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Reinterpretation of geophysical surveys of pre-Permian basement in SW Poland: structural evolution and its implications for prospecting Cu and other ores

Introduction

The study presents the results of research on the application of geophysical investigations to provide more details on the geological structure of the sub-Permian basement in SW Poland and more accurate geological model of Permian sediment-hosted Cu deposits within the area bounded from the south by the Middle Odra Fault and from the north by the Dolsk Fault (Fig. 1). The Sub-Permian basement, covered with a thick complex of Permian – Mesozoic rocks, is relatively poorly explored by only few boreholes that reached its top surface. Therefore, the results of geophysical surveys (the study area is transected by several geophysical

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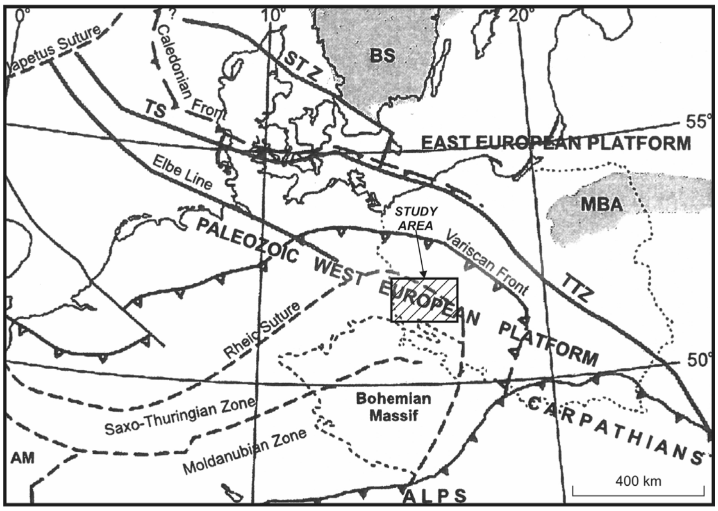

Fig. 1. Tectonic sketch showing location of the study area in a broader Central European context (based on Narkiewicz and Petecki 2017 with modification)
AM – Armorican Massif, BS – Baltic Shield, MBA – Mazury-Belarus Anteclise, STZ – Soregenfrei-Tornquist Zone, TS – Thor Suture, TTZ – Teisseyre-Tornquist Zone

Rys. 1. Szkic tektoniczny ukazujący lokalizację badanego obszaru w szerszym kontekście środkowoeuropejskim

profiles important for studying deep subsurface of Central Europe) are an interesting material for consideration (Fig. 2). Geophysical profiles, acquired over the past several decades using modern software, were reprocessed. The basic goal of this study was to analyze and interpret published and archival results of gravimetric, magnetic, seismic and magnetotelluric surveys to propose a new geological interpretation and correlation of structural elements of the sub-Permian basement. For seismic data reinterpretations, the use method of effective reflection coefficients (ERC) is proposed. The discussion and conclusions present new, important results and encourage to focus further works on a comprehensive reinterpretation of geophysical and geological materials.

1. Geological background

The research area is located in SW Poland built of sub-Permian rocks covered with an early Paleozoic unit being overlain by Permo-Mesozoic strata (Fore-Sudetic Monocline) (Żelaźniewicz and Aleksandrowski 2008). Its southern boundary is delineated by the Odra Fault located between the Fore-Sudetic Block (composed of crystalline rocks) and the South Wielkopolska Block. Its northern boundary is represented by the Dolsk Fault. The immediate basement of the study area is composed of folded Carboniferous sediments and

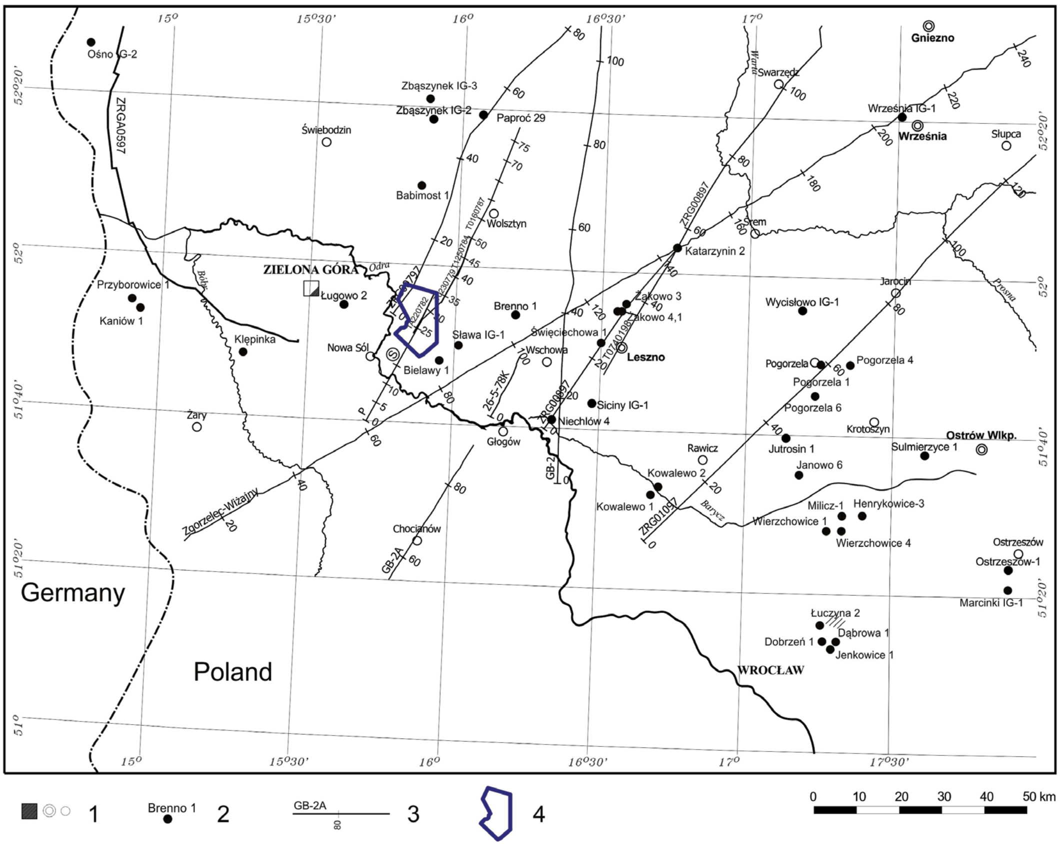

Fig. 2. Map of selected geophysical data and boreholes
1 – towns and others localities, 2 – selected deep boreholes, 3 – selected geophysical profiles,
4 – Nowa Sól Cu-Ag deposit boundaries

Rys. 2. Mapa wybranych profili geofizycznych i otworów wiertniczych

meta-sediments. They represent part of the Polish, WNW-ESE-trending Variscan Internides/Externides (with their range limits being subject to different interpretations), which can be correlated with sedimentary and metamorphic rocks from Eastern Germany (Górecka-Nowak 2008; Mazur et al. 2006, 2010a; Żelaźniewicz et al. 2003; Żelaźniewicz ed. 2011). The geological units shown in Figure 3 – the Wolsztyn–Pogorzela High, Bielawy–Trzebnica High, Poznań Basin and Lower Silesian Basin – represent deep structures that form the sub-Permian basement (Kiersnowski et al. 2010; Żelaźniewicz ed. 2011).

According to the tectonic regionalization of Poland, the study area should be considered as an eastern extension of the German Variscian Externides: the Rheno-Hercynian and Saxo-Thuringian zones, as well as the Mid-German Crystalline Rise (MGCR) (see: DEKORP RESEARCH GROUP 1994; Żelaźniewicz et al. 1997). The problem of the geological-

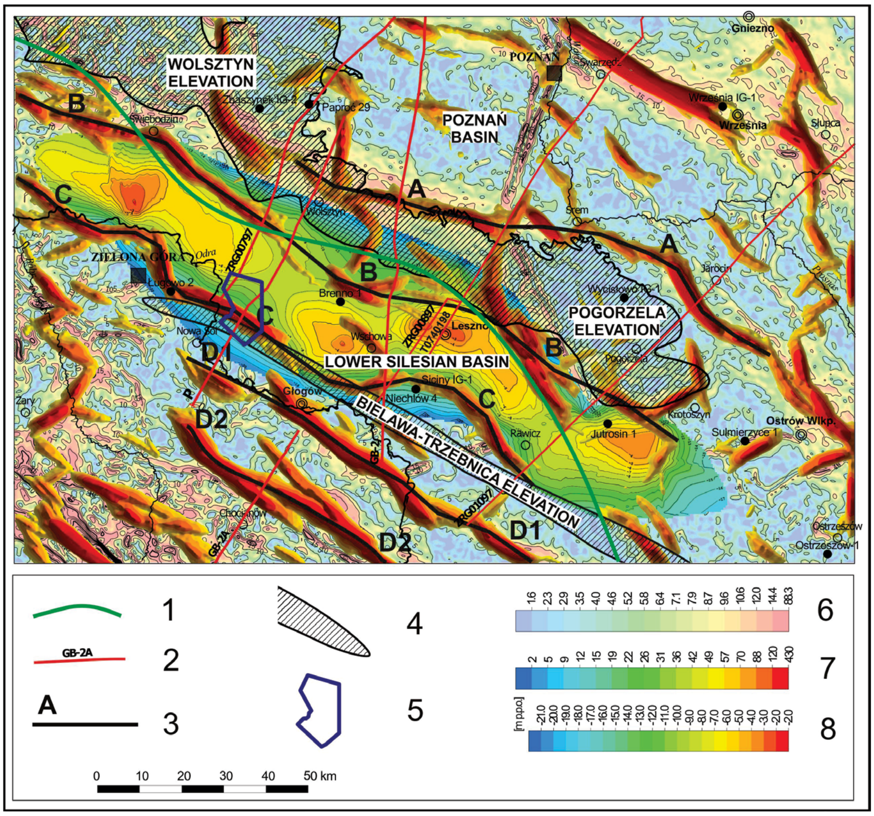

Fig. 3. Interpretative gravimetric map of deep sub-Permian basement with a density of observation points of approximately 3.5 pts/km^2

1 – Słubice–Leszno magnetic lineament, 2 – selected seismic profiles, 3 – major tectonic zones based on gravity lineaments, 4 – draft of major geological structures, 5 – Nowa Sól Cu-Ag deposit boundaries, 6 – horizontal gradient map, 7 – map of density of gravity lineaments, 8 – extent and depth of Bouguer anomalies (vide also Figs. 5 and 8).

