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# Application of advanced methods of interpreting gravity and seismic data in the exploration of Permian copper ore deposits of the Lower Silesian Basin, Poland

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The application of modern tools for processing and interpreting geophysical data allows for reinterpretation of geophysical measurements performed in the 20th century. A number of gravity maps drawn with modern frequency filters and extensions of Linsser's method, along with the conversion of amplitude-based seismic sections into the form of reflection coefficients, enabled investigation of the sub-Zechstein substrate down to a depth of ~10 km. Analysis of the deep geological structure resulted in the identification of a "pseudo-batholith", which was probably critical in the formation of copper and silver deposits in the Lower Silesian Basin. Comprehensive processing of effective reflection coefficient sections, transformed gravity maps and vertical gravimetric cross-sections identified the arrangement of sub-Zechstein rocks and the hypothetical morphology of the "pseudo-batholith". A combination of new geophysical information, with knowledge of the Nowa Sól deposit and geochemical analyses, was used to demarcate new exploration areas, narrowed down to a ~10–15 km wide zone extending parallel to the southwestern slope of the "pseudo-batholith".

Key words: Zechstein, gravimetry, effective reflection coefficients, copper and silver deposits.

## INTRODUCTION

The Lower Silesian Basin (Figs. 1 and 2) includes stratiform copper and silver deposits. The ore is present in the bottommost Zechstein deposits: shales, sandstones and limestones, and locally at the top of the Rotliegend. Exploration performed to date has documented the existence of Cu-Ag deposits in the zone contacting the Fore-Sudetic Block, and active mining operations have taken place in the Lubin-Sieroszowice district (Markiewicz, 2007). The exploration conducted in recent years by Lumina Metals Corp. (formerly the Miedzi Copper Corp.) in the vicinity of the Lower Silesian Basin and the Wolsztyn Elevation resulted in the discovery of new deposits: Nowa Sól, Mozów and Sulmierzyce North, which belong to the Northern Copper Belt of Poland (Fig. 1), at depths ranging from ~1,700 m to >2 km (Speczik et al., 2024). There is likely a continuation of the southern German ore series into the Lower Silesian Basin, probably at depths which in Poland reach several kilometres (Franke et al., 1993).

Speczik (1985) emphasized the role of tectonic shifts and the related magmatic and hydrothermal processes as a factor causing destabilization of the palaeohydrological balance in the ore-forming process in the Lower Silesian Basin. The existence of copper and silver in the Zechstein indicates a need to investigate the tectonic disturbances in its deep substrate, which would determine the pathways of migration and circulation of metasomatic solutions, invisible beneath the Permian and Mesozoic "screen", and which could have contributed to the creation of zones where metals and other elements were generated. The area of the documented Nowa Sól copper and silver deposit is particularly interesting in terms of investigating the sub-Zechstein substrate in the direct vicinity of the gravity anomaly. Such analysis provides information about the structural conditions and tectonic zones, useful for further exploration.

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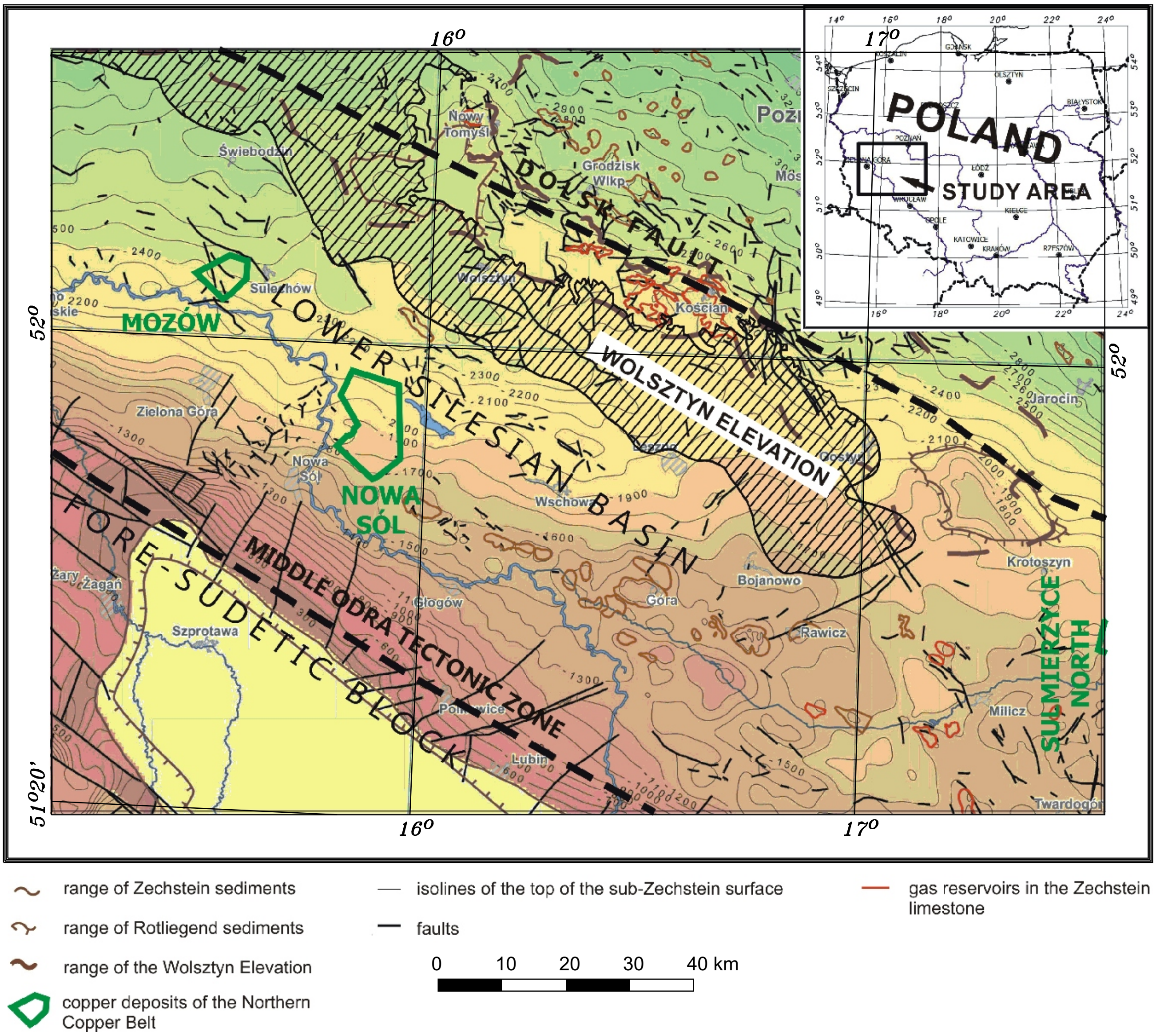


**Fig. 1. Structural map of the sub-Zechstein surface according to Kudrewicz (2007)**

## GEOLOGICAL BACKGROUND

The Lower Silesian Basin is located on the West European Platform of the Variscan orogen, covering the SW part of Poland. The elongated form of the basin is delimited by the Dolsk fault on the NE side, and by the middle Odra tectonic zone in the south-east (Żelaźniewicz et al., 2011). Among shallower geological units, the Lower Silesian Basin is delimited by the Wolsztyn Elevation, where Carboniferous rocks underlie the Zechstein unit of the Permian System (Kiersnowski et al., 2010; Kiersnowski and Petecki, 2017), and by the metamorphic Fore-Sudetic Block with Paleogene and Neogene overburden in the south-east (Fig. 2). The geology of the basin has been explored reasonably well within the Triassic and the Zechstein, whose bottom lies at depths from 500 to 2200 m, wedging out in a zone contacting the Fore-Sudetic Block. Numerous geophysical surveys and drilling operations performed in the Lower Silesian Basin in exploration for hydrocarbons and metals have provided information about geological strata down to the bottom of the Zechstein (Kudrewicz, 2007). Apart from features related to salt tectonics, the structure of the Zechstein and Triassic strata is not complex (Dadlez et al., 2000), being only modestly deformed, both in the Fore-Sudetic Monocline and in the Lower Silesian Basin. Below the Zechstein, beneath Rotliegend rocks of variable thickness, low-grade metamorphic Carboniferous and Devonian rocks of an overthrust origin have been identified as part of the Greater Poland mountain range (Kiersnowski and Petecki, 2017). Deep seismic studies have demonstrated that the thickness of the Paleozoic substrate exceeds 8 km (Guterch and Grad, 2006; Dziewińska et al., 2020). Interpretation of gravimetric and magnetic anomalies recognized in the years 2006–2008 indicates that their sources are related to the structure of metamorphic rocks at a depth of ~5 km, representing the amphibolite facies (cf. Petecki, 2006).

