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SEISMIC IMAGE OF THE TOP OF JURASSIC STRUCTURE UNDER POLISH OUTER CARPATHIANS IN THE ZONE SOUTHEAST OF KRAKOW

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Abstract: The modeling is a method well supporting seismic research during projecting, processing and interpretation of seismic data. In the presented paper, the multivariate seismic modeling was used for evaluation of influence of changing structure of Carpathian flysch on the seismic image of Upper Jurassic (Malm) rocks. This research investigated Podgrodzie structure in the marginal part of the Outer Carpathian fold-and-thrust-belt. The gas deposits in this area are localized on tectonic uplifts, bounded by thrust dislocations.The complex structure and tectonics of the Carpathian flysch makes the interpretation of seismic image of the reservoir Upper Jurassic carbonates somewhat difficult. The poor recognition of velocities of flysch sequences makes this interpretation even more difficult. The multivariate seismic modeling is necessary in this situation. It allows evaluation of influence of selected model elements of the originating wavefield. It is possible finding the model correctly approximating investigated orogen by matching registered and theoretical field. The Outrider (*Divestco Inc*.) and Omega (*WesternGeco)* system were used for offset and zero-offset modelings. The performed modeling shows that influence of changing velocity and geometry of reflecting boundaries on underlying stratigraphic stages is insignificant. This influence is only significant in the zones of steep dipping flysch layers where large horizontal contrast of velocity significantly influences the seismic image of Jurassic rocks. Outside these zones the seismic image of the top of Jurassic reliably restores the real boundary. The obtained results show that the multivariate seismic modeling is a method, which can be used with good results, under the complex seismogeological conditions. The modeling could be also helpful evaluating the reliability of register seismic data.

Keywords*:* Jurassic, Carpathians, structure, seismic modeling

1. Introduction

The problems of identification and correlation of lithostratigraphic boundaries exists in the complex structural regions, like Polish Carpathians and their foredeep. The multivariate seismic modeling is a valid method to solve these problems (Pietsch et al. 2007a, Frankowicz et al. 2008a). Changing possible basic seismogeological model and calculating theoretical field for modified models allows evaluating influence of selected model elements on originating theoretical field as well as finding most probable model correctly approximating investigated orogen by matching registered and theoretical field. This modeling is very important in exploration and production of hydrocarbons in the marginal part of Polish Carpathians (Pietsch et al. 2004, 2007b, 2008; Kobylarski et al. 2007). The proper modeling of seismic images helps locating oil and gas deposits in the Mesozoic basement under thrust allochthonous flysch sequences. This research investigated marginal part of the Outer Carpathian fold-and-thrust-belt southeast of Krakow in the Polish Oil and Gas structure Podgrodzie, Kamyk – Niepołomice area.

2. The geological background

The oldest rocks in the area southeast of Kraków are represented by Precambrian phyllites covered by Lower Cambrian sandstones and mudstones, Lower Devonian clastics, Middle and Upper Devonian carbonates, Lower Carboniferous carbonates, Upper Carboniferous coal-bearing series and Permo-Triassic red beds. Lower Jurassic rocks are represented by clastics, mainly claystones and mudstones with intercalations of sandstones. The Middle Jurassic claystones, mudstones, marls and sandstones with coaly layers are covered by Upper Jurassic carbonates, 200 - 400m thick. The Oxfordian limestones and dolomites with cherts belonging to Łękawica and Borzęta formations (Golonka 1978), pass into calcareous-marly Oxfordian-Kimmeridgian Niwki Formation and Tithonian Pilzno and Ropczyce formations composed of organodetrical, organogenic, oolitic, detritical, pelitic limestones, dolomites and marls (Moryc and Morycowa 1976; Golonka 1978; Moryc 2006a; Matyja 2009). The Upper Jurassic carbonates are often fractured and cavernous, this features enhance their reservoir properties (porosity and permeability). The Lower Cretaceous rocks are missing in this area. The development of Upper Cretaceous deposits depends upon the post-Jurassic morphology, formed by tectonic and erosional processes. The Cenomanian glauconitic sandstones and near-coast conglomerates fill erosional depressions reaching 110m in thickness. Turonian and Senonian limestones with cherts, marly limestones and sandy limestones with sandstones are more widespread, their thickness varies from 0 to 90 m. They were removed by latest Cretaceous- Paleogene erosion. The Miocene molasse 300 – 1000m thick complex, covering Mesozoic, contains Badenian (Serravalian – Langhian) clastics and evaporites (Florek et al. 2006).

The Carpathian orogen is thrust over the Miocene complex. It is composed of three imbricated tectonic units (nappes). The Zgłobice unit is built of Neogene folded formations representing Carpathian foredeep molasse (Florek et al. 2006; Ślączka et al. 2006). The 27 – 595 m thick Sub-Silesian Nappe is composed of Lower Cretaceous – Paleogene, pelagic, and flysch, mainly shaly deposits. The uppermost Silesian Nappe is built of few kilometers thick flysch represented by Lower Cretaceous Hradište, Veřovice, and Lhoty Formations, Upper Cretaceous Godula and Istebna Formations, Paleogene variegated shales, Hieroglyphic Beds (Rožnov Formation), Globigerina Marls, Menilitic Beds and Krosno Formation.

