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Sub-Permian basement in the Radom-Lublin area – geological and reservoir implications based on seismic geophysical data

Introduction

The study area is situated in SE Poland at the junction of two geological structures of European importance: the East European Platform (EE) and Paleozoic Western European Platform (EC), and in the Trans-European Suture Zone (TESZ), NW-SE direction. Thanks to its unique geological position, important for the understanding of geological-structural issues not only of Poland but also of Europe, this area is of interest to numerous geologists. The results of the seismic studies carried out so far are the basis for the exploration of the subsoil in the area in question; the mentioned studies include deep refraction profiling within the international CELEBRATION program (Janik et al. 2009), the POLCRUST-01 deep

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reflection profile (Malinowski et al. 2013), profiles from the POLAND SPAN project (Mazur et al. 2017), and the analysis of regional reflection profiles (Mężyk et al. 2021).

1. Geological position and geotectonic background of the study area

The study area is located in the western, marginal part of the East European Platform (EE), in its contact zone with the West European Paleozoic Platform (WE). Its key location in relation to adjacent areas is shown in the map "Poland against the background of tectonic structures in Europe" (Nawrocki and Becker eds. 2017), the map of the basement under the Permian-Mesozoic and Cenozoic cover "Geological map of Poland without Cenozoic, Mesozoic, and Permian formations" (Nawrocki and Becker eds. 2017) and the map "Tectonic units of Poland under the Permian-Mesozoic and Cenozoic cover" (Żelaźniewicz et al. 2011).

The study area under consideration (Figure 1) is limited from the NW by the Grójec fault, from the NE by the Kock fault, from the SW by the Skrzynno fault, and from the SE by the state border (Konon 2008). In the case of the sub-Permian basement of the Polish Lowlands, it includes the Lublin Synclinorium and the Świętokrzyskie anticlinorium (Karnkowski 2008). Within the tectonic structures of SE Poland (without the Permo-Mesozoic cover), it includes: the Łuków-Hrubieszów Uplift (the elevated part of the EE platform), the Lublin

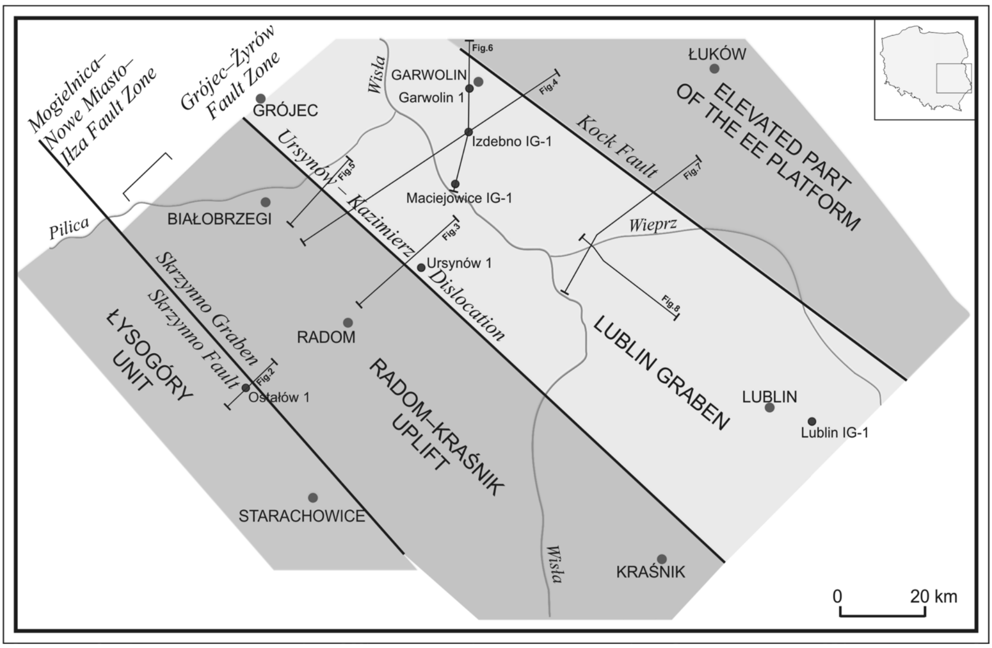

Fig. 1. Main geological structures draft of the study area

Rys. 1. Główne struktury geologiczne obszaru badań

Graben (part of the Mazowsze-Lublin Graben), the Radom-Kraśnik Horst (Radom-Kraśnik Uplift), and the Odrzywół-Ćmielów Graben (Żelaźniewicz et al. 2011). The boundaries of these units are defined by NW-SE and NE-SW dislocation zones.

Because of its location, the complex geological structure of this area is the subject of numerous discussions and analyses (Narkiewicz and Dadlez 2008; Żelaźniewicz et al. 2011; Stupnicka and Stępień-Sałek 2020). This includes the controversial thesis of the eastward shift of the boundary of the Palaeozoic platform in the SE part of Poland up to the Kock fault zone (Żelichowski 1979; Pożaryski 1990 and others). Several new tectonic solutions concerning the area under consideration adopted in the Geological Atlas of Poland (Nawrocki and Becker eds. 2017) were further justified in the article by Aleksandrowski and Mazur (Aleksandrowski and Mazur 2017), the results of seismic, gravimetric and magnetic studies of Krzywiec et al. (Krzywiec et al. 2017), the results of studies of deep refraction seismic profiles by Malinowski et al. (Malinowski et al. 2005), the results of quantitative interpretation of gravimetric and magnetic data integrated with seismic profile reflection data from the TT zone based on the POLAND SPAN survey (Mazur et al. 2017), and in studies by Mizerski and Olczak-Dusseldrop (Mizerski and Olczak-Dusseldrop 2017), Dadlez (Dadlez 2001), and Krzywiec (Krzywiec 2007).

The important publications on the exploration of the deep basement of this area include publications focusing on the interpretation of the depth of the basement of the EE craton and the TTZ zone in Poland based on data from potential reservoirs (Mikołajczak et al. 2019) or the analysis of regional reflection profiles presented by Mężyk et al. (Mężyk et al. 2021). Narkiewicz and Petecki (Narkiewicz and Petecki 2019) presented a critical review of the geophysical and geological research results concerning the course of the TTZ (Teisseyre-Tornquist Zone) structure. Magnetic anomalies and their role in the exploration of the crystalline complex of the Earth's crust in SE Poland were discussed by Grabowska et al. (Grabowska et al. 2017). It was also confirmed that the zone of positive residual anomalies parallel to the Ursynów-Kazimierz Fault, situated on its western side, may signal the presence of Caledonian orogeny folds overlying the craton (Żelichowski 1972; Pożaryski and Nawrocki 2000).

