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Analysis of the seismic image for the Carpathians and their basement resulting from the reprocessing of 2D seismic profiles

Presentation of the of seismic image analysis results obtained by reprocessing two seismic profiles is the main aim of the presented work. The profiles are located in the marginal part of the Outer Carpathians. The mentioned profiles were reprocessed in the Seismic Department of the Oil and Gas Institute – National Research Institute in Krakow, Poland. Proper selection of both the processing sequence and parameters, as well as verification of each stage of processing by simultaneous geological interpretation, resulted in a partly different mapping of the geological structures in comparison with the previous stage. Structural interpretation based on the obtained seismic imagery provides new information that could be used for more thorough interpretation of the Outer Carpathians tectonic units, as well as detailed reconstruction of the fault zones in the analysed area.

Key words: seismic processing, structural interpretation, seismic attributes, Polish Outer Carpathians, fault zones.

Analiza obrazu sejsmicznego dla Karpat i ich podłoża, uzyskanego w wyniku reprocessingu profili sejsmicznych 2D

Głównym celem prezentowanego artykułu jest przedstawienie wyników analizy obrazu sejsmicznego, uzyskanego na podstawie reprocessingu dwóch profili sejsmicznych, zlokalizowanych w brzeżnej części Karpat zewnętrznych. Opracowana w Zakładzie Sejsmiki Instytutu Nafty i Gazu – Państwowego Instytutu Badawczego sekwencja przetwarzania, wraz z zastosowanymi parametrami, pozwoliła na uzyskanie lepszego odzwierciedlenia budowy geologicznej Karpat zewnętrznych i ich autochtonicznego podłoża. Uzyskany w wyniku zastosowanego niekonwencjonalnego podejścia do procesu przetwarzania zapis sejsmiczny cechuje się wyraźnie lepszą jakością, biorąc pod uwagę ciągłość refleksów oraz stosunek sygnału do szumu. Na przetwarzanym profilu 1, położonym w przybliżeniu prostopadle do kierunków przebiegu głównych elementów strukturalnych, uzyskano zdecydowanie lepsze efekty w postaci bardziej wiarygodnego i przejrzystego obrazu sejsmicznego dla utworów poszczególnych pięter strukturalnych. Finalna wersja profilu 2, zlokalizowanego równolegle lub skośnie do głównych elementów strukturalnych, nie odbiega znacząco od dostępnej wersji archiwalnej, a największe różnice związane są z ciągłością i kierunkami upadów poszczególnych pakietów refleksów. Uzyskany obecnie obraz sejsmiczny ukazuje więcej szczegółów budowy geologicznej tego trudnego do interpretacji rejonu. Na jego podstawie możliwe było bardziej szczegółowe prześledzenie budowy wewnętrznej utworów fliszowych, jak również uszczegółowienie interpretacji płaszczyzn dyslokacji, przecinających utwory poszczególnych kompleksów skalnych. W wyniku przeprowadzonej interpretacji uzyskano bardziej klarowny obraz podłoża zapadliska przedkarpackiego, stopniowo obniżającego się w kierunku zachodnim i południowo-zachodnim, poprzez system uskoków normalnych o charakterze zrzutowym lub zrzutowo-przesuwczym.

Słowa kluczowe: przetwarzanie sejsmiczne, interpretacja strukturalna, atrybuty sejsmiczne, Karpaty zewnętrzne, strefy dyslokacji.

Introduction

The main goal of this paper is to increase the accuracy of the representation of the geological structures in the selected region of the Carpathian area on the basis of 2D surface seismic processing. Advances in seismic processing and interpretation allow for significantly improved seismic representation for areas with complex geological structures. The processing covered two seismic profiles located in the marginal part of the Outer Carpathians in the SE part of Poland, with the directions approximately perpendicular to each other (Figure 1).

A preliminary version of the processing of the first profile, together with its interpretation, is presented in the published papers [2, 19]. The implementation of the current stage of the works included a number of tests with a full range of parameters, which were analysed on an ongoing basis by checksums and interpreted using all available geological data from the studied region. The new elements of the processing sequence applied at this stage included a more detailed approach to the filtration process and the analysis of the velocity models used in the stacking process, which made it possible to calculate the residual static corrections in selected time gates. In addition, tests were conducted on several different velocity models constructed for the purpose of post-stack time migration, which were the subject of a separate study [21].

The seismic image of the analysed profiles, obtained as a result of an unconventional approach to processing, is characterised by significantly better quality in terms of the continuity of reflections and the signal-to-noise ratio. On profile no. 1 located approximately perpendicularly to the directions of the main structural elements, such as main dislocation planes and overthrust surfaces, it was possible to obtain much better results in the form of a more reliable and transparent seismic image. The final version of profile no. 2 located parallel or diagonally to the above-mentioned structural elements does not deviate significantly from the available archival version of this profile but differs from it in details in relation to the directions of dips and the continuity of individual reflection packets.

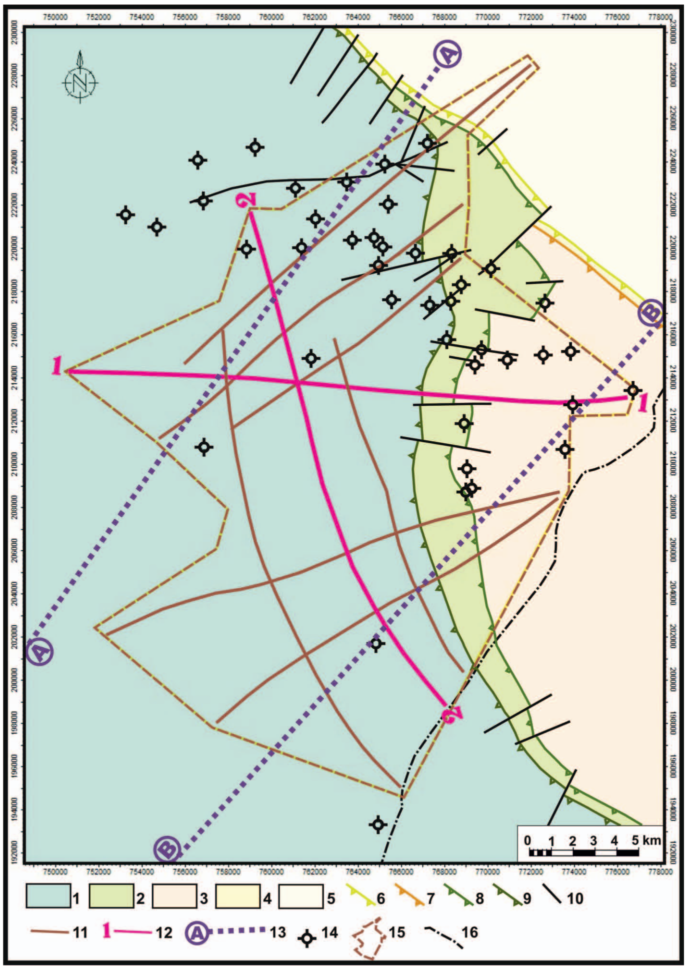

Fig. 1. The location of the reprocessed seismic profiles against the background of outcrops of the main geological units (the coverages of the geological units according to Jankowski et al. [7], Kuśmierek and Baran [10]);

1 – Skole unit, 2 – Boryslav-Pokuttya unit, 3 – Stebnik unit, 4 – Zgłobice Thrust-Sheet Belt, 5 - autochthonous Miocene, 6 – Zgłobice overthrust, 7 Stebnik overthrust, 8 – Boryslav-Pokuttya overthrust, 9 – Skole overthrust, 10 – faults, 11 – the location of seismic profiles, 12 – the location of reprocessed seismic profiles, 13 – the location of magnetotelluric profiles [17]: A – the NE part of Radoszyce–Przemyśl MT profile, B – the NE part of Maniów–Przemyśl MT profile, 14 – selected boreholes, 15 – interpretation area, 16 – state border

Outline of the geological structure of the analysed region

The detailed geological structure, which includes the different structural stages of the analysed region together with the applicable lithostratigraphic divisions for individual units, has been presented in recent publications [18–20]. Therefore, this paper briefly presents only the most important parts of the geological structure of the studied area.