Rys. 3. Interpretacyjna mapa grawimetryczna głębokiego podłoża podpermskiego o gęstości punktów obserwacyjnych około 3,5 pkt/km^2

-tectonic structure of Paleozoic and older formations in Central Europe were the subject of numerous studies (e.g. Aleksandrowski 1995; Dallmeyer et al. 1995; DEKORP RESEARCH GROUP 1994; Franke 2000; Franke et al. 1993; Geisler et al. 2008; Katzung 2001; Kroner et al. 2008; Lokhorst ed. 1997; Mazur et al. 2010 b; Żelaźniewicz ed. 2011).

In the study area, geological information about lower structural levels of the sub-Permian basement in the Fore-Sudetic Monocline are fragmentary. For example, deeper portions of the South Wielkopolska Block were intersected by very deep boreholes only within its elevated parts (these elements should be considered as horsts in terms of their tectonic characteristic): the Wolsztyn High and Bielawy–Trzebnica High.

The abovementioned structures are represented by strongly folded phyllites subcropping at the surface of the sub-Permian basement. The early Visean age of metamorphism determined in the phyllites indicates that these rocks are part of the Variscan orogen (Żelaźniewicz et al. 2003; Żelaźniewicz ed. 2011). These rocks represent the upper parts of tectonically elevated horsts that form a large mega-slice or a tectonic overthrust upon non-metamorphic Lower Carboniferous deposits, as suggested by Kiersnowski et al. (Kiersnowski et al. 2010). Those authors suggest that the phyllites (in analogy to the German Northern Phyllite Zone) might cover the eastward extension of the Mid-German Crystalline Rise, stretching to the western border of Poland. This zone is distinguished and well documented in the German section of the Variscides (Northern and Southern German Phyllite Zone, see: DEKORP RESEARCH GROUP 1994).

The presented concepts on the occurrence of the geological units identified in Germany are subject to divergent interpretations in Poland (e.g. Grad and Polkowski 2016; Malinowski et al. 2013; Mizerski and Olczak-Dusseldrop 2019; Kiersnowski et al. 2010; Żelaźniewicz et al. 1997; Cwojdziński et al. 1995). It should be noted that the correlation of described structural elements between Poland and Germany (where they are well known) is crucial for geological exploration in the Fore-Sudetic Monocline. Indeed, just like in Germany, it would be possible to discover new deposits of metal ores, rare earth elements and hydrocarbons also in SW Poland. Speczik (Speczik 1985) showed relations between the tectonic elements and the possibility of the occurrence of polymetallic deposits and hydrocarbon accumulations, and pointed to the role of tectonic movements and related magma intrusions and hydrothermal processes as the factors important in the formation of mineral deposits in this area. The tectonic deformation zones might be linked to the hydrocarbon migration paths, zones of circulation of metasomatic solutions, and thus areas of metals precipitation. The fault zones, identified by deep seismic surveys, can be considered as conduits for convecting heat necessary for mineralization processes. The location of discovered Cu deposits and prospective areas in Poland (Speczik et al. 2011, 2012; Zieliński and Speczik 2017) and in Germany (e.g. Hartsch 2015; Kucha and Bil 2017) point a research direction which is in line with that presented in this study.

Currently, the knowledge concerning structural elements in the Paleozoic basement of the study area is not satisfactory, although there is a number of boreholes and seismic profiles available to study. The limited depth range and the ineffectiveness of the previously used interpretation methods are the main reasons for the lack of sufficient information about the geological structure of the immediate basement of Zechstein rocks, within which most of the boreholes ended. The Fore-Sudetic Monocline is intersected to the base of the Zechstein by numerous oil and gas boreholes. Some drill holes reached the Rotliegend and Carboniferous formations, and only several drilled into the older Paleozoic. The geological characteristics of sub-Permian formations in the entire area of the Fore-Sudetic Monocline, including identification of the major structural elements and the outlines of main tectonic lines, are presented in Wierzchowska-Kicułowowa (Wierzchowska-Kicułowowa 1984, 1987). This picture, which is in line with the state of knowledge from decades ago, requires geophysical verification based on new materials and more sophisticated research tools. A few more recent studies provide interpretations of the geological structure without bringing new significant geological materials in the form of drill cores. The main goal of this paper is to present reprocessing of archival geophysical data: gravimetric, magnetic, seismic and magnetotelluric, and propose new geological and structural interpretation of sub-Permian basement with regard to origin of Permian sediment-hosted Cu and other metal deposits in Poland.

2. Method and data

The research objective required both the reinterpretation of data acquired using chosen geophysical methods and an integrated analysis of obtained results. The presented article includes the research results of previously published studies (Dziewińska and Tarkowski 2018). Unpublished data was sourced from archived documentations and reports regarding the results of seismic and magnetotelluric geophysical surveys (National Geological Archive, PGI NRI Warsaw).

The study area is covered by a homogeneous semi-detailed gravity survey, the density of observation points is approximately 3.5 pts/km^2. The homogeneous grid of gravity observation points is a very important source of geological information, especially in the places where no data from seismic surveys is available. To amplify the anomalies, which originate from the sedimentary complex related to Paleozoic rocks, the method of digital processing of gravity anomalies was applied (Dziewińska et al. 2017). The development of various gravimetric transformations enabled to visualize major components of the deep geological structure to create maps of residual anomalies and maps depicting the directions and trends of tectonic and/or lithological discontinuities. The discontinuity zones associated with lateral rock density contrasts have been identified based on the analysis of lateral gradient maxima of gravity anomalies.

The study area is covered with a semi-detailed magnetic survey of 1–4 points/km^2. The sources of gravity and magnetic anomalies are indicated on the geophysical picture, emphasizing correlation that can be obtained between these two methods. This shows new possibilities that might result from the implementation of appropriate gravity and magnetic data transformation to determine the location of regional and local tectonic zones important for prospecting mineral deposits.

A detailed seismic survey, conducted by the Geofizyka Toruń and Geofizyka Kraków companies in the study area using the 2D method, is illustrated by a dense network of profiles of highly variable quality and spaced at 1–2 km. The work carried out by the PBG Geophysical Exploration Company was focused on regional issues. Reflection seismic studies were conducted by oil&gas industry companies to identify the geological setting of horizons prospective for hydrocarbon resources. These studies resulted in rather limited information considering the depth of the boreholes and the scope of the ore geology analysis. The analyses carried out during this study were focused on the visualization of the geological structures based on the results of reflection seismic surveys with the possibility of their verification in the light of the current state of knowledge. The interpretation of the results was directed at identifying regional and local tectonic zones and blocks in the variscan basement, indicated by anomalies of potential (gravity, magnetic and magnetotelluric) fields. The selection of seismic profiles with a recording time exceeding into the depths beneath the Rotliegend strata was made to identify structural elements and lithological changes in the Paleozoic basement. The location of seismic profiles being the subject of more detailed interpretation is shown in Figure 2. These are: a compilation of seismic sections selected from individual seismic survey reports along the Nowa Sól–Ciosaniec–Wilcze–Wolsztyn line, marked with the letter S, and depth-converted composite reflection seismic sections: ZRGA0597, ZRG00797, ZRG00897 and ZRG01097.

To make better use of seismic record features in the interpretation, chosen sections of selected seismic profiles as the effective reflection coefficients (ERC) version, characterizing the geometric and physical pattern of the Wilków structure layers were included in the analysis (Dziewińska and Tarkowski 2016). The application of the method of transforming time seismic profiles into ERC sections enabled an image with a higher recording resolution in relation to the wave image to be obtained.

Refraction seismic surveys in the Fore-Sudetic Monocline were carried out in the period between 1964 and 1978. Their results in the form of seismic refraction horizons with variable boundary velocities Vg (Młynarski 1982) were used to obtain additional information regarding the geological structure of the lower parts of the Fore-Sudetic Monocline basement. Authors presented the interpretation of two major refraction boundaries for the Fore-Sudetic Monocline:

- one corresponding with the older Paleozoic rocks characterized by the Vg from 5,500 m/s to 6,000 m/s,
- one tied to the older consolidated basement of undefined age, with the Vg exceeding 6,000 m/s.

The analysis of the results of seismic surveys also included information obtained from the GB2A and GB2 profiles of deep seismic surveys (GBS) (Żelaźniewicz et al. 1997; Cwojdziński et al. 1995; Młynarski et al. 2000) and from the T0740198 profile with the recording time to 15 seconds. The aim of this project was to identify relations between the tectonic picture determined on deep seismic sections and results from other geophysical methods.

Magnetotelluric surveys, spaced 3–6 km apart and performed in 2005 along the Zgorzelec–Wiżajny profile, complete the set of geophysical materials used for the interpretation. 2D inversion results from two different versions of the MT field attributes (according to the NLCG and SBI algorithms, respectively) for the SW part of the profile were chosen as the most representative for the issues analyzed in this study.

The results of the comprehensive interpretation of geophysical data (see Figs. 3–7), which refer to the geological data from deep boreholes, obtained, among others, from archival geological documentations and scientific reports (National Geological Archive, PGI Warsaw), are illustrated in the form schematic geophysical-geological model (Fig. 8) along the Wschowa–Brenno–Śrem–Września line.

3. Results of geophysical surveys – analysis and interpretation of correlation relationships

3.1. Gravity and magnetic surveys

The Bouguer anomaly map of Poland (Królikowski and Petecki 1995) presents a gravimetric image, which is a superposition of gravimetric effects from Mesozoic and Paleozoic units as well as deep basement, resulting from variable morphology and density of each litho-stratigraphic complex. Appropriate methods of data reinterpretation (Speczik et al. 2012; Dziewińska et al. 2017) allowed a structural map of Paleozoic basement (Fig. 3) to be created. This map is consistent with an image of residual anomalies at the depth range of 10–20 km (Fig. 2 in: Dziewińska et al. 2017). Lithological heterogeneity (including changes of thickness) of Zechstein rocks represent local anomalies resulting from density variability of halite and anhydrite rocks. This heterogeneity has been eliminated in the Bouguer anomaly map.