Miocene and Mesozoic rocks constitute an interesting hydrocarbon exploration target in the Carpathian/foredeep area southeast of Krakow. Mudstone-claystone deposits with sandstone intercalations form main Miocene reservoir horizon. The Cenomanian sandstones, often together with uppermost part of Upper Jurassic cavernous limestones and dolomites build Mesozoic reservoirs. Deposits occur on tectonic uplifts connected with thrust dislocations. Upper Jurassic carbonates and Cenomanian rocks were partially uprooted and thrust during Late Cretaceous-Paleogene times. The Miocene claystones and Carpathian nappes form seals. The thrust dislocations within Mesozoic and Miocene often close deposits. The Łąkta deposit, located on 400 – 500m high elevation caused by thrust dislocations, contains 950 mln m^3 of natural gas (Florek et al. 2006).

3. Construction of seismogeological models

3.1. Geological and geophysical data

The seismic survey of area 2D Kamyk – Niepołomice (2004), was performed by Geofizyka Kraków Ltd. The oldest profiles were made in 1978 and the newest were made in 2007 (Fig. 1). 40 boreholes were drilled in the area. Unfortunately only 6 of them have full logging sets (velocity, density, porosity, permeability, lithology solutions).

3.2. Seismic-boreholes ties

The solution of geological problems by seismic modeling required, in first place, construction of seismogeological models precisely depicting investigated orogen. Necessary petrophysical parameters characterizing lithological layers were obtain from well logging. Layers geometry was obtain from structurally interpreted seismic cross-sections after migration tied synthetic seismograms SS. LogM – GeoGraphix (*Landmark Graphics Corp.*) program for boreholes with velocity, density, GR and lithological solutions was used to obtain ties.

The top of Upper Jurassic carbonates (**J3**) constitutes explicitly tied seismic boundary (Fig. 2). This horizon, visible in the seismic record as strongest positive reflection, is connected with significant increase of velocity and density on the boundary between Jurassic carbonates and Miocene clastics. Quite good tie and similar reflection structure in SS record is visible for undisturbed Miocene sandstones-claystones **M1** boundary – top of the oldest Miocene strata as well as M2, M3, M4 and M5 boundaries were marked on sandstone-claystone contact. The theoretical-recorded seismic correlation is poor for Carpathian flysch. It is caused by step-dipping flysch reflections. It was possible, however, correlating the following horizons: **FLsp**

– bottom of Carpathian flysch, F1 – top of Upper Cretacaeous sandstones and shales, F2 – Top of Cenomanian and Senonian sandstones and mudstones, F3 – Top of Cenomanian and Senonian lower shales, F4 – Top of Senonian and Paleocene sandstones and claystones, F5 – top of Paleocene Istebna Sandstones. Paleocene and Eocene variegated shales lay above the F5 boundary. F3a, F3b, F5a constitute intralayer boundaries, marked for construction of seismogeological model.

The seismic-boreholes ties allowed lithostratigraphic correlation of registered seismic profiles and construction of seismogeological model, which provided base for multivariate seismic modeling.

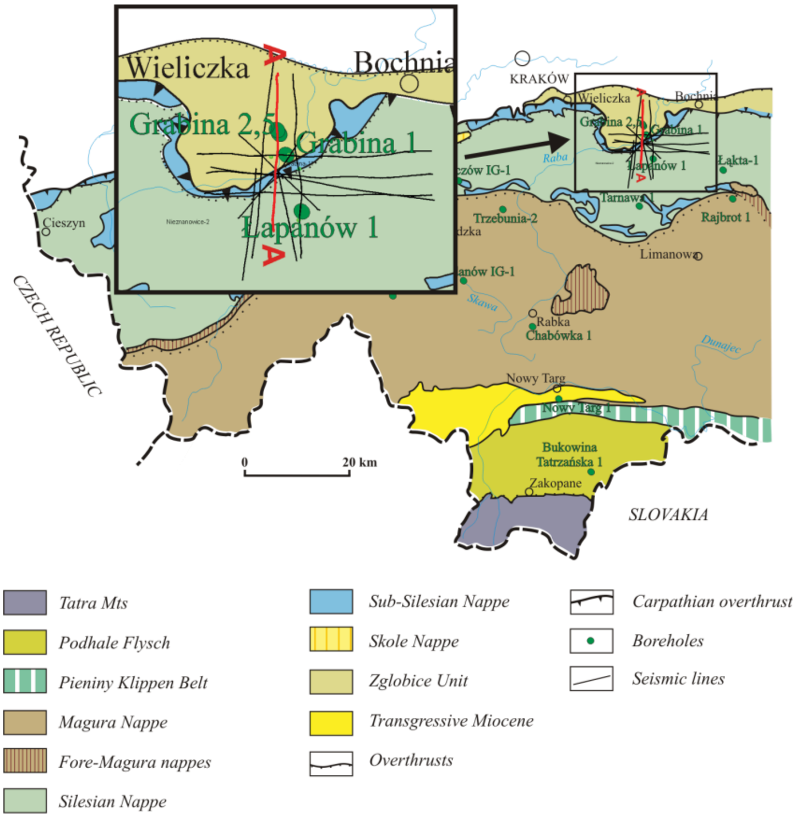

Fig. 1. Map of the Polish Carpathians south of Krakow with location of seismic profiles.