2. The degree of geological exploration

The current degree of exploration of the deep geological environment of the area under consideration is the result of many years of drilling and geological and geophysical studies, presented in numerous publications and archival studies.

The crystalline basement was drilled only in the Łuków-Hrubieszów Uplift, up to the Kock zone. The sedimentary cover of the Lublin Graben consists of four rock complexes: Old Paleozoic (Cambrian-Silurian), Young Paleozoic (Devonian-Carboniferous), Permo-Mesozoic (Permian-Cretaceous) and Cenozoic. The older Palaeozoic, with a total thickness estimated at approx. 3000 meters, lies in the sedimentation continuity on the Vendian sedimentary formations and consists of the Cambrian (?), Carbonate Ordovician, and Silurian mudstone-claystone formations. In the area of folded formations of the older Palaeozoic on the Radom-Kraśnik Uplift, the thickness of the package of layers between the top of the folded formations, including the lowest Devonian and the refraction level (consolidated basement), increases to 4–6 km (Żelichowski 1979).

The Devonian is most fully developed in the central part of the basin. The Lublin IG1 borehole, with a total thickness of about 2800 m, was drilled in the Lower Devonian; its thickness decreases towards the SE and NW (Miłaczewski 1981; Miłaczewski et al. 1983; Dziewińska and Jóźwiak 2000; Narkiewicz et al. 2011). The SW range of Carboniferous formations is limited by the Ursynów-Kazimierz fault zone and the Izbica-Zamość fault zone. The Kock structure divides the Carboniferous sedimentary basin into the NE part on the uplifted part of the EE platform and the central part – the Lublin Graben (Narkiewicz 2007; Narkiewicz et al. 2011; Waksmundzka 1998).

The tectonic-structural history of the Lublin Graben is marked by the influence of two phases – Bretonian and Asturian – which are responsible for the block-fold arrangement of anticlines (Modliński 1982; Narkiewicz 2003, 2007). The most important dislocation zones, with a NW-SE direction, are dislocations related to the Kock horst structure, separating the uplift of the EE platform from the Lublin Graben, and the Ursynów-Kazimierz dislocation zone, separating the Lublin Graben from the Radom-Kraśnik Uplift. The boundary between the latter and the Łysogóry unit is assumed to be the Skrzynno fault zone (Dadlez 2001; Dziewińska and Petecki 2004a, b; Narkiewicz 2003, 2007). The SW-NE Grójec Fault forms the NW boundary of the Radom-Kraśnik Uplift and the Lublin Graben. The Ursynów-Kazimierz Fault is interpreted as the surface equivalent of a major vertical Trans-European Fault associated with the Teisseyre-Tornquist (TTZ) zone or as the front of the Caledonian thrust fault on the Eastern European Craton. In the light of analyses, the Lublin Basin has the character of a fold and thrust belt formed during the Variscan orogeny. Towards the end of the Westphalian, the Lublin Basin underwent tectonic inversion along with the entire Variscan foreland, accompanied by the formation of SW-dipping reverse faults, most of which are rooted in the Lower Devonian formations (Krzywiec 2007).

3. Purpose and scope of the study

The aim of the study is to interpret the selected refraction and reflection seismic profiles to provide more detailed information on the geological and structural characteristics of the Palaeozoic complex in the Radom-Lublin region. In particular, it concerns changes in the thickness of individual rock formations and their degree of tectonic activity. The use of ERC methodology for this purpose was also aimed at examining the boundaries of lithostratigraphic units, which may be important for the assessment of hydrocarbon accumulation. Taking into account the results of the refraction analysis was considered important for characterizing the geological evolution of the Palaeozoic sedimentary complex, which remains in close relation to the structure and development of its older basement.

4. Research methodology

The ERC method was used to analyze the archival geophysical material, allowing amplitude recordings of the waveform to be converted into an impulse form of effective reflection coefficients (ERC). It increases the readability of seismic data, making it possible to map lithological and tectonic elements. Previous studies using this method confirm its usefulness and efficiency (Dziewińska and Józwiak 2000; Dziewińska and Petecki 2004b; Dziewińska et al. 2011; Speczik et al. 2011; Dziewińska and Tarkowski 2012; Speczik et al. 2012; Dziewińska and Tarkowski 2016a, 2016b; Dziewińska et al. 2017; Dziewińska and Tarkowski 2018; Dziewińska et al. 2020; Speczik et al. 2020). The methodological basis for the development and interpretation of ERC sections is presented in detail in, among other works, the monograph by Dziewińska and Tarkowski (Dziewińska and Tarkowski 2018).

The method of ERC interpretation used in this paper was applied for the detailed recognition of seismic complexes with different physical properties and tracking zones of thickness changes and lithological-stratigraphic pinch-out zones, as well as tectonic dislocations. Interpretation along seismic cross sections was carried out with particular attention to the arrangement of the reflections in these sediments. Under Mesozoic or Permo-Mesozoic formations, packets of reflections associated with Palaeozoic formations can be observed on ERC cross sections. In the Upper Palaeozoic, they are associated with Carboniferous-Devonian formations. Below this structural floor, the recorded series of reflected waves reflect the tectonic style of the deeper formations, and the seismic levels associated with Lower Palaeozoic formations relate to Silurian, Ordovician, and Cambrian formations.

Seismic data from reflection and refraction profiling were used. The cross sections were selected to cover, as much as possible, all four units located in the analyzed area: the Łysogóry unit, the Radom-Kraśnik Uplift, the Lublin Graben, and the Łuków-Hrubieszów Uplift.

The cross sections were constructed based on seismic data (Wojas ed. 1984) and publications by (Dziewińska and Jóźwiak 2000; Dziewińska and Petecki 2004a, b; Dziewińska et al. 2000; Bujnowski and Dziewińska 1981) and "Profiles of deep boreholes of Polish Geological Institute".

The analysis and interpretation of the geophysical survey results include several profile lines with a general NE-SW direction perpendicular to the main structural direction (18-II/III-81W, 6-V-88K, 1-V-87K, 16-IV-83T, 4-I-95T/185-IV-94T) and one (45-IV-86T) with a NW-SE direction. Two of these (6-V-88K, 16-IV-83T) were routed along the regional refraction profile 1-X/VI-63/71.

The primary research data used to process and interpret the results of the seismic reflection studies presented in this article are from part of the works of PGNiG by Geofizyka Kraków in 1987–1988 (Figures 5 and 3) and by Geofizyka Toruń in 1983 (Figure 6), 1986 (Figure 8), 1994/1995 (Figure 7). These works, which are part of the semi-detailed profile grid, aimed to recognize the area's geological structure to determine the prospects of searching for hydrocarbon deposits. Regional seismic surveys conducted by the PBG Geophysical Exploration Ltd., commissioned by the Polish Geological Institute, are represented by a reflection profile from 1991 (Figure 2) and a refraction profile from 1963/1971 reinterpreted in 1984 (Figure 4).