The Bouguer gravity anomaly map (Fig. 3) reveals a positive anomaly within the Lower Silesian Basin, extending between Zielona Góra and Leszno. The Wolsztyn–Pogorzela High is represented by the extensive gradient zone, located on the NE side of the anomaly. The Bielawy–Trzebnica High is located at the end of the SW slope of this anomaly. The Wolsztyn–Pogorzela High is difficult to identify on maps of magnetic anomalies (Petecki et al. 2017; Narkiewicz and Petecki 2017; Kiersnowski and Petecki 2017), while a noticeable, positive anomaly is clearly visible in the Lower Silesian Basin. This anomaly is similar in shape as an anomaly identified in the gravity image, which is probably associated with deep magnetic sources (Fig. 4). The presence of anomalies in a narrow, approx. 20 km-wide belt running south of Zielona Góra and Głogów, which show a relation with the Middle Odra Fault Zone, has also been noticed. Information on tectonic zones can be sourced from either magnetically active igneous rocks containing elevated amounts of ferromagnetic minerals or the sedimentary rocks associated with the migration of solutions along the fault zones.

The above-mentioned resulting map (Fig. 3) shows the results obtained from gravity data: horizontal gradient anomalies according to Rosenbach, directions of tectonic zones A, B, C, D1 and D2 determined on the basis of gravity densities in the linear elements map and the isolines of conventional depth to the positive gravity anomaly.

The positive anomaly that occurs throughout the entire analyzed depth interval, determined in the Lower Silesian Basin, seems to be related to a geologic structure exhibiting high density contrast values. The possible occurrence of a complex showing clearly elevated density (about 2,900 kg/m^3) in relation to country rocks (2,700 kg/m^3) is confirmed by the results of seismic-gravity modelling along the GB2 profile (Młynarski et al. 2000). Assuming that the faults are vertical, the boundaries of the block would, in this case, be the continuation of deep fracture zones delineated at the base of the Earth's crust. The general conformity of the density contrast boundaries, determined on the basis of seismic results and applied gravity profile, confirms the thesis adopted in the present study that the anomaly is caused by high-density masses. The source of this high-density unit might occur at a significant depth in the upper crust, probably in the Paleozoic formations. The linear nature of the gravity and magnetic anomalies suggests that we are dealing with intrusive rocks in deep fracture zones, located in the basement of the Fore-Sudetic Monocline. The fault zone lines might have been the migration paths for material originating from the lower crust or from the upper mantle.

The major fault zones presented on the resulting map (Fig. 3) are those trending NW-SE or similar, associated with deeper faults cutting older geological formations and those occurring directly beneath the Zechstein. It cannot be ruled out that most of the faults do not penetrate into the Mesozoic cover. The identified directions are arranged in characteristic strings consisting of at least two or even three lines that mark the fault zones. Tectonic zones bounding the Wolsztyn–Pogorzela High (A and B), a positive anomaly in the Lower Silesian Basin (B and C), and faults in the vicinity of the Odra River (D1 and D2) are especially noticeable. The course of the tectonic zone, identified with the southern boundary of the Wolsztyn–Pogorzela High (B) and separating it from the Lower Silesian Basin, is probably more complicated and disturbed by additional transverse tectonic displacements. It is also a gradient zone associated with a rapid change in the nature of the magnetic field, which was the subject of analysis of magnetic anomaly maps in the past (Narkiewicz and Petecki 2017; Kiersnowski and Petecki 2017).

The nature of the magnetic field indicates a fault-type contact of the Earth's crust blocks along the LMSL (Słubice–Leszno Magnetic Lineament) separating areas of different magnetic properties. The Słubice–Leszno Magnetic Lineament breaks near Leszno and continues towards the SSE, separating the SE part of the positive gravity anomaly associated with the Lower Silesian Basin, which adjoins the Pogorzela High on the south. New fault zones defining two crossing tectonic directions have been located north from the Wolsztyn High. The less noticeable extensions of the aforementioned tectonic discontinuities towards the S reach the southern fault that borders the Wolsztyn–Pogorzela High. The shifts of the axes of the maximum values of the gravity anomalies divide the string of positive anomalies into several blocks. The southernmost (Pogorzela) block is located directly east of the above-mentioned magnetic lineament. The Poznań – Oleśnica zone represented by the NS-trending tectonic line that separates the Pogorzela area from the rest of the High is the most distinct and interesting part of the Wolsztyn–Pogorzela Elevation. This is a manifestation of a different geological and maybe lithological structure of these (Wolsztyn and Pogorzela) units.

The possibility of interpreting the Wolsztyn–Pogorzela High as a branch off of the anomaly associated with the Lower Silesian Basin with a structural unit of higher density contrasts within the Bouguer anomaly that dominates in the image requires confirmation by

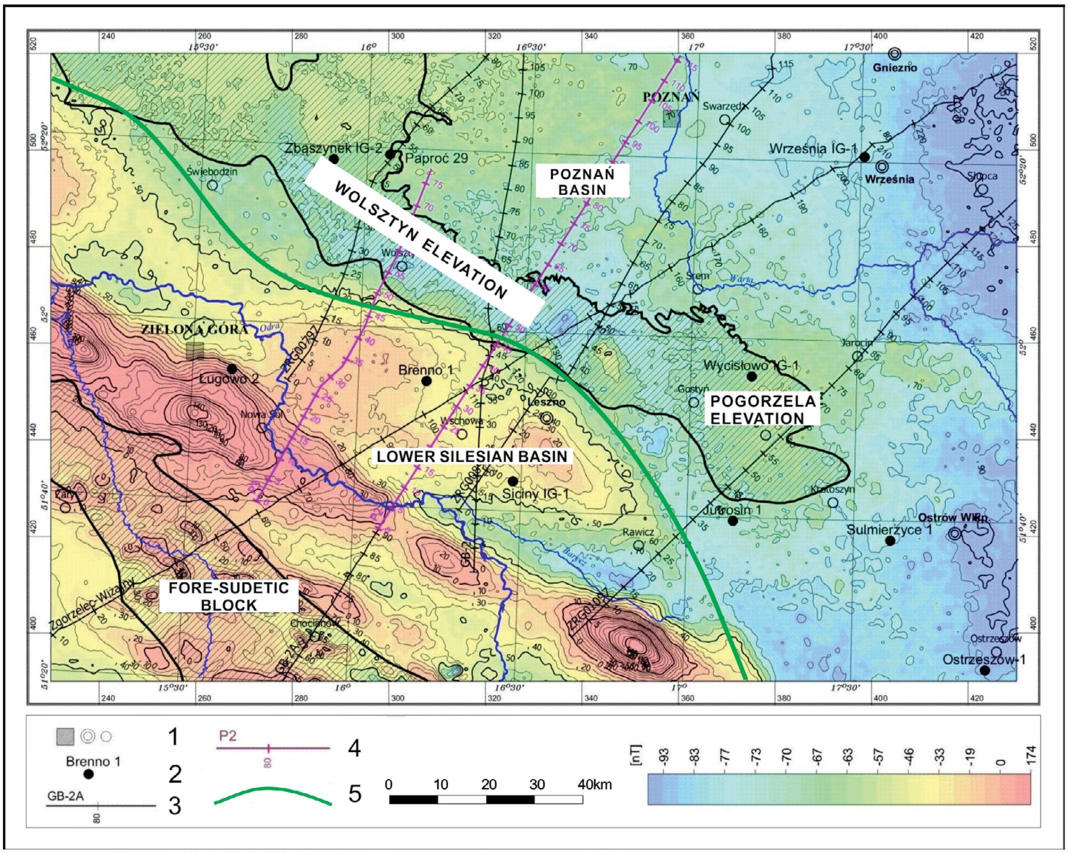

Fig. 4. Magnetic anomaly map of the study area (based on Petecki et al. 2017; Koblański 2007 modified), semi-detailed magnetic survey with a density of 1–4 points/km^2
1 – towns and others localities, 2 – selected deep boreholes, 3 – selected geophysical profiles, 4 – geophysical section line, 5 – Słubice–Leszno magnetic lineament.

Rys. 4. Mapa anomalii magnetycznej badanego obszaru (na podstawie Petecki i in. 2017; Koblański 2007 zmodyfikowana), półszczegółowe badanie magnetyczne o gęstości 1–4 punktów/km^2

further interpretative work. The anomalies associated with the Wolsztyn High occur within a depth interval of 0–8 km, while the anomaly in the Lower Silesian Basin covers the entire depth range from 5 to 20 km (Fig. 4 in: Dziewińska et al. 2017).

3.2. Reflection seismic surveys

The research area is covered with semi-detailed reflection seismic profiles acquired in the period between 1977 and 1999 using the 2D seismic method, supplemented with 3D seismic surveys from 2000–2002. Four composite seismic profiles, arranged along selected lines across the Permian-Mesozoic basin (Fig. 2), complement this material. Groups of intense reflections within a wide time interval are visible in seismic sections, characterizing deep structural elements. They additionally confirm the feasibility of obtaining results from greater depths. The Wolsztyn–Pogorzela High and the Bielawy–Trzebnica High can be traced in seismic sections (e.g. profile ZRG008797 – Fig. 5).

