig. 4) and correlation (Fig. 7) data with a sudden increase in the thickness of older deposits of the Reda Member. This means that the fault formed in the Lower Silurian was still active until the Llandovery. If extensive movements started at the transition of the Ordovician and Silurian, local thickness increases of the Jantar Formation are theoretically possible. This theory is difficult to verify on seismic data, because the Pasłęk Formation, which pinches out toward the Jantar Formation, creates complex interference systems. In the correlation section flattened on the Silurian top in the O3 well, there is a slight increase in the thickness of the Llandovery and Wenlock in relation to the Ko1 well. It is not as visible as in the case of the Kościerzyna structure, but it may indicate the reactivation of the older faults or the formation of new ones, generally throwing down to the north. At the same time, the authors observed that the top Cambrian is shallower than in the Ko-1 well. This means that these faults were inverted in the Upper Silurian or during the Variscan Orogeny. The lack of deposits of Devonian and Carboniferous makes more accurate dating of the tectonics impossible. An analysis of both O3–Darżlubie sections (Figs 6, 8) showed that the tectonic block on which the O3 well is located has the strongest inversion (the Ordovician top is the highest), which means

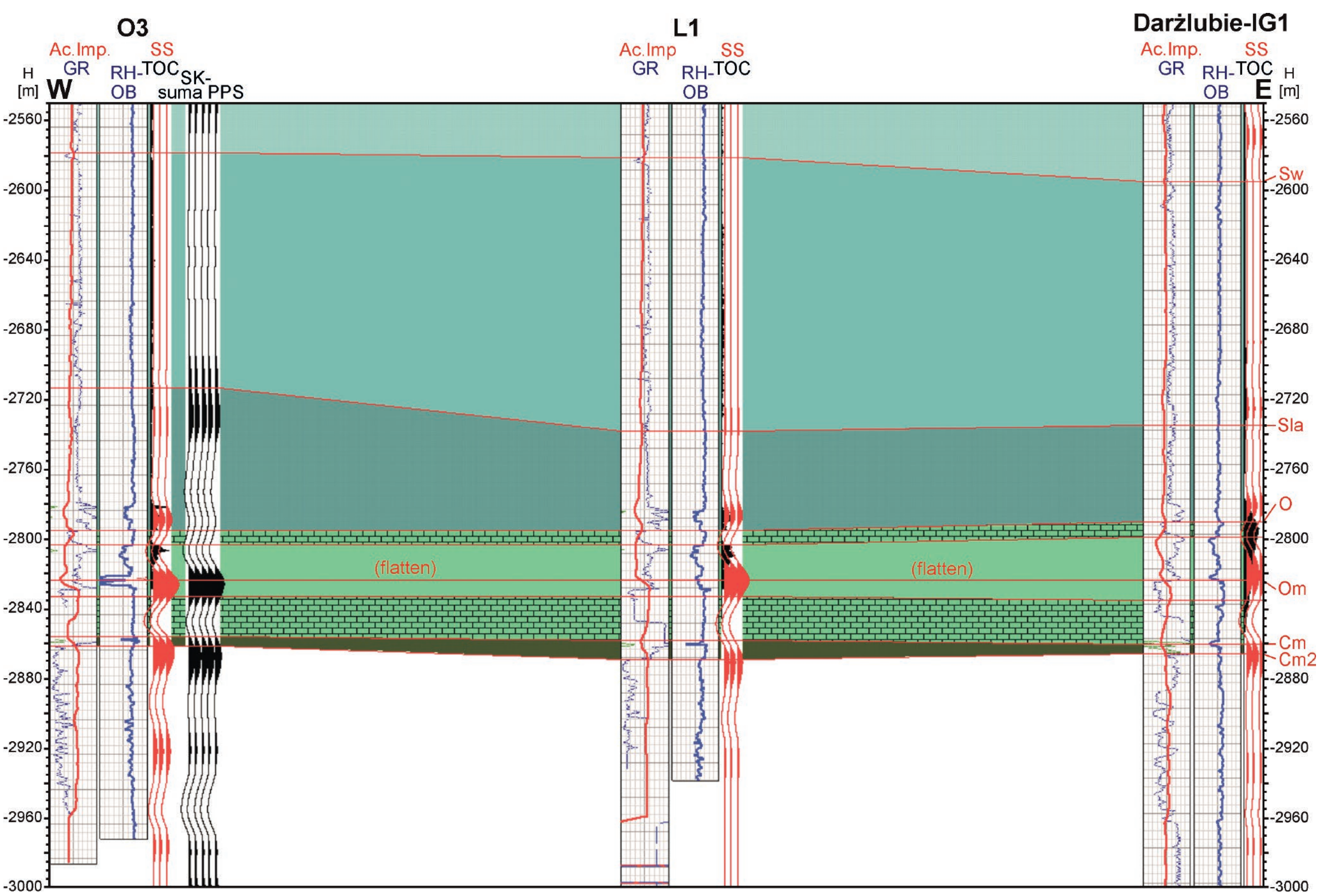

Fig. 6. Lithostratigraphic well correlation section O3–Darżlubie-IG1 (depth domain) flattening on the Middle Ordovician (Kasperska *et al.*, 2017).

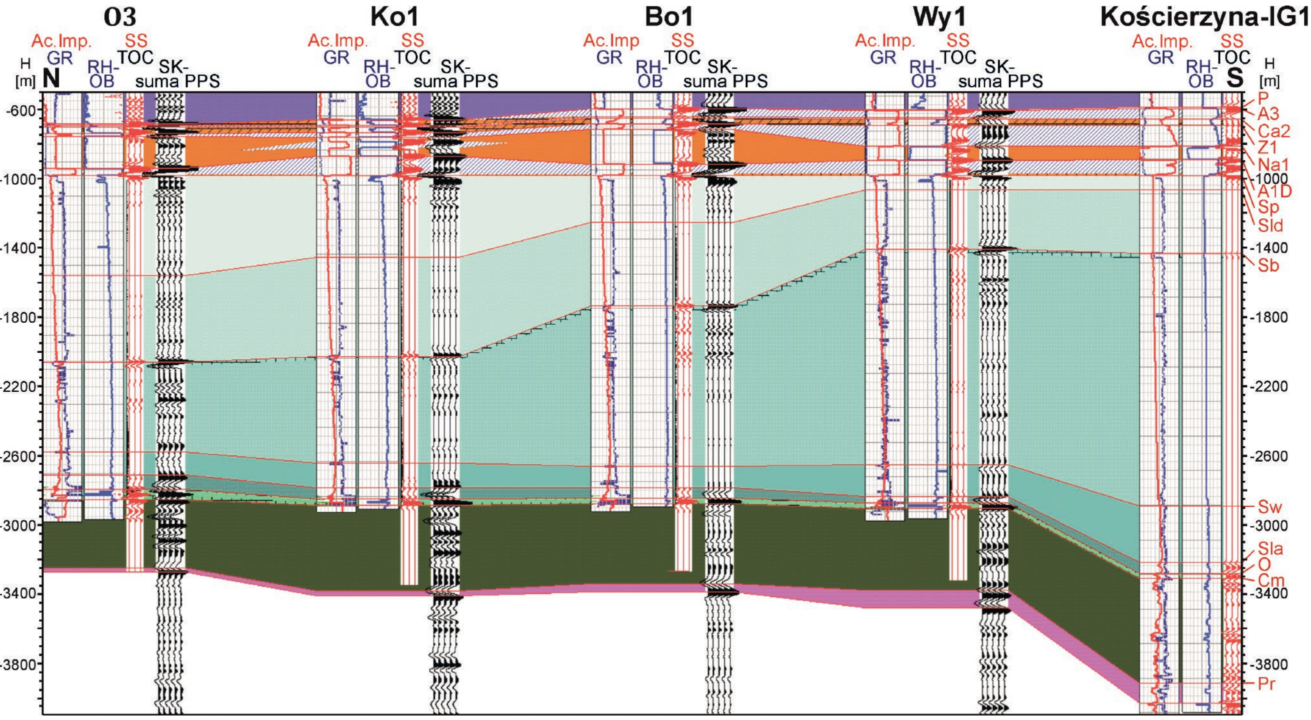

Fig. 7. Lithostratigraphic well correlation Kościerzyna-IG1–O3 (depth domain) flattening on the top of Silurian (Kasperska *et al.*, 2017).