3.3. Structural interpretation of seismic data

Multivariate seismic modeling of A-A profile, directed S – N (Fig. 1) lead to evaluation of influence of flysch sequences variability on the seismic image of the top Jurassic strata and reliability of seismic image of important hydrocarbon deposit. The strongly deformed flysch sequences reach sub-Quaternary surface in the southern part of investigated profile (Fig. 3). Hard to investigate intraflysch boundaries were correlated with the surface geological map. The near horizontal Miocene strata reach sub-Quaternary surface in the northern part of profile. The seismic image is significantly disturbed in the G-5 and N-2 boreholes area, in the middle part of the profile. The gas, accumulated in the Miocene sandstones and mudstones, causes slight increase of amplitude and significant (on the northern side) change of phase. The Upper Jurassic rocks (**J3**) constitute the Miocene basement. High amplitude reflexes on the Jurassic top allows investigations of this boundary along the entire profile under the thick flysch complex (F1, F2, F3, F4, F5 and F6 horizons) and thin layer of oldest Miocene (**M1**). This top boundary (**J3**) is strongly cut by faults. The Łąkta thrust fault, first from south, with 50 ms displacement, is cutting Mesozoic basement, Miocene (**M1**), and reaching Cretaceous flysch shales and sandstones (F1). The other small faults in this area disturb only Mesozoic basement. Further northward, thrust faults that uplift the Podgrodzie structure show greater displacements. The uplifted zone is located directly under steep-dipping flysch formations. As a result of poor seismic records in that zone, the localization of the interpreted faults is not certain. The southern fault, which limits the Grabina–Nieznanowice graben, is of great importance to oil prospecting. The multivariate modeling was performed in this zone. Its goal was to check the influence of steep-dipping flysch formations on the seismic image of Jurassic rocks.

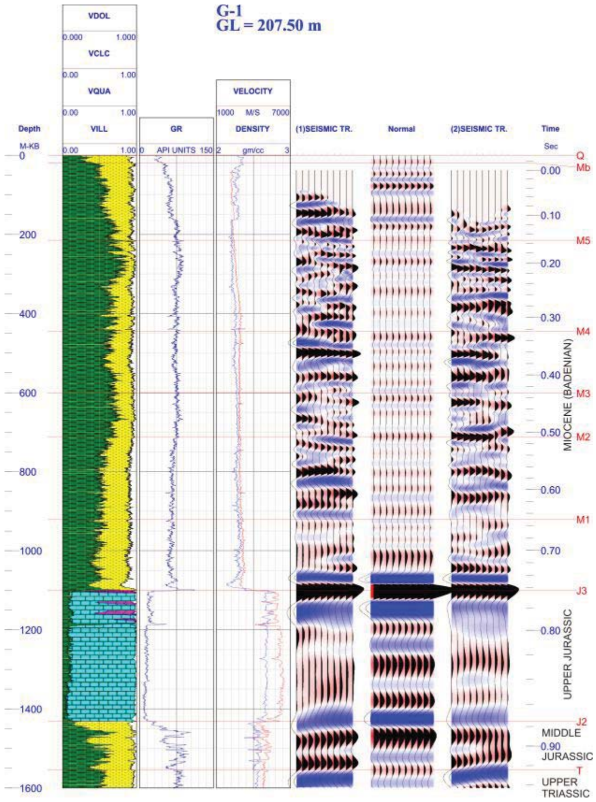

Fig. 2. Correlation of seismic data with stratigraphy, lithology and well-logging data. Borehole G-1.

3.4. Construction of velocity models

The two-dimensional model of P-valves velocity along the A-A profile (BASIC profile) was constructed in the GeoGraphix system, using STRUCT program. The Hampson-Russell program was used for seismic inversion.

The following data were used for input: correlated and interpreted stratigraphic well data, velocity logs in boreholes, seismic boundaries obtained using geological interpretation of A-A seismic profile and average wavelet extracted from seismic data, approximately matching zero-phase Ricker 28Hz signal.

The Model Based Hampson-Russell program utilizing method for inversion was used because of poor quality of seismic record and lack of boreholes along the A-A profile. The velocity was calculated from the acoustic impedance obtained from inversion (Fig. 4), assuming the density changes according to Gardner dependence.

The velocity image of Miocene shows its undisturbed, layered structure. Velocities increase with depth from about 2200m/s in shallowest (M5) layer up to about 3500m/s in deepest Miocene layer (sandstone series M1). The obtained layout of velocities reconstructs generalized structure of Miocene rocks. The velocity image of flysch shows its layered structure and compatibility of velocity layers with structural scales. The lower shales show the highest velocities from above 4500m/s in the southern, deepest part to above 2200m/s in the outcrop zone. The sandstone-mudstone beds display velocities about 3000m/s. Another low velocity (about 2500m/s) occurs within Istebna Sandstones. The uniform 5500m/s. velocity was assumed for the entire complex below top of Upper Jurassic J3. This velocity was used for staring inversion model.