The lowest structural stage present in the basement of the Carpathian Foredeep in the analysed region is a series of anchimetamorphic Neoproterozoic rocks genetically related to the Małopolska Block (Figure 2). This series is lying directly in the basement of Neogene formations; thus, the discussed area is completely free of the cover of Palaeozoic and Mesozoic deposits. The late Ediacaran age of the deposits of the discussed complex is documented by biostratigraphic research carried out on samples from numerous boreholes [3, 5, 12, 23].

The middle structural stage is a complex of Miocene clastic sediments with evaporite inserts. The sedimentary basin of the Carpathian Foredeep developed on the Carpathian foreland was a part of a large sedimentary basin stretching along the entire Carpathian arc. The discussed complex is characterized by a very large thickness differentiation resulting mainly from its erosional reduction by overlapping allochthonous tectonic units

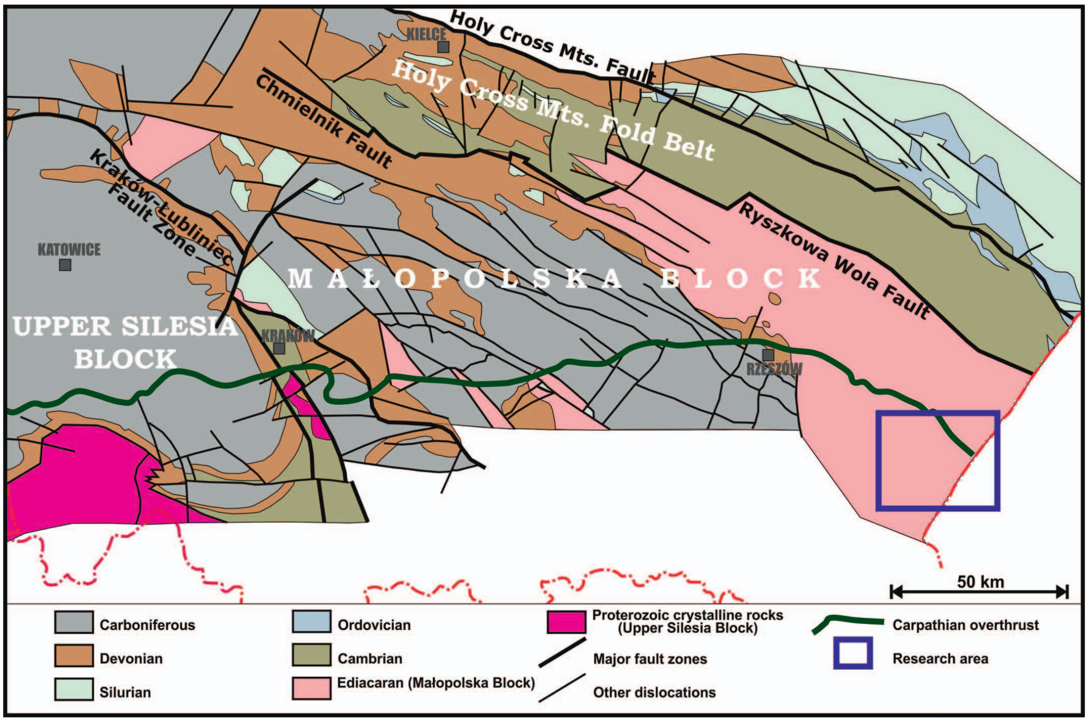

Fig. 2. Location of the research area in comparison with Poland's main tectonic units under the Permo-Mesozoic and Cenozoic cover (according to Żelaźniewicz et al. [22], partially modified)

of the Outer Carpathians, as well as from a large morphological diversity of the bottom surface of this complex [vide 18].

The highest structural stage in the analysed region is represented by allochthonous formations of the tectonic cover included in three large tectonic units: Stebnik, Boryslav-Pokuttya and Skole units. The Stebnik unit is made up of molasse Miocene formations and has a maximum thickness of more than 3,700 m (including a series of flysch olistoliths) in the analysed region. The Boryslav-Pokuttya unit is composed of a sequence of sediments formed between the Late Cretaceous to Early Miocene. Its profile contains both formations which are considered flysch sediments in traditional terms and the oldest molasse formations. Thus, it forms a structurally transitional element between the Outer Carpathians and the Carpathian Foredeep [22], although according to other researchers, these are elements of the same depositional system, which has evolved over time [6, 8]. The Skole unit, also often referred to as a Skiba unit, is composed of sediments that formed between Early Cretaceous and Early Miocene. Its thickness dramatically increases southwards, exceeding even 7,000 m in the vicinity of the analysed region. One of the most characteristic features of a flysch orogen in the analysed zone is its very intensive thrust slicing, with the tile-like arrangement of individual slices overlapping each other [9].

Very important information on the geological structure of the studied area was provided by the reinterpretation of magnetotelluric and gravimetric data by Stefaniuk [16] and Stefaniuk et al. [17] along two regional magnetotelluric profiles (Radoszyce–Przemyśl and Maniów–Przemyśl; profiles location – Figure 1). The clear contrast in resistivity between the low-resistive complex of flysch and Miocene formations and the high-resistive Neoproterozoic basement quite unambiguously determines the present morphological surface of the Neoproterozoic basement.

Processing methodology with general characteristics of the sequence used

Processing was performed in SeisSpace (ProMax) – Seismic Processing and Analysis Release 5000.10.0.1. In order to achieve this goal, a large amount of time was devoted to performing tests and selecting appropriate processing procedures and composing them into a sequence to bring the best possible results.

In processing, the following elements were of particular importance: checking the acquisition geometry, the calculation of static refractory corrections, muting, the calculation of kinematic corrections and residual static corrections, the selection of appropriate parameters of migration. After each stage of the work, a checksum was performed to perform a detailed analysis and verification of the obtained image, depending on the adopted parameters.

The processing sequence is shown in a block diagram in Figure 3. An important element of the applied processing

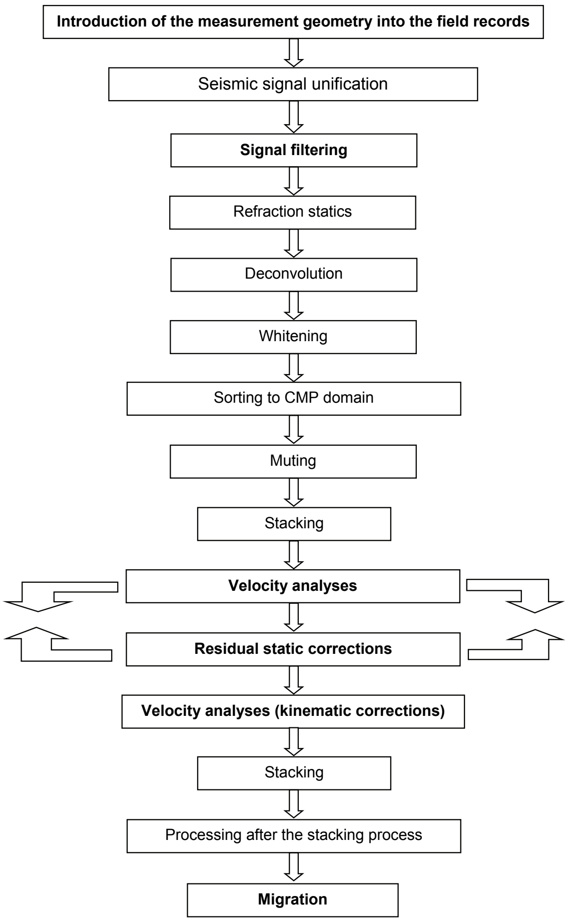

Fig. 3. Block diagram of the applied processing sequence

sequence was the elimination of linear disturbances after the geometry introduction phase by using LMO linear moveout kinematic corrections. For this purpose, algorithms were tested and applied to eliminate linear disturbances in the analysed time gates using the applied LMO correction. After the elimination of linear disturbances, an algorithm was introduced into the processing sequence to eliminate coherent disturbances recurring for more than one seismic route in the analysed time gates. Figure 4 shows an example record after the amplitude equalisation procedure and Figure 5 shows a record after the muting reduction procedures but before the deconvolution and whitening procedures.