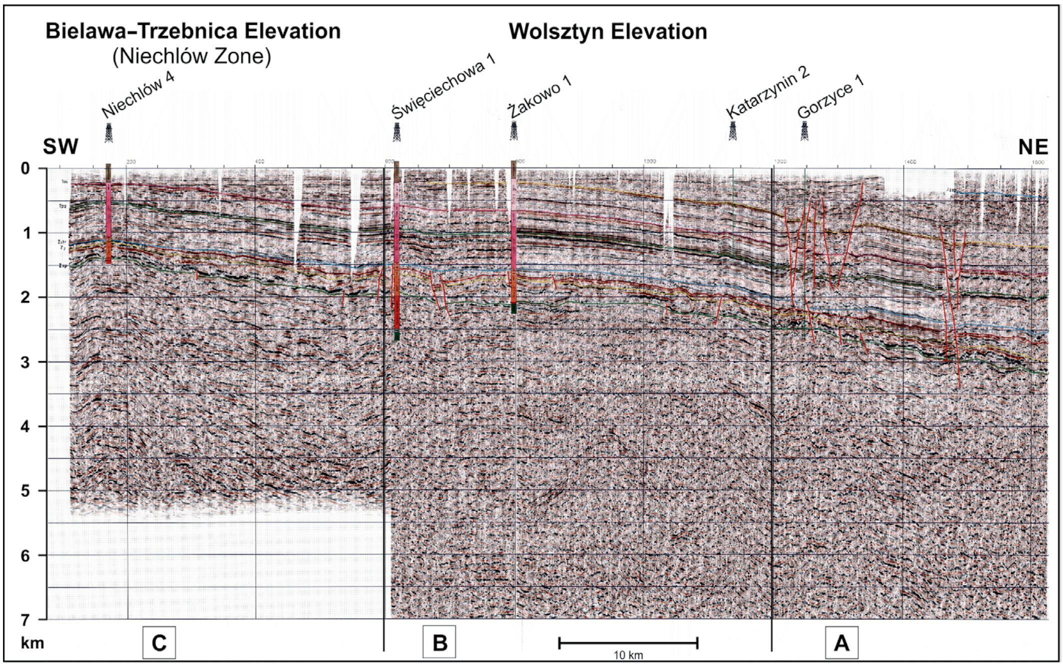

Fig. 5. Depth-converted seismic section (SW part of profile ZRG 00897)
with location of tectonic zones (A, B, C tectonic zones – vide Fig. 3) defined based on gravity data

Rys. 5. Głębokościowy przekrój sejsmiczny (SW odcinek profilu ZRG00897) z lokalizacją stref tektonicznych (strefy tektoniczne A, B, C – patrz rys. 3) wyznaczonych na podstawie wyników badań grawimetrycznych

In wave seismic sections, the outlines of sub-Permian blocks are manifested as complicated forms. Figure 5 shows a selected section showing the location of tectonic zones in the seismic wave image, determined in the basis of the results of gravity surveys.

Applying transformation of the amplitude wave recordings into the impulse form – i.e. effective reflection coefficients (ERC) – significantly increases both the readability of seismic data and the ability to visualize lithological and tectonic elements of a section. The determination of the sign and the value of reflection coefficients for individual layers is of particular importance here. This enables to determine fault zone parameters and recognize blocks of distinguished structural units. The method is particularly useful in the interpretation and identification of layers in Paleozoic formations, the correlated stratigraphic complexes, and the recognized tectonic discontinuities. This is due to the lower dynamics of recorded reflected waves and the use of additional correlation criteria allowing for the better tracking of the reflection boundaries and identifying layers on both sides of a fault zone, including low-amplitude faults. The abovementioned structural elements are authenticated by previously presented numerous examples (e.g. Dziewińska and Petecki 2004).

Dziewińska and Tarkowski (Dziewińska and Tarkowski 2016) proved the usefulness of this method to recognize the deep basement in NW Poland. One more example is the interpretation of the Wilków structure (Dziewińska et al. 2011) located within the Middle Odra Fault Zone. This is a major tectonic element defined as a system of deeply rooted strike-slip faults (Kiersnowski and Petecki 2017). The ERC seismic sections indicate a bipartition of the interpreted object in the Lower Zechstein, Rotliegend and sub-Permian formations. The sub-Permian formations are characterized by faulting tectonics, and the faults are arranged in a distinct system of blocks. A tectonic discontinuity zone (within the range of the gravimetrically determined fault (C), occurring near the central part of the structure and parallel to its extent in the surface image, coinciding with the location of the Bielawy–Trzebnica Horst, divides it into two (NE and SW) parts. The SW side of the structure shows a less intensive faulting and dips more gently, compared to the NE side that is cut by a fault of higher amplitude.

3.3. Deep seismic surveys

The geological interpretation of the results of deep reflection seismic profiles acquired within the framework of the Dekorp project (DEKORP RESEARCH GROUP 1994; DEKORP-BASIN RESEARCH GROUP 1999; Franke et al. 1990) provided relatively good insight into the Earth's+crust structure of the Variscides in Germany, directly west of Poland. The results of geophysical surveys and their geological interpretation are presented, among others, in the Dekorp Group Research 1994 publication (e.g. Figs. 5.9, 5.10, 5.11, 7, 8). This zone forms a complex of anticlines, which cores are composed of Lower Devonian and Ordovician-Silurian rocks that probably underlie the entire zone, and synclines composed of Middle and Lower Devonian rocks and Carboniferous (Namurian) flysch sediments in spatially limited cores.

The complexes of overlapping reflections and the crustal stratification could result from a compressional thrust tectonic regime. Deep seismic surveys carried out in SW Poland using a reflection seismic method are the contribution of the Polish side to the implementation of international program of deep seismic surveys (GBS). The Wolsztyn High is transected by the deep seismic survey profile GB2 (Młynarski et al. 2000). In the southern part of the Lower Silesian Basin borders it is crosscut by profile GB2A (Cwojdziński et al. 1995; Żelaźniewicz et al. 1997) (see Fig. 2). Taking the Moho surface which is cut by numerous faults into account, it can be assumed that system of blocks and fault zones possibly occur in the upper geological complexes.

Geophysical models from the abovementioned studies, developed on the basis of the regional background (Grad and Guterch 2006; Deep location of the Moho surface, Seismic cross-section based on deep seismic soundings in: Nawrocki and Becker eds. 2017) show evidence of the continuation of the geological structures identified in Germany towards the territory of Poland. However, the lack of sufficient data from the sub-Permian basement impedes a full verification of these conclusions. New interpretations resulting from this study can be a valuable contribution to the debate about geological setting of the sub-Permian basement in Poland. The crystalline crust on the GB2 profile (Fig. 6) is defined by two reflection levels: the lower level M (Moho boundary) and the upper one (top of the crystalline crust). The upper crust reveals a sub-horizontal zone of poor reflectivity and well-defined boundaries. Counting the depth from a common reference level, which is determined 1 km below the 0 depth scale point, its surface is located at a depth of 5–6 km (under the Wolsztyn High at 2–3 km) and shows coincidence with the location of the crystalline basement top

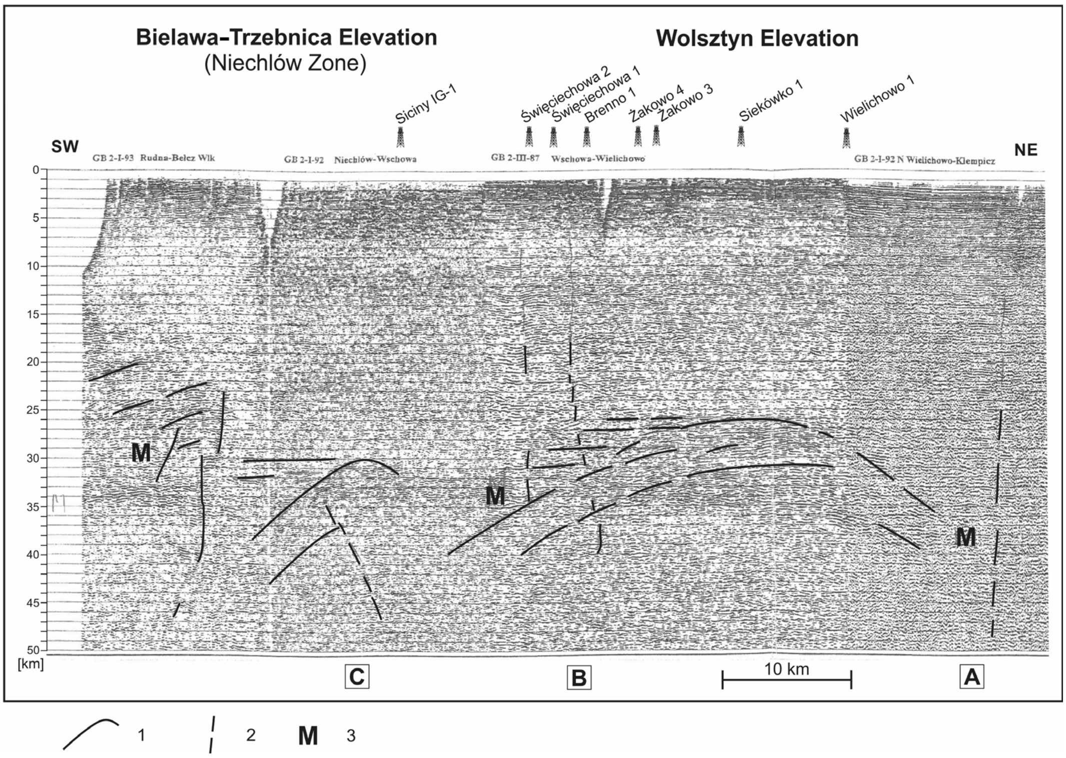

Fig. 6. Deep seismic section GB 2 with the author's interpretation and location of tectonic zones defined based on results of gravity surveys

A, B, C – tectonic zones – vide Fig. 3; 1 – selected reflection boundaries, 2 – deep fault zones presumed, 3 – seismic horizons correlated with the Moho

Rys. 6. Przekrój głębokich badań sejsmicznych GB2 z interpretacją autorów i lokalizacją stref tektonicznych wyznaczonych na podstawie wyników badań grawimetrycznych determined from refraction seismic data (Młynarski 1982), identified with a seismic boundary delineating the base of the sedimentary complex.

The lower boundary of the Earth's crust is marked by a set of reflections occurring at depths of 32–39 km. Single reflections or their strings arranged horizontally or at low angles are located in the middle part of the crust. Their identification enables reconstructing, to a limited extent, the range of individual fault zones or local thrusts. More distinct structures of this type concentrate in the southern part of the profile, in the immediate foreland of the Middle Odra Fault Zone. The imaging of the Middle Odra Fault Zone can be found in the GB2A section (Cwojdziński et al. 1995), the interpretation of which also reveals changes in the crust thickness along a short distance beneath the fault zone. Positive gravity and linear magnetic anomalies, running along the N and S boundary of this zone, indicate the presence of massifs of alkaline rocks in this area.