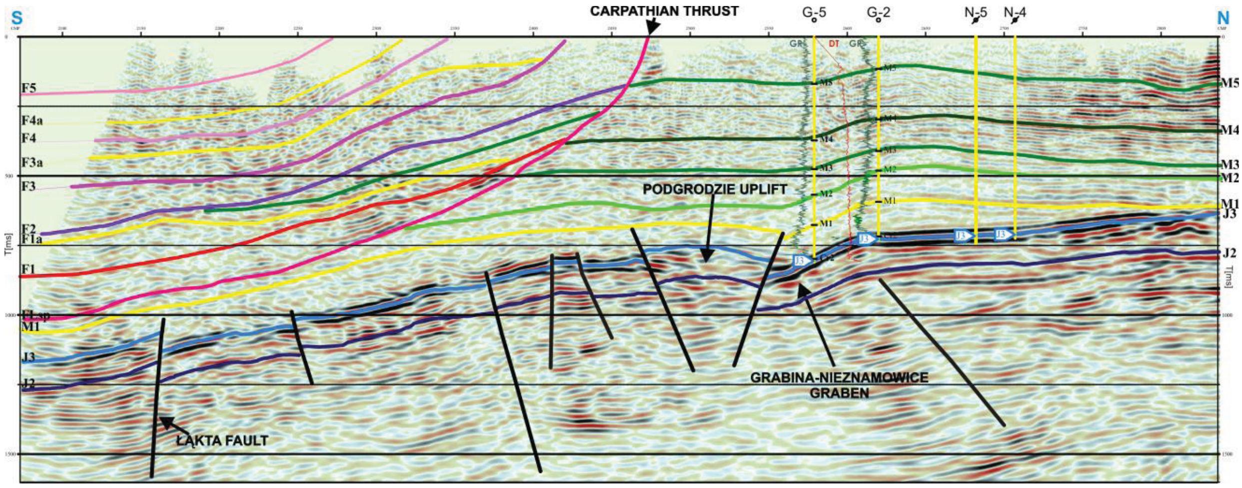

Fig. 3. Interpreted S-N seismic profile A-A, through G-5, G-2 N-5 and N-4 boreholes. Horizons abbreviations explained in text.

The construction of velocity models were performed in GeoGraphix system, in STRUCT module and in Outrider (*Divestco Inc*.) system. Seismic boundaries, interpreted in time section, as well as layers velocities obtained from well logging and seismic inversion, constituted input data.

4. The multivariate seismic modeling

The theoretical wavefield calculations were performed using Outrider (*Divestco Inc*.) program, based on ray theory of seismic wave's propagation (Marzec et al. 2004). Both offset and zero-offset modelings were carried out. The Ricker signal with

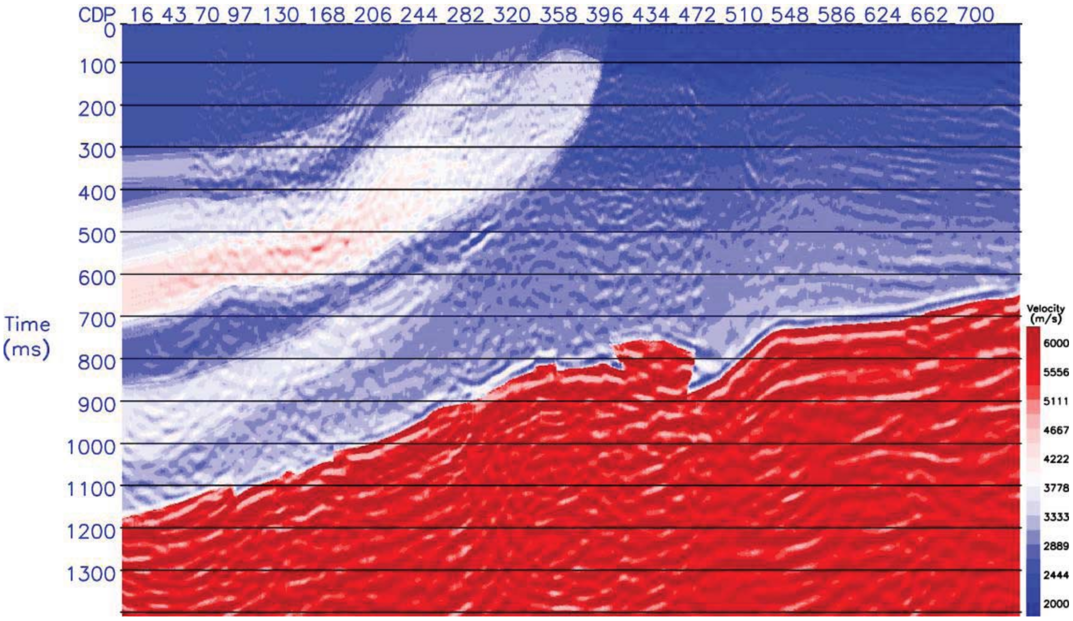

Fig. 4. Inversion velocity time model. Profile A-A.