The correct calculation of static corrections has the dominant influence on the reliable mapping of a geological medium. These corrections are applied to the recorded seismic data in order to eliminate the influence of the surface elevation, as well as both velocity and thickness changes in the subsurface zone. The so-called first impulses are used to determine the changes in the velocity and thickness in the subsurface zone. On their basis, we obtain information about the number of refractors (reflective boundaries). In the analysed case, it was necessary to test the algorithms include a greater number of refractors, which resulted in a much better way of solving the issue of statics.

An important element in the process of summation and kinematic corrections phase was testing the percentage

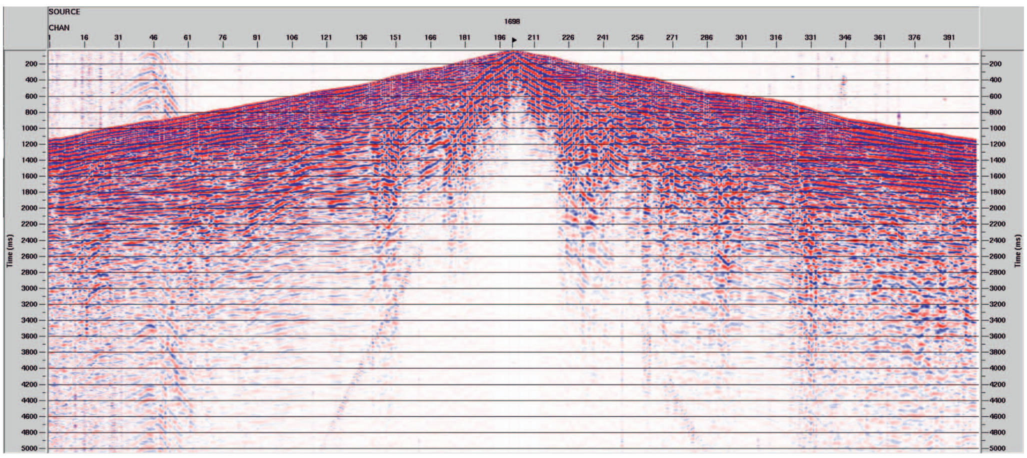

Fig. 4. Example seismic record after amplitude equalisation procedure

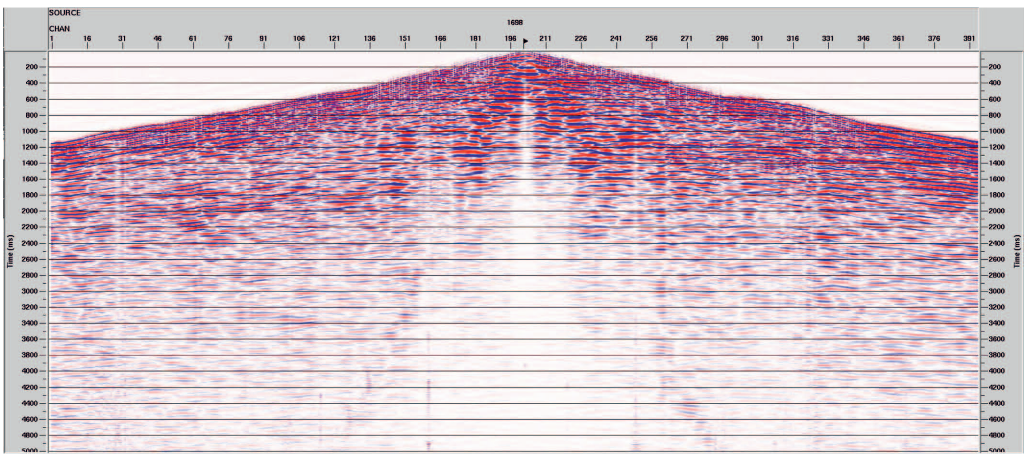

Fig. 5. Example seismic record after the above-mentioned filtration procedures

distribution of velocities on CMP collections in order to obtain the best possible wave image on the stacked seismic section. The analysis of the stacking velocities used in the summation process (stacking on CMP collections) made it possible to calculate the residual static corrections in time gates selected on the basis of the analysis of reflection angles in the seismic record. The resulting seismic section was processed after the summation process (Figure 6).

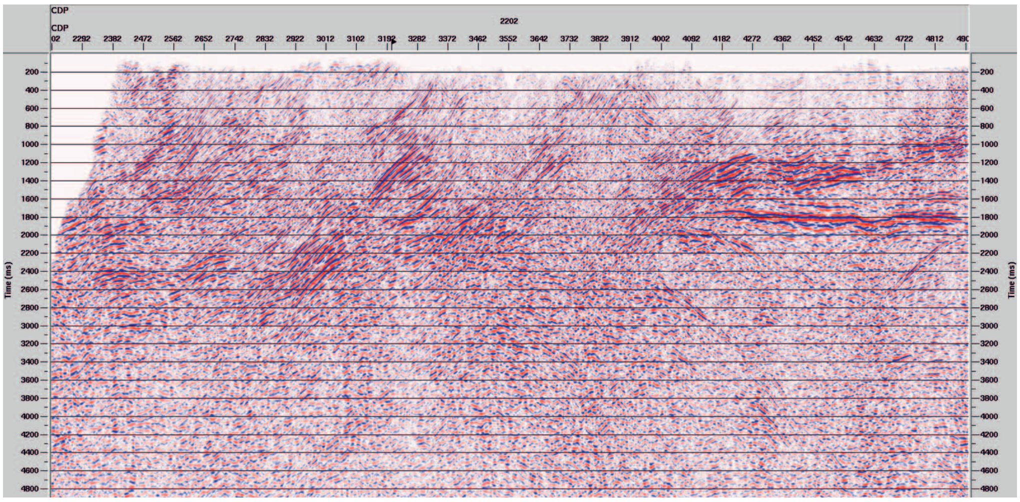

Fig. 6. Seismic section no. 1 after the stacked process

An important element was also the application and testing of different velocity models for post-stack time migration, which were the subject of a separate study [21]. In order to determine the optimal velocity model for the migration for the purposes of this paper, an entire series of calculations and tests were carried out on several velocity models. The next step was the selection of migration parameters, such as the range of the seismic ray, the aperture and the dominant frequency. On the basis of analyses of the images of the obtained seismic sections, a velocity model which was considered the most optimal in terms of the representation of the geological structure of the region was finally selected (Figure 7). The final migration image obtained using the selected velocity model (Figure 7) is shown in Figure 8.