Location of the Nowa Sól deposit (Speczik, 2019) took place with reference to existing geophysical and geological reports, illustrating selected structural elements of the Zechstein

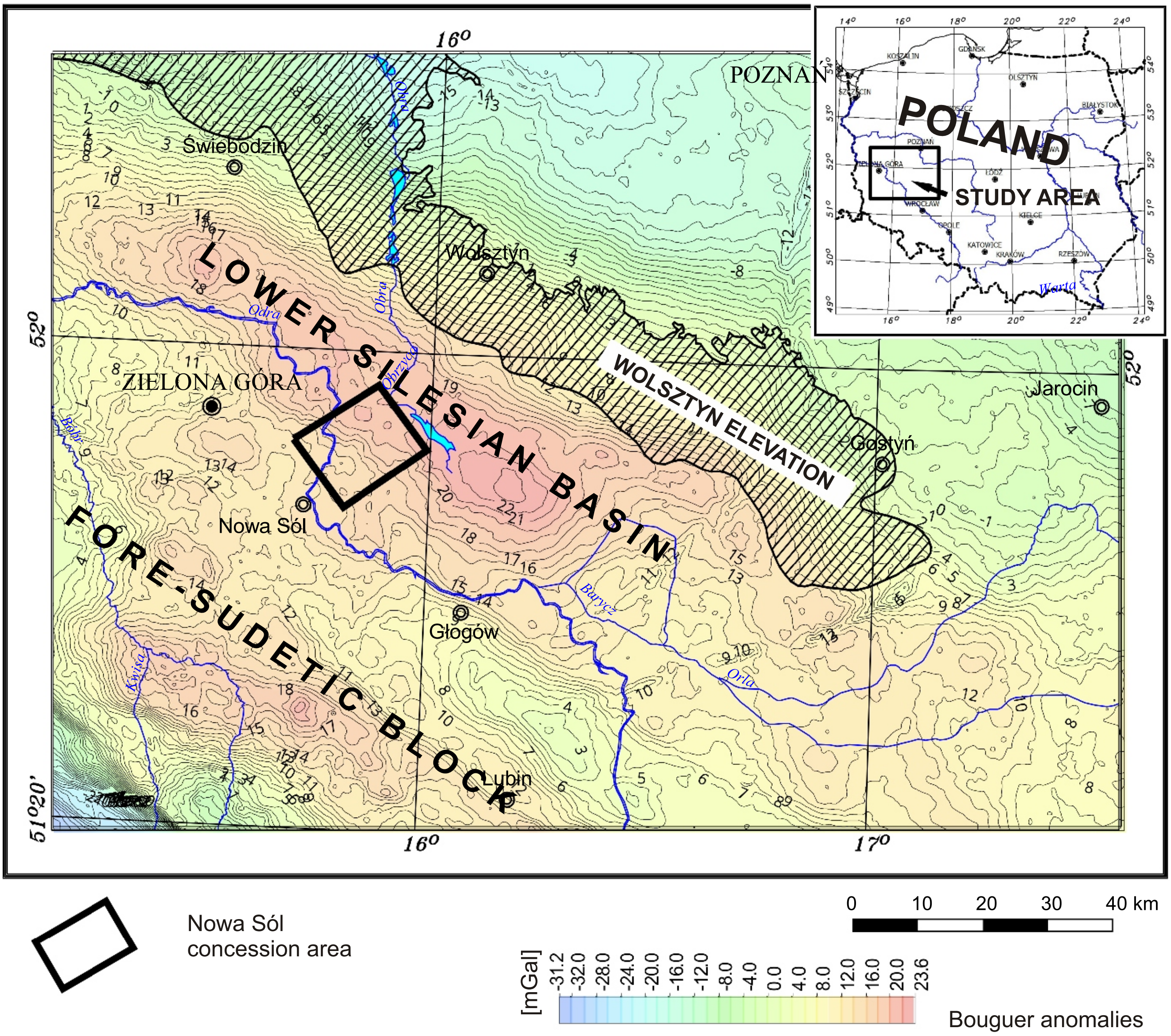


**Fig. 2. Bouguer anomaly map of the area shown in Figure 1 according to Królikowski and Wybraniec (1996)**

in the area of a gravity anomaly in the Lower Silesian Basin, near the Wolsztyn Elevation. A map showing the density of linear gravity elements indicates the complex geological structure of the sub-Zechstein substrate (Fig. 3). A deep structural form identified in the Lower Silesian Basin and a dominant feature in the gravity anomaly image is characterized below in this paper. Supplementing the processing of gravimetric data with a seismic cross-section in the form of reflection coefficients, and with comprehensive interpretation of both methods, allows examination of the geological structure within a depth interval of up to 10 km. The result is a map of structural elements occurring below the bottom of the Zechstein, within the Paleozoic and metamorphic rocks, in a form arbitrarily called a "pseudo-batholith" and its accompanying tectonic zones. The geophysical image, produced with the use of specially selected algorithms without the input of an interpreter, may constitute a basis for analysing the structure of the sub-Zechstein basin substrate, and its more detailed interpretation determines further prospects for the exploration of mineral deposits in the Lower Silesian Basin.

As on geological maps, the seemingly undisturbed geological structure of the Fore-Sudetic Monocline is also visible on a Bouguer anomaly map (Fig. 2; Królikowski and Wybraniec, 1996). Moreover, it is indicated by the results of processing involving a dense grid of seismic sections. One exception in the gravimetric image shown (Królikowski and Petecki, 1995) is a large positive Bouguer anomaly in the Lower Silesian Basin, separating the Fore-Sudetic Block area from the bland image of Bouguer anomalies up to the Kuyavian-Pomeranian synclinorium. Notably, the "Wolsztyn Elevation" geological structure located on the northern slope of this anomaly is virtually invisible on the gravimetric image. The image shown, of Bouguer anomalies in the Lower Silesian Basin, can be considered to be associated with the deep Paleozoic and Precambrian substrate. In order to investigate the deep stratigraphic successions and tec-

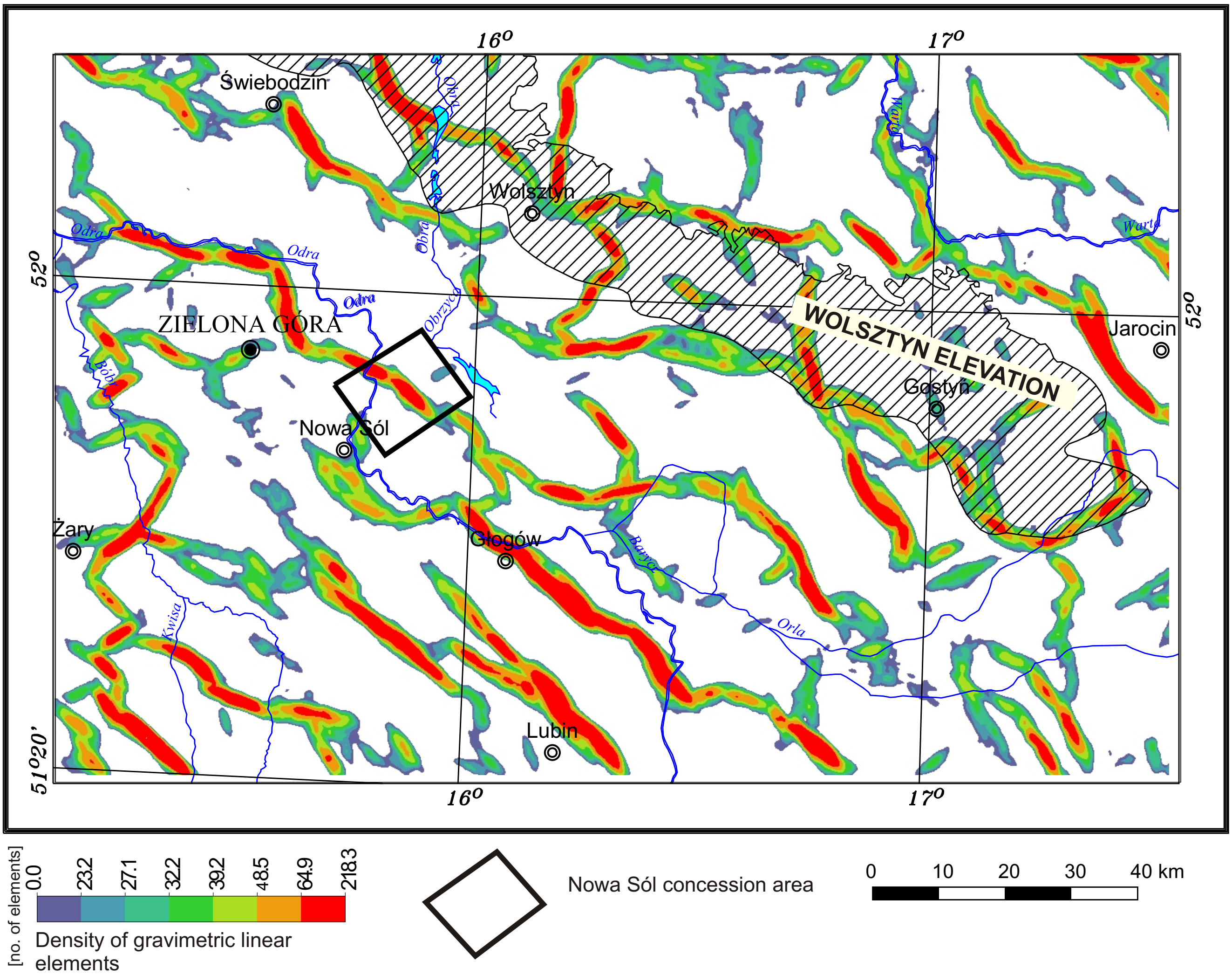


**Fig. 3. Density map of linear gravity elements in the arbitrary depth interval of 4–7 km (white areas are below the density threshold)**

tonic elements, it is necessary to perform transformations of Bouguer anomalies in the form of residual anomalies and vertical gravimetric sections, as well as an analysis of the few existing seismic sections with an extended recording time.

## PROCESSING OF GRAVIMETRIC AND SEISMIC DATA

Advances in the interpretation of geophysical surveying data, as well as the beginning of mineral exploration, for example focused on copper and silver, have created conditions for a new look at the deeper structure of the Fore-Sudetic Monocline, and primarily the Lower Silesian Basin. The processing of gravimetric and seismic data collected in the years 2012–2014 by Lumina Metals Corp., using newly chosen and improved numerical methods, has allowed the reconstruction of certain deep structural elements of the sub-Zechstein substrate within a depth interval of up to 10 km (Speczik et al., 2024). The topography of the sub-Zechstein substrate is particularly interesting in the area of the known Nowa Sól copper and silver deposit, including the determination of its origins. The Nowa Sól deposit is part of the Northern Copper Belt, which consists of a total of three deposits discovered and documented by Lumina Metals Corp. as well as numerous prospective areas (Speczik, 2019; Speczik et al., 2024).