The deeply rooted Silesia–Lubusz fault on the GB2 profile occurs in a similar position as at the NE end of the GB2A section, where a change in the crust thickness is observed, increasing towards the NE. South of the Święciechowa 2 borehole, a synclinal pattern of reflections is noticeable. The sequence of reflections in the whole recorded depth interval indicates both a change in seismic-geological conditions in this region and the presence of a synclinal form. Between Wschowa and Wielichów, disturbances in the pattern of reflections are observed in the lower crust (it could be identified even as the Moho complex). The lower crust is bent upwards to form a kind of dome-shaped stack with its axis located at the latitude of the Siekówko 1 borehole. The reflection field within the dome reveals increased reflectivity. Inclined reflections dip on both sides: towards the S (Wschowa region – Święciechowa 1 and Brenno 1 boreholes) and towards the N (Wielichowo region). There is a divergence of dip directions of the boundaries in the form of a horizontally arranged complex of reflections on the southern slope of their monotonous dipping and slightly above the top of the uplifted element.

A similar structure (lenticular complex), but of lower amplitude, occurs in the Niechlów region at the latitude of the Niechlów 1 borehole. Such a significant stacking of complexes in the lower crust, reaching a maximum thickness of 10 km, can be interpreted as the effect of thrusts within the crust, analogous to those detected by seismic surveys in the area of German Variscides. As revealed by the presented materials, there is evidence that the basement rocks of the Variscan complex forming part of the Wolsztyn and Bielawy–Trzebnica highs were probably uplifted along fault zones extending deep into the lower crust, down to the Moho surface. The location of all of the mentioned faults (fracture zones), determined on the basis of the interpretations of disturbance zones, such as the discontinuity of reflections and the corresponding changes in the Moho surface level, correlates with the tectonic zones identified in the basis of gravimetric linear elements: A, B, C, D1 and D2 (in Fig. 3), down to a depth of 20 km. This situation appears most clearly at the latitude of the Brenno 1 borehole. According to the record within the entire depth range, the existence of a fault corresponding to the S boundary of the Wolsztyn High (zone B) can be suggested in this region. The zone is also very clearly marked in the upper depth interval. This can be observed, e.g., in seismic section ZRG010097 (for location see Fig. 2) down to a depth of 6.5 km, as a strongly disturbed wave image.

Figure 7 shows the experimental 23 km long profile T0740198, in a depth version to 15 sec., acquired as part of work of the Oil and Gas Industry in the Kościan–Krobia region,

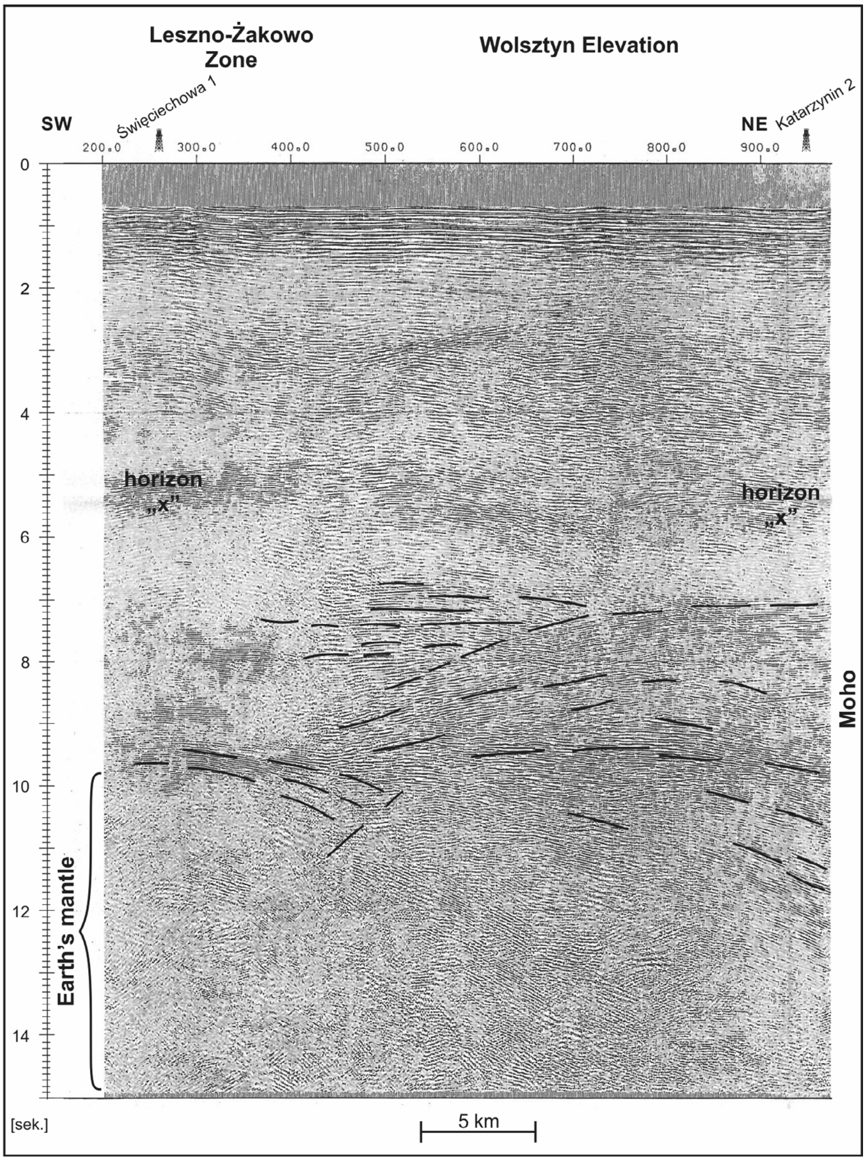

Fig. 7. Seismic section T0740198 with the time recording extended to 15s and with authors' interpretation
M – seismic horizons correlated with the Moho

Rys. 7. Sekcja sejsmiczna T0740198 z wydłużonym czasem rejestracji do 15 sek. z interpretacją autorów
M – horyzonty sejsmiczne skorelowane z Moho

with the authors' interpretation for the area between the Święciechowa 1 and Katarzynin 2 boreholes. These are the results of processing aimed at finding and maximizing packages of reflected energy to define the transition from the Permian-Mesozoic cover to the medium showing properties of the crystalline crust. A package of reflections recorded within a time interval of 7–10.5 sec. can be distinguished in the profile. They show much higher recording dynamics in relation to the surroundings, with a distinct Moho boundary at the base. The results confirm and justify the concepts of the main tectonic features presented in this article.

Discordance of the reflection pattern, marking the complex in which the energy of reflections remarkably increases, outlines a seismic structure similar to that interpreted in an analogous part of section GB2. The inclined reflections extend below the basement of the lower crust. The variable direction of dips, the inclination angle of the reflections, and their dynamics emphasize the recorded tectonic forms and the changes in the thickness of the complexes existing between the boundaries. The nature of the reflection field – packages of horizons showing different dips, separated by zones of seismic discontinuities, illustrate the contact between rocks of different physical properties in this part of the crust. The structural discordance of the reflection pattern indicates the existence of a seismic structure that was probably formed as a result of collisional-strike-slip tectonics. At about a 5.5 sec. time record, there is a distinct boundary of horizon "x" associated probably with a transitional zone between the middle and lower crust. The different nature of the wave field below the Moho discontinuity reflects the Earth's mantle structure. The higher quality of the results compared to those obtained on the GB2 section can be justified by the direction of the profile which is perpendicular to the strike of structures in deep complexes.

The preliminary SW-NE-trending geophysical-geological model (Fig. 8) along the selected Wschowa–Brenno–Śrem line, crossing the individual tectonic units and zones of the study area, is an up-to-date result obtained using a part of the historical Zgorzelec–Wiżajny section. The section was constructed based on the results of geological investigations and geophysical seismic and gravity surveys, taking different versions of magnetotelluric sections from the Wolsztyn High area and its surroundings into account. It presents the subsurface geological structure, emphasizing correlation between data from different geophysical methods. The marked location of the major tectonic zones, delimited in accordance to the results of gravity surveys (Fig. 3), illustrates the correlation with tectonic elements obtained from the wave image. The section contains information on the geological structure of both the Zechstein-Mesozoic complex and the sub-Zechstein formations, and on the directions of prominent tectonic discontinuities. Due to its regional nature, it is a synthetic form of presenting results of geophysical and geological studies against a broader geological background of the region, highlighting elements important for the needs of further geological interpretation, also from the point of view of exploratory work.

Seismic surveys in the Fore-Sudetic Monocline show that all the reflecting boundaries dip towards the NE monoclinally. Starting from the SW, the sub-Permian surface gradually sinks from 3,500 m.b.g.l. to 4,500 m.b.g.l. (except in the Wolsztyn High, where it reaches