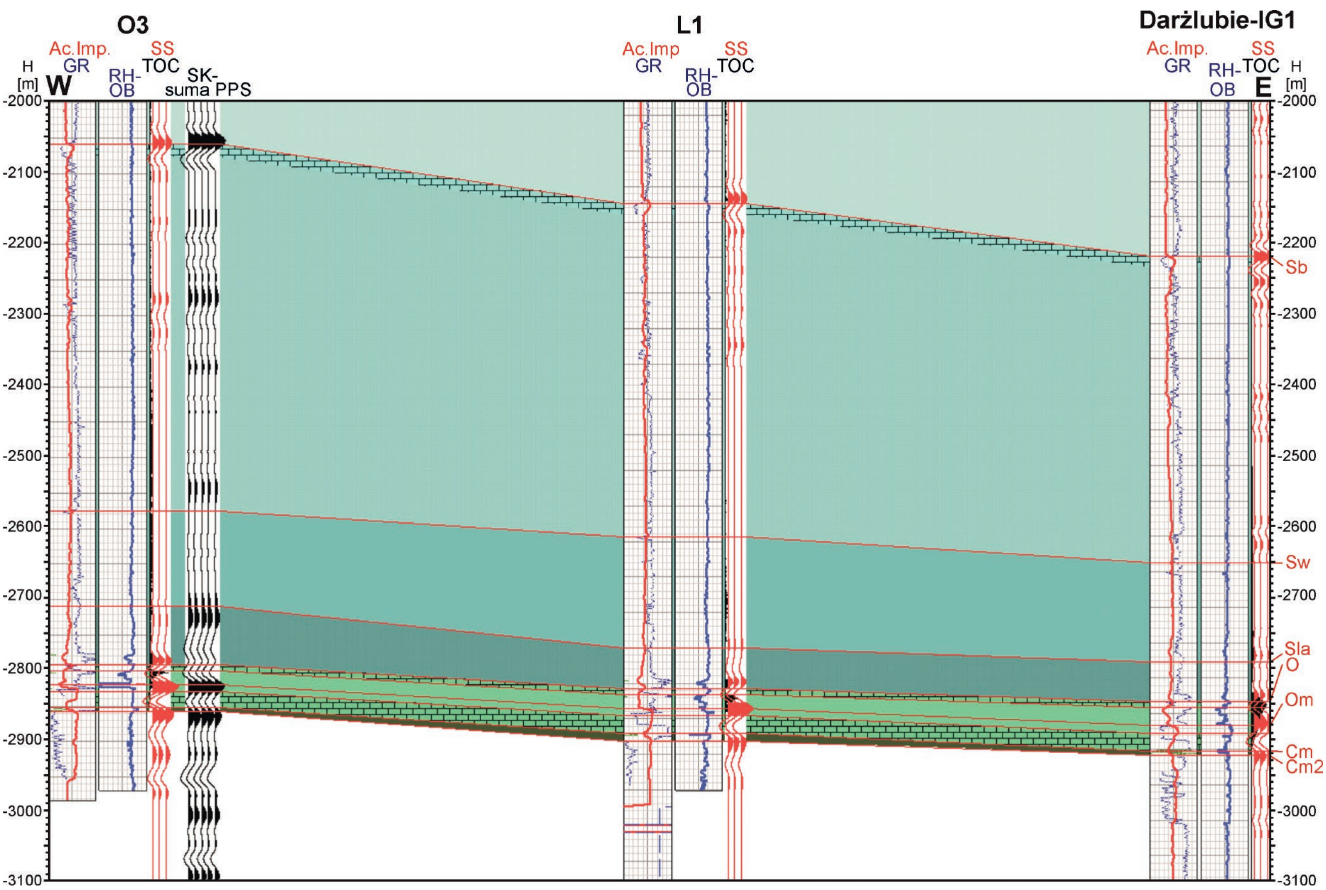

Fig. 8. Lithostratigraphic well correlation section O3–Darżlubie-IG1 (depth domain) flattening on the top of Silurian (Kasperska *et al.*, 2017).

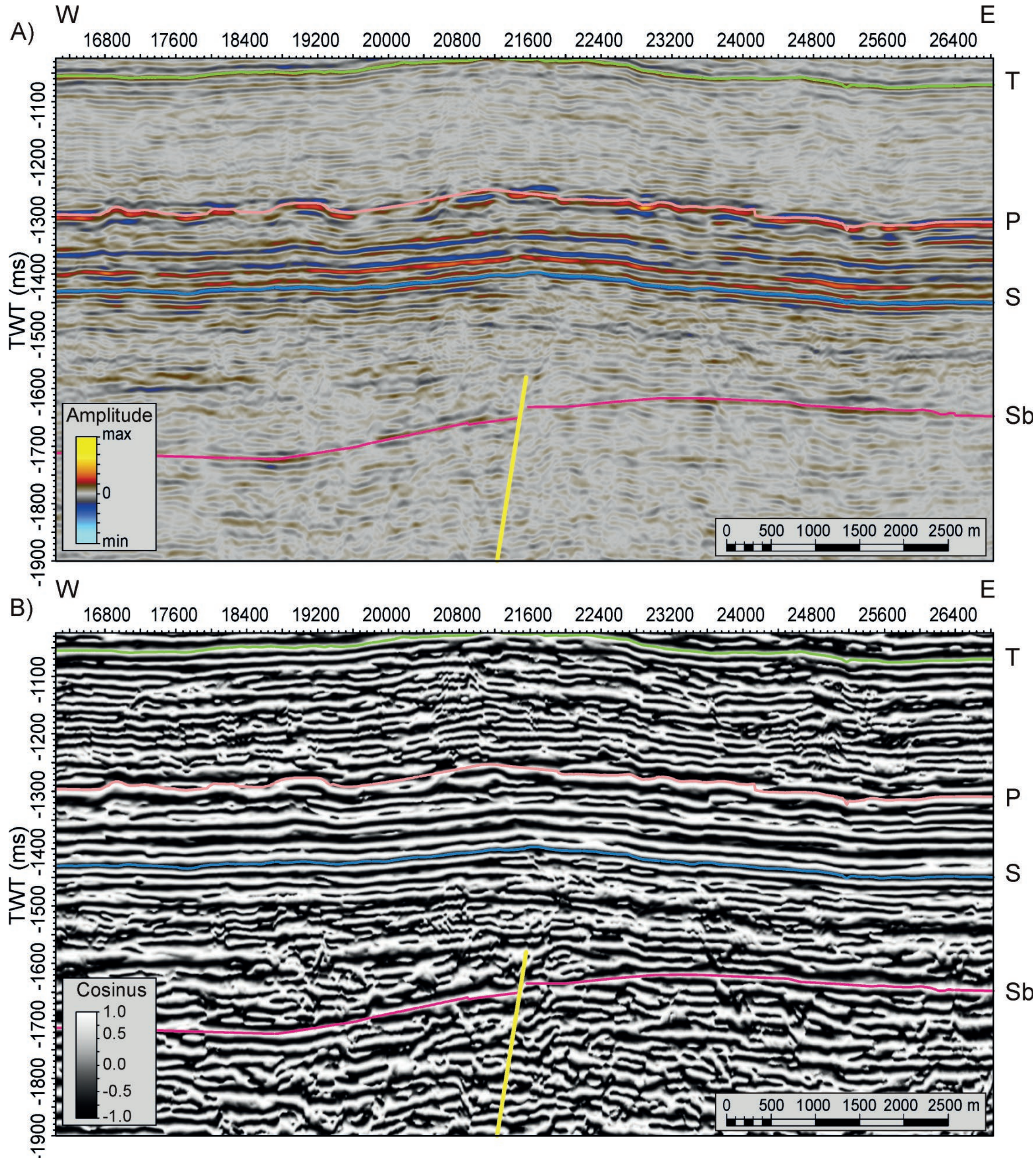

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Fig. 9. Part of the K0110903 seismic section expressed in (**A**) amplitude and (**B**) cosine of instantaneous phase (Kasperska *et al*., 2017).