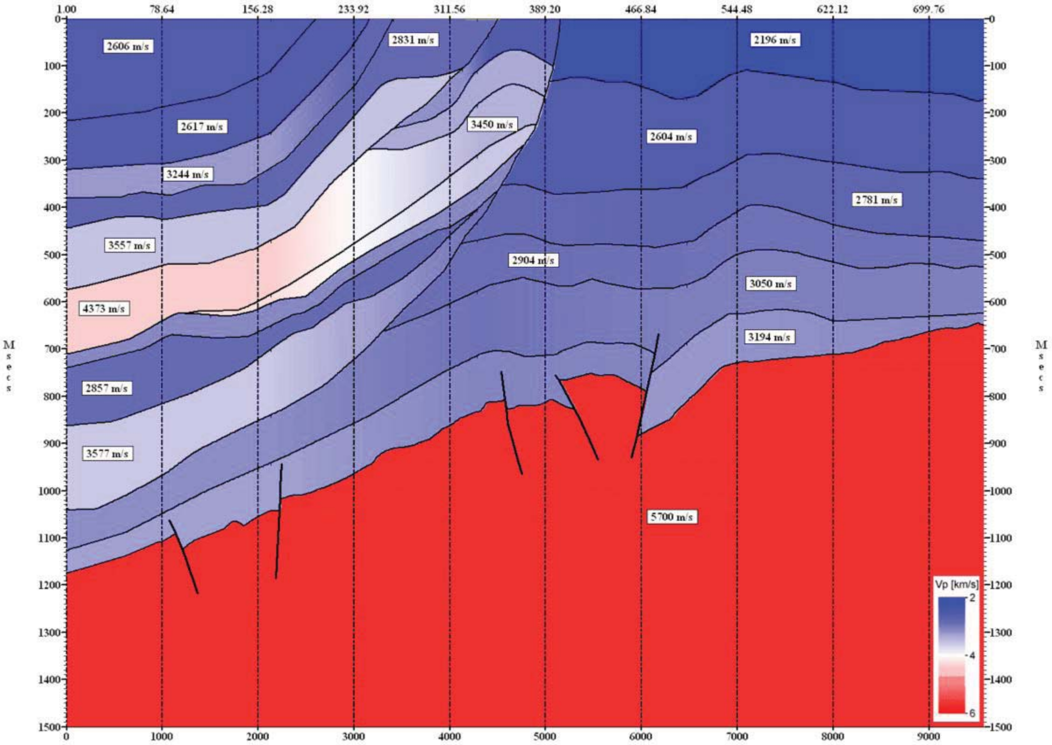

Fig. 5. Basic seismogeological time model.

28Hz frequency served as an elementary signal used for modeling.

The zero-offset modeling was done in Normal Incidence version. The offset modeling was carried out according to acquisition parameters of the A-A profile. It allowed obtaining the same range of offsets and multiplication of profiling. The obtained seismic records required farther processing using Omega system (*WesternGeco*). The processing sequence was similar to one used in registered data. The after FX migration theoretical seismic section constitutes final results.

4.1. Seismic modeling for basic model

The basic seismogeological model in time (Fig. 5) and depth version (Fig. 6) was supported by A-A profile (Fig. 3), going close to N-2 and -4 (without acoustic velocity logging) and G-2 and -5 boreholes, which have one measured and one synthetic ΔT logs. Univocal correlation of top of Jurassic allows identification of two distinctive fault zones. The Łąkta thrust fault zone is located at the S end of profile. Further northward the uplift limits the Grabina–Nieznanowice graben from south. The constant velocity, corresponding to the velocity in the Jurassic rocks was assumed for the entire complex below the top of Jurassic.

The reliability of the basic seismogeological model in depth version was checked by comparison of registered wavefield (Fig. 3) with theoretical wavefield after FX migration calculated in the offset version (Fig. 7). The boundary, restored in the theoretical wavefield, corresponding to the top of Jurassic, is fully reliable. It is consistent in geometry and amplitude value. The wave image of the other complexes is not identical. The reflection arrangement is chaotic in some fragments of the profile and correlation of continuous seismic boundaries is not possible. These differences result from the lack of interfering waves in the theoretical wave field as well as from assumption of the continuity of boundaries and lack of thin layers in the model. Lack of v near-surface layer, displaying very variable thickness and velocity, is especially important in the model. Regardless of this difference, the arrangement of the seismic boundaries in the theoretical wavefield well restores structure of flysch and Miocene rocks, especially undisturbed Miocene strata. Summing up this stage of modeling, it was assumed that the elaborated model approximates well the structure of orogen in the investigated region, so it was acknowledge as a basic model.

4.2. Seismic modeling of alternative models

The analysis of influence of flysch sequences variability on the seismic image of the top Jurassic