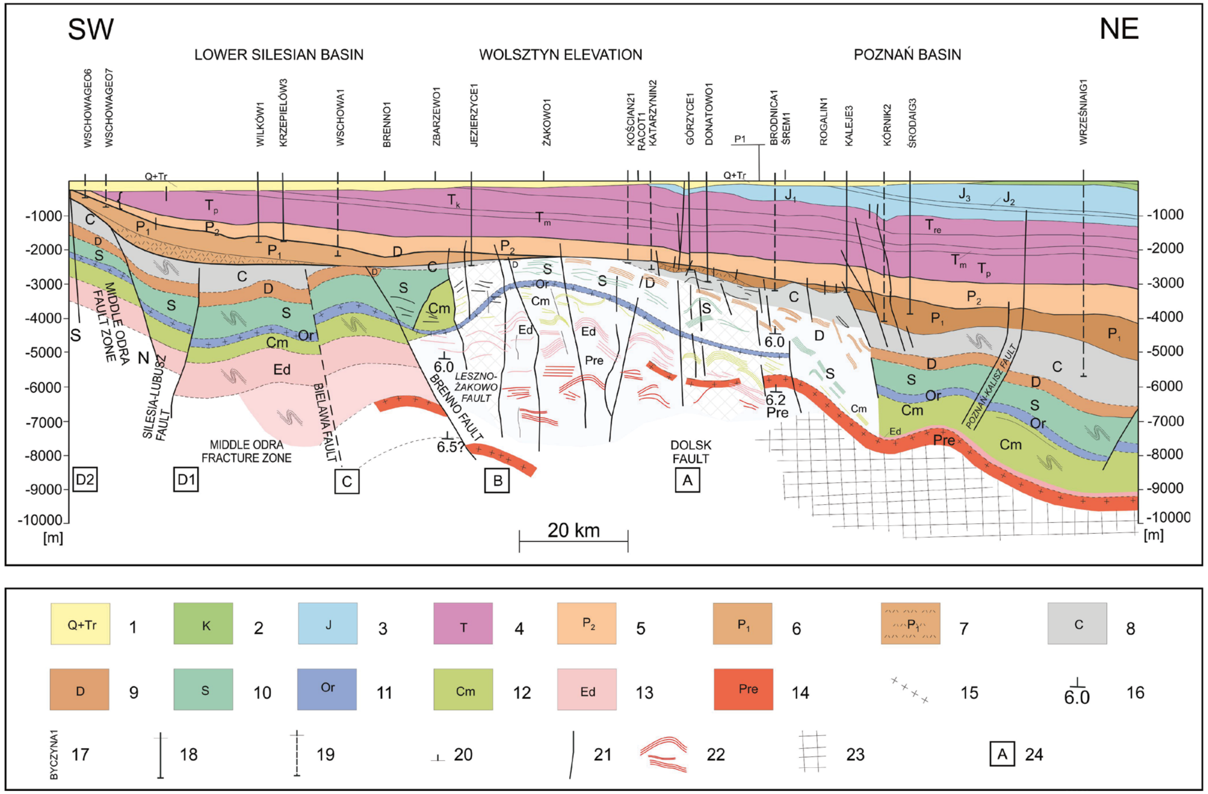

Fig. 8. Geophysical-geological model along the Wschowa–Brenno–Śrem–Września line
1 – Cenozoic, 2 – Cretaceous, 3 – Jurassic, 4 – Triassic, 5 – Upper Permian (Zechstein), 6 – Lower Permian (Saxonian), 7 – Lower Permian (Autunian), 8 – Carboniferous, 9 – Devonian, 10 – Silurian, 11 – Ordovician, 12 – Cambrian, 13 – Ediacaran, 14 – Precambrian, 15 – refraction boundaries, 16 – boundary velocities from refraction surveys [km/s], 17 – boreholes, 18 – projection from a distance less than 1 km, 19 – projection from a distance of 1-3 km, 20 – projection from a distance greater than 3 km, 21 – fault, 22 – fault zones, 23 – high-resistivity basement, 24 – major tectonic zones from gravity surveys (vide Fig. 3)

Rys. 8. Model geofizyczno-geologiczny wzdłuż linii Wschowa–Brenno–Śrem–Września a depth of about 2,000 m). The descent of the basement is accompanied by the increasing thickness of Mesozoic deposits. The total thickness of Zechstein deposits varies slightly, oscillating between 500–700 m, and generally decreases towards the SW in accordance with the direction of the ascending top of the Rotliegend P1 surface along the section.

The results derived from the sub-Permian basement are presented in a generalized and partly hypothetical manner due to the lack of information from sufficiently deep boreholes. The major geologic structures occurring along the section, probably reaching a depth of 5–6 km, emphasize the block-fault tectonic setting of the Variscan complex in the basement of the Fore-Sudetic Monocline. The outlines of particular series under the Permian sediments, as well as their thickness and distribution, can be determined only approximately. The Wolsztyn High appears as a heavily folded, distinctive horst-type structure bounded by strongly deformed tectonic zones and divided by faults into a number of smaller blocks. Within this unit, the Rotliegend (P1) strata rapidly thin and completely decline. The section reveals an area where the Zechstein (P2) is in direct contact with Carboniferous or older Paleozoic rocks, thus defining the range of the P1 sedimentary series. In the vicinity of the Żakowo 1 and 3 boreholes, it is covered with very thin P1 sediments. According to the borehole data, most of the High in its axial part is devoid of P1 strata.

In the Wolsztyn High area, the sub-Permian basement includes a morphological-tectonic element composed of uplifted older epimetamorphic rocks (Drill hole documentations, National Geological Archive PGI-NRI, Warsaw). The boreholes located on the High, such as: Siekówko 1, Święciechowa 1, Żakowo 1 and Żakowo 3, provide data on the sub-Permian basement represented by a series of phyllites and shales. There have been different age determinations of the sub-Permian basement over the years: from Eocambrian (Ediacaran) through older Paleozoic to younger Paleozoic. In local tectonic depressions, younger rocks may be preserved. For example, in the Brenno 1 borehole, the older Paleozoic phyllites are covered by a 100-m complex of claystones, probably Carboniferous in age.

Strongly deformed tectonic zones are found on the slopes of the Wolsztyn High (Fig. 8). Several structural elements are visible in this area. From the SW, it is the Leszno–Żakowo fault zone accompanied by a fault zone referred to the Brenno Fault in this study, located to the west. The reinterpretation of a portion of the nearby localized GB2 section (Fig. 6), performed as part of this study, confirms the existence of such a fracture zone. A down-dropped zone is associated with the abovementioned (Leszno–Żakowo, Brenno) faults. It separates the Wolsztyn High from a uplifted area located to the SW in the Wschowa region. The local Leszno anomaly is visible in this area within the gravity high.

An extensive trough that probably involves Paleozoic rocks runs between the Middle Odra Fault Zone and the Wschowa High. It emerges towards the SW. This part of the Fore-Sudetic Monocline is characterized by the occurrence of Rotliegend sediments and igneous effusive rocks of considerable thickness, thinning towards the NE and SW from the trough axis (Fig. 8). Among the tectonic-structural elements identified in this part of the section, the Silesia-Lubusz, Bielawy and Brenno faults, the Middle Odra Fault Zone and the Bielawy–Trzebnica High should be mentioned. The basis for seismic correlation in this region was the nearby deep borehole of Bielawy 1, which was the only drillhole that intersected the whole Rotliegend in this area, and reached the Carboniferous.

The geological significance of the Middle Odra Fault Zone is underlined in the paper by Kiersnowski and Petecki (Kiersnowski and Petecki 2017). The nature of this zone is presented by the Wilków structure described in that paper, located within the string of the Bielawy–Trzebnica highs.

In the area corresponding to the location of the Brenno Fault and the lowered Leszno–Żakowo zone, the refraction level with the boundary velocity of approx. 6,000 m/s, attributed to the younger crystalline basement, is raised by approx. 1,500 m and occurs at a depth of ca. 3,500 m. The top of the older crystalline basement with the boundary velocity of approx. 6,500 m/s is at a depth of ca. 7,000 m and rapidly descends towards the NE to more than 11 km beneath the ground level. The elevated deposits of the crystalline complex in the Wschowa region, lying at a depth of 5–12 km, probably affect the gravity high observed in this area. The cited thesis on the trend of the MGCR in Poland finds its justification in the presented image. Considering the results of refraction seismic surveys, which are involved in the model, it is possible to postulate a further NE-ward shift of the continuation of the German MGCR in Poland – west of the Brenno fault zone, probably in the Middle Odra Fault Zone.

Results of magnetotelluric measurements along the Zgorzelec–Wiżajny profile are an additional data source for the study. The magnetotelluric surveys show that the Wolsztyn High is a structure of high electrical resistivity, with the maximum elevation in the center, corresponding to the most uplifted portions of the sub-Permian basement. Geoelectric sections confirm the block nature, also indicating that the fault zones of this structure are very deeply rooted. The high resistivity may point to high-grade metamorphic rocks and likely igneous rocks of unknown age, as in the crystalline zone of the Middle Odra faults, which is considered the NE boundary of the Fore-Sudetic Block.

The well-marked faults, down-throwing the Carboniferous blocks to the NE, are identified on the cross-section on the NE side of the Wolsztyn High. In geoelectric profiles, the Poznań–Oleśnica tectonic system is particularly well marked. NE of it, the thickness of the uplifted Carboniferous rocks, cut off in the Kaleje region by a fault zone with an amplitude of approx. 1,000 m, increases considerably. A gradual increase in the thickness of Upper Rotliegend sedimentary rocks are observed NE of the Wolsztyn High, reaching its maximum in the center of the Poznań Basin.

4. Reinterpretation of geophysical data as a new tool for exploration of Permian sediment-hosted Cu and other metal deposits in SW Poland

Exploration works on the Fore-Sudetic Monocline (FSM) in Poland started in the 1950s (Wyżykowski 1958; Tomaszewski 1978). At first, the exploration was focused mainly on the southern margin of the FSM, adjacent to the For-Sudetic Block. These operations quickly led to the discovery of significant copper and silver resources in SW Poland. Later geophysical studies and oil&gas drilling, as well as deep drilling commenced by the Polish Geological Institute – National Research Institute broadened the prospective areas of copper ore occurrences within the FSM, including high-grade copper and silver mineralization present at depths larger than 1200 m.b.g.l. Archival geological and geophysical studies have provided data, which reinterpretation (Speczik et al. 2011, 2012; Oszczepalski et al. 2016; Zieliński et al. 2017) enabled the designation of prospective areas with hypothetical and speculative copper resources within the deeper parts of the FSM. Some of these works were done by the authors and chosen results regarding the reinterpretation of seismic data using the method of effective reflection coefficients (ERC) are presented in this publication.

In the Nowa Sól region (Nowa Sól, Wilcze, Jany and Zatonie exploration concessions) drilling operations, in the area where the new Cu deposit was currently documented, were preceded by the reprocessing of archival geological and geophysical data. Samples from the archival drill cores were studied regarding metal content and organic matter alteration, which is recognized as an important exploration guide for the sediment-hosted Kupferschiefer-type deposits (Speczik and Püttmann 1987; Speczik 1995; Bechtel et al. 2001). Reprocessing of archival geophysical data – gravimetric, magnetic and seismic, was used to determine the most prospective areas for copper mineralization in the region of Nowa Sól, Jany and Mozów, where no deep drillings intersecting the base of the Rotliegend have been done before the start of "Miedzi Copper Corporation" exploration program (so called *greenfield exploration*). Excluding the reinterpretation of gravimetric and magnetic data, which has been described earlier in the text, the reprocessing of seismic data covered a total of 318 km of seismic lines located within 4 exploration concessions (Speczik 2019). Nine seismic lines, only within the newly discovered and documented Nowa Sól deposit, prior to drilling operations, have been reinterpreted by the authors of this publication, using the method of effective reflection coefficients (ERC). New, reprocessed seismic profiles enabled:

1) location of major faults,
2) delineation of local paleo-highs in the base of Zechstein unit (mainly Rotliegend dunes),
3) revision of depth of the base of Zechstein unit within the prospective area.