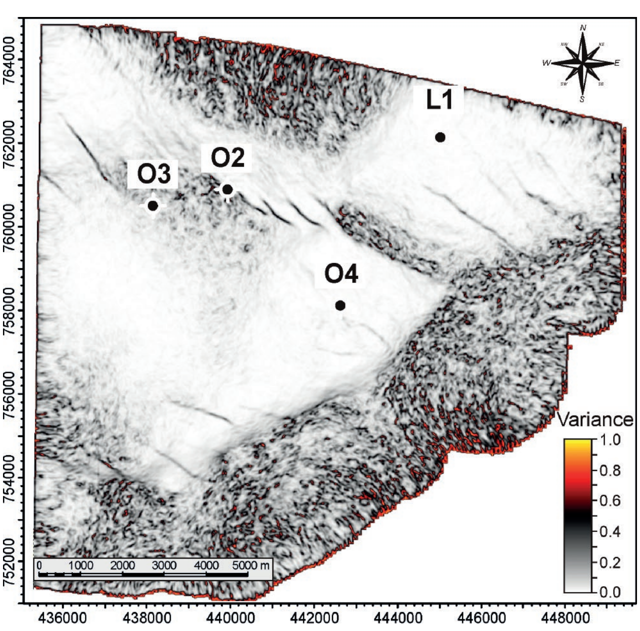

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Fig. 10. Time slice (1470 ms) from the Opalino 3D a seismic survey expressed in Variance version (Kasperska *et al*., 2017).

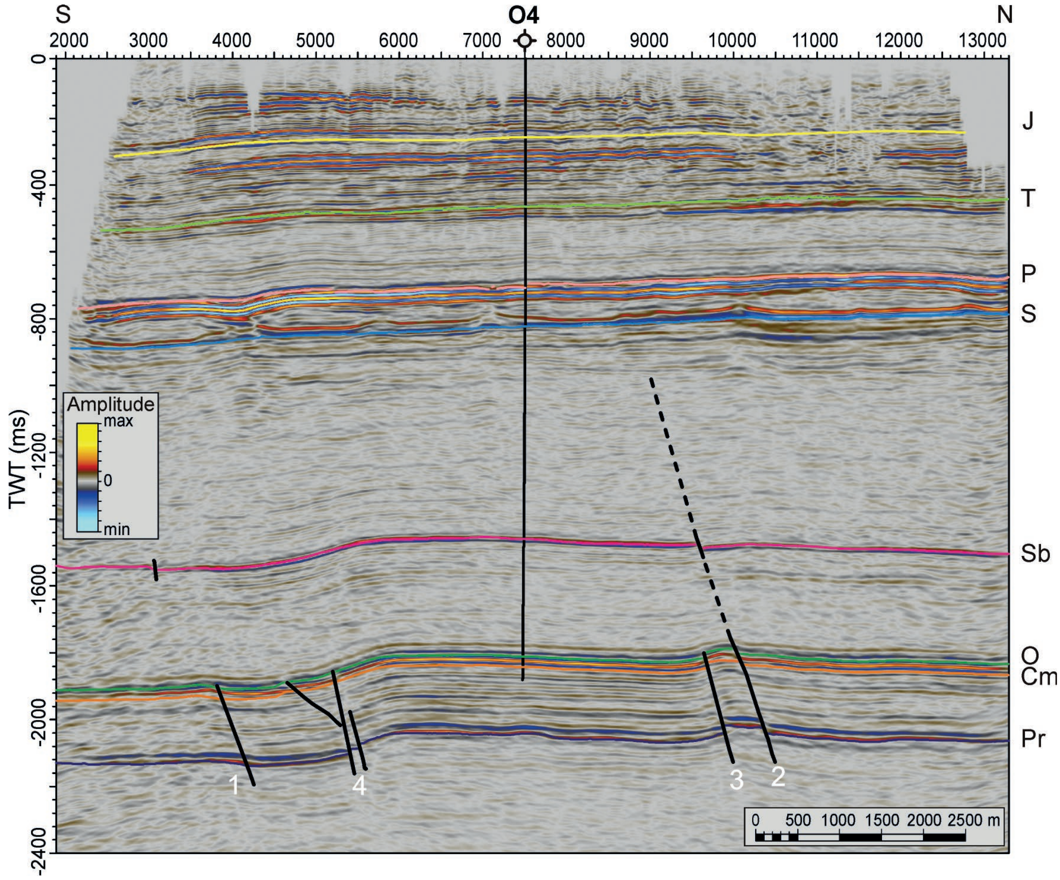

Fig. 11. Structural interpretation of 357 Inline (Opalino 3D seismic survey). 1–4 number of fault zones (Kasperska *et al.*, 2017).

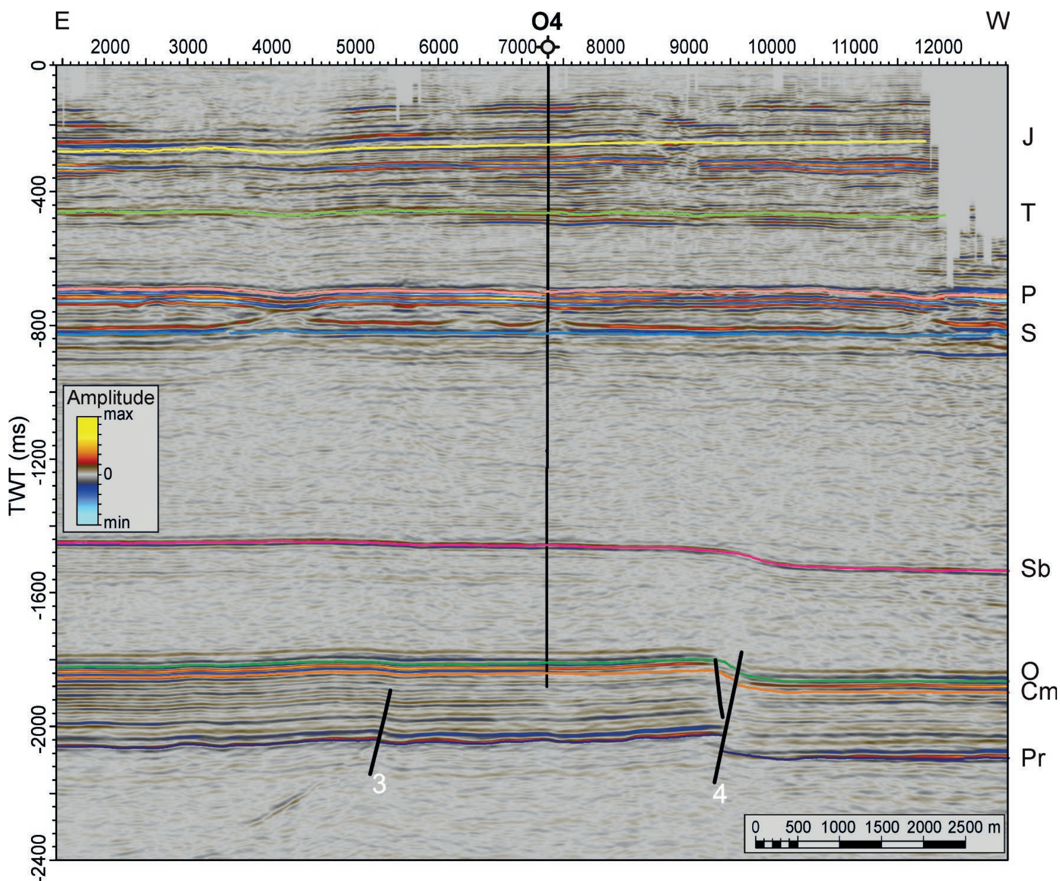

Fig. 12. Structural interpretation of 372 Xline (Opalino 3D seismic survey). 3–4 number of fault zones (Kasperska *et al.*, 2017).