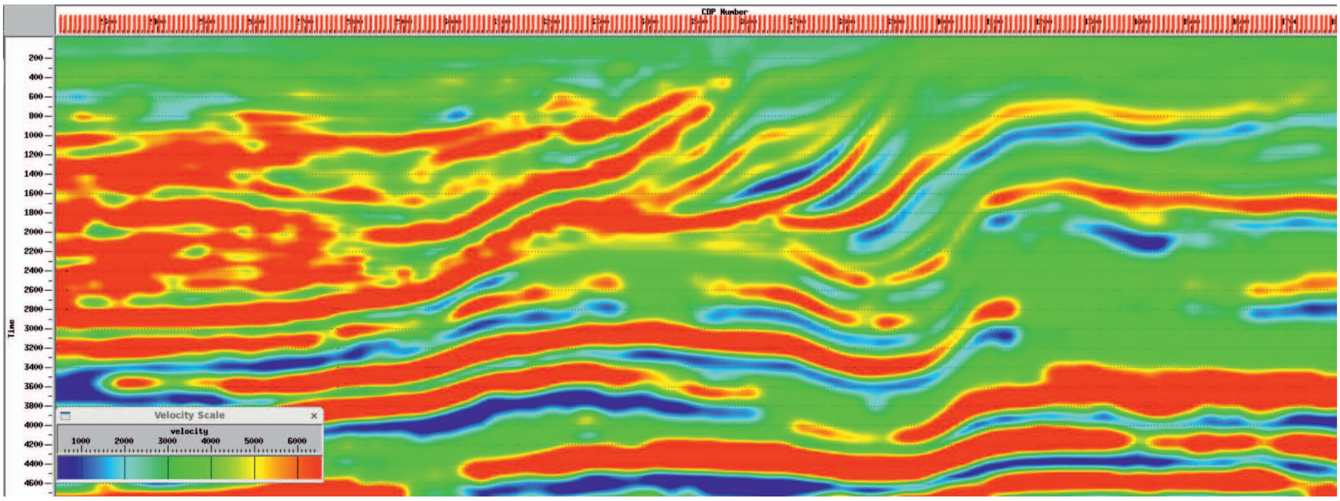

Fig. 7. Velocity model for profile no. 1 used for post-stack migration

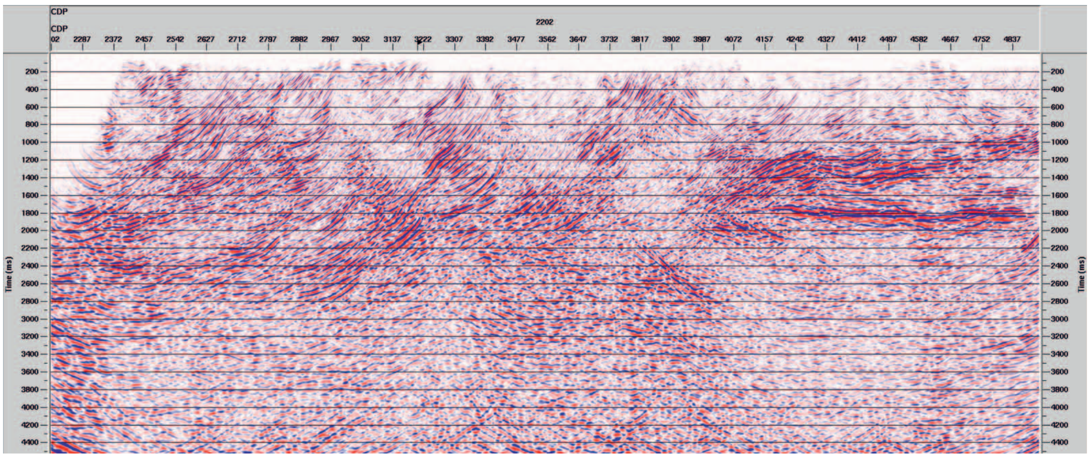

Fig. 8. Seismic section no. 1 after post-stack time migration

Results of the analysis of the obtained seismic image based on seismic attributes

As mentioned above, two seismic profiles with the directions approximately perpendicular to each other were processed (Figure 1). The profile named profile no. 1 is located approximately perpendicularly or diagonally to the course of the main structural elements in the region, therefore it better reflects the complex geological structure of the analysed region. This profile produces a visually better image in terms of both the continuity of reflections and the signal-to-noise ratio. In the case of profile named profile no. 2, such a significant improvement in wave image quality was not achieved despite the use of the above-mentioned velocity models. The main cause for this is probably the location of the profile parallel or diagonally to the course of the main elements of the geological structure.

Selected versions of seismic attributes (instantaneous phase, envelope, structural azimuth, chaos, variance) were used in the analysis of the quality of the obtained seismic image and in the structural interpretation phase (for more precise positioning of interpreted seismic boundaries and fault planes). Due to the limited volume of the article, only some of the mentioned attributes will be discussed.

Profile no. 1

On the basis of a detailed analysis of the seismic image obtained as a result of the applied advanced processing procedures, it was found that the obtained image was much more continuous and transparent than in the archival version (see Figure 2A in [19]). The most visible differences in the seismic image manifest themselves in the form of significantly different angles of inclinations of individual reflection packets (especially in the western part of the profile) and in the form of changes in the degree of continuity and amplitude of the reflections. The differences in the seismic image are generally discernible within all the structural stages present in the geological profile of the analysed region but are most emphasized in the flysch formations of the Skole and Boryslav-Pokuttya units, as well as in the complex of sediments of the Stebnik unit (Figure 9).

On the basis of the final seismic image, it was possible to carry out a more detailed structural interpretation within the flysch formations of the Skole unit. Additional surfaces in the form of thrust fault planes of successive thrust sheets were correlated. Moreover, on the basis of obtained seismic results, the additional probable dislocations were interpreted (in relation to first stage [1, 19]). These faults intersect the Neoproterozoic basement and then suppress within the autochthonous Miocene complex (Figure 9).

Variance (edge method) is the attribute that enables tracing the continuity of reflections. This attribute uses local variance as a measure of seismic signal unconformity [15]. It is mainly used for the detection of discontinuity zones of tectonic or stratigraphic nature, such as faults, angular unconformities, larger sequence boundaries, but also for the detection of the channel zones [e.g. 4, 13, 14]. In the examined case, the attribute *variance* highlights the continuity of reflections in the formations of the autochthonous Miocene and the lowermost part of the Stebnik unit in the eastern part of the profile in question, as well as the presence of continuous reflection packets within the flysch formations of the Carpathian units in its central part (Figure 10). At the same time, the zones with the greatest tectonic disturbance in the area of the Stebnik unit were highlighted (indicated using arrows in Figure 10). Within the flysch formations, there are also zones with a noticeably higher disturbance, along which the main dislocation planes