5. Analysis of key tectonic elements

5.1. Skrzynno fault zone

The results of the analysis of the Ostałów 1 and Ostałów PIG2 boreholes, presented on seismic profile (18-II/III-81W) using the ERC method (Figure 2) are of great importance for the exploration of the contact area between the Radom-Kraśnik Uplift, the Łysogóra unit and on the sub-Zechstein formations. The ERC section presents the complicated nature of the folded Palaeozoic rocks deposited in the area. Boundary sections correlated with drilling were assigned to Carboniferous, Devonian, and Silurian formations.

Based on the series associated with the C-D and deeper boundaries determined using effective reflection coefficients, a regional fault was identified to the NE of the Ostałów 1 borehole, deeply rooted in the sub-Permian and Lower Palaeozoic basements, with an

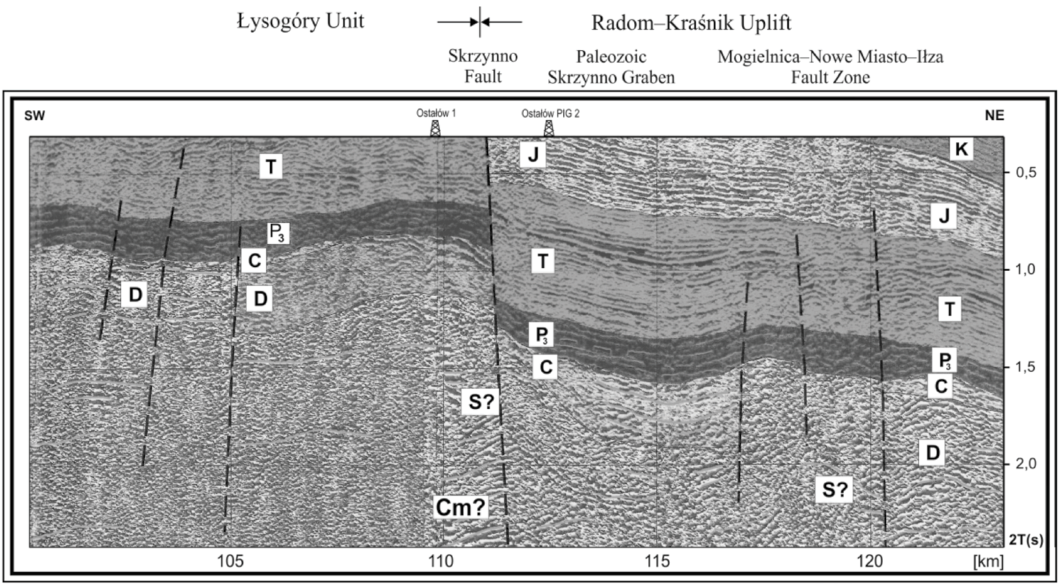

Fig. 2. Interpretation of the seismic section in the ERC method – the Ostałów area
K – Cretaceous, J – Jurassic, T – Triassic, P2 – Upper Permian, C – Carboniferous, D – Devonian, S – Silurian, Cm – Cambrian

Rys. 2. Interpretacja przekroju sejsmicznego w wersji EWO – rejon Ostałów
K – kreda, J – jura, T – trias, P2 – górny perm, C – karbon, D – dewon, S – sylur, Cm – kambr

amplitude of about 1000 m, previously referred to as the Skrzynno Fault by Kowalczewski (Kowalczewski 1998, 2002). This fault divides the presented section into two parts: NE with a deep Zechstein floor and SW where the Zechstein basement is much shallower. In the SW direction, the different seismic image may indicate that this part of the line is located in an area with a different geological structure. In the elevated zone (Ostałów 1 borehole), Zechstein lies directly on the Devonian, and in the lowered area (Ostałów PIG2 borehole), on the Upper Carboniferous series. The structural arrangement of the Permo-Mesozoic, with little deformation, is different from that of the Late Paleozoic. The greatest deformations of Palaeozoic rocks occur in the area of the Skrzynno dislocation and directly NE of it. On the SW side of the fault, under Lower Devonian rocks drilled in the Ostałów 1 borehole, an elevated element composed of Silurian and Cambrian formations can be expected. It is also possible to suggest the presence of, for example, diabases in the discussed zone of intrusions of magmatic volcanic rocks into Palaeozoic sediments with rock densities higher than those of the surroundings, which could be related to areas of deep tectonic fractures. This is evidenced by the complex image of the internal geological structure mapped in a characteristic dome-shaped pattern of seismic reflection coefficients.

In the area lowered to the NE of the Skrzynno dislocation, attention is drawn to the systematic subsidence of seismic horizons in the case of Jurassic to Carboniferous and deeper formations. The synclinal structure recorded here, flanked from the NE by a complex fault zone, forms a Palaeozoic Graben consistently named in this work as the Skrzynno Graben (Odrzywół-Ćmielów trench in Żelaźniewicz et al. 2011). The arrangement of reflections in the NE part of the cross section indicates the possible presence of an elevated element, probably Silurian formations.

5.2. Ursynów-Kazimierz Fault

The nature of contact of the Radom-Kraśnik Uplift with the Lublin Graben is revealed by the interpretation of seismic results (6-V-88K) on the Białobrzegi-Magnuszew section in the Lisów-Ursynów area (Figure 3). The ERC seismic data confirm the complex nature of the basement below the Carboniferous formations. The information obtained by transforming wave seismic sections into ERC indicates a rock series with elevated reflection values associated with sand or limestone layers, facilitating the interpretation of Carboniferous, Devonian, and Silurian formations. The cross section (Figure 3) shows tectonic discontinuities dividing the area into individual blocks.