This processing showed that, in spite of the use of measurements performed in the 20th century mainly for the needs of hydrocarbon exploration using methodology adjusted to the examination of the Zechstein, the datasets obtained provide information about the deep Paleozoic, and perhaps reaching the Precambrian substrate. This has been achieved due to new methods of processing geophysical data, as well as a comprehensive integration of gravimetric and seismic information. The results, as regarding the documented copper deposit and the hypothesis of its origin, have identified a need to explore relationships between new elements of the deep geological structure and the well-constrained Zechstein and Triassic succession. Interpretation of the data was limited by the coarse sampling of the gravimetric data and the brief seismic recording time (no more than 4 seconds), as well as by the placement of the seismic sections, which do not always precisely follow the structures analysed.

## GRAVITY SURVEYING

Historical data from a semi-detailed gravimetric image covering the entire area of the Fore-Sudetic Monocline were used to prepare a Bouguer anomaly map and perform the transformations. The density of measurement points, amounting to 2.2 points per $km^2$ on average, enables the identification of anomalies associated with the Zechstein strata and their substrate. The measured values of gravity were converted using a methodology which corresponds to the current data concerning the shape of Earth, and new formulae for calculating gravity anomalies. The calculation of Bouguer anomalies used the IGSN 71 system, a normal gravity field calculation formula for the WGS 84 ellipsoid, and a constant density of 2.25 $g/cm^3$ in the reduced layer. The catalogue of anomalies prepared in this manner constituted a basis for further calculations. The Bouguer anomaly map used a reference level which corresponded to sea level. Sets of Bouguer anomalies were converted into a regular grid with a unit length of 250 m; this grid served as a basis for all transformations.

The interpretation of residual gravity anomalies characterizing geological objects in selected depth intervals became possible due to the use of the Butterworth (BTWR) frequency filter method, the preparation of vertical gravimetric sections, and the extension of the Linsser method for detecting linear features in the gravity field and allowing their statistical analysis.

The BTWR filter with a specific central wavenumber value (related to the respective depth of a prismatic source body) was used to compute residual gravity anomalies. The BTWR frequency filter has been used due to the ease of adjusting its slope without changing the central wavenumber. The forms of the low- and high-pass filter are expressed by the following formulae:

$$L(r) = \frac{1}{1 + \left(\frac{r}{r_o}\right)^n} \quad \text{Low-pass filter} \qquad [1]$$

$$L(r) = 1 - \frac{1}{1 + \left(\frac{r}{r_o}\right)^n} \quad \text{High-pass filter} \qquad [2]$$

where: $r$ – wavenumber, $r_o$ – central wavenumber of the filter, $n$ – degree of the filter (this paper uses a value of 6).

The band-pass filter is a product of both filters. The formulae for a prismatic body spectrum was used to calculate the central wavelength, which is dependent on the depth of the body (Bhattacharyya, 1966; Švancara et al., 2008).

In the filtering process, the assumption is that the filter cutoff wavelength and source depth are mutually related. The greater the depth of the source, the greater the wavelength, and vice versa. The central wave number of an ro filter for a prismatic body is calculated according to the following formula [Geosoft Software, MAGMAP (FFT-2D)]:

$$r_o = \frac{Ln\left(\frac{Hb}{Ht}\right)}{Hb - Ht} \qquad [3]$$

where: $Ht$ – depth of upper body edge (prism); $Hb$ – depth of lower body edge (prism).

The gravity anomaly map is supplemented by vertical gravimetric sections prepared along selected lines – e.g. along seismic sections. In order to prepare the vertical gravimetric sections, a number of residual gravity maps were prepared for equal depth intervals of up to 10 km using the band-pass BTWR filter, and subsequently intersected by a vertical plane, resulting in an image of the distribution of local anomalies in a depth domain for a given section line. Compiling the maps with the sections allowed for linking the anomalies from the map with the respective interval of a depth-based gravimetric section. The wavelength values used in the preparation of vertical gravimetric sections fell within a range of 1.5–60 km.

A modified Linsser's method (Linsser, 1968) was used for tracing linear gravity elements related to the tectonics. As used in this paper, the method is based on the comparison of a gravimetric field section in the form of a curve with a reference model constructed for a vertical half-plane of specific depth and density contrast. Calculations are performed in a regular grid node in several profiles of varying directions, with selection of the profile with the highest coincidence with the reference model. The calculations are repeated in all nodes of the grid. Linear gravity elements identified by means of Linsser's method are presented in the form of lines. The lines are divided into elementary segments with a regular mesh size of 250 m, and subsequently filtered with a statistical surface filter to show the density of linear gravity elements on the maps. The numbers in the colour chart in Figures 3 and 4 represent the number of elementary segments in the filter window. The linear elements traced are assumed to represent vertical density interfaces comparable to lithological and tectonic boundaries, such as faults, intrusions, or other density contrasts (Švancara, 1993).

In order to map the residual gravity anomalies associated with the sub-Zechstein strata, the band-pass BTWR filter with specific passing wavelengths for the depth range up to 10 km was used. The tectonic elements of the Paleozoic rocks are characterized by a map of the density of linear gravity elements (Fig. 3), prepared on the basis of vertical density interfaces calculated for specific depth intervals.

The prevalent directions of anomalies on the map of density of linear gravity elements calculated for an assumed depth interval of 4 to 7 km (Fig. 3) are NW–SE, approximately consistent with the elongated form of anomalies in the Lower Silesian Basin, constituting the result of Variscan activity. This is indicated by two predominant zones located at a distance of ~25 km from each other – characteristic, relatively narrow zones, extending along longer gradient zones on both sides of the anomaly, which can be associated with deep tectonic fractures. The tectonic zone located on the southwestern slope of the gravity anomaly, and thus in the vicinity of the central part of the Lower Silesian Basin, seems more distinct. Both predominant tectonic zones outline a previously unknown structure referred to as a "pseudo-batholith" in the Lower Silesian Basin. The absence of anomalies between regional tectonic zones and the pronounced nature of both tectonic zones (almost parallel) indicate the homogeneous nature of the structure delineated, wedged between the two geological units. The clearly defined shape of the predominant tectonic zones in the gravimetric image indicates that they represent geological structures with considerable differences as regards depth, and thus probably also lithology. In the surroundings of the regional tectonic zones and in their close vicinity, less distinct horizontal and vertical fractures with an NE–SW direction are visible, probably associated with older tectonic movements. The image of gravity anomalies in the wider surroundings of the structure in question, highlighting the regional nature of the structural elements

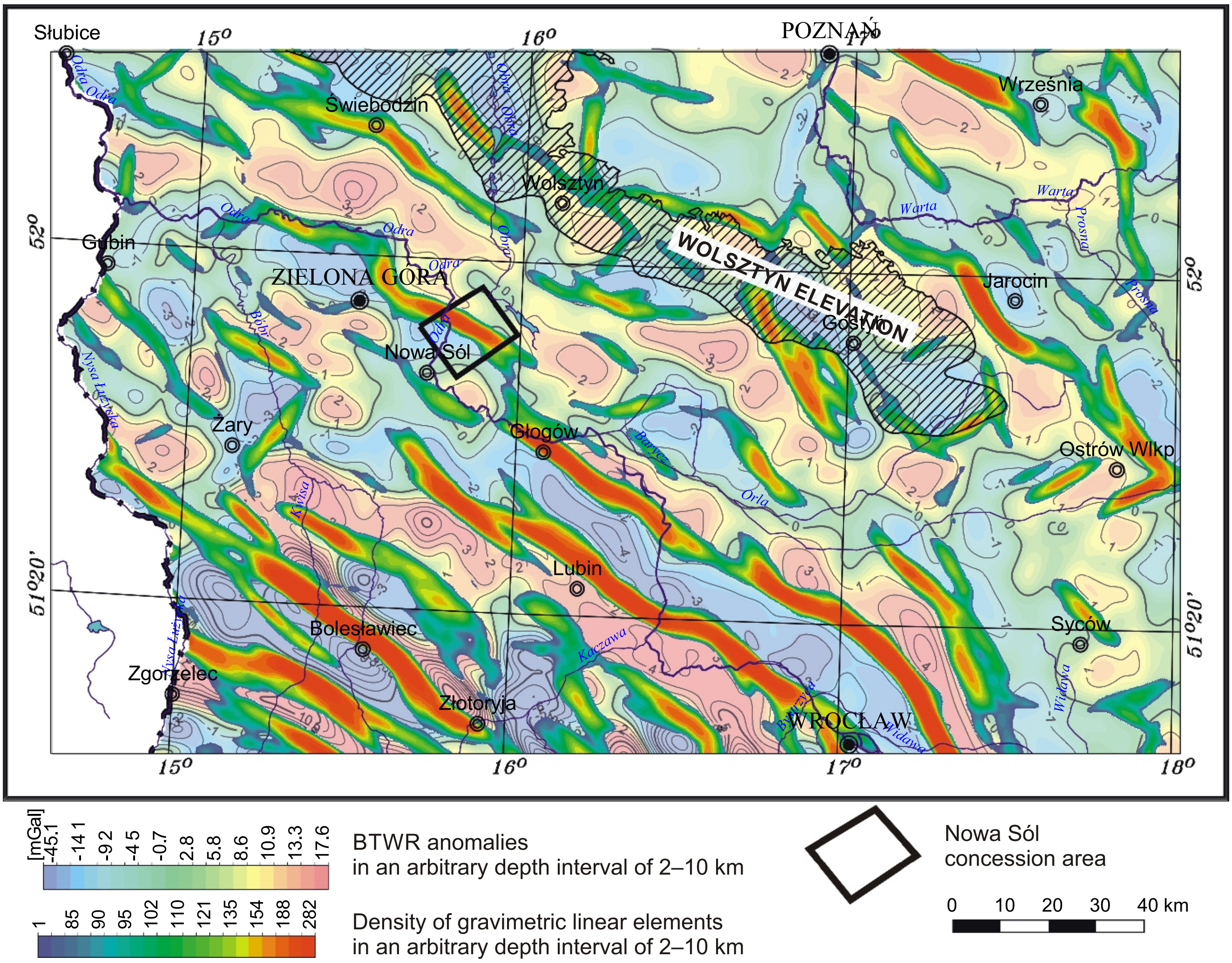


**Fig. 4. Density map of linear gravity elements against a BTWR anomaly map in the arbitrary depth interval of 2–10 km**

delinated in the form of a map of density of linear gravity elements and a map of BTWR anomalies, is shown in Figure 4.