Analyses of archival seismic data were focused on the transition between the Rotliegend sediments and the Zechstein unit, especially in areas where lithological heterogenity seemed to be significant. The lithological units exhibiting a substantial contrast of effective reflection coefficients' values were interpreted as a potential mineralized intervals of elevated thickness. Moreover, the attempt to locate zones of extensive micro-faulting within the potential ore intervals has been made.

The delineation of major, regional faults, cutting both Zechstein sediments and its basement was the most important result of the reinterpretation of seismic data using the method of effective reflection coefficients (ERC). Along with abovementioned results, it was used to evaluate the previous tectonic model and modify it to better understand the geology of the upper Rotliegend unit and the lower Zechstein strata in the area of interest before the start of the drilling program.

New, previously unpublished geophysical data regarding the sub-Permian basement, presented here are complementary to the results of reprocessing of archival seismic studies carried out during exploration works in Nowa Sól-Jany-Mozów region (Fig. 9). These results indicate that the Nowa Sól deposit is located within the (normal-)fault-controlled continental basin with numerous horst-graben structures visible on the seismic profiles (Speczik 2019).

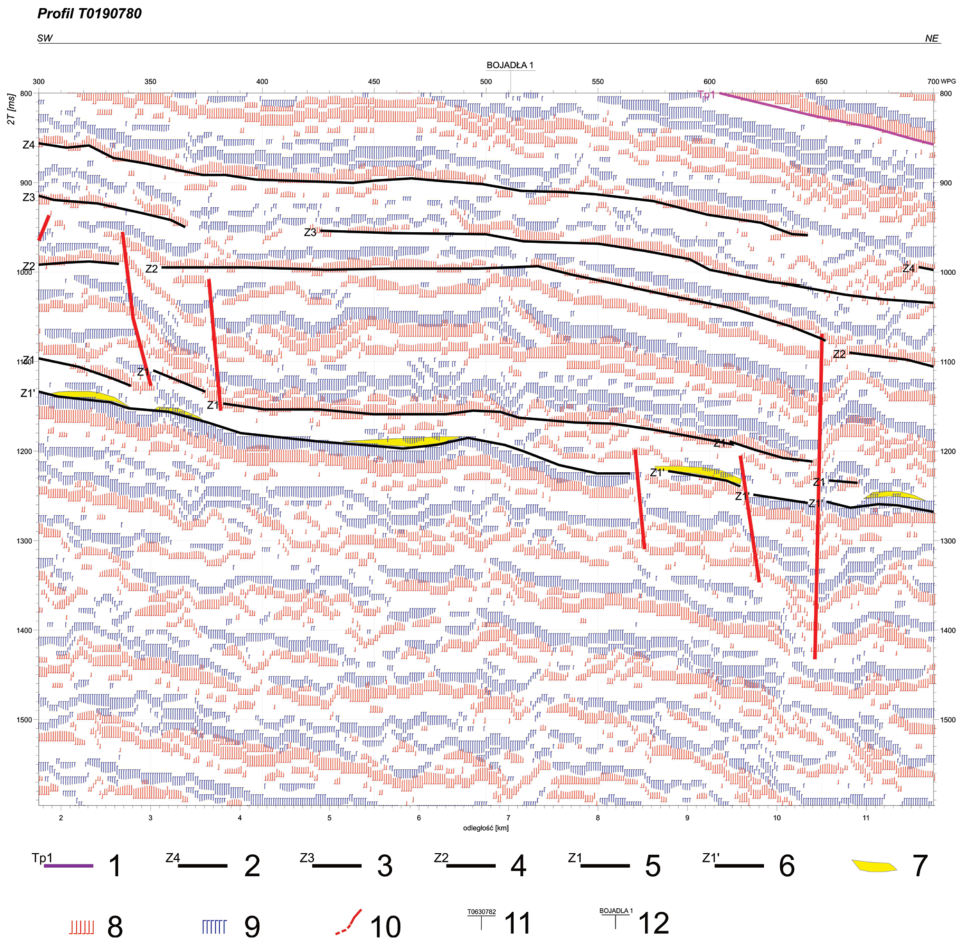

Fig. 9. Seismic section along the northern part of the Nowa Sól Cu-Ag deposit reprocessed using method of effective reflection coefficients (ERC)
1 – top of the Bundsandstein (Triassic), 2 – top of the Zechstein unit, 3 – top of the main anhydrite, 4 – top of the basal anhydrite, 5 – top of the lower anhydrite, 6 – base of the Zechstein unit, 7 – zones of elevated thickness of potential ore-bearing series, 8 – effective reflection coefficients (positive), 9 – effective reflection coefficients (negative), 10 – faults, micro-tectonics and zones of lithological heterogeneity, 11 – intersection with another seismic line, 12 – intersection with archival borehole

Rys. 9. Sekcja sejsmiczna efektywnych współczynników odbicia (EWO) profilu zlokalizowanego w północnej części obszaru złoża rud Cu-Ag Nowa Sól

It is highly probable that the central and northern part of the deposit belongs to the Lower Silesian Basin, while the southern part of the deposit is located within the Middle Odra Fracture Zone. The Middle Odra Fracture Zone is a regional elongated, narrow elevation which can be identified on the gravimetric and magnetic images as strong, linear anomaly. In the Nowa Sól region, the Middle Odra Fracture Zone is represented by the NW-SE-trending Bielawa–Trzebnica High, which is interpreted either as a fault zone of elevated blocks of sub-Permian basement or anticline-shaped structure of sub-Permian basement (Kiersnowski and Petecki 2017) (Fig. 3 and 9).

Reinterpreted seismic profiles reveal that the southern part of Nowa Sól deposit is cut by the NW-SE-trending faults, parallel to the Bielawa–Trzebnica High. These faults exhibit good continuity both in gravimetric and seismic images and cut depths greater than was previously expected. Faults located within the southern part of the Nowa Sól deposit have been observed cutting both lower (and locally upper) Zechstein sediments and Rotliegend strata. We believe that this shear zone is a part of a greater structure – the Middle Odra Fracture Zone. In the central and northern part of the Nowa Sól deposit less major faults have been detected using: method of effective reflection coefficients (ERC), gravimetric and magnetic data and thus this area is interpreted as a part of the Lower Silesian Basin. Few faults that can be seen on reprocessed seismic profiles are generally parallel to faults detected in the southern part of the deposit and cut both lower Zechstein sediments and Rotliegend strata. Gravimetric studies show that the Brenno Fault, which is a marginal fracture zone of Wolsztyn–Pogorzela Elevation, is another regional, large-scale fault that may control tectonic setting of the Nowa Sól–Jany–Mozów region. This fault is located north of the Nowa Sól deposit and can be detected as strong, linear gravimetric anomaly delineating southern edge of the Wolsztyn–Pogorzela Elevation (Fig. 3, 6, 9).

A detailed geophysical study carried out in the Nowa Sól region, including the reprocessing of seismic data using the method of effective reflection coefficients (ERC), led to an assumption that the prospective copper mineralization in this area forms a 10 to 15 km-long belt approximately parallel to the eastern rim of Zielona Góra oxidized field (Oszczepalski 1999; Blundell et al. 2003; Oszczepalski et al. 2019). We believe that this prospective area most likely extends further east, towards the Kotla region and north-west, towards the Mozów region. The presented tectonic model of the Nowa Sól area can be correlated with the extent of geochemical zones (*sensu* Oszczepalski 1999) determined during the drilling program of the "Miedzi Copper Corporation". Boreholes drilled within the southern part of the Nowa Sól exploration area, which is cut to a considerable extent by normal faults, forming numerous horst-graben structures, intersected oxidizing Rote Fäule facie within the lower Zechstein strata (oxidation reaches lowermost part of the Lower Anhydrite) (Speczik 2019). In this part of Nowa Sól prospective area copper mineralization does not occur, only sulfide relics are observed. Further north, in the southern part of the Nowa Sól deposit and within the northern edge of the Middle Odra Fracture Zone, transition zone, characterized by the elevated Au and PGE contents, has been designated. In this part of Nowa Sól deposit very rich, high-grade copper intervals are observed next to barren areas dominated by the oxidized facies (Speczik 2019). Drilling operations revealed that the boundary between oxidized and the transition zone in the Nowa Sól region is not sharp and may fluctuate throughout the eastern rim of the Zielona Góra oxidized field. The central and northern part of the Nowa Sól deposit, located within the Lower Silesian Basin, belongs to high-grade, copper-rich zone exhibiting elevated silver concentrations. In addition, boreholes located adjacent to major faults intersected very rich polymetallic mineralization. In these zones, copper-bearing interval is enriched in lead, zinc, cobalt and REE (*Rare Earth Elements*) (Bieńko 2019).

In the Nowa Sól region, before the start of drilling operations only approximate position of the eastern rim of the Zielona Góra oxidized field has been known – the two closest boreholes that reached the top of Rotliegend were Borowiec-2 and Przyborów IG-3 (both intersected oxidized rocks of lower Zechstein unit). Localization of:

- major faults,
- zones of lithological heterogenity as well as
- local horst-graben structures within the so-called lower-Zechstein copper-series

was possible only by applying multidimensional reprocessing of archival geophysical data. Shear zones are important elements of the Nowa Sól tectonic model, because it is believed that these fracture zones may have acted as permeability conduits for mineralizing fluids, which precipitated large amounts of copper and other metal sulfides within the FSM in Poland and in Germany. According to our studies, in the Nowa Sól region the main fracture zone through which low-temperature, metalliferous brines might have percolated was the Middle Odra Fracture Zone from the south and, to a lesser extent, Brenno Fault from the north. High-grade polymetallic intervals documented in the close vicinity to Paleozoic faults within the central and southern part of the Lower Silesian Basin support the theory that major faults, most likely active throughout Permian-Triassic, were important conduits for mineralizing fluids in this part of the FSM.