Four boundaries were delineated on the refraction cross section (1-X/VI-63/71) in the Lublin Graben (Figure 4). With regard to the two deepest boundaries with Vg >6 km/s, the deeper reaches a depth of 12 km and the shallower reaches a depth of more than 10 km. The third boundary from the bottom with Vg 5.8–6.2 km/s, has a maximum depth of 9 km and rises gently towards SW and NE. The shallowest boundary, with Vg oscillating between 4.9 and 5.5 km/s, occurs at depths of about 3 km and follows almost the entire length

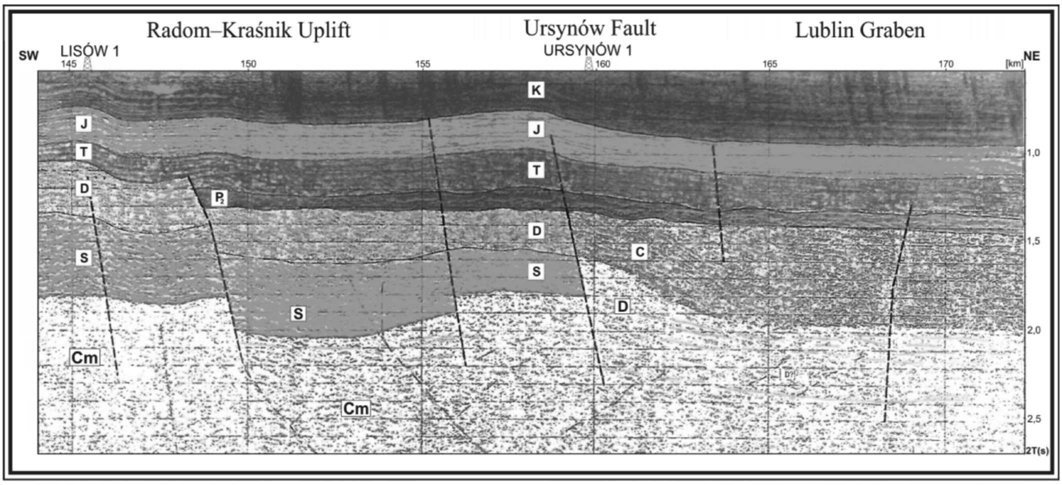

Fig. 3. Interpretation of the seismic section in the ERC method – Lisów–Ursynów–Magnuszew area (based on Dziewińska and Tarkowski 2018 with changes); explanations as in Figure 2

Rys. 3. Interpretacja przekroju sejsmicznego w wersji EWO – obszar Lisów–Ursynów–Magnuszew

of the presented section. In the area of the Lublin Graben, the two deepest boundaries, in comparison with other cross sections (because we do not have direct benchmarks), may be connected with formations of the consolidated basement, respectively older and younger ones. Regarding the third boundary from the bottom, it can be assumed that it is related to the Lower Silurian or the carbonate floor of the Cambrian formations. The shallowest boundary, penetrated by several deep boreholes (Magnuszew IG1, Maciejowice IG1, Izdebno IG1), correlating with carbonate complexes of Lower Carboniferous and Upper Devonian age, is the most related boundary. It is associated with a complex of formations tracked on the basis of the reflection cross section and generally following the reflection boundaries.

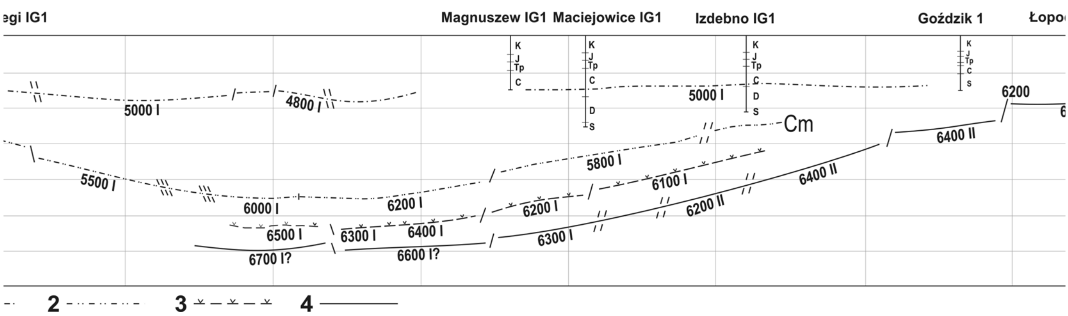

Fig. 4. Interpretation of the refractive seismic study results in the Białobrzegi–Goździk section (1–X/VI–63/71); 1 – boundary traced within the Palaeozoic; 2 – boundary associated with the Cambrian; 3 – boundary associated with younger ground; 4 – boundary associated with older ground

Rys. 4. Interpretacja wyników refrakcyjnych badań sejsmicznych na odcinku Białobrzegi–Goździk (1–X/VI–63/71)

The remaining boundaries do not follow this pattern. In the area of the Radom-Kraśnik Uplift, the picture of the cross section changes radically. Two deeper boundaries (the area of the Lisów structure) related to the consolidated basement are no longer traceable. However, the boundary in the Lublin Graben, related to the Cambrian (S/Cm), passes consistently into the area of the Radom-Kraśnik Uplift, forming an elevation in the Białobrzegi area. The seismic horizon associated with the Cambrian formations, after reaching the culmination at the location of the Białobrzegi IG1 drilling site, drops significantly to W, to about 6 km, with a simultaneous increase in Vg to the value of 6.2 km/s. This information is important because in the SW direction, we do not have borehole data for Sub-Silurian seismic reflection horizons.

Additional information concerning the Ursynów fault zone is presented by the seismic cross section (ERC version, 1-V-87K), (Figure 5) located along the Pilica River on the line approx. Białobrzegi IG1-Warka IG1, to the NE of the presented one. The obtained results indicate the extension of the fault zone, very clearly marked in the area of the Ursynów 1 borehole towards the NW to the Warka area. The dip of the pinch-out zones of the Carboniferous deposits on the SW edge of the Lublin Graben is smoother compared to the Ursynów area (Figure 3). In this part of the area, due to the lack of a direct geological benchmark, the form of contact between the SW part of the Lublin Trough and the Radom-Kraśnik Uplift is less clear. In the Białobrzegi area, within the range of the fault zone (continuation of the Mogielnica-Iłża zone), an elevated element, probably connected with Silurian formations, is clearly visible.

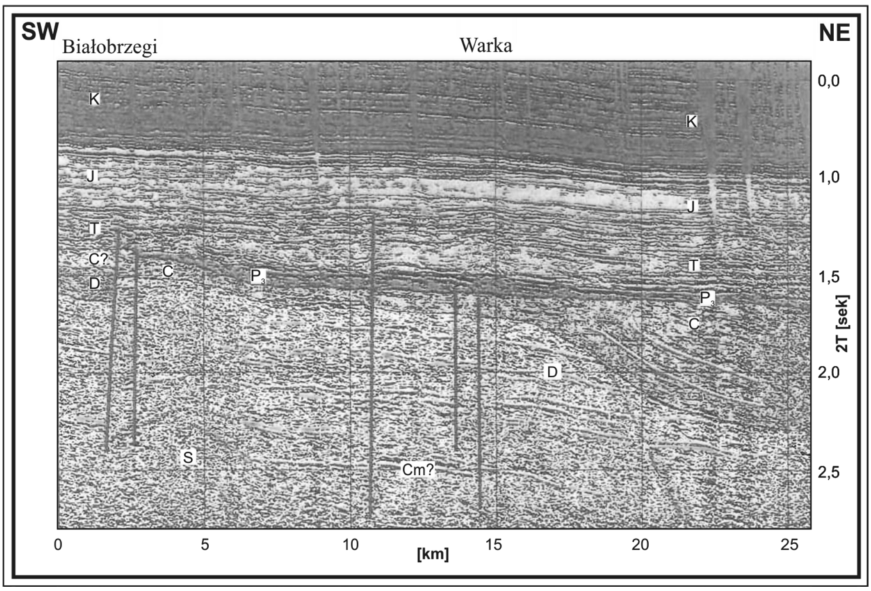

Fig. 5. Interpretation of the seismic section in the ERC method – Ursynów zone (Warka region) (based on Dziewińska and Petecki 2004 with changes); explanations as in Figure 2