On the resulting vertical depth-based gravimetric sections (Fig. 5), there is a distinguishable structural form of increased density between the regional tectonic zones, which is referred to as a "pseudo-batholith", whose top in the area studied (Lower Silesian Basin) lies at a depth of 6–7 km below ground surface. The structure stands out due to its vertical or nearly vertical slopes within a depth interval of up to 10 km. The position of the vertical boundaries of the structure in close proximity to regional tectonic zones may indicate that both dislocations demarcate the boundaries of the "pseudo-batholith" with both the Lower Silesian Basin and the Wolsztyn Elevation. In the gravimetric image in the form of tectonic zones, there are particularly distinguishable vertical contacts, which can be associated with differences in the density of the "pseudo-batholith" and its surroundings.

Changes in the shape of the structure discerned are shown on several parallel gravimetric cross-sections transverse to the predominant gravity anomaly. Due to range in its depth, the cross-sections are located so as to show the most important changes in the depth of the top of the "pseudo-batholith". Compilation of the cross-sections (Fig. 5) shows the most distinct elements of the structure causing the generation of a gravity anomaly as well as its consistent, relatively homogeneous and similar form over the entire area analysed. Supplementing the gravimetric sections with both regional dislocations allows for more precise reconstruction of the source structure of the interpreted gravity anomaly and the geological structure of the Lower Silesian Basin in the area indicating the possible presence of copper and silver ore deposits (Zieliński and Speczik, 2017).

The inferred contours of the "pseudo-batholith" served as a basis for the preparation of a map showing the hypothetical depth of its surface, shown in Figure 6. In the morphology of the structure detected, there are pronounced elevations, among which one can trace possible tectonic lines of NE–SW trend. In a number of places, the vertical boundaries of the structure remain consistent with the regional tectonic zones, suggesting that the slopes of the pseudo-batholith have the form of regional faults. The prepared map is an approximation due to the assumed depth of the top of the "pseudo-batholith" for the se-

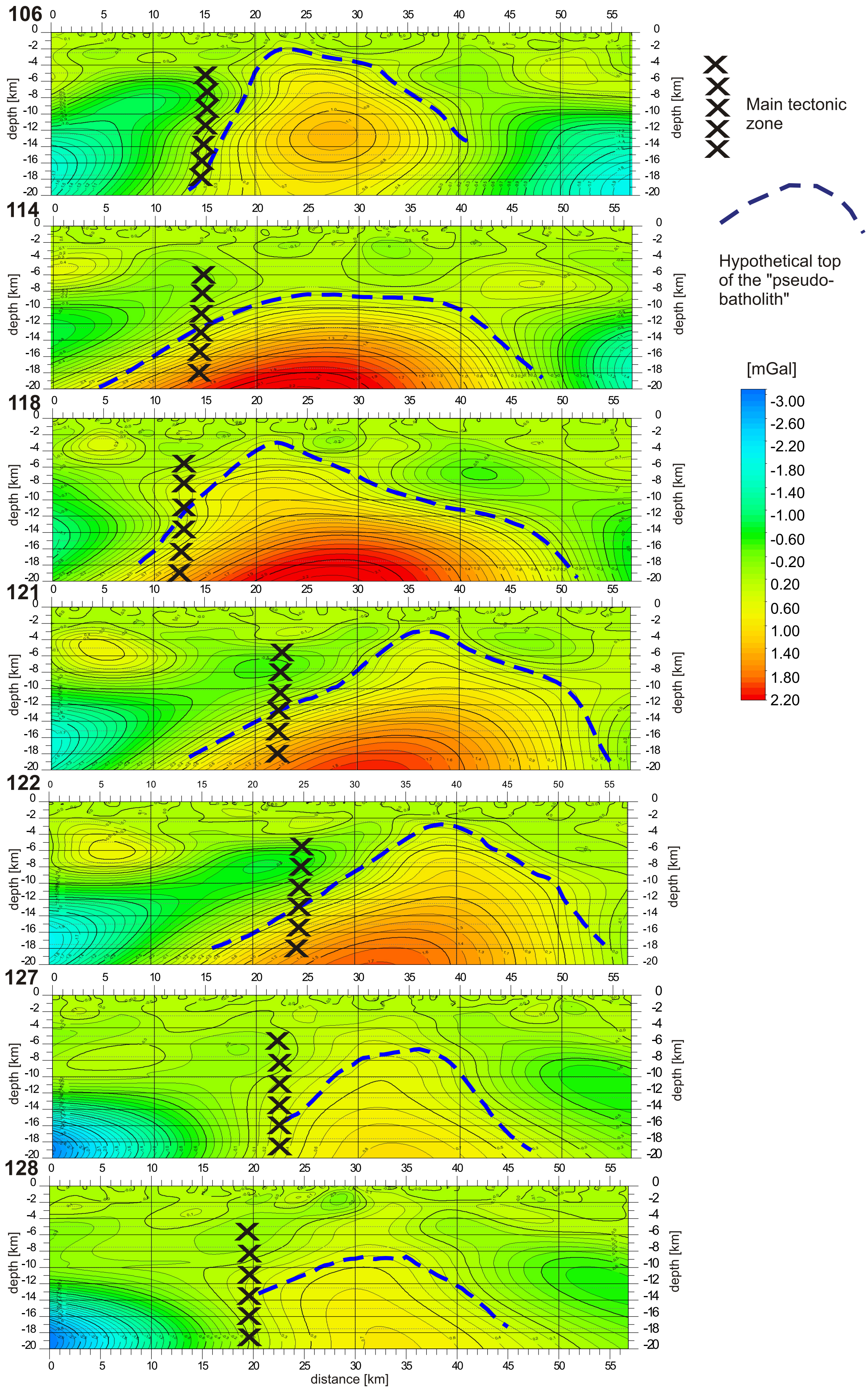


**Fig. 5. Compilation of vertical gravimetric sections situated perpendicularly to the length of the anomaly**

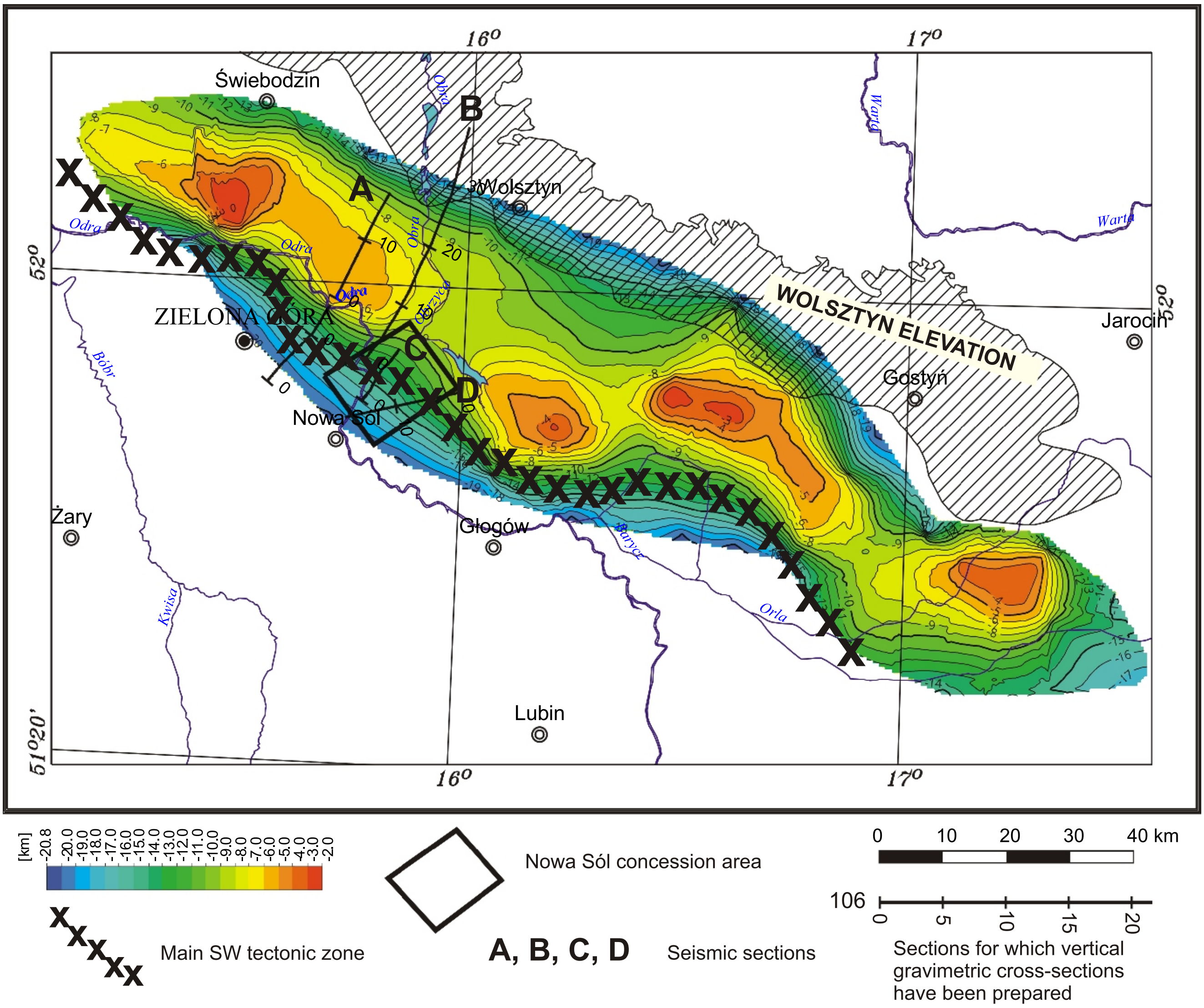


**Fig. 6. Structural map of the inferred top of the "pseudo-batholith"**

lected contour line on the vertical gravimetric section in close proximity to major changes in the gravity anomalies on the cross-section.