The presented results should be referred to as the theory on the genesis of sediment-hosted Kupferschiefer-type Cu and other metal deposits of Central Europe, where two migration pathways for low-temperature, metalliferous, chloride, oxidizing brines towards reduced lower Zechstein sediments, acting as a red-ox barrier, are proposed (e.g. Speczik et al. 1986; Oszczepalski 1999; Blundel et al. 2003; Alderton et al. 2016). In the first place, it is assumed that the vast volumes of metalliferous fluids, originating in the deeper portions of Permian basin, percolated along the major fracture zones developed at the margins of pre-Permian paleo-highs (e.g. Wolsztyn–Pogorzela Elevation and Fore-Sudetic Block; Fig. 4 and 8). Large-scale Rote Fäule oxidized zones (e.g. Zielona Góra oxidized field) have been developed around this paleo-elevations both in Poland and Germany. Copper and silver mineralization occur usually in the distal parts of these oxidized fields, on the reduced side of the red-ox boundary (Speczik et al. 2015; Kopp et al. 2012; Oszczepalski et al. 2019; Speczik 2019). Drilling results in the Nowa Sól exploration area revealed that a major permeability conduits for metalliferous brines, responsible for precipitation of copper-silver and polymetallic ores within the Nowa Sól deposit were present in the Nowa Sól (and probably also in Jany and Mozów regions) tectonic faults system, representing the Middle Odra Fracture Zone, together with Brenno Fault Zone. In addition, an exploration program carried out in the area of interest supported the theory that in the zones where no major faults occur, small-scale structures of elevated permeability, like Rotleigend dunes or micro-tectonics within the top of Roltiegend strata, could have constituted an additional pathway for metal-carrying brines (Speczik 1995; Blundel et al. 2003). Indeed, drilling operations proved that Rotliegend dunes have acted as permeability conduits in the part of the Nowa Sól deposit distant from both Middle Odra Fracture Zone and Brenno Fault (Wolsztyn–Pogorzela High).

Conclusions

According to presented results of new geophysical studies, the following conclusions can be made:

- The complexity of the geological setting of the analyzed area is manifested by the occurrence of numerous fault zones and other tectonic zones indicated in the article.
- The presented interpretation of seismic sections (shallow and deep seismics) shows that the relationship between the tectonic setting of the sedimentary cover and the arrangement of reflections in the deeper parts of the Earth's crust is ambiguous. The stacking of complexes in the lower crust occurs in the area between Wschowa and Wielichów and in the Niechlów region. It may be the result of thrusts within the crust, which correspond to the elevations of the sub-Variscan basement in the Wolsztyn High and Bielawy–Trzebnica High, respectively.
- It is postulated that the zone equivalent to the Mid-German Crystalline Rise (MGCR) in Poland is situated in the analyzed area further to the N than the hitherto accepted horst of the Middle Odra Metamorphic Complex. This was earlier suggested by Żelaźniewicz (Żelaźniewicz et al. 1997) without specifying the location of this deep structural unit. The current interpretation, based on the results of refraction seismic surveys, indicates that this zone is located in the Lower Silesian Basin between the Bielawa–Trzebnica High (Siciny IG1 borehole) and the Wolsztyn–Pogorzela High (Święciechowa 1 borehole), and it coincides with the trend of positive magnetic anomalies.
- Phyllite zones of the Wolsztyn High and Bielawy–Trzebnica High can be correlated with the phyllite zones in Germany (southern and northern zone, respectively). Thus, the limit of the Saxo-Thuringian Zone in the territory of Poland would be marked by the NE boundary of the Wolsztyn High, also contacting with the Rheno-Hercynian Zone, that probably continues towards Poland.
- Results of the interpretation of geophysical data indicate the dominant role of the identified structural unit in the Lower Silesian Basin in relation to the Wolsztyn–Pogorzela High structure.
- The research results are significant in prospecting for hydrocarbons and metal ores, where the location of deposits is related to the complex tectonic setting and the occur-

rence of deep fracture zones in the Paleozoic basement. In terms of mineral resource prospects, this creates the possibility of correlating the study area to similar zones located along the ore-bearing region in the corresponding part of Germany, which is the area between the phyllite zone and the Harz Mountains with the very diverse and rich mineralization. Studies showed, that anomalies on the seimsic profiles reprocessed using the method of effective reflection coefficients (ERC) are a useful tool in the prospection in the areas with hypothetical and speculative copper and silver resources. Assumptions regarding the reinterpretation of seismic profiles presented in this publication allow for the identification of lithological heterogeneity zones and the location of the most prospective areas as well as major fault zones, even in the parts of the basin where depth of ore series exceeds 2000 m.b.g.l. Anomalies representing lithological heterogeneity can be interpreted as ore-bearing zones of an elevated thickness and therefore can be helpful in planning exploration drilling grid.

- The presented conclusions should be treated partly as a hypothesis requiring confirmation. The obtained results justify the need to continue work to provide more evidence (on a regional scale) on the extent and distribution of the analyzed structural-tectonic elements with the reference to the results of research in the western part of Poland and adjacent areas of Germany. This requires, among others, improving the quality of seismic materials selected for further analyses and collected under this study, including those covering the middle part of the Earth's crust, which are very important for tectonic interpretation. The application of appropriate seismic wave image processing procedures, such as the method of effective reflection coefficients (ERC), should enable the identification of a number of changes in the course of seismic boundaries invisible in the traditional record, with accuracy and at depths unavailable so far. As a consequence, this will provide the basis for a better correlation of the Polish profiles with the results of seismic surveys in Germany, and for the creation of a common concept of the structural-tectonic setting.

The source data has been made available by its owner – Polskie Górnictwo Naftowe i Gazownictwo SA (Polish Oil Mining and Gas Extraction SA), with limited use only for the purposes of this publication and in the scope and form presented in the article, for which the authors would like to thank. The authors also thank Geofizyka Toruń SA for the preliminary processing of seismic sections and Miedzi Copper Corporation for providing necessary information on the Nowa Sól deposit.

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REINTERPRETATION OF GEOPHYSICAL SURVEYS OF PRE-PERMIAN BASEMENT IN SW POLAND: STRUCTURAL EVOLUTION AND ITS IMPLICATIONS FOR PROSPECTING Cu AND OTHER ORES

Keywords

reinterpretation of historical geophysical data, sub-Permian basement, Poland, Germany, Central European Variscides, sediment-hosted Cu deposits

Abstract

Based on the reinterpretation of gravimetric, magnetic, seismic and magnetotelluric studies, new features of the sub-Permian basement in the area between the Dolsk Fault and the Middle Odra Fault, SW Poland, are identified. Among numerous faults and lineaments indicated in the article, those limiting both the Wolsztyn–Pogorzela High and a positive anomaly in the Lower Silesian Basin, as well as the faults in the vicinity of the Odra River are particularly prominent. N-S oriented structural elements are also visible in the gravity image. One of them separates the Pogorzela High from the Wolsztyn High. In light of the obtained results, according to refraction seismic surveys, the Polish equivalent to the Mid-German Crystalline Rise is located farther north from commonly accepted position within the Middle Odra Metamorphic Complex.

The study results, supported by data from the neighboring area of Germany, may be important for further prospecting for sediment-hosted Cu and other metal deposits. The reprocessing of archival geophysical data using method of effective reflection coefficients (ERC) enabled the creation of more accurate structural model of ore series within the area of the Nowa Sól deposit in SW Poland. In terms

of mineral resource prospects, this creates the possibility of applying new results from the study area to the similar zones in the corresponding part of Germany, which is the area between the phyllite zone and the Harz Mountains hosting very diverse and rich mineralization.

REINTERPRETACJA BADAŃ GEOFIZYCZNYCH PODPERMSKIEGO PODŁOŻA W POŁUDNIOWO-ZACHODNIEJ POLSCE: EWOLUCJA STRUKTURALNA I JEJ KONSEKWENCJE DLA POSZUKIWAŃ MIEDZI I INNYCH RUD

Słowa kluczowe

reinterpretacja danych geofizycznych, podpermskie podłoże, Polska, Niemcy, waryscydy środkowej Europy, złoża rud miedzi

Streszczenie

Przedstawiono pogląd na budowę geologiczną podpermskiego podłoża przedpola Sudetów w Polsce na tle koncepcji tektonicznych zasięgu waryscydów Europy Środkowej, z uwzględnieniem tematyki surowcowej, co ma znaczenie dla odtworzenia ewolucji środkowej Europy. Zaprezentowano wyniki badań i reinterpretację materiałów geofizycznych (grawimetrycznych, magnetycznych, sejsmicznych i magnetotellurycznych) dla ustalenia związków korelacyjnych, w tym pomiędzy tektoniką obserwowaną na przekrojach sejsmiki płytkiej i głębokiej. Interpretacja przetworzonych danych grawimetrycznych pozwoliła na wyznaczenie charakterystycznych struktur oraz regionalnych stref zaangażowania tektonicznego.

Wstępny model geofizyczno-geologiczny wzdłuż linii Wschowa–Brenno–Śrem (SW-NE) obrazuje efekty kompleksowej interpretacji wyników badań geofizycznych i otworowych. Rezultaty pokazują, że odpowiedni dobór i sposób zastosowanych metod stwarza szanse na uzyskanie realnych wyników w zakresie rozpoznania budowy geologicznej podłoża podpermskiego rejonu, z możliwością nawiązania do sąsiedniego obszaru Niemiec. Wyniki badań stanowią wkład do dyskusji dotyczącej hipotezy kontynuacji podłoża krystalicznego platformy wschodnioeuropejskiej pod paleozoiczną platformę zachodnioeuropejską, sięgającego ku SW aż po strefę uskokową środkowej Odry. Artykuł prezentuje również przykład kompleksowego wykorzystania metod geofizycznych (grawimetrycznych, magnetycznych i sejsmicznych) w prospekcji głębokich złóż rud miedzi na obszarze monokliny przedsudeckiej w SW Polsce.