Rys. 5. Interpretacja przekroju sejsmicznego w wersji EWO – strefa Ursynów (rejon Warki)

The attached ESC seismic cross sections (Figures 3 and 5) show a complex picture of the Ursynów-Kazimierz fault zone. Here, you can observe the overlapping of two reflected waves. The pinching out Carboniferous reflections are cutting through the horizons. This may prove that the direction of the pinching out of Carboniferous formations is not perpendicular to the main direction of the Ursynów-Kazimierz tectonic zone.

5.3. Kock fault zone

The Kock fault zone was characterized on the example of two profiles (16-IV-83T and 4-I-95T/185-IV-94T). Promo-Mesozoic floors were mapped on the sections; Carboniferous, Devonian, Silurian, and Cambrian complexes were mapped in the basement. The cross section presented in Figure 6 shows the interpretation of the results of the seismic reflection surveys (ERC method) conducted in the Maciejowice-Izdebno-Garwolin region. The Maciejowice IG1, Izdebno IG1 and Garwolin 1 deep boreholes located on the profiles facilitate the interpretation of the formations, including the sub-Permian formations. The roof of the Silurian strata, examined using the Izdebno IG1 and Maciejowice IG1 boreholes, is overlain with the Lower Devonian formations with a thickness of up to 1000 m.

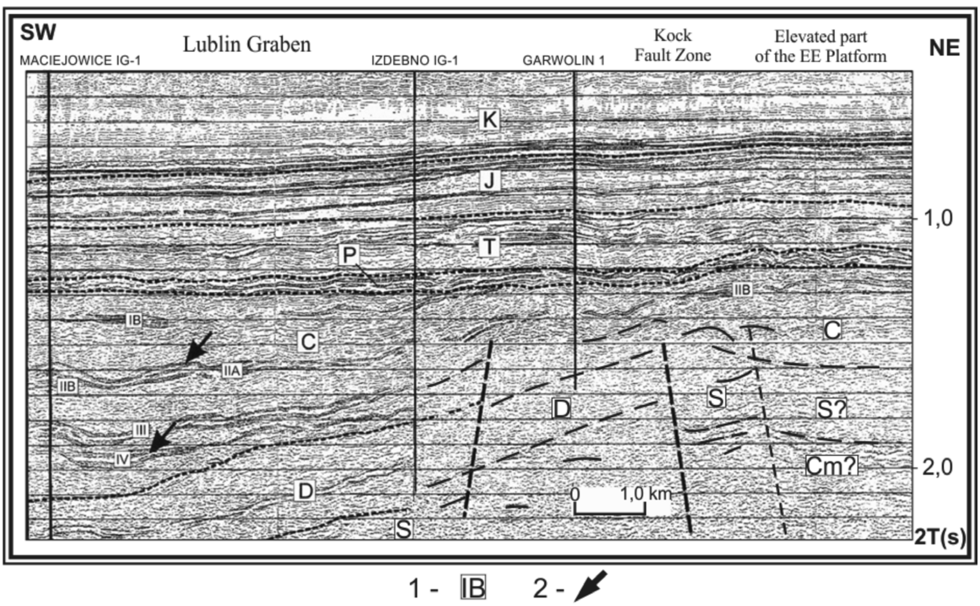

Fig. 6. Interpretation of the seismic section in the ERC method – Maciejowice–Izdebno–Garwolin zone (based on Dziewińska and Tarkowski 2018 with changes)
1 – markings of sandstone horizons (Dziewińska and Jóźwiak 2000); 2 – mid-layer pinch-outs of Carboniferous sandstones, potential hydrocarbon traps; other explanations as in Figure 2

Rys. 6. Interpretacja przekroju sejsmicznego w wersji EWO – strefa Maciejowice–Izdebno–Garwolin

The high resolution of the ERC section enabled a more complete use of the features of the seismic record and thus increased the efficiency of lithological interpretation. Numerous lithological series of Mesozoic, Zechstein, Carbon, and Devonian formations and related tectonic zones are presented along the cross section. Well-recognized sediments of the Permo-Mesozoic formation with relatively small thicknesses (approx. 2 km) lie almost horizontally on the surface of the Younger Paleozoic. The ERC section yielded significant information regarding the boundaries of the Carboniferous and Devonian sediments that dip towards the SW. Towards the NE, a gradual reduction in the thickness of the Carboniferous sediments, locally pinching out, can be observed.

Within the older Paleozoic section, there are several lithological complexes, distinguished by different values of reflection coefficients. The boundaries between Devonian, Silurian, and Cambrian were marked. Particular attention is paid to the interpretation of results obtained in the NE part of the section, in the area of the Kock fault zone. To the east of the Izdebno IG1 borehole, newly recognized tectonic zones are observed in the older Palaeozoic formations. A highly disturbed ERC image can be observed corresponding to Permian formations which form an elevated fold. It is located above a fault rooted in deeper Palaeozoic formations. The reflection coefficients capture the complex nature of this disturbed tectonic zone and accurately locate the pinch out points of the various Carboniferous horizons.

The second seismic section (4-I-95T/185-IV-94T) developed using the ERC methodology (Figure 7) covers the Dęblin swell area and the Kock structure. A series of sandstone layers are marked on the cross section. The Carboniferous boundaries, starting from the Dęblin