The image of the magnetic field of the Fore-Sudetic Monocline (Petecki et al., 2003, Petecki and Rosowiecka, 2017) stands out due to a positive anomaly in the Lower Silesian Basin, probably caused by deep rocks, analogous to the gravity anomaly. The correlation between anomalies of the magnetic field *T* and the gravity anomaly shows that the outlines of the anomalies are of similar shape, and their position in the Lower Silesian Basin indicates that they originate from the same source with distinct magnetic properties and density. The anomaly correlation area covers most of the northeastern part of the Lower Silesian Basin along its boundary with the Wolsztyn Elevation, partially encroaching on its area.

## SEISMIC SURVEYING

In the area of the Fore-Sudetic Monocline, semi-detailed seismic surveying was performed in 1975–1995, and detailed investigations followed into selected structural objects for the exploration of crude oil and natural gas reservoirs in the Zechstein and Carboniferous strata. Seismic surveying used the method of 12- and 24-fold multiple coverage by 48-channel apparatus and 2 ms sampling. Dynamite excitation was used in individual blast holes. The seismic sections were distributed in a 2–4 km grid. The recording time for seismic waves usually did not exceed 4 seconds, and those times were extended for selected sections to reach depths down to ~10 km. Seismic surveying performed in this manner constituted a certain constraint for the analyses discussed in this paper. Primary constraints of the research included poor seismic coverage and occasionally the unavailability of the original unchanged seismic record to work with. Another problem was the location of seismic sections, often not extending in a manner optimal for analysis of and correlation with the pseudo-batholith. In order to fully understand its structure, an ideal grid should have been perpendicular to its long axis. However, the historical grid of seismic sections had been designed for exploring for hydrocarbons, in a pattern that did not always overlap with that of the "pseudo-batholith". However, the biggest problem was the length of the seismic records, ending after 2 seconds, adjusted to the identification of potential oil and gas reservoirs. Longer seismic records was made in only a handful of cases, and these allowed analysis of deeper structures.

Field records were initially reprocessed in the *Sysis* system, followed by the *Omega* and *Geomaster* systems in the 1990s. The results of seismic surveying are reflective interfaces on time-based sections, showing the structure of the Permian and Mesozoic succession. Interfaces correlated in the Triassic include: Tk, associated with the lower Keuper; Tm, corresponding to the Muschelkalk; and Tp2, linked with the top of the middle Buntsandstein. The top of the Zechstein is traced by the Z4 interface, usually less pronounced in the seismic record and difficult to correlate; Z3, Z2 – interfaces associated with the top of the Main Anhydrite and the Basal Anhydrite, reflecting changes in the thickness of anhydrite ridges and salt, Z1 – the contact of the Oldest Salt with the Bottom Anhydrite, and Z1' – the bottom of the Zechstein, also representing the top surface of the Rotliegend. The seismic image below the Zechstein shows the complex structure of the Paleozoic rocks; the waves are distorted by multiple reflections in a number of places, but they are considered to mostly reflect the geological structure of the Paleozoic.

In order to make full use of the seismic data, SEG-Y amplitude records were converted into effective reflection coefficients (ERC) (Rudnitskaya et al., 1987; Speczik et al., 2011). This process can be considered as a continuation of the standard reprocessing of seismic data, in which the amplitude is assumed as proportional to the reflection coefficients for specific geological interfaces.

Calculation of the reflection coefficients included the following steps:

– determining the elementary signal – an impulse representative of the medium examined;
– correlation of a wave-based seismic trace with the elementary impulse, which enables elimination of distortions and the construction of a more precise image;
– splicing the traces of the reflection coefficients with the elementary signal, which leads to transformation of amplitude data into the time series of the reflection coefficients.

The application of this method enables more detailed depiction of a geological cross-section compared to a traditional, amplitude-based seismic section. Not only does this transformation allow for determination of the reflective interfaces, but it also enables description of the geometrical and physical properties of the strata forming a given geological unit.

Lithological units are identified on sections developed in this manner on the basis of a similar nature of records on neighbouring seismic traces. In addition, the sign of a reflection coefficient allows for the identification of a lithological succession along a seismic section. Amplitude-based seismic traces converted into rows of reflection coefficients stand out due to the exact position of their reflective interfaces, and due to the ability to discern individual strata as thin as 10 to 15 m.

Conversion of seismic waves into impulses provides better approximation of seismic data to geological reality, with the ability to identify and trace strata of smaller thickness, for example sandstones, limestones, or rock salt. The complex structure of the Paleozoic rocks is demonstrated by the records of reflected waves in a time interval below the Zechstein. In spite of potential interference associated with multiple reflections, the resulting images in most cases are a faithful recreation of the Paleozoic structure.

Determination of the elementary impulse and mutual correlation of this impulse with each seismic trace are critical in the process of transforming an amplitude-based seismic record into ERC. The resulting time series of reflection coefficients provides better approximation of the geological image, taking into consideration the time, the value of a reflection coefficient, and the polarity of the signal. On ERC sections, reflective interfaces between strata of different velocities are marked with horizontal lines, while vertical lines indicate the sign and value of the reflection coefficient, proportionally to the difference in acoustic hardness of the adjacent strata.

This method makes it possible to trace reflective interfaces which are separated from each other by a distance of at least L’ of the period of the elementary signal, which leads to much more detailed representation of a geological cross-section compared to amplitude-based sections. The reflection coefficients provide precise information about the geometrical and physical arrangement of geological strata, enabling, for example, identification of thin strata, detection of small faults, and identification of lithological changes along a seismic section. This method is particularly useful when searching for potential mineral deposits, such as copper ore.

The two seismic sections processed in order to study the sub-Zechstein substrate were situated directly north of the Nowa Sól exploration concession, arranged approximately perpendicular to the gravity anomaly (sections A and B in Fig. 6). Selection of the sections was limited by the access to the few seismic sections with a recording time of up to 4 s, most being prepared for the needs of exploring the Zechstein strata in time intervals of 2 s. Both sections were converted into the form of reflection coefficients, and time – depth conversion was performed for a constant velocity, due to the absence of data for sub-Zechstein strata. Being almost perpendicular to the axis of the Lower Silesian Basin, both sections provide a new approach to the complex structural image below the Zechstein strata (Wierzchowska-Kicułowa, 1984, 1987). The recorded arrangement of correlated seismic interfaces on sections placed close to each other is similar, which can be considered as an improvement in the reliability of the information acquired. In the NE segments of the sections (Fig. 7), in the direct vicinity of the Wolsztyn Elevation, there is a noticeable undisturbed or almost undisturbed arrangement of strata in the sub-Zechstein substrate. The arrangement of reflective interfaces and the nature of the lithological and stratigraphic successions discerned document the lack of reflection of the Wolsztyn Elevation on seismic sections, which requires confirmation by further study. SW of the Kargowa borehole, and thus close to the edge of the gravity anomaly and above the anomaly, the seismic image changes drastically; the seismic sections feature a number of elevations and discontinuities limited by changes which are probably tectonic in nature, and distorted by groups of diffracting waves. By contrast with the relatively undisturbed position of the Zechstein and the Triassic in the SW parts of both sections, the seismic cross-sections here are highly complex along the entire depth interval interpreted.

It seems obvious that particular attention in the analysis of the seismic data was paid to the reflection of both regional tectonic zones in the Zechstein strata which are usually mapped with high precision. The two seismic sections selected, intersecting the more distinct tectonic zone and shown in the form of reflection coefficients, constitute an image above the tectonic zone noted. For the seismic image to be more legible in terms of tectonic zones and lithological changes, time-based sections were supplemented with calculations of velocity within the Zechstein succession (Fig. 8).

Reflection coefficients combined with changes in velocity allow for the delineation of changes of both tectonic and a