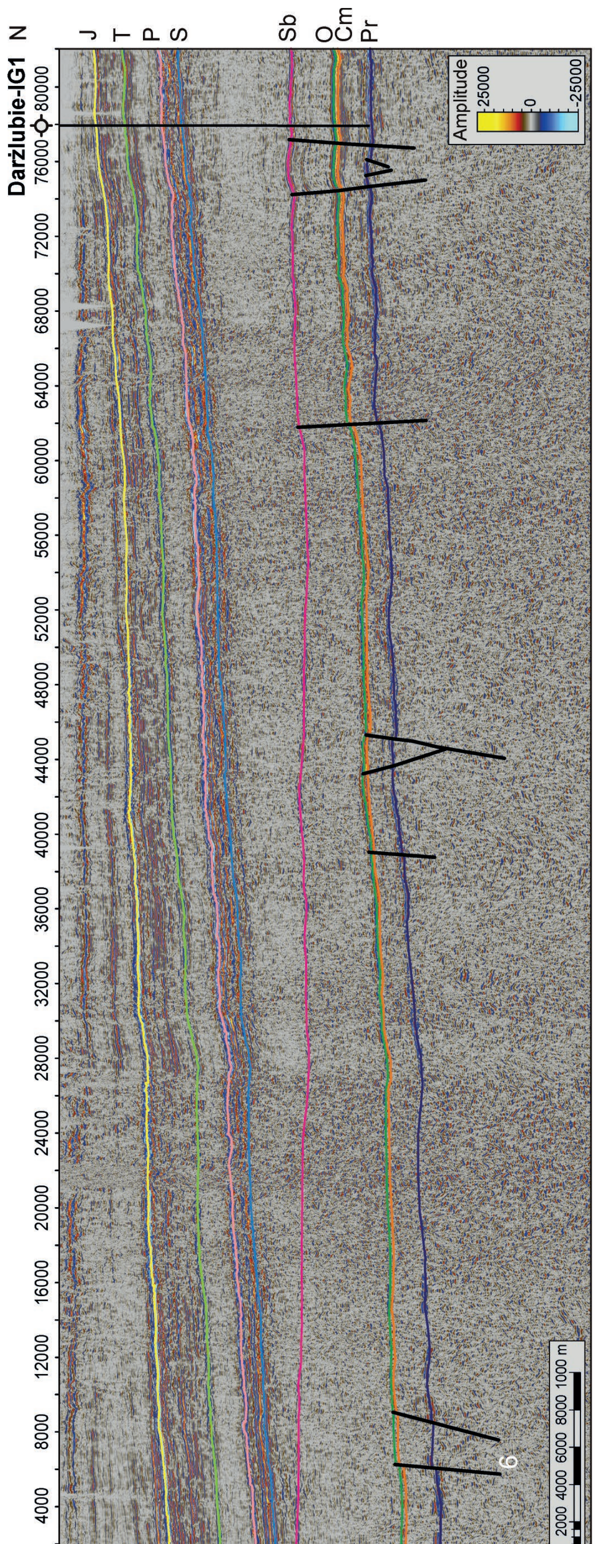

Fig. 13. Structural interpretation of K0140903 time seismic section. 6 number of fault zone (Kasperska *et al.*, 2017).

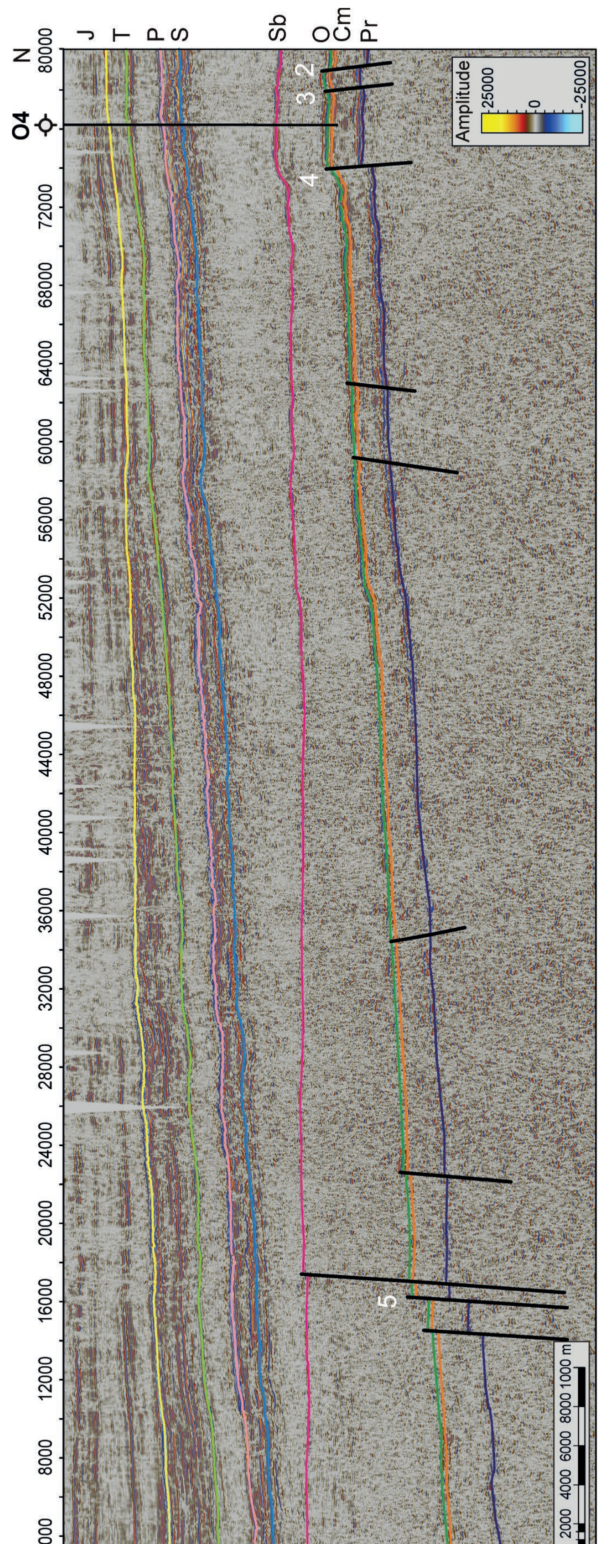

Fig. 14. Structural interpretation of K0120903 time seismic section. 2–5 number of fault zones (Kasperska *et al.*, 2017).

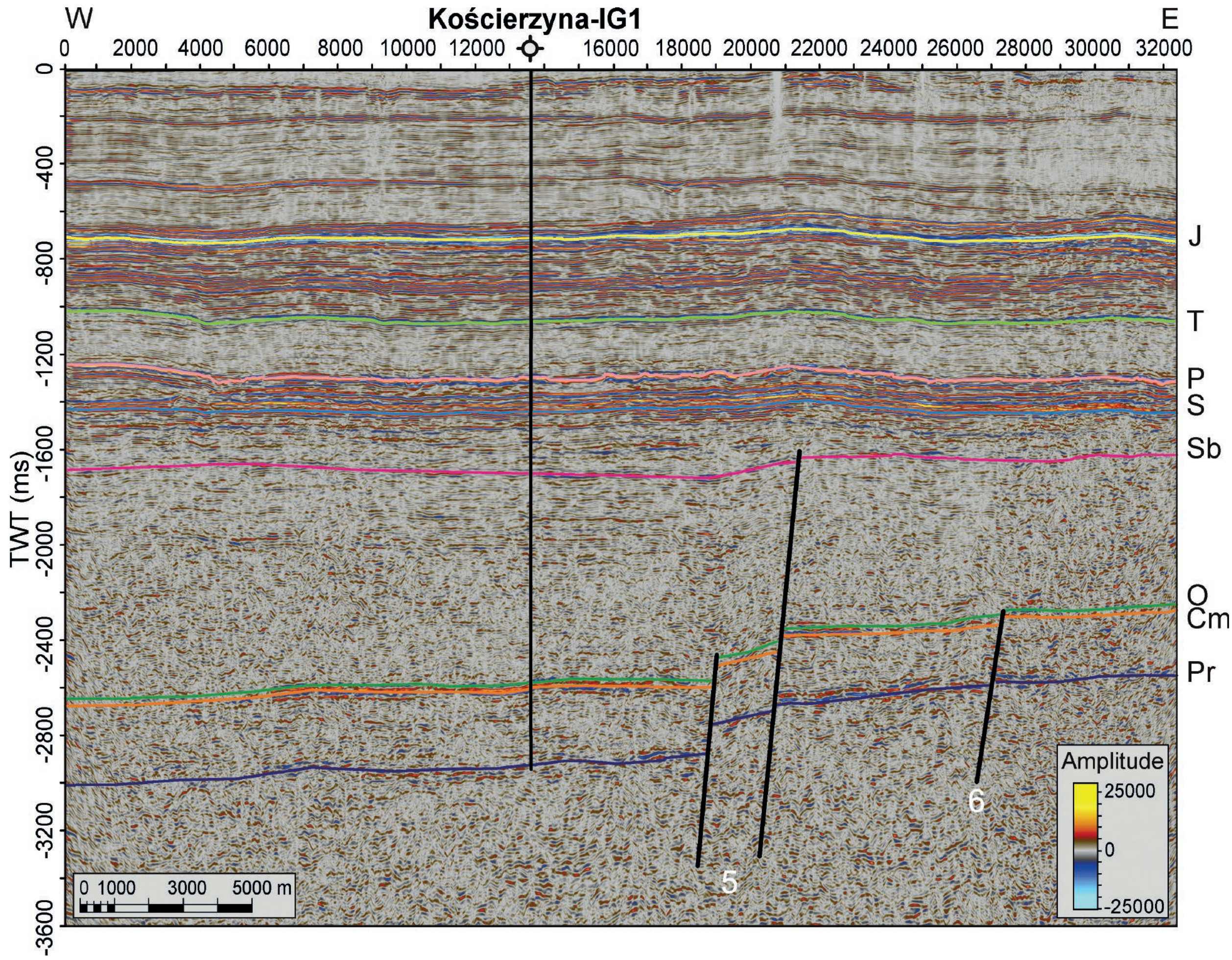

Fig. 15. Structural interpretation of K0110903 time seismic section. 5–6 number of fault zones (Kasperska *et al*., 2017).