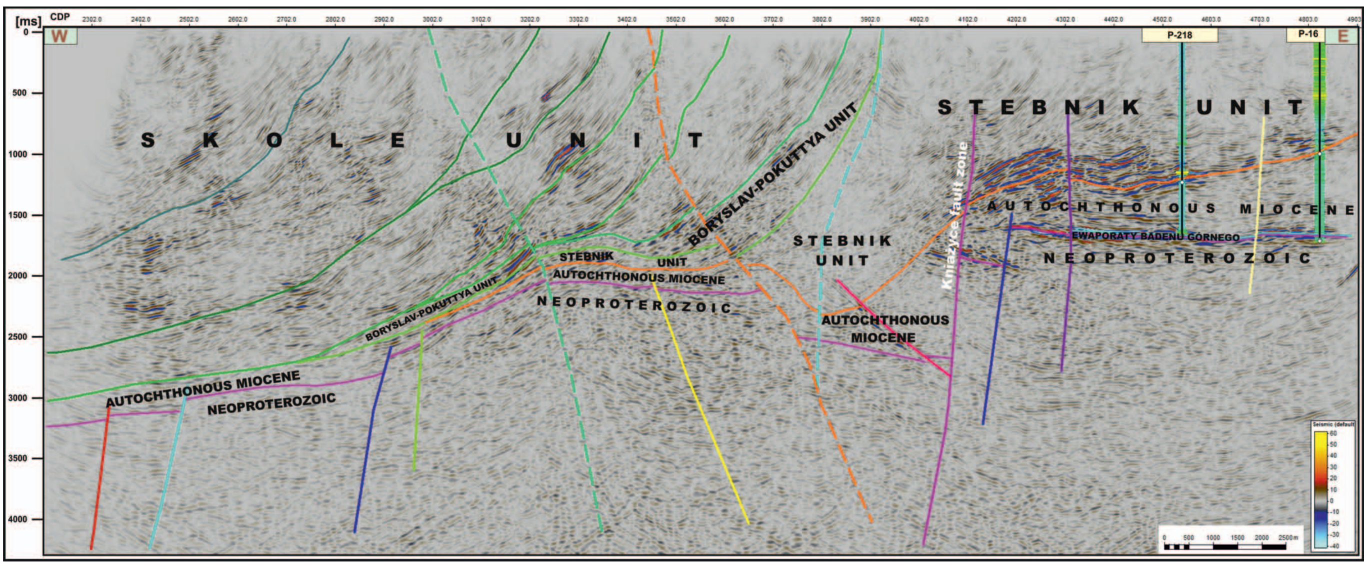

Fig. 9. Geological interpretation of seismic profile no. 1 after reprocessing

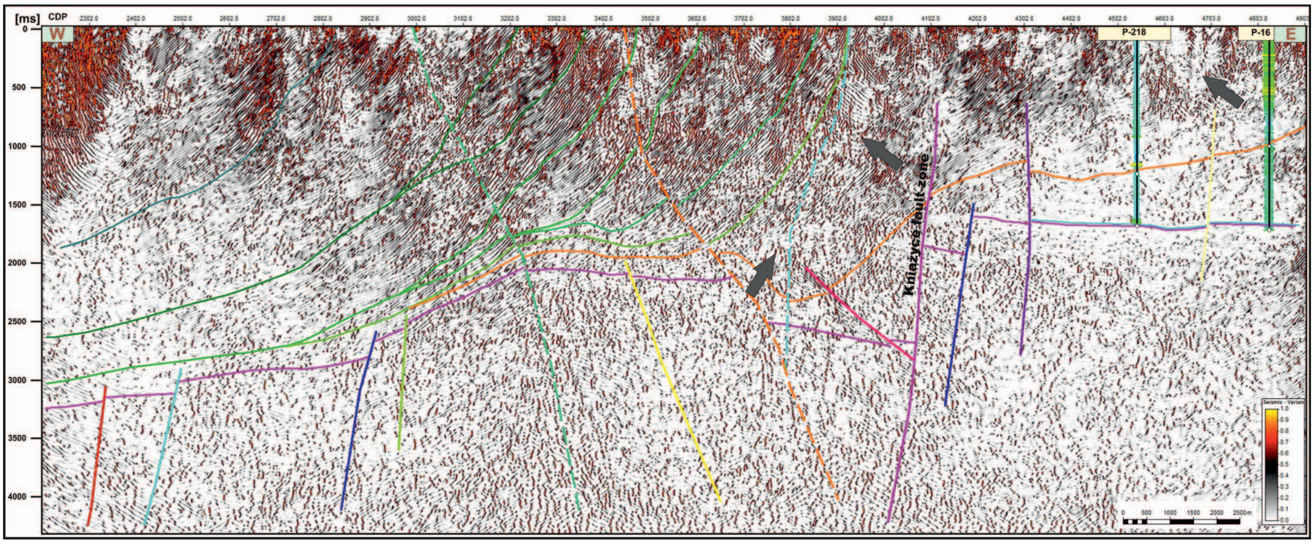

Fig. 10. Variance attribute – seismic profile no. 1; arrows indicate the most disturbed zones within the Stebnik unit

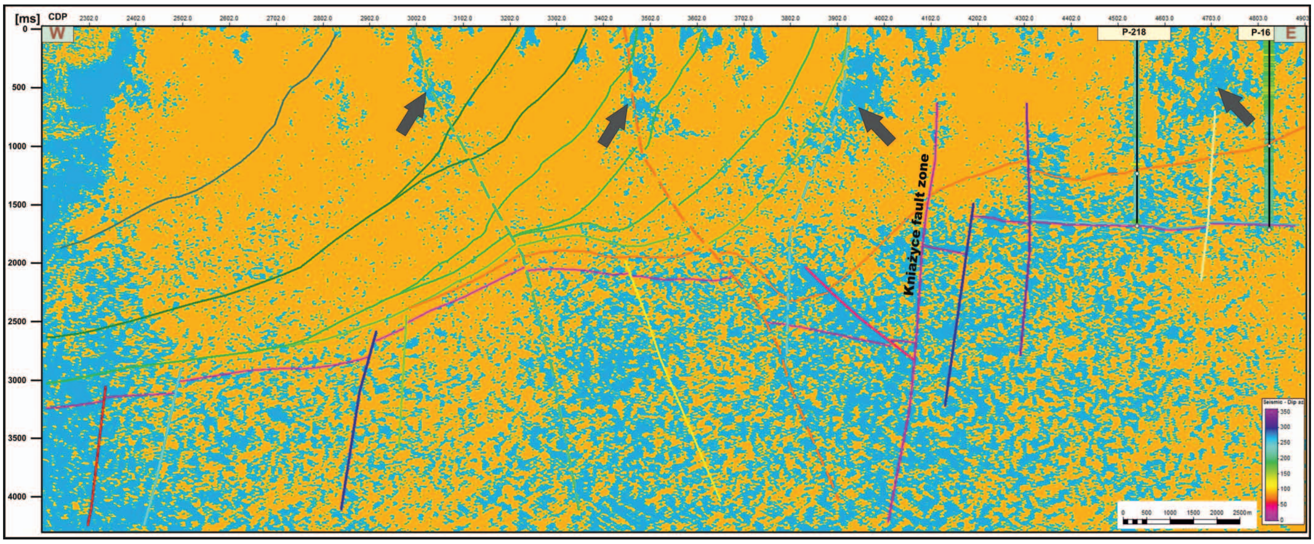

Fig. 11. Local structural azimuth attribute – seismic profile no. 1; arrows – the zones of discontinuity or disturbance in the Carpathian flysch formations and the Stebnik unit

were correlated. The analysis of the seismic image in the discussed attribute version reveals the strongly anisotropic nature of the Neoproterozoic basement (and to some extent also the overlying Miocene complex), especially in the zone located in the footwall of Kniażyce fault system, as well as in the zone of the horst in the central part of the analysed profile (Figure 10). Moreover, the nature of the seismic record in the extreme western part of the interpreted profile, where the bottom surface of the flysch formations decreases considerably, indicates its much lower reliability, compared to the other parts of the profile.

Further information is provided by the analysis of the local structural azimuth attribute, which shows the variability of the spatial distribution of azimuths, thus indicating and detailing the course of the discontinuity or tectonic loosening zones [11]. The analysis of the seismic profile in the version of this attribute confirmed the existence of discontinuity zones within the formations of Skole and Stebnik units (indicated with arrows in Figure 11), which were mentioned during the analysis of the *variance* attribute.