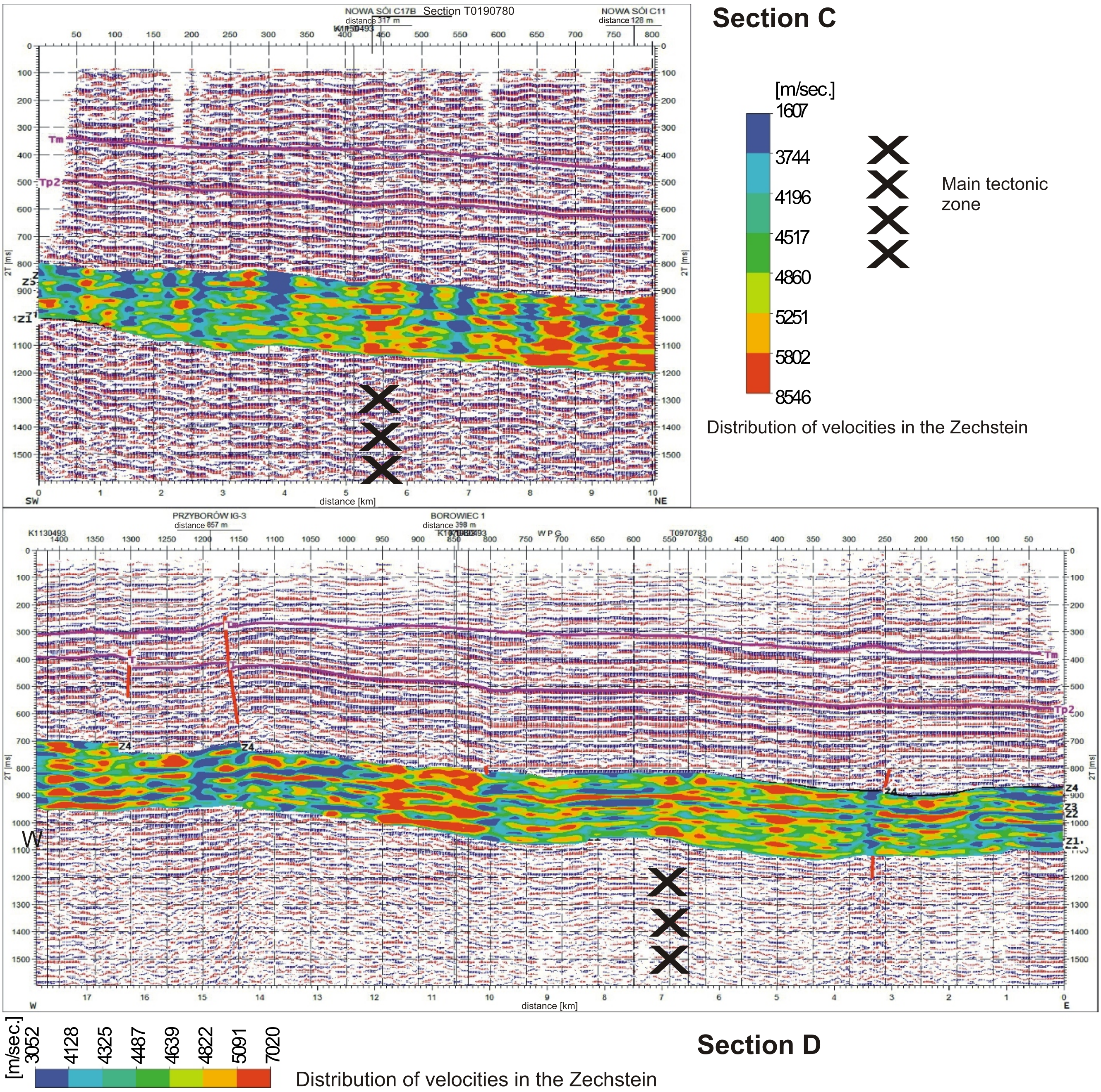


**Fig. 7. ERC time sections according to Figure 6 with the distribution of velocities in the Zechstein succession**

lithological nature. The examples shown prove the absence of even the slightest impact of regional faults on the Zechstein rocks, which act as a barrier to the deformation of the structures present below. It is possible to create stresses in the Zechstein strata which would cause faults invisible in the seismic image.

The image of reflection coefficients on the seismic section below the Zechstein (Fig. 7) allows for the discernment of 4 units with an arrangement of strata characteristic of sedimentary successions. Such an image is maintained over the entire depth interval recorded. The first unit below the Zechstein strata stands out due to its horizontal or nearly horizontal arrangement of strata compared to deeper seismic units. Another distinguishing feature of this unit is its variable thickness, decreasing in a zone of considerable inclinations of the deeper units. The position and thickness of deeper strata of the Paleozoic is uniform, surrounding the uplifted "pseudo-batholith", with parallel arrangement of strata both in the area where they lie horizontally, and in the uplifted zone. Above this succession, in the NE part of the section (Fig. 8) a trough has formed due to the uplift-

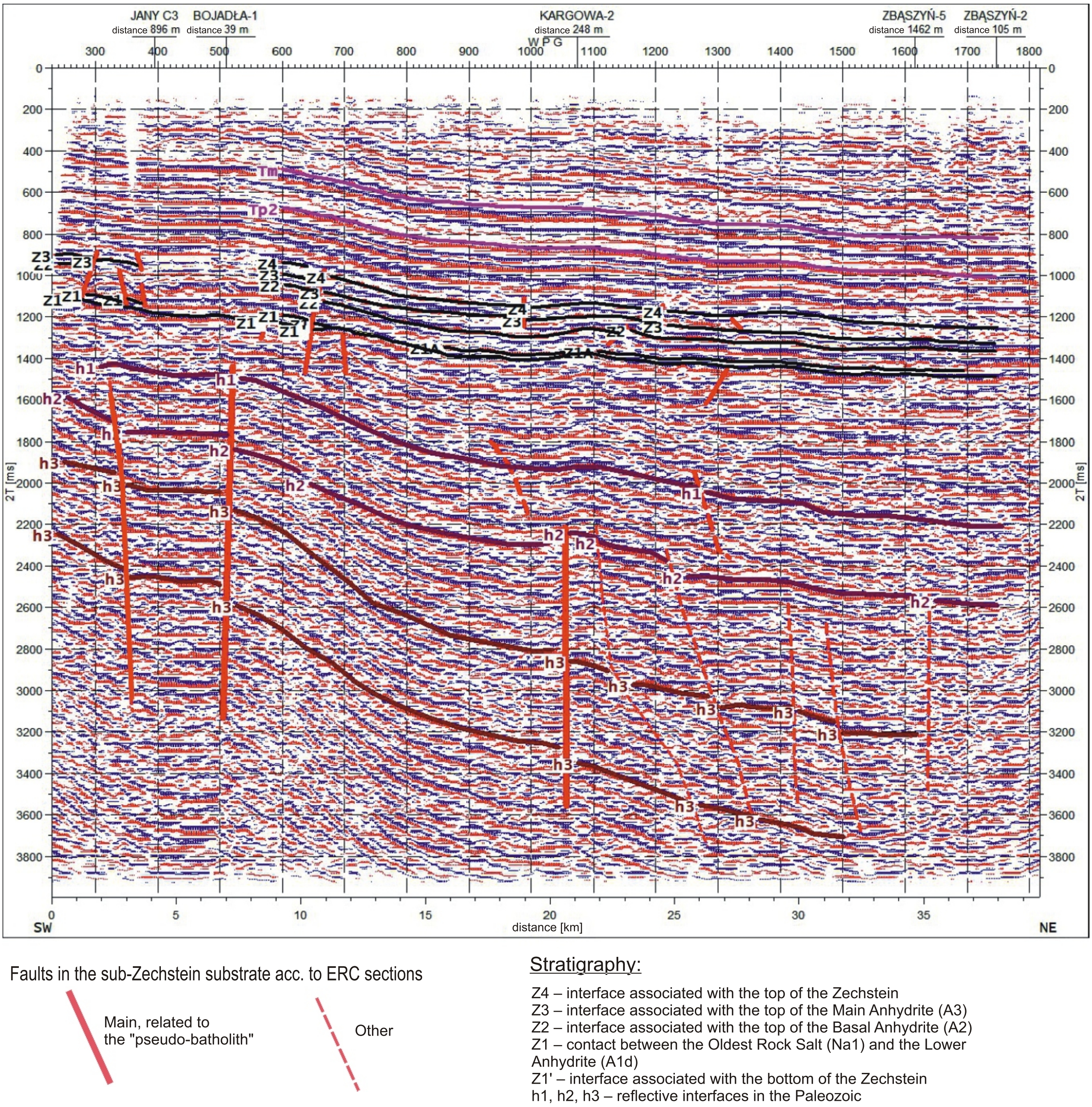


**Fig. 8. Time-based ERC section – section B of Figure 6**

ing of the "pseudo-batholith", filled with sediments which noticeably wedge out on the slope of the elevation.

In the area of undisturbed strata, the faults affect all three successions in the lower part of the section. One characteristic element is the end of the fault plane below the strata underlying the Zechstein strata in the entire area NE of the Kargowa borehole, where the thickness of the sub-Zechstein substrate falls within a range of 1500 m and more. SW of the Kargowa borehole, in a zone of considerable variation and uplift of the reflective interfaces, the thickness of the substrate is reduced and slightly exceeds 500 m. With a small thickness of the sub-Zechstein substrate, the distinct tectonic zones seem to reach the bottom of the Zechstein, intersecting the entire sub-Zechstein substrate. In identifying faults, a number are delineated on the seismic section, versus only a single one in the gravimetric image.

In the seismic image recorded, above the "pseudo-batholith" structure, the Zechstein and Triassic strata seem to be somewhat monolithic, with faults penetrating the sub-Zechstein rocks rooted in its bottom. This particularly applies to the sub-Zechstein substrate in the vicinity of the Nowa Sól exploration concession and deposit, overlapping the SW end of the "pseudo-batholith" and the tectonic zones identified by the dislocation in the Bojadła borehole – according to seismic data – and the Ługowo borehole, where according to seismic data the tectonic zone coincides with the regional gravimetric tectonic zone. Geological interpretation of the deep substrate became possible due to the inclusion of gravimetric data in the interpretation of the seismic cross-section.

## COMPREHENSIVE INTERPRETATION AND EXPLORATION OF THE COPPER DEPOSITS

The processing of gravimetric data which evenly cover the research area allowed for comprehensive examination of the tectonic structure with the main tectonic zones, and the identification of the "pseudo-batholith", which is characterized by increased rock density (by ~0.05–0.08 g/cm$^3$) compared to the surroundings. Comprehensive depth-based sections confirmed the existence of the "pseudo-batholith" in the seismic image at a depth of <6 km, in a place pinpointed by gravimetry (Fig. 9). On section B, there are visible discontinuities of reflections on the slope of the "pseudo-batholith", particularly noticeable on the southeastern side. From the SW, the area of the "pseudo-batholith" is delimited by 3 parallel faults extending NW–SE, most likely associated with Variscan activity. The southernmost fault coincides with a large fault zone visible on gravity maps (Fig. 2). The dislocations delineated may be interpreted as migration pathways for hydrothermal solutions responsible for the origin of the ore deposits.

The thickness of the overburden above the "pseudo-batholith" is another important element. Areas which are tectonically disturbed, and those where the overburden is thin, constitute sites predisposed to the formation of ore deposits. The geophysical data analysed indicate that this area is a zone between the southern fault delimiting the "pseudo-batholith" and a fault zone interpreted on the seismic sections, delimited by the fault near the Bojadła 1 borehole. This zone spans ~10–15 km. In terms of geology, the area of the "pseudo-batholith" is most likely surrounded by metamorphic rocks (phyllites) of Devonian-Carboniferous age, overlain by sedimentary Carboniferous rocks as well as by sedimentary and volcanic rocks of the lower Permian (Kiersnowski and Petecki, 2017).