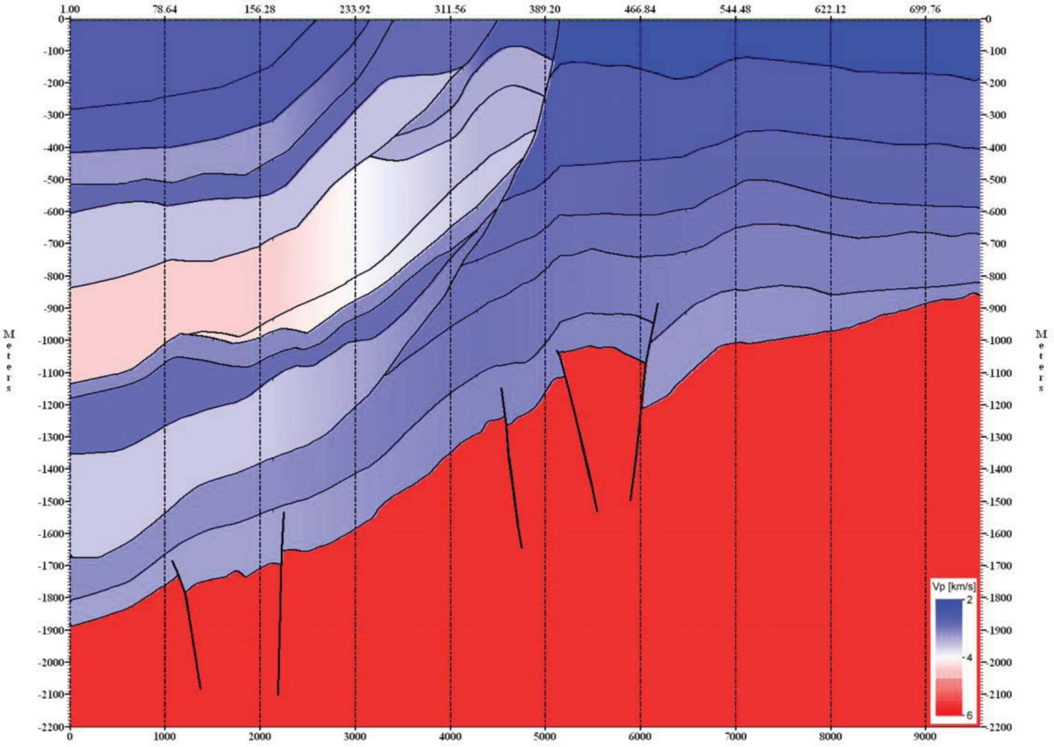

Fig. 6 .Basic seismogeological depth model.

was the goal of this investigation. According to the assumption, the performed analysis was based on the multivariate seismic modeling. The modeling used modification of the time model within the Carpathian flysch (Fig. 5).

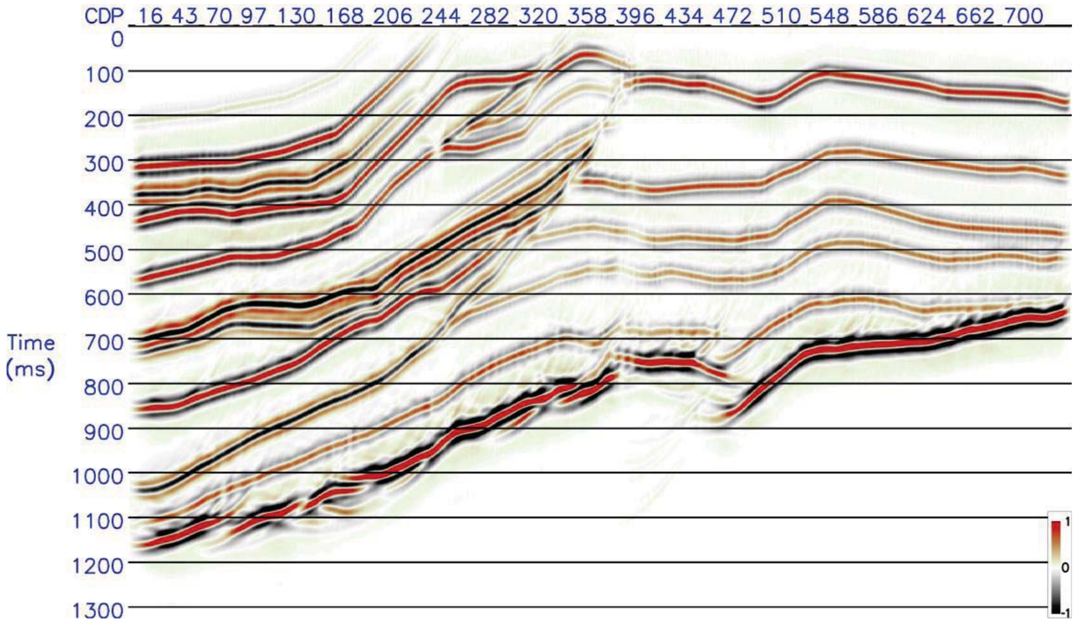

Fig. 7. Theoretical wavefield after FX migration calculated according to basic depth model.

The comparison of field calculated for the basic depth model (Fig. 7) with the theoretical fields computed for the modified time models show as follows:

The change of velocity of steep-dipping flysch layers in the near-surface zone, the lack of continuity of Jurassic boundary is well visible, regardless of lower amplitudes of top of Jurassic (see Pietsch et al. 2008). On the other hand, the change of velocity in the internal layers results in the change of seismic record. Increase of velocity (Figs. 8a and 8b) causes reinforcement of internal flysch boundaries and decrease of their tome thickness while decrease of velocity (Figs. 9a and 9b) causes distinctive decrease of amplitude of reflections. In both cases, significant decrease of legibility of Jurassic reflection was visible, especially in the zone of southern uplift bounding Grabina-Nieznanowice graben that is in the outcrop zone of steep-dipping flysch boundaries.