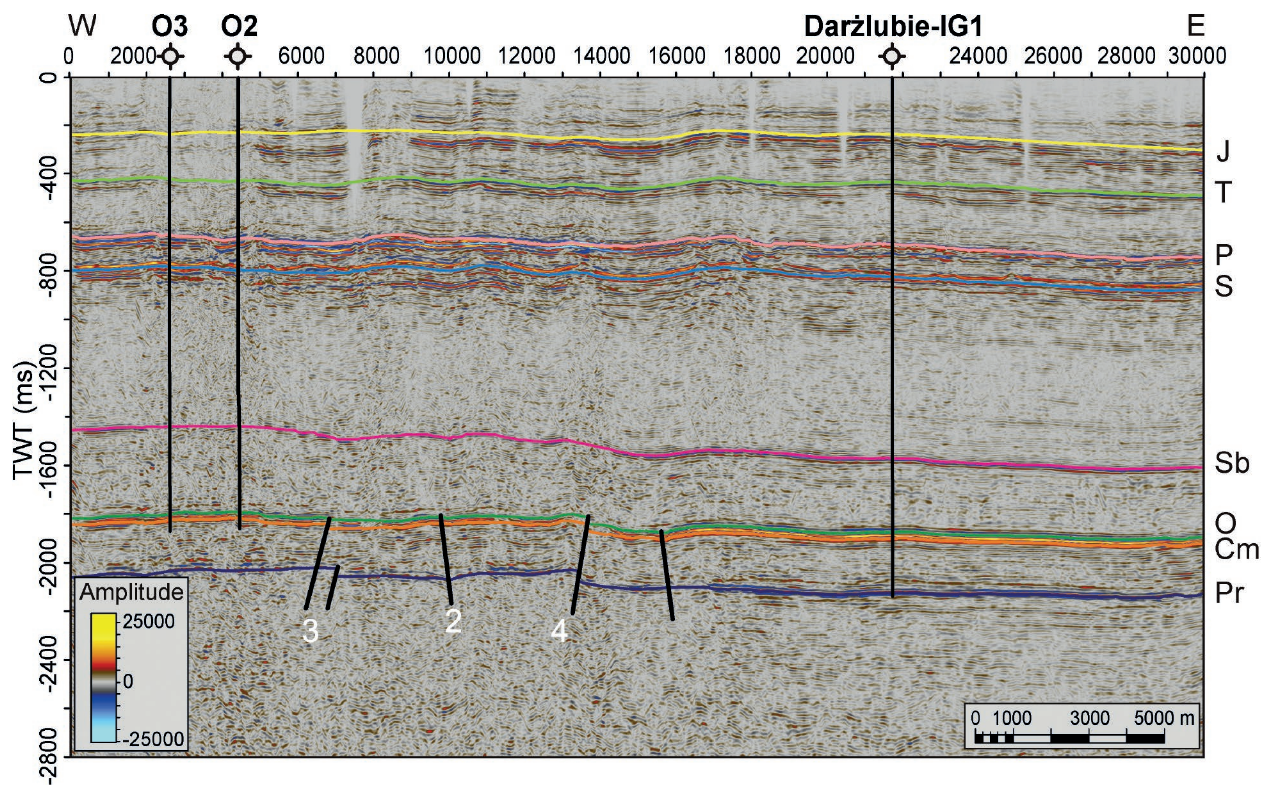

Fig. 16. Structural interpretation of K0020903 time seismic section. 2–4 number of fault zones (Kasperska *et al*., 2017).

that at that time, the fault zones separating these wells must have been created or were active. Similarly, the area around the well Bo1 showed slight signs of rising during this period. The current structural system (Fig. 4) is the result of the Upper Cretaceous inversion, the movements of which are visible more on a regional scale (the rotation and elevation of Palaeozoic structures towards the north) than on the scale of individual dislocations. Well cross-correlation creates a framework for interpretation of the faults observed on individual seismic lines. It also facilitates the subsequent interpretation of balanced cross-sections.

Seismo-geological interpretation

Geologically tied seismic data were interpreted in the time domain. To improve the interpretation of seismic sections, further datasets were considered. These include seismic sections expressed in the cosine of the instantaneous phase. They are very helpful in the correlation of seismic horizons, because they show seismic reflections in the same way: strong with large amplitudes, and weak with small amplitudes. This was particularly useful in the area covered only with a 2D survey (Fig. 9). When interpreting the dislocation zones in the Opalino 3D survey area, the Variance attribute was used (Fig.10). It is an attribute from a group of structural attributes, which are based on the similarity of neighbouring seismic traces. This attribute allowed the recognition of horizontal changes in the continuity of the amplitude of seismic reflections, which was useful when interpreting dislocation zones with very small throw, at the limit of seismic resolution. Examples of interpreted seismic profiles are shown in Figures 11–16. The horizons correlated throughout the research area were used to create structural maps of specific lithostratigraphic boundaries. For the purpose of time-depth conversion, a three-dimensional model of complex velocities was used. It is based on the average velocity logs available in the O3, O2, Ko1, Wy1, Darżblubie-IG1 and Kościerzyna-IG1 wells (Fig. 17). The northern part of the research area was developed on the basis of the interpretation of the Opalino 3D survey. Maps of selected horizons in the depth domain are shown in Figures 18, 19. In the remaining area, the maps were based on the Kościerzyna–Gdańsk 2D survey (Figs 20, 21).

In the study area, the greatest structural complexity occurs within the Lower Palaeozoic stage. The main dislocation zones occur in the Precambrian, the Cambrian and the Ordovician, partly continuing to the Silurian. Generally, it can be assumed that there are three types of fault. The first one includes the faults that intersect the top of the Precambrian and terminate in the Cambrian deposits (Figs 11, 16). The second one includes the faults that end in the Ordovician or Lower Silurian (Figs 11–16). The third one includes the faults that cut off the Cambrian and the Ordovician and continue above as a flexure (Figs 11–13, 16) or locally dislocate the level of the Reda Member (Figs 14, 15). Reverse faults are predominant in the northern part of the research area (Opalino 3D seismic survey), as shown in Figures 11 and 12. There are two general fault trends: NE–SW and NW–SE (Fig. 18). Structure no. 1 is formed by a reverse fault with a NW–SE strike (Fig. 18). The increase in the thickness of the Cambrian deposits in the hanging wall (Fig. 19D) indicates that this structure (Fig. 16) was already active in the Cambrian as a normal fault. This fault resulted from the reactivation of an older Proterozoic fault structure, traces of which can be seen on the Precambrian erosion surface in the form of a lineament (a dashed line in Fig. 18D). The probable cause of extensional movements was the breakdown of the Pannotia supercontinent and the formation of the Tornquist Sea (Golonka *et al.*, 2017). In the Ordovician and probably the very early Silurian, this structure was inactive (no differences in thickness in Fig. 19C). In the early Silurian, the structure again was activated and