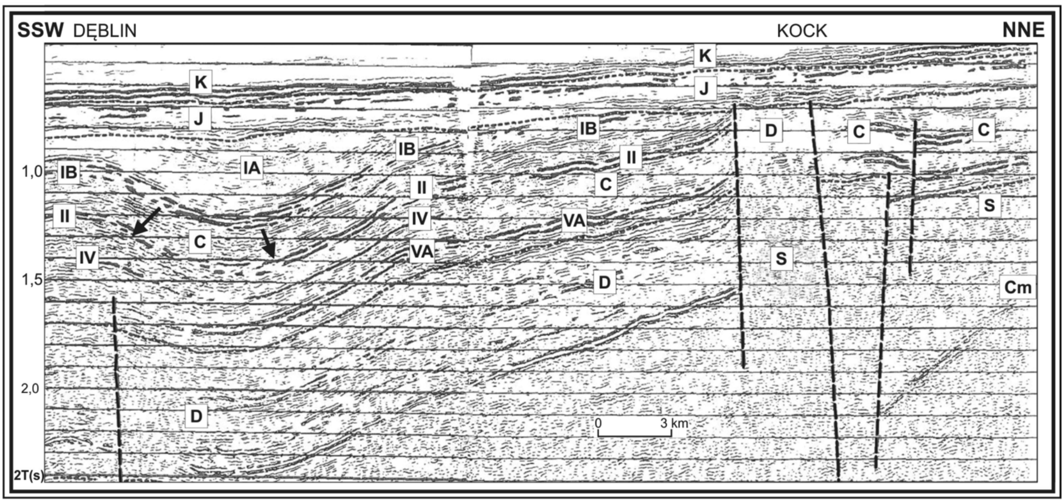

Fig. 7. Interpretation of the seismic section in the ERC method – Central part of Lublin Graben (based on Dziewińska and Tarkowski 2018 with changes)
1 – markings of sandstone horizons (Dziewińska and Jóźwiak 2000); 2 – mid-layer pinch-outs of Carboniferous sandstones, potential hydrocarbon traps; other explanations as in Figure 2

Rys. 7. Interpretacja przekroju sejsmicznego w wersji EWO – centralna część rowu lubelskiego

Uplift, dip in the NE direction and then rise in the same direction up to the area of the Kock structure forming a very extensive basin. The profile line crosses the Kock dislocation zone, which consists of several steep dislocations occurring in older Palaeozoic formations, reaching the sub-Mesozoic basement. The pinching out of Carboniferous formations can be observed. Jurassic formations are deposited directly above the Devonian formations. The thickness of the Upper Carboniferous is visibly decreasing in the direction of its uplift (i.e. towards the NE) until it completely pinches out in the Kock zone. The ERC section illustrates the successive pinching out of individual sandstone horizons. Seismic boundaries associated with Devonian formations occur to the SW of the Kock structure. The thicknesses of the Devonian formations decrease systematically from SW to NE. Of the Devonian horizons, the most continuous and dynamic are the reflective boundaries associated with the Middle and Lower Devonian formations, which generally show a position consistent with the Carboniferous boundaries. Beyond the Kock structure, the Carboniferous boundary becomes shallower, rising gently towards the NE. The reflection coefficients attributed to the Silurian works were correlated directly below the Carboniferous reflections. These are the oldest sediments to have been explored by drilling. On the NE wing of the Kock structure, the prominent Palaeozoic complex probably corresponds to the Cambrian roof assemblages. The arrangement of the boundary correlated with the Cambrian reflects a characteristic, inconsistent alignment with the higher-lying strata.

6. Use of the ERC methodology to identify the presence of hydrocarbons in the Devonian and Carboniferous formations

The Lublin region is prospective for hydrocarbon accumulations. Exploration works in this region have been performed since 1956. Oil and natural gas were found in Carboniferous, Devonian, and Cambrian formations, within the following structural sequences: Łęczna–Kock–Żelechów, Minkowice–Świdnik–Dęblin–Abramów, Trawniki–Wilczopole––Zemborzyce, Komarów–Rachanie–Bełżyce–Kazimierz, Opole Lubelskie–Pionki–Zwoleń (Kaczyński 1984; Karnkowski 1988; Karnkowski and Górecki ed. 1999; Karnkowski 2003; Kaczyński 2005). As a result of prospecting works, oil fields and methane-rich natural gas reservoirs were discovered: the Świdnik oil field (lithology – sandy Upper Carboniferous formations, depths of 900–960 m), the Komarów natural gas reservoir (sandy-carbonate formations of the Middle Devonian, 2080–2190 m), the Minkowice natural gas reservoir (sandy Upper Carboniferous formations), the Ciecierzyn natural gas reservoir (carbonate formations of the Upper Devonian, 3840 m), and the Mełgiew natural gas reservoir (similarly, 3600 m). Some of these deposits have already been depleted. The concentration of prospecting works in this area took place in the NW part of the Lublin Graben, where the profile of Carboniferous formations is the most complete. It is represented by the clay-mud complex with limestone (Visean) and the clay-mudstone series with sandstone interbeds (Namurian, Westphalian), where sandy horizons are often characterized by good reservoir properties. Traces of oil and natural gas were also found in the Famennian carbonate formations and the Lower Devonian (Old Red) sand horizons (Karnkowski and Górecki ed. 1999; PSG 2021).

In hydrocarbon exploration, recognition of the deep geological structure of an area (identification of deep structures, tectonics, depositional systems, depositional architecture, the evolution of sedimentary complex and other factors) is of fundamental importance. The results of the following works are important in the context of the exploration of the geological structure of the studied area (Dadlez 2001; Karnkowski 2003; Krzywiec 2007; Mazur et al. 2010), Narkiewicz 2003, 2007, 2011a, b; Narkiewicz et al. 2011; Waksmundzka 1998).

In the context of hydrocarbon exploration, the results of ERC methodology, allowing the obtaining of seismic images with increased recording resolution, may also be important for the recognition of changes in the lithology of the Carboniferous and Devonian formations of the Lublin Trough. Based on the results of previous studies by Dziewińska and Jóźwiak (Dziewińska and Jóźwiak 2000) and Dziewińska and Tarkowski (Dziewińska and Tarkowski 2018) it can be concluded that the main reservoir horizons in the Carboniferous complex are associated with sandstone horizons in the Namurian and Lower Westphalian. The mid-layer pinch-out zones within the Carboniferous sandstones, or areas indicative of zones of increased limestone thickness within the Devonian, are of particular interest as potential lithological traps. The value of the deep heat flux can be seen as an additional hint (Szewczyk and Gientka 2009). These data, together with information from drilling, provide the basis for determining changes in thickness between reflections, which is important for interpretation in terms of searching for lithological traps and structural traps. The comparison with the structural image made it possible to conclude that these zones are mostly associated with anticline limbs.

The interpretation of the seismic section using ERC, presented in two figures (Figures 6 and 7), for the Maciejowice-Izdebno-Garwolin zone (Figure 6) and the central part of the Lublin Graben-Dęblin region and Kock structure, is an example of tracking thin layers of Carboniferous-Devonian sediments. The results of reflection seismic studies (ERC) in the area of the Dęblin and Abramów structures (the central part of the Lublin Graben) are shown in Figure 8.