Profile no. 2

The applied processing procedures partly improved the seismic image in the profile no. 2, but to a much lesser extent than in profile no. 1 described above. The differences in the seismic image are manifested mainly in the variable angles of dips of individual reflection packets (especially in the northwestern and central part of the profile), as well as in the form of changes in amplitude and the continuity of reflections (Figure 12). These differences are more or less discernible within the area of all the structural stages present in the geological profile of the analysed region. However, the greatest changes were observed in the topmost part of Neoproterozoic basement and in the autochthonous Miocene complex, where the

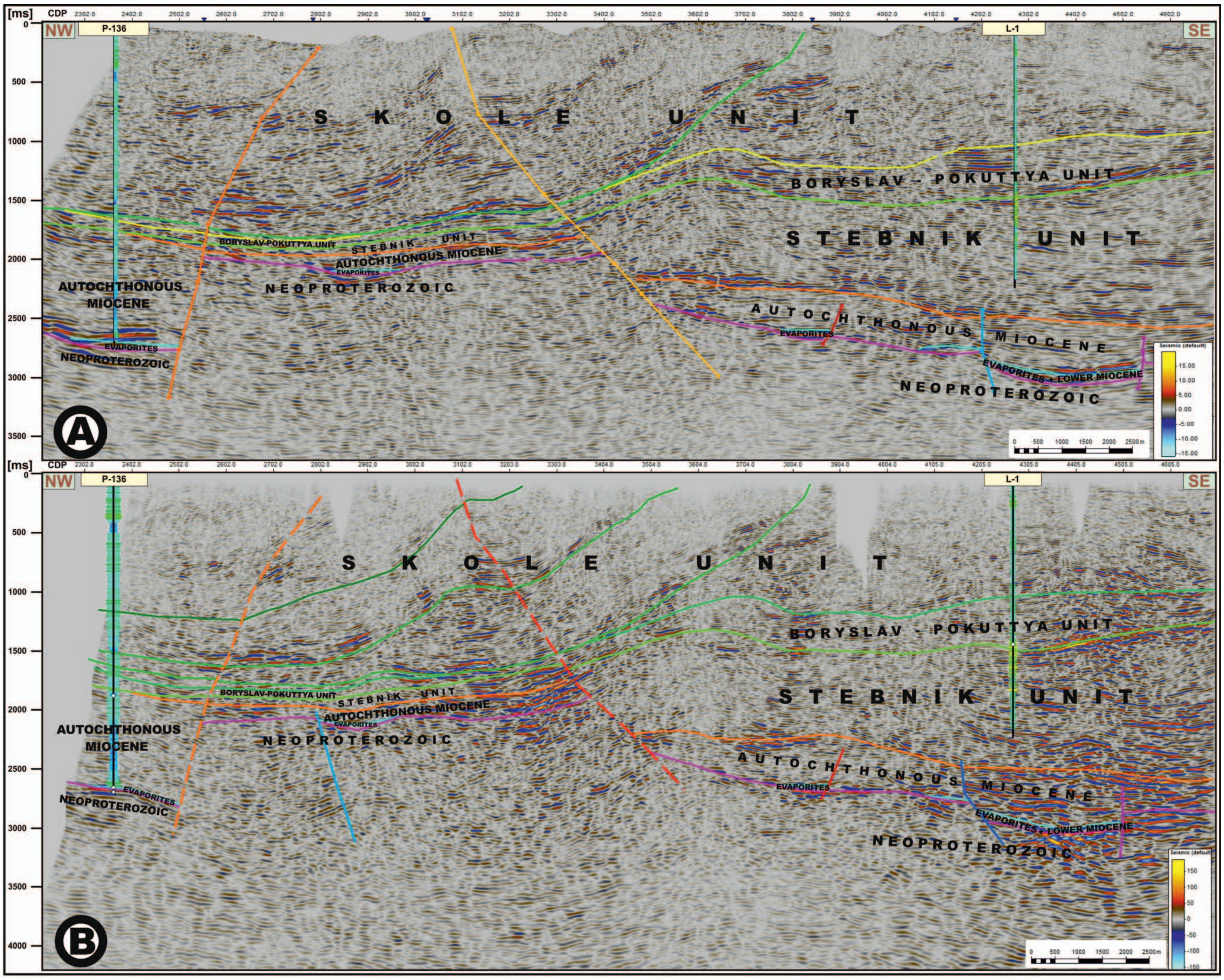

Fig. 12. Comparison of the time versions of profile no. 2: A – archival version (pre-stack); B – INiG – PIB post-processing version (post-stack)

difference in the inclination of individual reflection packets is often quite significant.

The variance attribute version of this profile highlights the zones with a bit better horizontal continuity in the autochthonous Miocene formations and some part of the Carpathian units (Figure 13). In the north-western part of the analysed profile, below 2500 ms, there is a packet of more continuous and distinct reflections determining the erosion boundary of Neoproterozoic/Miocene and the Miocene series of evaporites. Zones with a higher degree of disturbance are located mainly in the SE part of the profile within the Stebnik unit (indicated with arrows in Figure 13). As in the case of the previous profile, a very complicated image of the Neoproterozoic basement with multi-directional dips was confirmed too, which indicates its tectonic complexness.

The image of the local structural azimuth attribute is not as clear as on the previously discussed profile no. 1. This image includes the confirmation of the disturbed zones in the profile of the Stebnik unit in the SE part of the section (black arrows in Figure 14). The zones of discontinuity within the Carpathian tectonic units are not as clear as in profile no. 1. The two main dislocation zones, interpreted on the basis of correlations with adjacent profiles, limit the horst-elevated Neoproterozoic basement block, and then continue towards higher structural units, mainly as strike-slip faults (Figures 12–14). Additionally, the analysed profile contains a zone marked with red arrows (Figure 14), which also shows the character of a distinct discontinuity zone, which is even more visible in the image of the envelope attribute (the zone indicated with arrows in Figure 15).

In the envelope attribute, the above-mentioned zones with an increased degree of discontinuity are characterized by a decrease in the absolute amplitude value (Figure 15). On the other hand, high-amplitude reflections in the lowermost part of the Miocene complex are most often associated with evaporites. The ranges of the evaporite sediments are confirmed by drill hole profiles or interpreted on the basis of a seismic image analysis [18].

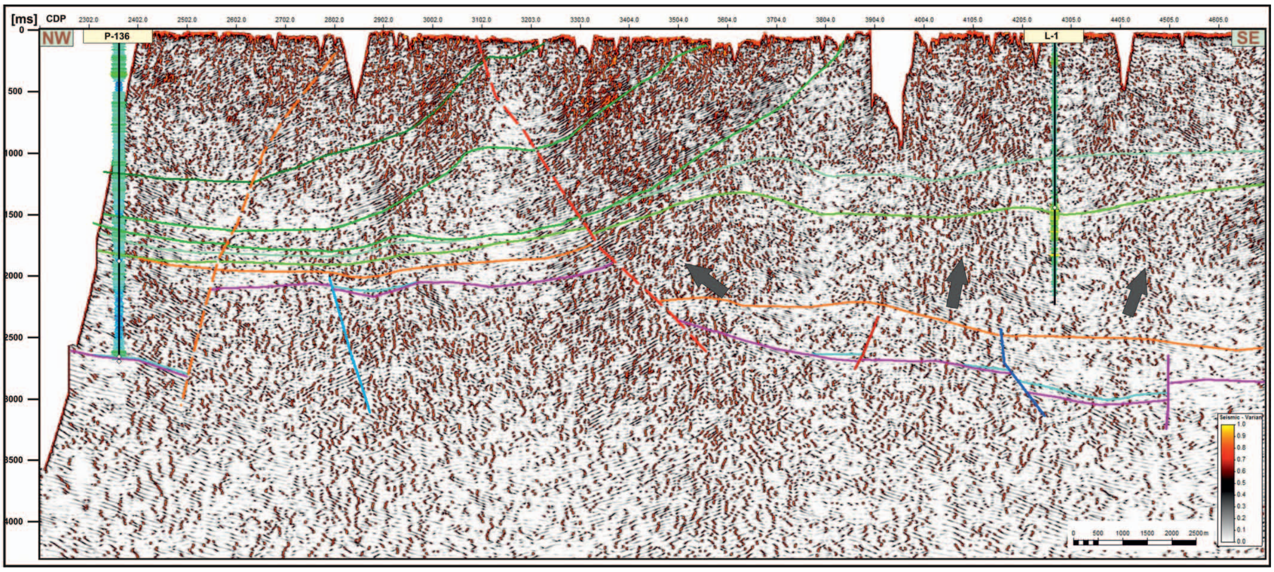

Fig. 13. Variance attribute – seismic profile no. 2; arrows indicate the most disturbed zones within the Stebnik unit