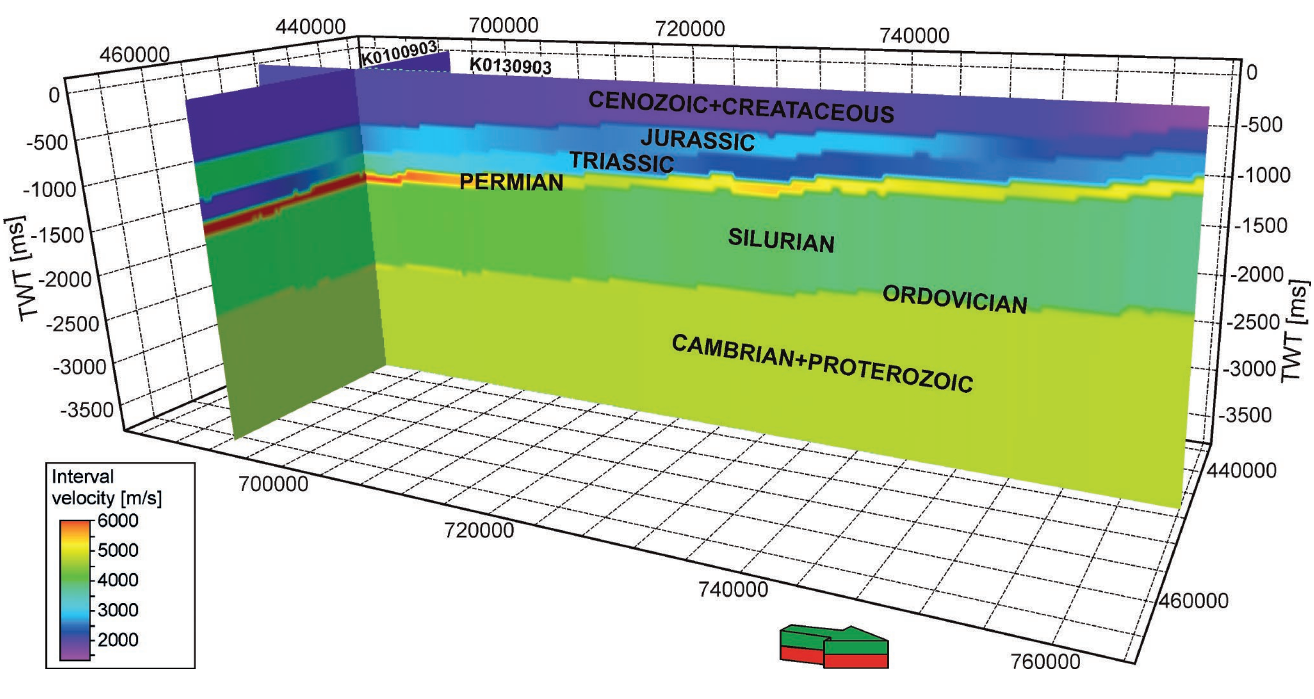

Fig. 17. Interval velocity model used for time-to-depth conversion (Kasperska *et al.*, 2017).

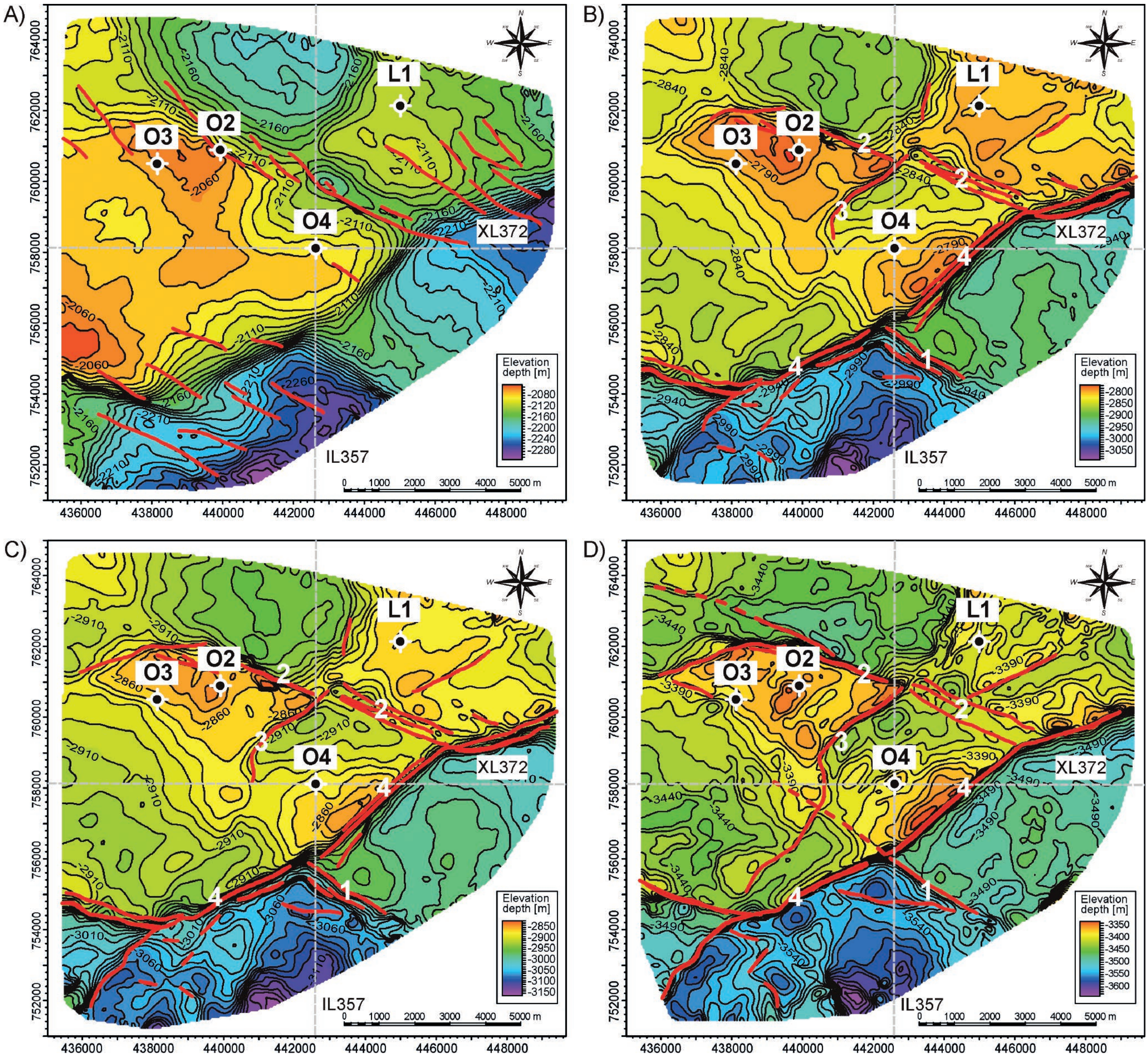

Fig. 18. Structural map of (**A**) Sb seismic horizon, (**B**) O seismic horizon, (**C**) Cm seismic horizon, (**D**) Pr seismic horizon (Opalino 3D seismic survey). Grey dashed lines – seismic section. 1–4 number of fault zones (Kasperska *et al*., 2017).

an inversion occurred. This is evidenced by the increase in the thickness on the side of the hanging wall, observed on the map of the Silurian thickness below the Reda Member (Fig. 19B). Movements leading to the intensified inversion of the structure following deposition of the Reda Member (Fig. 19A), but exact dating of them is not possible owing to the absence of the youngest Palaeozoic deposits. Perhaps the final form of the structure was created by the movements shaping the Silurian Basin in the foreland of the Caledonian Orogeny (Poprawa *et al*., 1999; Nawrocki and Poprawa, 2006).

Parallel to the previous one, fault zone no. 2 (Figs 11, 18) is composed of normal and reverse faults. It can be divided by an oblique-slip fault with a NE–SW trend (Fig. 18 – zone No. 3) into two subzones: northwest and southeast. The increase in the thickness of the Cambrian deposits on the hanging wall (Fig. 19D) indicates that similarly to the previous one, the formation of this dislocation was associated with the extensive stress field, accompanying the breakdown of Pannotia (Golonka *et al*., 2017). In the SE part, because of strike-slip movement compensation, zone no. 2 was reactivated and partly inverted already in the early Silurian (Figs 11, 19B). On the structural map of the Reda Member (Fig. 18A) along the structure No. 2, a series of almost parallel normal faults can be observed with a small throw, spherically arranged in relation to deeper dislocations. This may indicate a small, clockwise reactivation of faults which gave rise to structure no. 2 in the final stage of the Caledonian or in the Variscan tectonic cycle. Fault zone no. 2, as in the case of zone no. 1, changes towards the NW direction in a clear lineament observed on the top of the Precambrian (Fig. 19D). This observation indicates that this