The combined processing of gravimetric and seismic data shows the complex structure of the sub-Zechstein substrate in the Lower Silesian Basin. At the same time, correlation of the information acquired with the newly discovered Nowa Sól copper ore deposit provides useful guidance for further exploration of metal ores (Oszczepalski, 2007; Oszczepalski and Chmielewski, 2019). This should be based on the tectonic zones, which provide a simple explanation for the origins of the deposits. Our paper describes possible migration pathways for solutions between the "pseudo-batholith" and the bottom of the Zechstein, which ultimately triggered the formation of copper and silver ore deposits beneath the Zechstein succession.

Comprehensive preparation of depth-based sections using gravimetric and seismic data allowed for investigation of the structure of the sub-Zechstein substrate and geological interpretation of the results. The undisturbed position of Paleozoic successions was disrupted by the appearance of the "pseudo-batholith", which significantly deformed the strata and caused the emergence of predominant tectonic zones. The dislocations traced in the vicinity of the southeastern side of the batholith, together with the small thickness of the sub-Zechstein substrate, probably identify migration pathways in the Paleozoic. The Zechstein and Triassic strata restricted the migration pathways. In the area of the newly discovered Nowa Sól copper and silver ore deposit, the results indicate a relationship between the structure of the deep Paleozoic substrate and the existence of metal ore deposits in the Zechstein, consistent with the views of Speczik (1985) and Speczik et al. (2011).

Identification of the position of the "pseudo-batholith" and the tectonic zones which could constitute migration pathways for the solutions should shape further exploration in the Lower Silesian Basin (Oszczepalski and Speczik, 2011). The zone indicated for further exploration seems to be particularly promising in the central part of the Lower Silesian Basin, in the vicinity of a regional fault traced in the gravimetric and seismic data, as well as a nearby fault visible on the seismic cross-sections.

The exploration zone suggested by the present study is shown in Figure 10. The copper-bearing area corresponds with the NW part of the Northern Copper Belt identified as a result of the exploration program of Lumina Metals Corp. (Speczik et al., 2024), while the probable copper-bearing area suggests possible extension of the belt. Investigation of the area of the entire gravity anomaly should provide guidance for further copper and silver exploration in the Lower Silesian Basin.

## CONCLUSIONS

Mineral exploration requires a comprehensive approach and the use of varied geological and geophysical data. An analysis of historical geophysical information originally obtained for the needs of oil and gas exploration, supported by proper analytical tools, enabled the acquisition of new important data on the structure of the deep sub-Zechstein substrate in the Lower Silesian Basin. Research based on gravimetric results allows for the identification of specific tectonic elements critical for identifying the possible occurrences of copper deposits. In addition, integration of seismic results with gravimetric data makes it possible to create a coherent tectonic image, which is especially important for areas with copper and silver ore deposits.

Interpretation of the gravity anomaly resulted in the demarcation of a "pseudo-batholith" structure, which played a key role in the copper ore-forming process in the bottom strata of the Zechstein. Research indicates that tectonic zones near the southwestern boundary of the "pseudo-batholith", and the thickness of rocks between this area and the bottom of the Zechstein, form an important factor when establishing prospecting areas for new ore deposits. The probability of receiving metal-rich metasomatic solutions increases along with a decrease in the thickness of rock strata and an increase in the number of tectonic zones. The "pseudo-batholith" constitutes a considerable source of potential mineral resources, and it should be a subject of further geophysical research, especially seismic surveying with a long recording time.

The area of the "pseudo-batholith" interpreted from geophysical surveying overlaps the previous zones of potential occurrence of copper ore deposits, identified on the basis of geochemical analyses (Oszczepalski and Chmielewski, 2019). It is limited to the NE and SW by deep Variscan tectonic zones, and cut by Alpine faults perpendicular to the batholith (Żelaźniewicz et al., 1997).

The identification of a zone of future exploration, which extends parallel to the southwestern slope of the "pseudo-batholith" with a width of ~10–15 km, is an important step as regards exploration for mineral resources. This is corroborated by