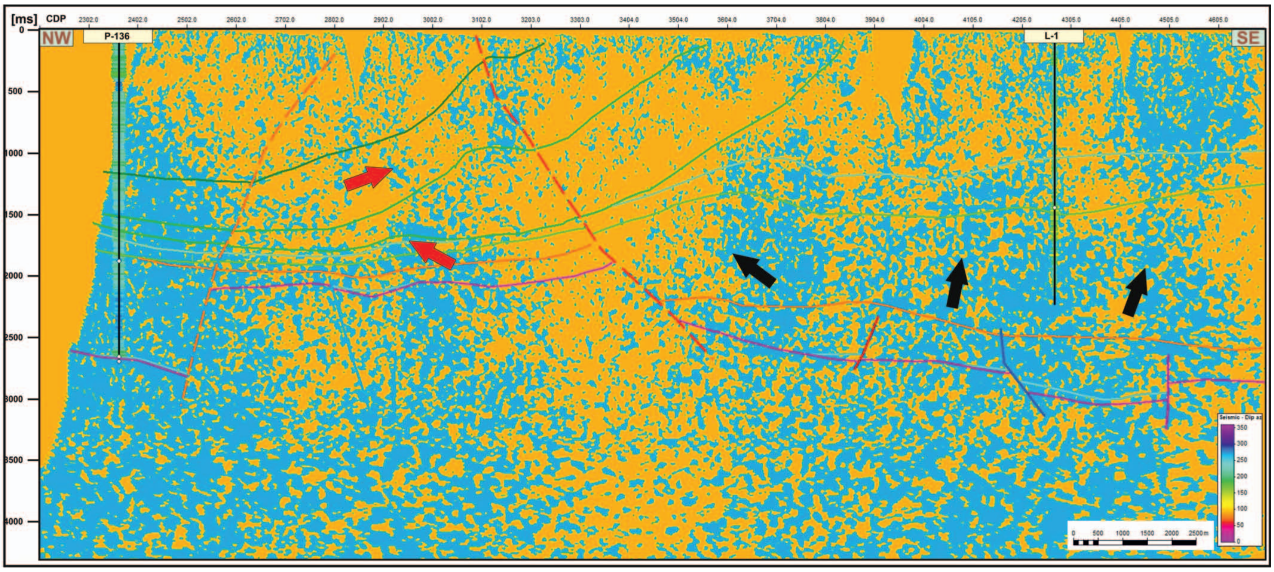

Fig. 14. Local structural azimuth attribute – seismic profile no. 2; black arrows – zones with greater disturbance within Stebnik unit; red arrows – the probable zone of discontinuity in the Carpathian flysch formations

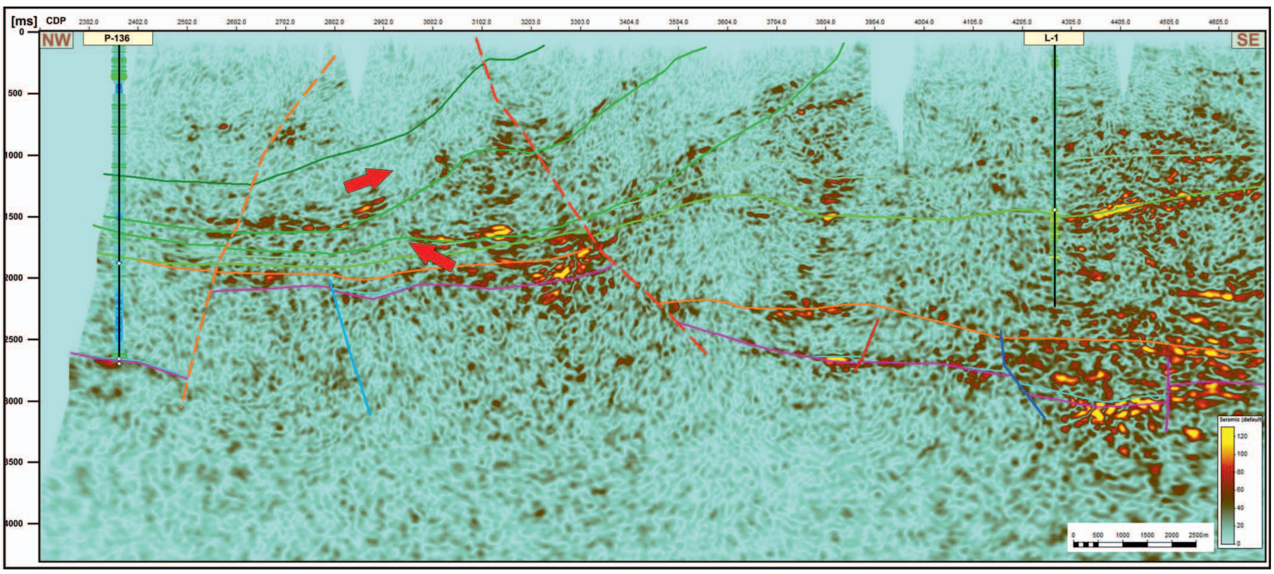

Fig. 15. Envelope attribute – seismic profile no. 2; red arrows – the probable zone of discontinuity in the Carpathian flysch formations

Possibility for detailing the tectonics of the analysed area

The most important information providing the basis for developing a new concept of structural interpretation for the examined region was provided by the version of seismic profile no. 1, after the processing carried out in 2016 at the Seismic Department of the Oil and Gas Institute – National Research Institute [1, 2]. A preliminary version of the structural interpretation based on the aforementioned processing results of this profile is presented in earlier publications [18, 19]. As part of this stage, the interpretation was further detailed based on the final post-stack version of the above-mentioned seismic profile (Figure 9) as well as the currently processed profile no. 2 (Figure 12B). The more reliable representation for the topmost part of the Neoproterozoic complex, together with the lowermost part of the autochthonous Miocene complex, allowed for a detailed interpretation of the dislocation system for these structural stages. In addition, on the basis of the obtained seismic image, it was possible to analyse, in more detail, the internal structure of the flysch formations belonging to the Skole unit through the correlation of additional seismic horizons corresponding to the thrust fault planes of individual thrust sheets (Figures 9, 12B).

The results in the form of a seismic image obtained already in the first stage on profile no. 1 provided the basis for the interpretation of regional dislocations intersecting the flysch formations diagonally to the main surfaces of overthrusts and then passing through the autochthonous Miocene complex and penetrating down into the Neoproterozoic basement [18, 19]. These elements connect deep dislocations from the Neoproterozoic basement with the discontinuity zones in flysch formations. The character of the seismic record of the above-mentioned fault zones on the interpreted seismic profiles, including in particular their contacts with the formations of individual units in the geological profile of the examined region, indicates their very old tectonic genesis. These fault zones have certainly been repeatedly reactivated in their history.

Most of the previously interpreted dislocations found their confirmation in the final seismic image, and only minor changes, which resulted from minor differences in the image, were made in their course. Larger differences occur only in the western part of profile no. 1, because the seismic image changed the most in this belt (especially in the lowermost part of the flysch complex). The Neoproterozoic basement is markedly hollowed in this zone, and the thickness of the flysch cover, which belongs mainly to the Skole unit, grows quite sharply. Both within the tectonically elevated block in the central part of the profile and within the tectonically lowered zone in its western part, additional fault planes were interpreted, which intersected the Neoproterozoic basement and were suppressed within the Miocene complex (Figure 16). The analysis of the final seismic version after processing did not provide grounds for the confirmation of the presence of a reverse fault in the western part of the discussed profile, which had been interpreted on the basis of the earlier processing version [19].