The entire Carboniferous and Devonian complexes have a good record. Based on the cross section, it can be observed that Triassic, Permian, and Westphalian sandstones are pinching out towards the post-Jurassic section, going from NW to SE. Consequently, the Carboniferous is covered by flat-lying Jurassic formations. The best quality results were obtained in the area of the Abramów and Dęblin boreholes. The seismic section in this area indicates the reduction of sandstones of successive Carboniferous formations. Along the whole profile, the D3 horizon, in the roof part of a high-velocity limestone formation with Frasnian dolomites, is very dynamic. The upper boundary of the limestone series is particularly pronounced when covered with marly Famennian deposits. The bottom layers of the Upper Devonian and the top of the D2 sediments are also clearly visible. Towards the NW, a reduction in the thickness of the D3 formations and the pinching out of the D2 formations

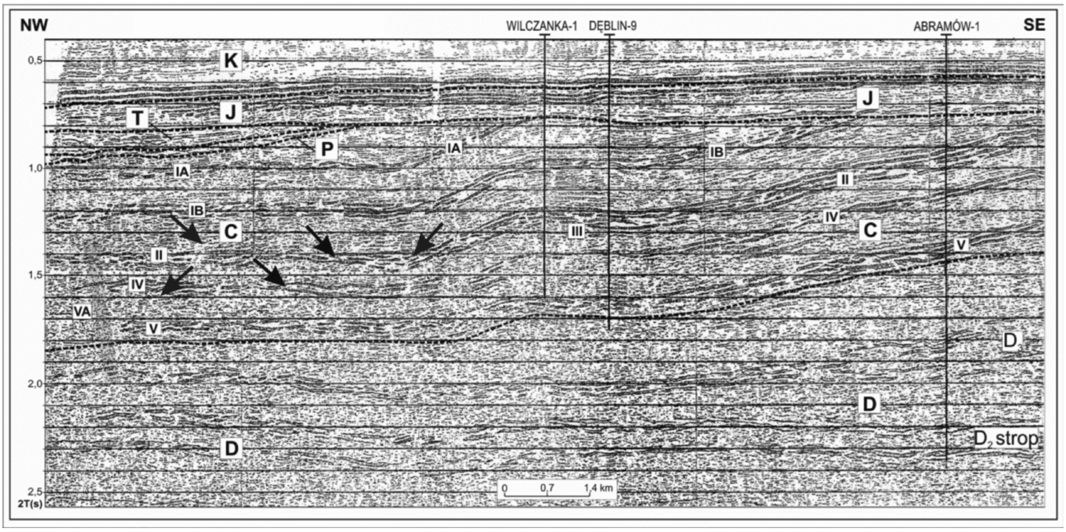

Fig. 8. Interpretation of the seismic section in the ERC method – the region of the Dęblin and Abramów structures (the central part of the Lublin Graben); in the NW part, the region near the Stężyca deposit (based on Dziewińska and Tarkowski 2018 with changes and additions); explanations as in Figures 2 and 6

Rys. 8. Interpretacja przekroju sejsmicznego w wersji EWO – rejon struktur Dęblin i Abramów (centralna część Grabenu Lubelskiego); w części NW rejon w pobliżu złoża Stężyca

can be observed. Below the Devonian, one can trace the reflection coefficients attributed to the Ordovician.

7. Discussion and summary

In the article, special attention is paid to the zones important for determining the course of the boundaries between the main structural units (Figure 1) of the Radom-Kraśnica Uplift, the Łysogóra region and the Lublin Graben. The Skrzynno Fault, associated with the location of the edge of the EE platform, the zone of occurrence of the Paleozoic Skrzynno Graben, the Nowe Miasto-Mogielnica-Iłża fault zone, Ursynów-Kazimierz fault zone, and the Kock Fault are shown.

The Skrzynno Dislocation (Figure 2) is a fault with an amplitude of up to 1000 m, the NE hanging wall dips very steeply in that direction. The results indicate that it is deeply rooted, related to older Palaeozoic and crystalline strata. It cannot be ruled out that the main fracture plane is accompanied by tectonic discontinuities with different inclinations of the fault planes.

The Skrzynno fault and the accompanying set of structures on the NE side (i.e. the Skrzynno Graben, flanked on the NE side by the Nowe Miasto-Mogielnica-Iłża fault zone) are located within the assumed refraction boundary of horizons of different nature (Skorupa 1974) and the zone of a large magnetic horizontal gradient associated with a step in the crystalline basement (lower slope) (Nawrocki and Becker eds. 2017). According to the geological concept confirmed by the results of geophysical surveys, the above-mentioned structural elements in the surface image have a direction close to NW SE and run in the SE direction in the Iłża-Starachowice belt and the NW direction through the area to the east from Skrzynno to the Nowe Miasto-Mogielnica-Szwejki area.

The results of the interpretation of the ERC section in the area of the Skrzynno Fault became the basis for the tectonic development study of this regional dislocation zone conducted by Kowalczewski (Kowalczewski 2002). The quoted author states that the narrow and long Skrzynno fault zone may have formed in the continental suture zone along which the EE and EC platforms converge. A similar SW position of the edge of the crystalline basement has been indicated by various scholars, for example, Pożaryski (Pożaryski 1997), Grabowska and Bojdys (Grabowska and Bojdys 2001), and by electromagnetic data (Semenow et al. 1998).

The Skrzynno fault line determines the SW waveform of the EE platform edge. The aforementioned set of structures associated with this edge illustrates the accompanying belt of later tectonic structures. They form a peripheral transition zone. To some extent, this explains the discrepancies in the location of the EE platform edge presented in the works of various researchers (eg., Narkiewicz 2007).

It is assumed that the Ursynów-Kazimierz fault zone limits the SW extent of Carboniferous formations of the Lublin Graben. The present work highlights some new elements within the Radom-Kraśnik Uplift that may suggest a local larger extent of the Carboniferous towards the SW. These are interpreted as presumed synclines, filled with Carboniferous formations, of low thickness, respectively: at a certain distance to the SW from the Lisów borehole 1 (Figure 3) and to the NE from the Białobrzegi IG1 borehole (Figure 5).

It is not only the SW extent of the Carboniferous sediments but also the nature of their pinching out that is discussed. According to the available publications, they are usually different from the traditional "graben" model (Żelichowski 1979) and are associated with changes in the tectonic setting of the Devonian-Carboniferous Lublin Basin (e.g., Antonowicz et al. 2003; Narkiewicz 2003; Krzywiec 2007). The information presented in the article, based on interpretation work, contributes to the discussion on the geological and tectonic model of the Lublin area as a graben and/or thrust system. The steep tectonic dipping observed in the seismic reflection cross sections (Figures 3 and 5) at the pinch-out line of the Carboniferous formations in the SW direction indicate the share of faults in the development of this area. The obtained results enable marking the dislocations emphasizing the contact with the Devonian rocks of the Radom-Kraśnik Uplift. The data obtained by interpretation of geomagnetic sounding measurements (Semenov et al. 1998) and seismic refraction data (Figure 4) confirm the deep roots and disjunctive character of the boundary between the Radom-Kraśnik uplift and the Lublin Graben. The interpretation of the POLCRUST PL1–5100 deep reflection seismic profile shows a deeply rooted dislocation interpreted as the Ursynów fault (Narkiewicz and Petecki 2019). The above correlations enable the determination of the dislocation sequence in the NW-SE surface area from Ursynów to Warka (Figure 5), and even their further continuation towards the Grójec Fault (Dziewińska and Petecki 2004a, b).