- The change of velocity of gentle-dipping flysch layers in the near-surface zone only insignificantly influences seismic image of the entire orogen (see Pietsch et al. 2008).
- The change of velocity in the internal layers results in the distinct change of seismic record. Increase of velocity (Figs. 8a and 8b) and its decrease (Figs. 9a and 9b) causes significant decrease of legibility of Jurassic reflection. It is especially visible in the zone of southern Podgrodzie uplift bounding Grabina-Nieznanowice graben. This zone is concordant with very steep dipping surface of the Carpathian thrust and steep dipping flysch boundaries coming to this surface.

5. Conclusion

The main goal of this investigation was checking the influence of flysch sequences variability on the seismic image of the top of Upper Jurassic using analysis of multivariate seismic modeling. According to this goal, the seismogeological basic model (Fig. 6) was changed within flysch. The agreement of computed theoretical wavefield (Fig.7) with registered seismic section (Fig. 3) confirms the correctness of basic model

The theoretical field was computed for two modified models. In the first one (see Pietsch et al. 2008b) only velocities were changed in the outcrop zone of flysch and in the Lower Cretaceous shales (highest velocities within flysch). In the second model, the intra-flysch boundaries were changed with analogous change of velocity (Figs. 8, 9).

The multivariate seismic modeling show that influence of changing distribution of velocity and geometry of reflecting boundaries on lower flysch complexes and Miocene strata is small, but visible. The biggest changes along the Jurassic boundaries are visible in the zone of very steep dipping surface of the Carpathian thrust and steep dipping flysch boundaries coming to this surface. The large horizontal velocity changes are also related to this structure. The observed changes are not large enough to entirely change the **J3** boundary as well as location of cutting thrust faults.

The obtained results show the validity of the multivariate seismic modeling method under complex seismogeological conditions. This method can be effectively utilized interpreting seismic record and