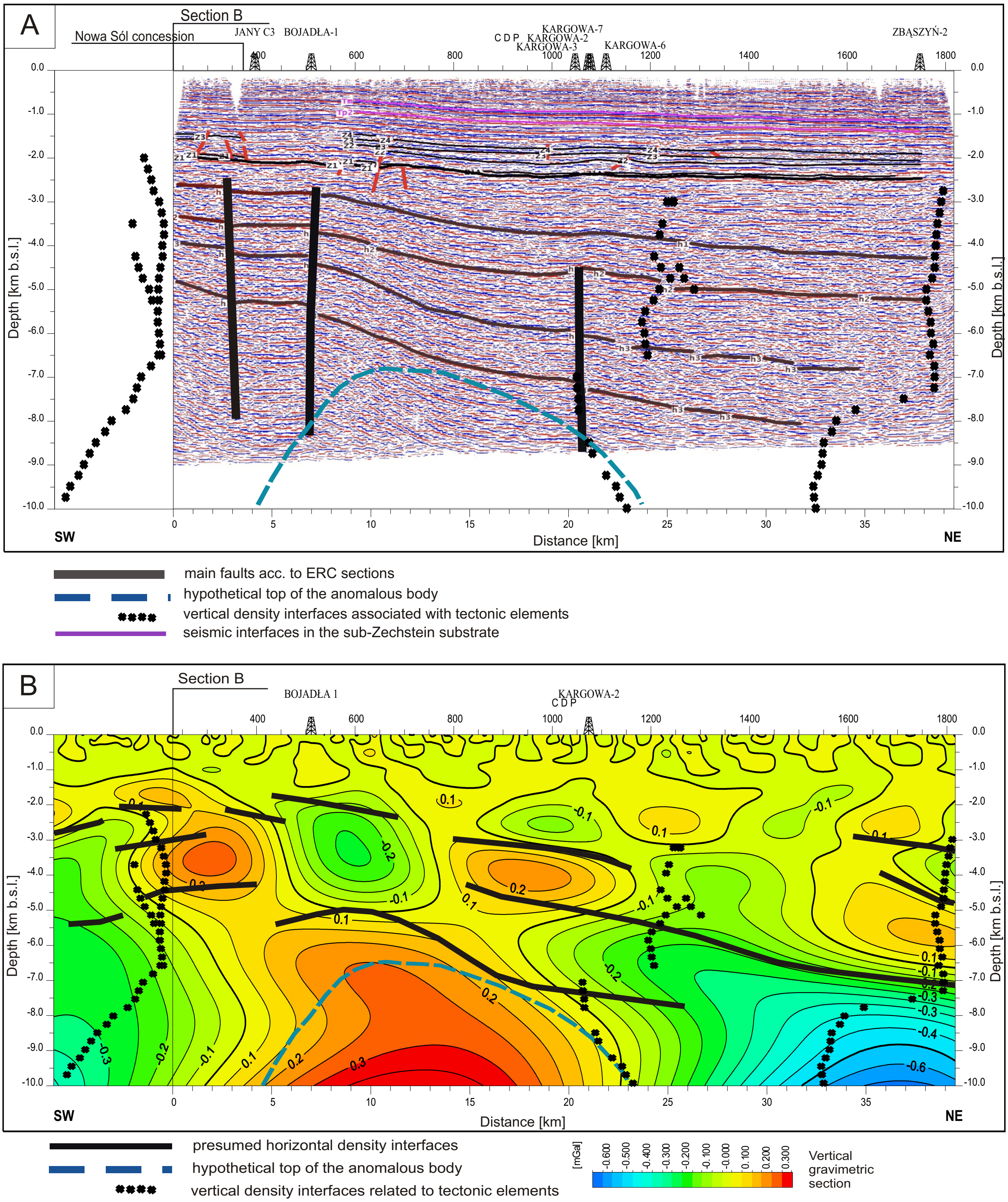


**Fig. 9. Section B of Figure 6: A – depth-based comprehensive cross-section; B – vertical gravimetric section**

For other explanations see Figure 8

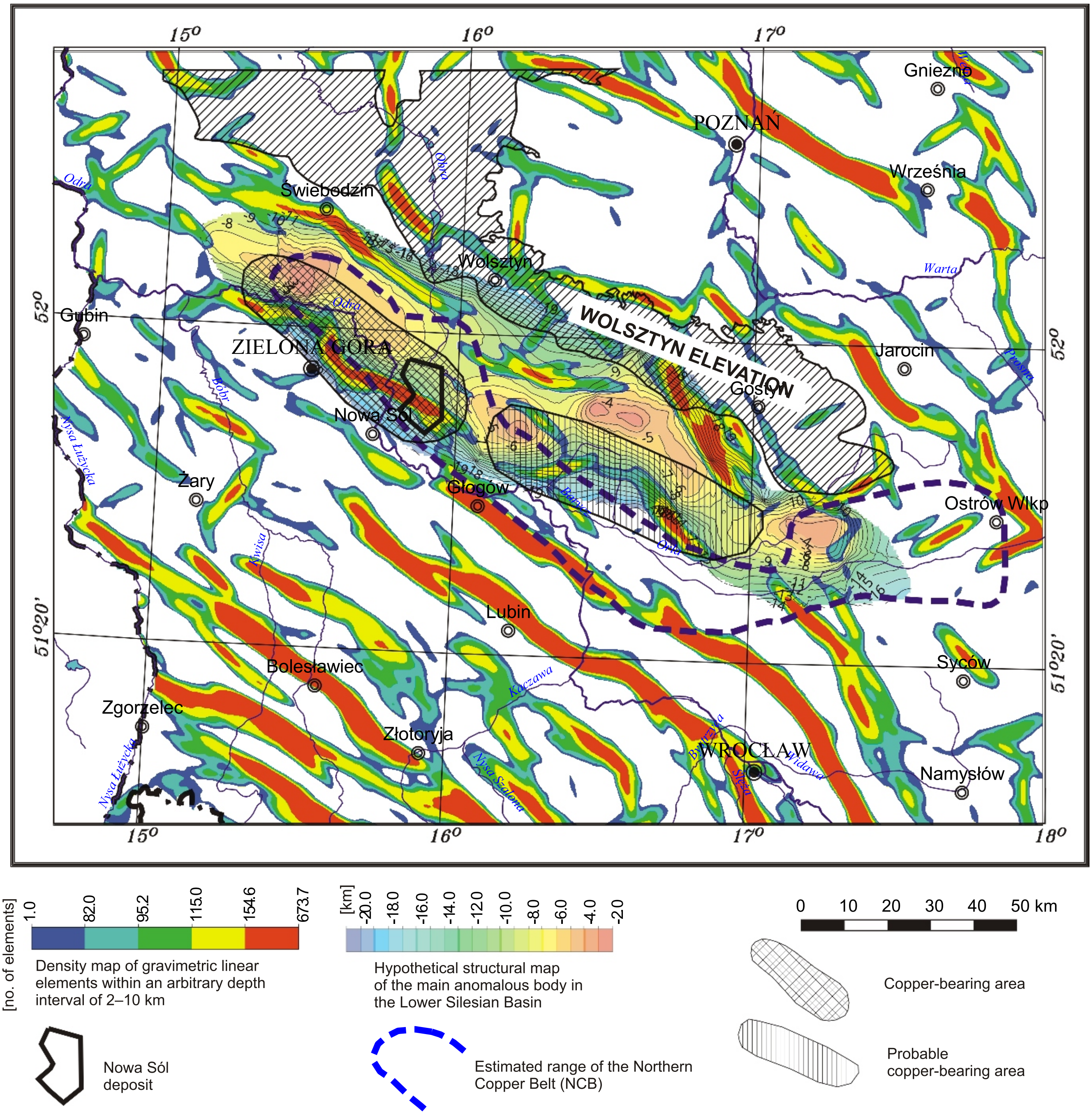


**Fig. 10. Map of copper exploration prospects in the Lower Silesian Basin**

the discovery of the Nowa Sól deposit located in a prospective zone established on the basis of mineralogical and geophysical studies. Integration of seismic, gravimetric and geological data provides a comprehensive and coherent approach, enabling the acquisition of new information from existing historical sources.

The use of historical geophysical data is a key element of effective geological research, even in spite of certain shortcomings. It allows for acquisition of important geological information while avoiding the high costs of new seismic surveying. This is critical in terms of exploration budgets, as it allows more efficient and cost-effective handling of exploration. Therefore, the application of historical geophysical data in contemporary mineral exploration constitutes a valuable and economical way of managing geological research, one which can offer valuable results and contribute to the discovery of new deposits.

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## REFERENCES


**Bhattacharyya, B.K., 1966.** Continuous spectrum of the total magnetic field anomaly due to a rectangular prismatic body. Geophysics, **31**: 97–121; https://doi.org/10.1190/1.1439767

**Dadlez, R., Marek, S., Pokorski, J., 2000.** Mapa geologiczna Polski bez utworów kenozoiku 1:1000 000 (in Polish). Państwowy Instytut Geologiczny, Warszawa.

**Dziewińska, L., Tarkowski, R., Bieńko, T., 2020.** Reinterpretation of geophysical surveys of pre-Permian basement in SW Poland: structural evolution and its implications for prospecting Cu and other ores. Mineral Resources Management, **36**: 187–216; https://doi.org/10.24425/gsm.2020.133947

**Franke, W., Żelaźniewicz, A., Porębski, S.J., Wajsprych, B., 1993.** Saxothuringian zone in Germany and Poland: differences and common features. Geologische Rundschau, **82**: 583–599; https://doi.org/10.1007/BF00212418

**Guterch, A., Grad, M., 2006.** Lithospheric structure of the TESZ in Poland based on modern seismic experiments. Geological Quarterly, **50**: 23–32.

**Kiersnowski, H., Petecki, Z., 2017.** Geology of the Zechstein basement of the Legnica-Głogów copper district (LGOM) and its surroundings: a critical overview (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **468**: 175–198; https://doi.org/10.5604/01.3001.0010.0111

**Kiersnowski, H., Peryt, T., Buniak, A., Mikołajewski, Z., 2010**. From the intra-desert ridges to the marine carbonate island chain middle to late Permian (Upper Rotliegend-Lower Zechstein) of the Wolsztyn-Pogorzela high, west Poland. Geological Journal, **45**: 319–335; https://doi.org/10.1002/gj.1189

**Kłapciński, J., Peryt, T.M., 1996.** Budowa geologiczna monokliny przedsudeckiej (in Polish). In: Monografia KGHM Polska Miedź S.A. (ed. A. Piestrzyński): 75–88. KGHM Cuprum Sp. z o.o., Lubin.

**Królikowski, C., Petecki, Z., 1995.** Atlas grawimetryczny Polski 1:500 000 i 1:750 000 (in Polish). Państwowy Instytut Geologiczny, Warszawa.

**Królikowski, C., Wybraniec, S., 1996.** Gravity and magnetic maps of Poland. Publications of the Institute of Geophysics, Polish Academy of Sciences, **273**: 87–89.

**Kudrewicz, R., 2007.** GIS-based Structural Geology for Petroleum Exploration within the Polish Permian Basin. AAPG Annual Convention 2007, Long Beach, CA.

**Linsser, H., 1968.** Transformation of magnetometric data into tectonic maps by digital template analysis. Geophysical Prospecting, **16**: 179–207.

**Markiewicz, A., 2007.** Surveying the tectonics of the Lubin-Sieroszowice deposit during its management (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **423**: 151–172.

**Oszczepalski, S., 2007.** Au-Pt-Pd mineralization in the Zechstein Kupferschiefer series on the reserved areas for copper mining (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **423**: 109–124.

**Oszczepalski, S., Chmielewski, A., 2019.** Cu-Ag Zechstein-hosted mineralization – an outline of the history and research by the Polish Geological Institute (in Polish with English summary). Przegląd Geologiczny, **67**: 587–593.

**Oszczepalski, S., Speczik, S., 2011.** Mapa występowania prognostycznych złóż miedziowo-srebrowych w cechsztyńskiej serii miedzionośnej, 1:200 000 (in Polish). Państwowy Instytut Geologiczny, Warszawa.

**Petecki, Z., 2006.** Zintegrowane modelowanie grawimetryczno--magnetyczne wzdłuż profilu sejsmicznego P4 (in Polish). Prace Państwowego Instytutu Geologicznego, **188**: 77–88.

**Petecki, Z., Rosowiecka, O., 2017**. A new magnetic anomaly map of Poland and its contribution to the recognition of crystalline basement rocks. Geological Quarterly, **61**: 934–945; https://doi.org/10.7306/gq.1383

**Petecki, Z., Polechońska, O., Cieśla, E., Wybraniec, S., 2003.** Mapa magnetyczna Polski 1:500 000 (in Polish). Państwowy Instytut Geologiczny, Warszawa.

**Rudnitskaya, D.L., Dannenberg, E.E., Belozerov, V.B., 1987.** Printsipy vydeleniya seysmotsiklitov v kontinentalnykh otlozheniyakh yury Zapadno-Sybirskoy plity v sviazi c poiskami neantiklinalnykh zalezhey nefti i gaza (in Russian). Prikladnye Voprosy Sedimentatsionnoy Tsyklichnosti i Neftegazonosnosti Nauka. Novosybirsk.

**Speczik, S., 1985.** Metallogeny of the pre-Zechstein basement of the Fore-Sudetic Monocline (SW Poland) (in Polish with English summary). Geologia Sudetica, **20**: 37–111.

**Speczik, S., 2019.** Dokumentacja geologiczna złoża rud miedzi i srebra Nowa Sól (in Polish). Zielona Góra Copper Sp. z o.o. Warsaw.

**Speczik, S., Dziewińska, L., Pepel, A., Jóźwiak, W., 2011.** Possible use of impulse seismic record for recognition of prospective deposits of copper and silver in the northern part of the Fore-Sudetic Monocline (in Polish with English summary). Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią Polskiej Akademii Nauk, **81**: 117–135.

**Speczik, S., Zieliński, K., Pietrzela, A., Bieńko, T., 2024.** Modern geochemical and tectonic exploration – the key factor in discovering the Northern Copper Belt, Poland. Processes, **12**, 1592; https://doi.org/10.3390/pr12081592

**Švancara, J., 1993.** Programm LINSSER. Bericht NLfB, Hannover.

**Švancara, J., Havir, J., Conrad, W., 2008.** Derived gravity field of the seismogenic upper crust of SE Germany and West Bohemia and its comparison with seismicity. Studia Geophysica et Geodaetica, **52**: 567–588.

**Wierzchowska-Kicułowa, K., 1984.** Geology of the pre-Permian series of the Fore-Sudetic Monocline (in Polish with English summary). Geologia Sudetica, **19**: 121–142.

**Wierzchowska-Kicułowa, K., 1987.** Geological features of the Permian basement in the Fore-Sudetic area (in Polish with English summary). Geological Quarterly, **31**: 557–568.

**Zieliński, K., Speczik, S., 2017.** Deep copper and silver deposits – a chance for Polish metal mining industry (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **468**: 153–164; https://doi.org/10.5604/01.3001.0010.0109

**Żelaźniewicz, A., Cwojdziński, S., England, R., Zientara, P., 1997.** Variscides in the Sudetes and the reworked Cadomian orogen: evidence from the GB-2A seismic reflection profiling in southwestern Poland. Geological Quarterly, **41**: 289–308.

**Żelaźniewicz, A., Aleksandrowski, P., Buła, Z., Karnkowski, P., Konon, A., Oszczypko, N., Ślączka, A., Żaba, J., Żytko, K., 2011.** Regionalizacja tektoniczna Polski (in Polish). Komitet Nauk Geologicznych PAN, Wrocław.