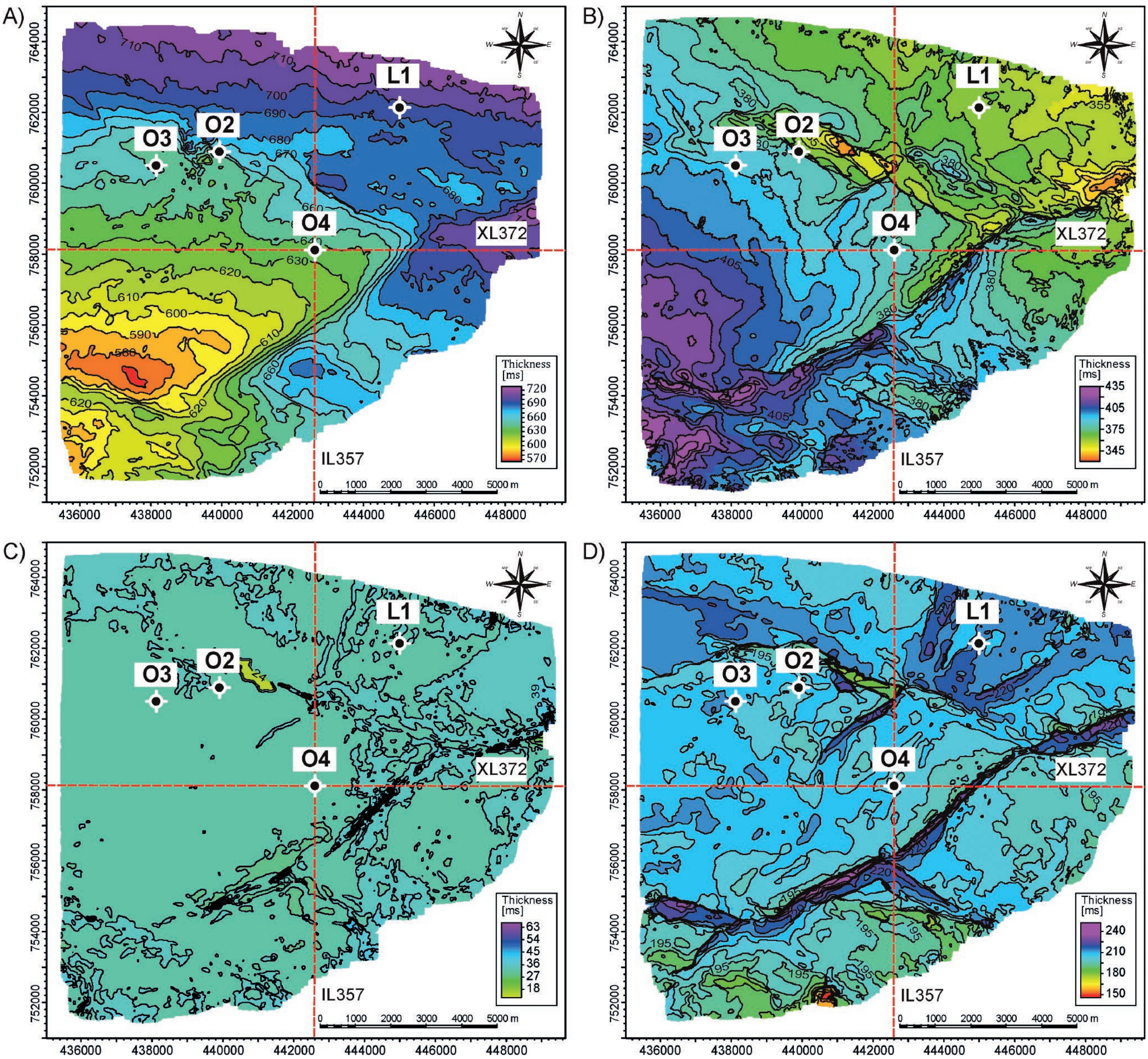

Fig. 19. Time thickness map of (**A**) Sb–Sst horizons, (**B**) O–Sb horizons, (**C**) Cm–O horizons, (**D**) Pr–Cm horizons. Red, dashed lines – seismic sections (Kasperska *et al*., 2017).

zone was created in a similar way as the previous one – by reactivating an older dislocation in the crystalline basement.

Fault zone no. 3 (Fig. 18) was formed by a reverse, strike-slip fault (Fig. 12) with a NNE–SSW strike. In the northern part, zone no. 3 dies out as a horsetail splay, characteristic of strike-slip faults (Koprianiuk, 2007). This fault originated only in the Lower Silurian as indicated by the lack of significant changes in thickness (Fig. 19D) in the Cambrian and Ordovician sediments (Fig. 19C) and the increase in thickness in the foot wall in the Silurian deposits (Fig. 19B). The fault underwent compression (Fig. 19A) in the final stage of the Caledonian or the Variscan tectonic cycle (Poprawa *et al*., 1999).

The largest fault zone is located south of the O4 well (Fig. 18 – fault zone no. 4). It consists of a reverse fault with NE–SW orientation that terminates in the Ordovician, passing upwards into the flexure (Figs 11, 12). In the southern part of the Opalino 3D survey, the orientation of this fault changes to NE–SW. The reduction in thickness in the Silurian sediments in the hanging wall below the Sb horizon (Fig. 19B) and the lack of explicit thickness changes in the Cambrian and Ordovician (Fig. 19C) indicate that this zone was created as a result of the formation of the Silurian basin in the foreland of the Caledonides (Poprawa *et al*., 1999). Flexural type reflections above the Reda Member and large thickness increments on the foot wall (Fig. 19A) show that, as with the previous structures, this zone was active in the late Silurian. Owing to the lack of younger Palaeozoic sediments, it is difficult to determine whether it was finally formed in the final phase of Caledonian or in the Variscan Orogeny. The lack of distinct deformations in the Permian–Mesozoic structural stage and the continuity

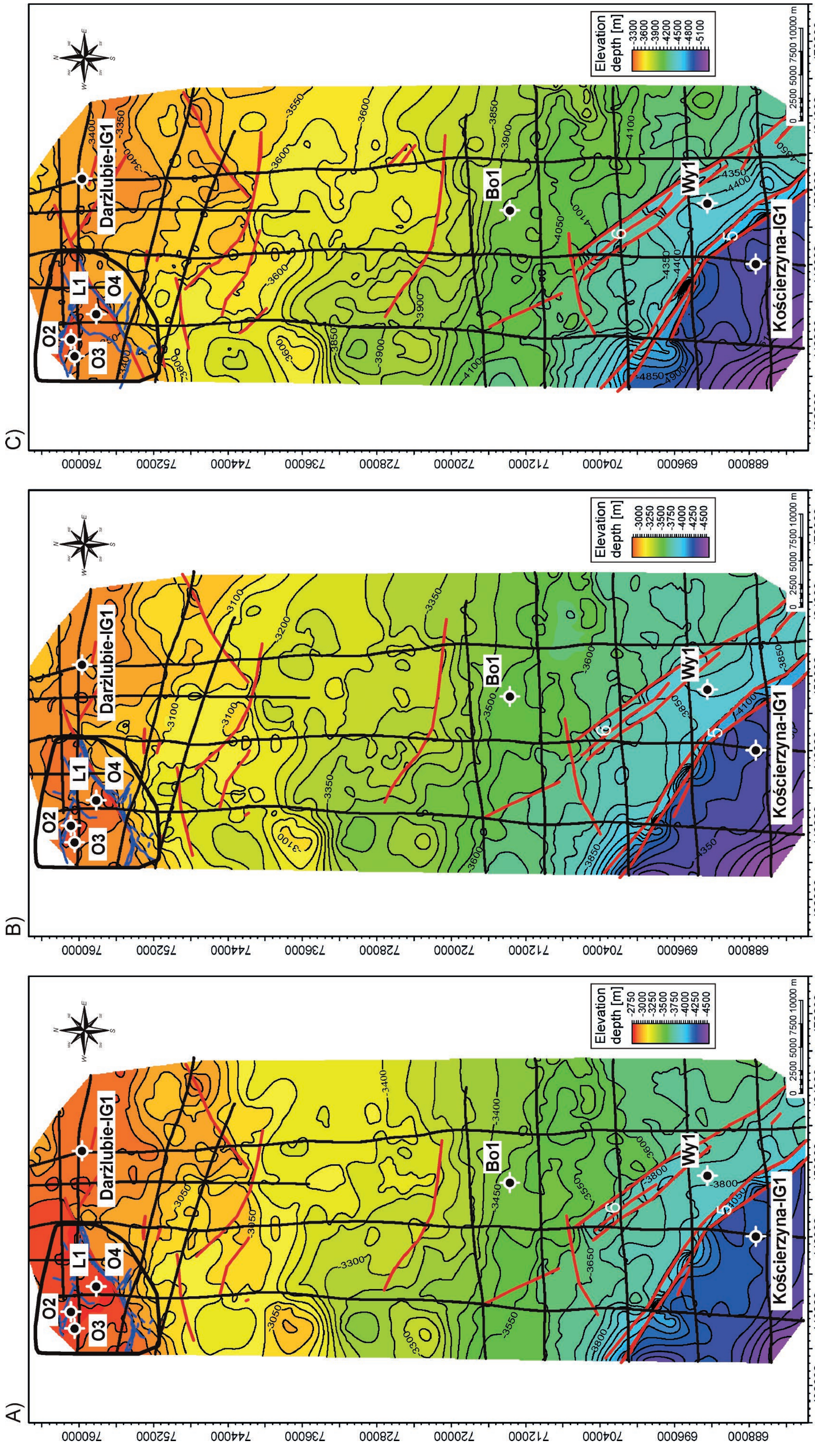

Fig. 20. Structural map of (**A**) O seismic horizon, (**B**) Cm seismic horizon, (**C**) Pr seismic horizon (Kościerzyna–Gdańsk 2D seismic survey). 5–6 number of fault zones (Kasperska *et al.*, 2017).