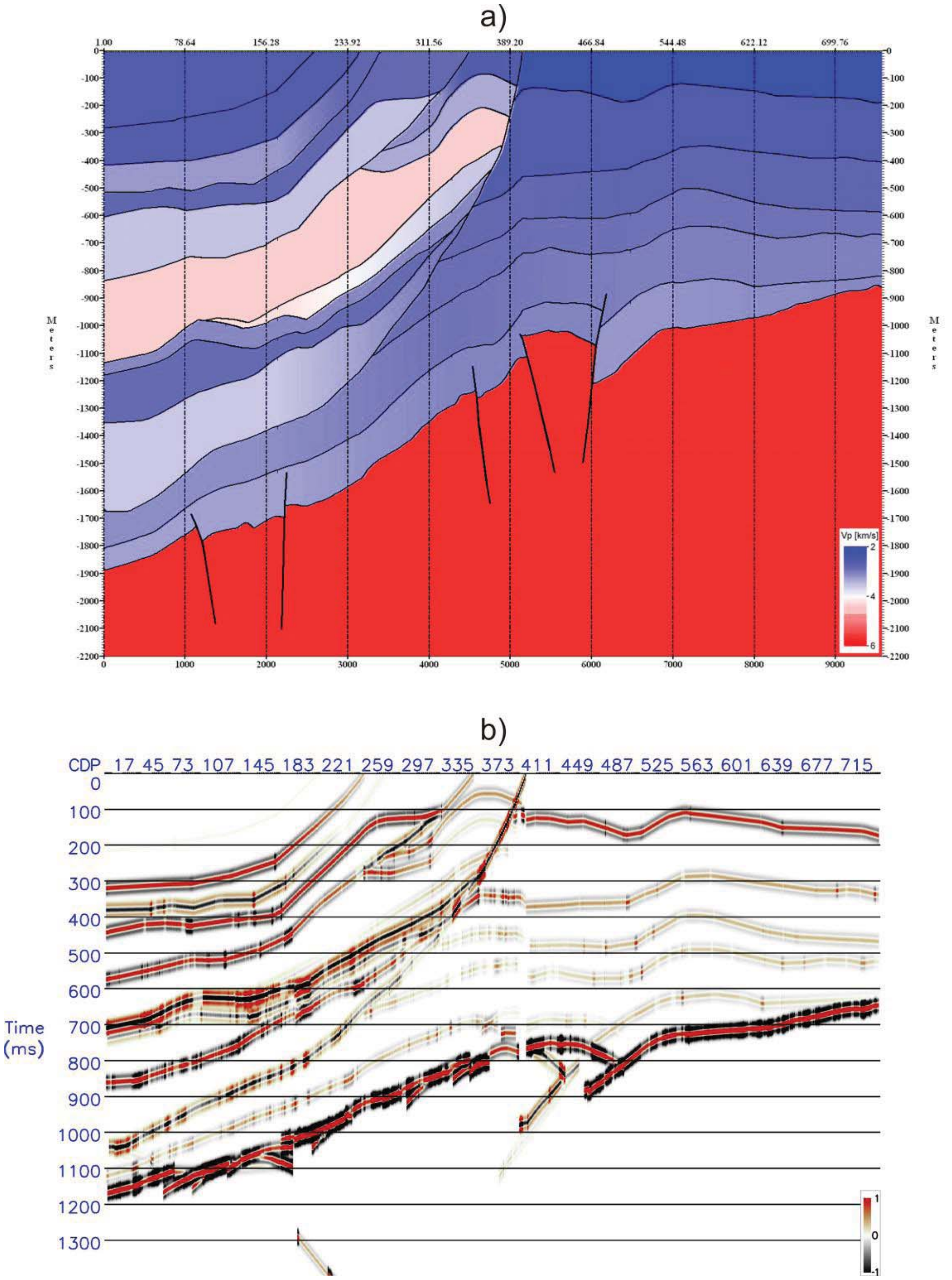

Fig. 8. (a) Modified seismogeological depth model – increase of velocity in internal layers of thrust-sheet, (b) Theoretical wavefield calculated according to model on Fig. 8a.

evaluating reliability of the registered seismic data. In first case, with the consistency of theoretical wave field with registered seismic record, the constructed seismogeological model approximate well the geological structure. In the second case, analysis of theoretical wavefield, computed for the assumed variants of model, shows univocal influence of individual model elements on the wavefield.

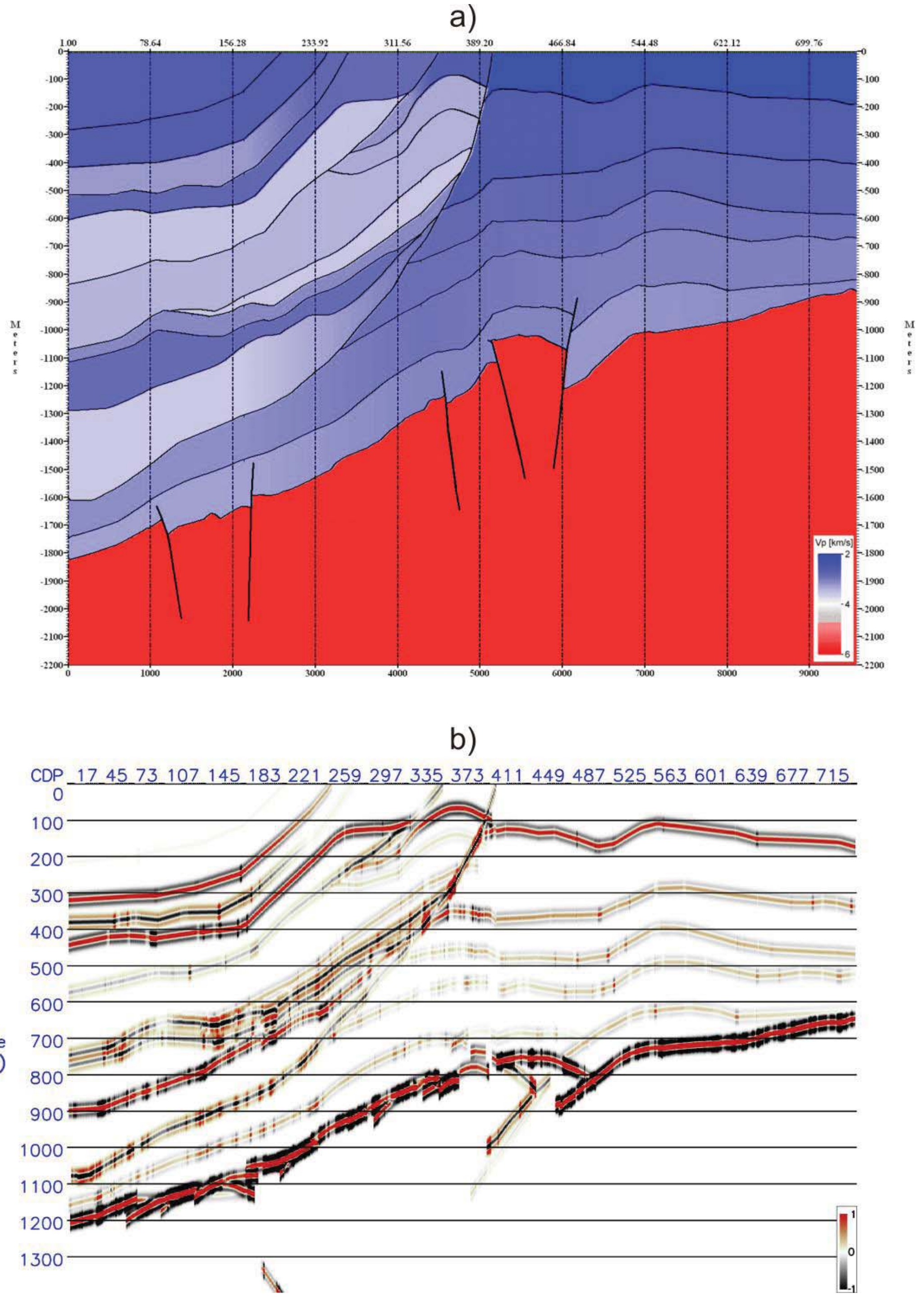

Fig. 9. (a) Modified seismogeological depth model – decrease of velocity in internal layers of thrust-sheet, (b) Theoretical wavefield calculated according to model on Fig. 9a.

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