The final version of interpretation corresponds very well to the regional trend of the Precambrian basement configuration, which was presented by Stefaniuk [16] and Stefaniuk et al. [17] on the basis of the interpretation of the regional magnetotelluric profile (Maniów–Przemyśl). The Miocene/Neoproterozoic boundary is unambiguously indicates by strong resistivity contrast between the low-resistive complex of flysch and Miocene formations and the high-resistive basement made up of anhimetamorphic rocks of the Late Ediacaran. The comparison of the interpretation of the magnetotelluric profile (Figure 17B) with the interpretation of the final versions of the reprocessed seismic profiles no. 1 and 2 (Figure 17A) reveals a very large similarity in the configurations of the Neoproterozoic surface. Attention is also drawn to the quite similar direction and arrangement of dislocation lines, interpreted completely independently on the images obtained by using dif-

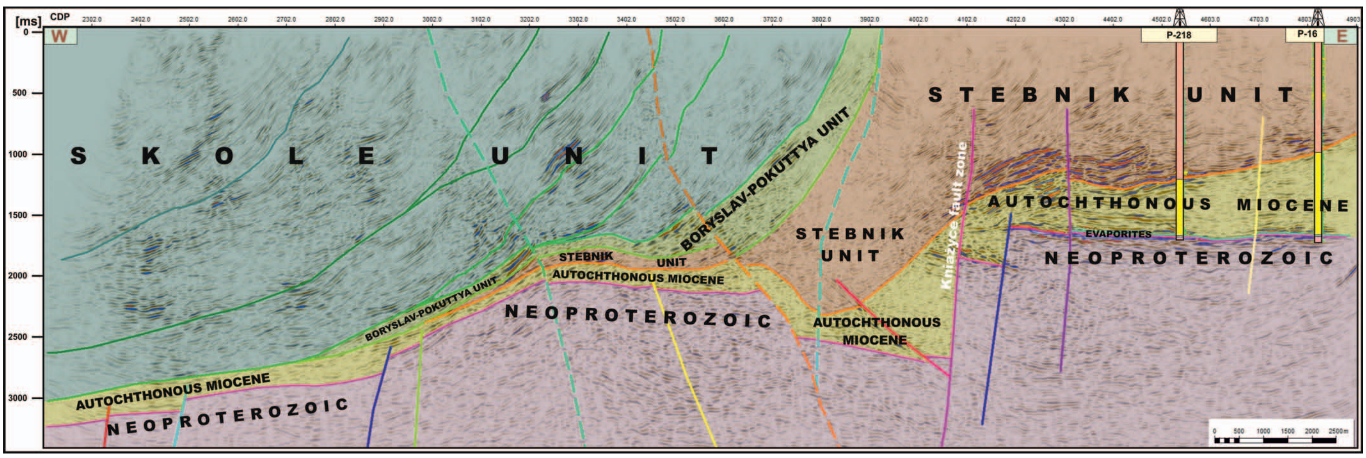

Fig. 16. The geological model of the research area against the seismic time section no. 1

ferent geophysical methods. Several tectonic blocks, separated by the planes of regional dislocations, can be interpreted in the examined area on the basis of magnetotelluric and seismic sections [18, 20] (Figure 17).

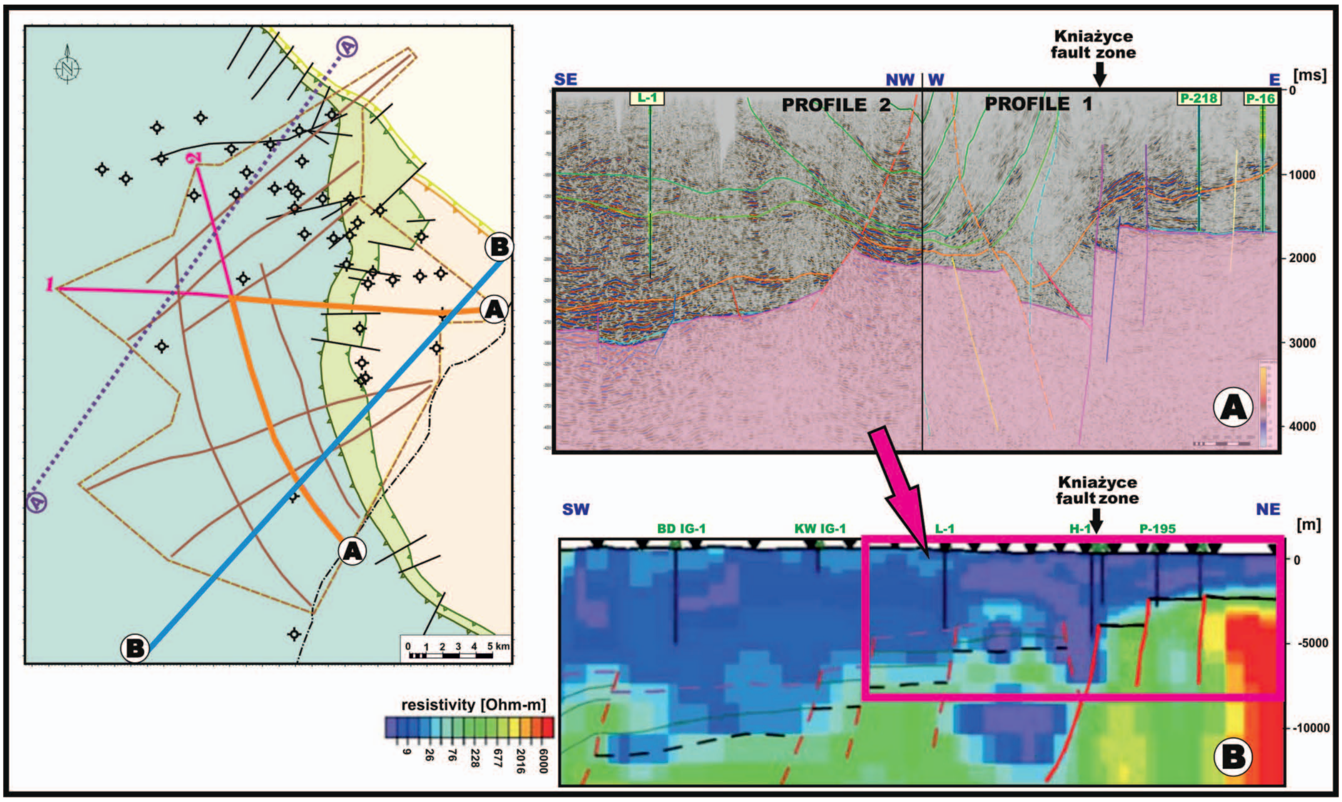

Fig. 17. Comparison of the interpretation of the top surface of the Neoproterozoic complex on profiles 1 and 2, performed within the presented subject (A) with the interpretation of the magnetotelluric profile of Maniów–Przemyśl by Stefaniuk et al. [17] (B)

Summary and conclusions

The processing procedures used as part of the presented subject were tested on two 2D seismic profiles with directions that were approximately perpendicular to each other (Figure 1). One of the most important stages, which was given the greatest amount of time, was the selection of the velocity model for the post-stack time migration procedure.

The unconventional approach to seismic processing and the construction of the velocity model for time migration resulted in a visibly better image quality in terms of both the continuity of reflections and the signal-to-noise ratio. The most interesting effects were achieved on profile no. 1 because the current seismic image shows more details of the geological structure of this difficult-to-interpret region, allowing for a more precise correlation of thrust fault zones within the Carpathian tectonic units and more detailed reconstruction of dislocations within the uppermost part of the Neoproterozoic complex.

On the basis of the conducted interpretation, it was possible to obtain a relatively clear picture of the Carpathian Foredeep basement, which gradually decreased in the westwards and south-westwards through the system of normal and strike-slip faults. This model corresponds very well to the regional trend of the Precambrian basement configuration presented by Stefaniuk et al. [17] based on the interpretation of regional magnetotelluric profiles (Figure 17). This very similar system of dislocations, independently interpreted on the basis of images obtained as a result of different geophysical methods (magnetotelluric and seismic) provides very important information on the configuration, depth and block nature of the Neoproterozoic basement in the studied area.

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