The NE boundary of the Lublin Graben is the Kock dislocation zone (Figure 1). The complex nature of the tectonically disturbed structure of Kock is reflected in the ERC sections presented in Figures 6 and 7. The mapping of thin geological layers made it possible to track the pinch-out zones of individual Carboniferous and Devonian horizons and seismic levels attributed to Silurian and Cambrian formations. The designated tectonic zones in the older Paleozoic formations confirm the hypothesis of the occurrence of the Kock thrust fault rooted in Silurian shales located above the Kock Fault (Kijewska 2018). The results of the interpretation of the refractive boundary (Figure 4) suggest that the Kock dislocation zone is located above a step in the deep crystalline basement. This fact and a similar course of zones – the large horizontal magnetic gradient (upper slope) and strong horizontal gravity gradients on the map of Bouguer's gravimetric anomalies (Nawrocki and Becker eds. 2017) – enable us to locate the NE border of the Lublin Graben in the Garwolin-Lubartów-Tomaszów Lubelski belt.

The verification of discontinuity boundaries, their character and geometry presented in this paper required a detailed analysis of higher resolution reflection seismic materials, which was achieved by applying the EWO method in interpretation. Another example is the complex arrangement of the Ursynów-Kazimierz fault zone mapped on the ERC sections (Figures 3 and 5) in the form of superposed reflected waves. The interpretation may indicate the involvement of strike-slip movements during the evolution of this formation. Such examples include a seismic image of Silurian uplifts in ERC sections (Figures 2 and 5). The method was also used to delineate pinch-out zones of Carboniferous sandstones (Figures 6–8), which is very important for the exploration of potential hydrocarbon traps.

It should be noted that the two types of boundaries distinguished using refraction waves (Figure 4) related to the different degrees of consolidation of the basement (the older and the younger) constitute the material for discussion on the type of rocks occurring at certain depths in a given area. The zones of simultaneous recording of strong seismic contrasts for two types of waves are worth noting.

Conclusions

The use of EWO methodology in the interpretation of seismic reflection materials enabled the tracing of the boundaries of lithostratigraphic separations in Carboniferous, Devonian, and older formations. This made it possible to define in detail the course of boundaries between the main units of this area, in the area of the Skrzynno Fault, the Ursynów-Kazimierz tectonic zone, and the Kock fault.

The interpretation of the refraction of seismic materials made it possible to delineate two boundaries connected with formations of the older and younger Palaeozoic which contributed new information on the geological structure of the Palaeozoic complex of the Radom-Lublin area and its relations with the tectonics of the basement.

The ability to map thin geological layers with the use of the ERC method made it is possible to track the pinch-out zones of Carboniferous and Devonian horizons, which may be of great importance in the context of prospecting and exploration of hydrocarbon deposits.

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SUB-PERMIAN BASEMENT IN THE RADOM-LUBLIN AREA – GEOLOGICAL AND RESERVOIR IMPLICATIONS BASED ON SEISMIC GEOPHYSICAL DATA

Keywords

Radom-Lublin area, subsoil, geology, effective reflection coefficients (ERC), hydrocarbon reservoirs, seismic

Abstract

This paper presents the results of an analysis of selected seismic profiles (reflection and refraction data) from the Radom-Lublin area aimed at obtaining a better understanding of geological structure and the identification of hydrocarbon deposits. To accurately reproduce the seismic reflection covering the sub-Permian formations, seismic cross sections were interpreted based on effective reflection coefficients (ERC). In interpreting the results, reference was made to the results of studies of the area using other geophysical methods.

The results of these studies made it possible to obtain new information on the geology and structure of the Paleozoic complex of the Radom-Lublin area and its relationships with the basement tectonics. The structural arrangement of Carboniferous and Devonian formations as well as older Silurian, Ordovician, and Cambrian series were recognized. Selected significant tectonic and lithological discontinuities and the nature and directions of their course were characterized. Special attention was given to regional tectonic zones: the Skrzynno Fault, the Ursynów-Kazimierz fault zone and the Kock zone. The use of ERC methodology made it possible to define the boundaries of lithostratigraphic units in Carboniferous, Devonian, and older formations. The obtained results can be used to assess hydrocarbon accumulation in the area under consideration.

PODPERMSKIE PODŁOŻE NA OBSZARZE RADOMSKO-LUBELSKIM – IMPLIKACJE GEOLOGICZNE I ZŁOŻOWE NA PODSTAWIE SEJSMICZNYCH MATERIAŁÓW GEOFIZYCZNYCH

Słowa kluczowe

geologia, złoża węglowodorów, obszar radomsko-lubelski, EWO, sejsmika

Streszczenie

Artykuł prezentuje wyniki analizy wybranych profili sejsmicznych (refleksyjnych i refrakcyjnych) z obszaru radomsko-lubelskiego w celu uszczegółowienia budowy geologicznej oraz rozpoznania występowania złóż węglowodorów. W celu precyzyjnego odwzorowania danych sejsmicznych refleksyjnych obejmujących utwory podpermskie wykorzystano interpretację przekrojów sejsmicznych w wersji efektywnych współczynników odbicia EWO. W interpretacji wyników odwołano się do rezultatów badań tego obszaru z wykorzystaniem innych metod geofizycznych.

Wyniki badań pozwoliły na uzyskanie nowych informacji o budowie geologiczno-strukturalnej kompleksu paleozoicznego obszaru radomsko-lubelskiego i jego związkach z tektoniką podłoża. Rozpoznano układ strukturalny utworów karbonu i dewonu oraz starszych serii syluru, ordowiku i kambru. Scharakteryzowano wybrane, istotne nieciągłości tektoniczne i litologiczne oraz charakter i kierunki ich przebiegu. Szczególną uwagę poświęcono regionalnym strefom tektonicznym: uskok Skrzynna, strefa uskokowa Ursynów–Kazimierz oraz strefa Kocka. Wykorzystanie metodyki EWO pozwoliło na prześledzenie granic wydzieleń litostratygraficznych w utworach karbonu i dewonu oraz starszych, a uzyskane wyniki mogą być pomocne dla oceny akumulacji węglowodorów na rozważanym obszarze.