of the reflection at the base of the Zechstein rule out any significant activity of faults in zone no. 4, as well as previous zones, during the Alpine Orogeny. In the general structural plan, the Opalino 3D survey indicates the presence of block tectonics in this area. The previously discussed reverse fault 4 divides the whole area into two blocks: a northern elevated one and a dropped southern one. Within them, smaller blocks separated by faults can be identified (Fig. 18B, C, D). This system is most likely a small part of a large block system that continues throughout the entire 2D survey area (Fig. 19; Kisłow, 1976; Stolarczyk, 1979).

The Lower Palaeozoic faults in the southern part of the research area (Kościerzyna–Gdańsk 2D survey) are generally aligned in a NW–SE direction, and more rarely in a NNW–SSE direction (Fig. 21). The largest tectonic zone occurs northwest of the Kościerzyna IG-1 well. This borehole lies in the hanging wall (Figs 15, 20 – zone No. 5). This zone is rooted in Precambrian sediments and continues in the Lower Palaeozoic. It is formed by normal, homothetic faults with a throw of up to 400 m. It is highly likely that this zone extends beyond the area covered by seismic data. The second, a slightly smaller dislocation zone, parallel to the previous one, lies to the north of the Wy1 well (Figs 13, 20 – zone no. 6). It consists of a set of normal and reverse faults, with the same NW–SE orientation as described above, but with a much smaller throw. The quality of the seismic data does not allow any clear statement of whether both zones are connected in the crystalline basement. The increase in thickness of the Cambrian deposits in the hanging walls of both dislocations indicates that they already were active in the Cambrian (Figs 11–13). Similar changes in thickness were observed in the Silurian formations below the top of the Reda Member (Sb). Accordingly, these zones may be related to the development of the Silurian basin in the foreland of the Caledonian Orogeny (Poprawa *et al*., 1999; Nawrocki and Poprawa, 2006).

The level of the Reda Member (Sb) is inaccurate in relation to the direction of both the older and younger boundaries (Figs 13, 14). The tectonic image of this horizon is formed by normal, probably oblique-slip faults with a NW–SE trend, developed over the older deformations with a genesis similar to *en echelon* faults from the vicinity of the Opalino 3D image (Fig. 18A). Their throw is so small that with the poor vertical resolution of 2D data below the Permian, they are difficult to identify. These faults occur above or near the largest tectonic zones in the basement. This tectonic style that is different from that affecting the older deposits may indicate an episode related to the reorganization of the stress field in the Silurian and the appearance of a strike-slip component on older pre-existing faults. The thickness of the Sb–O complex varies considerably within the research area, the smallest being in its northeastern part (about 600 m), and the largest in the southwestern part (about 2100 m).

The seismic image of the zone between the horizons O and Sb and that above the Sb, up to the Silurian (S) top, does not show the details of the tectonic structure of this interval (Figs 11–16). It is composed mainly of silt-clay heterolithic deposits, susceptible to deformation, which results in failure to isolate clear seismic horizons in these intervals. The faults propagating from the crystalline basement through

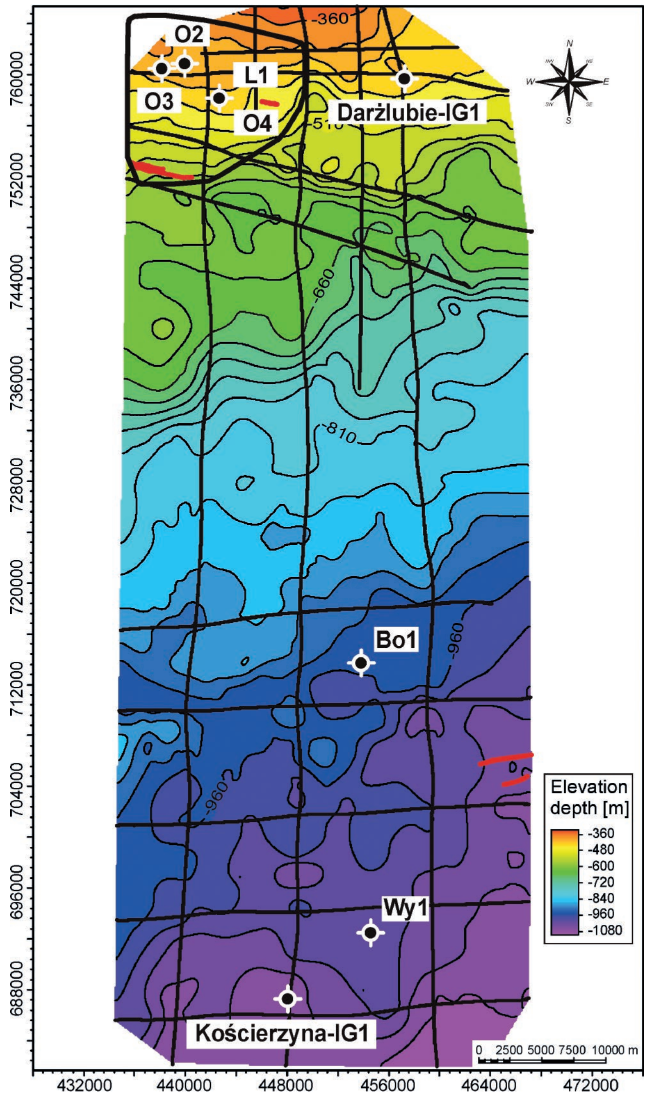

Fig. 21. Structural map of J seismic horizon, Kościerzyna–Gdańsk 2D seismic survey (Kasperska *et al*., 2017).

Lower Palaeozoic deposits in the Silurian continue or appear to continue on the seismic record in the form of flexures (Figs 11, 12, 14). This makes it difficult to date these faults.

The Permian–Mesozoic complex has a monocline structure in the whole region, dipping towards the south. As is clearly visible on the map of the top of the Jurassic (Fig. 21), the larger dislocation zones are not present here. A similar tectonic style is demonstrated by the remaining seismic boundaries of this complex. Therefore, neither the Triassic–Jurassic extension of the Mid-Polish Trough nor its Upper Cretaceous–Palaeogene inversion had a major impact on the construction of this part of the Baltic Syneclise (Witkowski, 1989).

CONCLUSIONS

The two seismic surveys Kościerzyna–Gdańsk 2D and Opalino 3D and borehole data available in the study area were tied and interpreted. The research area is in the western part of the Baltic Syneclise and although it does not cover the western boundary formed by the Teisseyre-Tornquist zone, the processes taking place along this zone had a dominant influence on the tectonic style. This is demonstrated by the fact that some of the dislocations resulting from the reactivation of old Precambrian faults have a NW–SE trend. Thus, it can be stated that in general the current shape and structure of the Baltic Syneclise and the development of the Palaeozoic sedimentary cover were significantly influenced by the structure of the pre-existing crystalline basement.

Four structural stages can be distinguished within the part of the Baltic Syneclise discussed: Precambrian, Caledonian, Permian-Mesozoic and Cenozoic. The Caledonian stage shows the greatest tectonic complexity. Most of the large Palaeozoic dislocations already had been formed in the Cambrian. They underwent reactivation and/or inversion in the Silurian, or in the final stages of the Caledonian and/or the Variscan Orogeny, at the latest.

In the general structural plan, the Opalino 3D survey indicates the occurrence of block tectonics in this area (Figs 18B–D, 19). This system is a small part of a large block system, extending also throughout the entire 2D survey area. The dislocations of the Lower Palaeozoic stage are characterized by a general NW–SE and NE–SW orientation, where the first of these seems to be dominant. The largest Late Cretaceous – Palaeogene inversion of the Mid-Polish Trough did not cause a major reorganization in the Lower Palaeozoic structural complex of this part of the Baltic Syneclise.

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