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APPLICATION OF 2-D FORWARD SEISMIC MODELLING FOR IMPROVED IMAGING OF SUB-SALT ROTLIEGEND STRATA IN POLISH BASIN

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Abstract: Forward seismic modelling can aid seismic studies of the pre-Zechstein strata in areas of developed salt tectonics, such as the Obrzycko–Szamotuły region, NW Polish Basin. The results not only can be used for seismic interpretation, but also can support the planning of survey methodology and the workflow of seismic data processing.

This paper presents the results of modelling that was carried out, before the acquisition of the regional-scale, seismic line Obrzycko-1–Zabartowo-1–Zabartowo-2 (Górecki, 2010). An interpreted, seismic transect was used to build a basic, seismic-geological model. The modelling was based on seismic ray theory. The zero-offset modelling (theoretical wave field) for different geometries of salt structures showed that an increase in salt thickness resulted in a pull-up of reflection events, related to the sub-salt horizons. The incorporation of faults and salt overhangs into a model significantly complicated the seismic wave field. The results of offset modelling, presented in this paper as seismic ray tracing and common-shot gathers, proved that (1) the seismic response of the Rotliegend (Permian) formations can be recorded, despite the presence of the overlying salt pillows and diapirs, if offsets several kilometres long are used, and (2) the complex configuration of seismic reflectors (diapirs with salt overhangs, faults) gives rise to complicated, seismic ray paths that may cause difficulties in common-depth-point stacking and therefore decrease the quality of the seismic records.

Key words: salt and subsalt structures, salt diapirs, seismic methods, seismic modelling, Permian, Poland.

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INTRODUCTION

Difficulties in seismic exploration for hydrocarbon resources, associated with the eolian Rotliegend (Permian) deposits, are often related to the presence of the overlying Zechstein salt, i.e. salt pillows and diapirs. Extensive salt tectonics gave rise to strong, seismic reflectors, characterized by complex geometry. As a result, the distribution of seismic ray paths is highly non-uniform, which in turn means that seismic imaging does not provide a reliable model for the pre-Zechstein strata. If this is the case, seismic modelling can support seismic exploration in every stage, i.e., seismic survey design, data processing and interpretation (Pietsch *et al.*, 2007a, b, 2008; Kobylarski *et al.*, 2008).

Forward seismic modelling, testing different geometries in the subsurface, was carried out along the regional-scale, seismic test line, Obrzycko-1–Zabartowo-1–Zabartowo-2 (Górecki, 2010), located in the SW part of the Polish Basin, in the Mid-Polish Trough. The objectives of the modelling were: (1) testing of the proposed survey methodology, (2) investigation of the relationship between seismic wave field variations and the nature of the overlying salt structures, and (3) interpretation of the geological structure of the salt diapir, sampled by the seismic transect.

The basic seismic and geological model was calculated based on 2-D seismic data: the Obrzycko–Szamotuły seismic lines, acquired in 2001 and 2007 by Geofizyka Toruń POGC Group, and the Murowana–Goślino–Klecko seismic lines, acquired in 2008, by the Geofizyka Kraków POGC Group (Fig. 1). The seismic profiles were situated to the SW of the Mid-Polish Trough (Fig. 1). In this area, the system of salt diapirs (Drawno–Dzwonowo–Człopa–Szamotuły) was described by Krzywiec (2006a). The seismic profile T009 4207 – 13-1-08K, of the SW–NE orientation (Fig. 1B), was selected for analysis. From the SW to NE, the profile crosses the Obrzycko Salt Pillow, the Szamotuły Salt Diapir, and the Rogoźno Salt Pillow (Wagner, 2012).

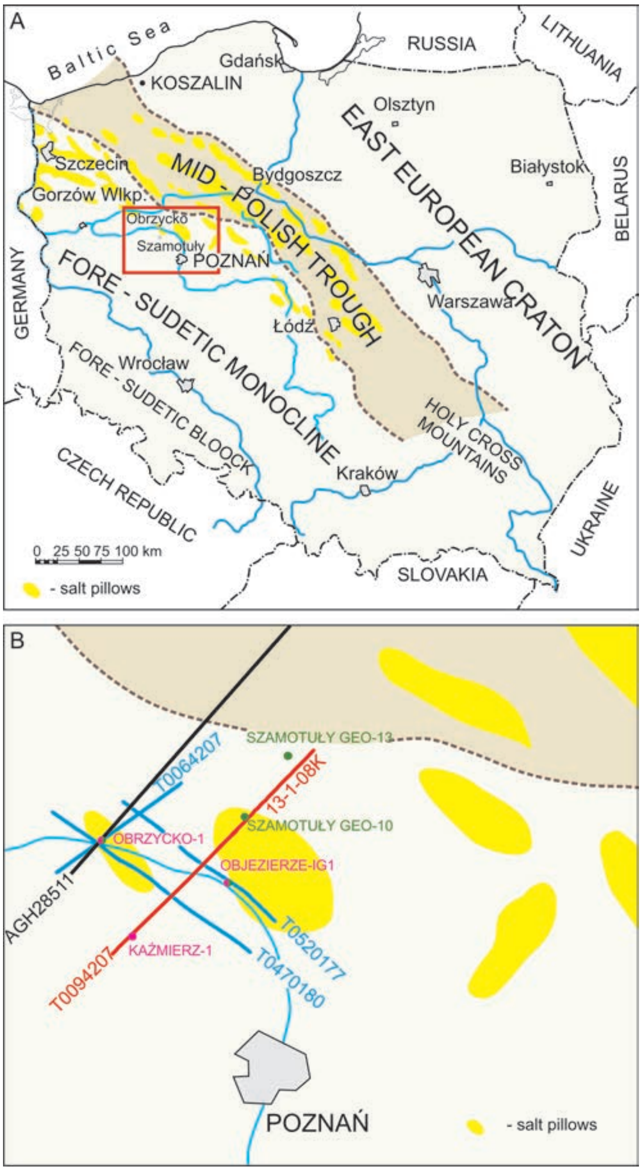

Fig. 1. Outline of geology of study area. **A** – Map of salt structures within Mesozoic cover of Mid – Polish Trough (Dadlez and Mark, 1998, modified). **B** – Location map for seismic (1) and borehole (2) data. Seismic data: seismic transect T0094207 – 13-1-08K (red line); seismic profiles, used in structural interpretation (blue lines); regional, seismic profile Obrzycko-1–Zabartowo-1–Zabartowo-2: AGH28511 (black line). Borehole data: well with PA measurement (red point); well with $\bar{v}$ measurement (green point) (Pietsch *et al.*, 2010, 2012)

GEOLOGICAL SETTING

The study area is located in the NW part of the Permo-Mesozoic Polish Basin, an eastern segment of the Central European Basin System (Ziegler, 1990:, Pharaoh *et al.*, 2010). The Polish part of this system, including the Mid-Polish Trough, originated at the beginning of Rotliegend sedimentation. Subsidence initially resulted from continental rifting during the Early Permian, which was followed by a post-rift phase, starting in the Zechstein (Van Wees *et al.*, 2000). At that time, the Polish Trough was the depocentre of a saline basin, in which over 1500 m of rock salt were deposited (Wagner, 1994). The structure of this area is dominated now by intense salt tectonics. The presence of a thick evaporite complex at the base of the sedimentary infill resulted in the regional detachment of the Mesozoic sedimentary succession from the sub-Zechstein strata and the formation of faults and folds, as well as pillows and salt diapirs, genetically related to the fault zones (Krzywiec, 2006a; Krzywiec *et al.*, 2006). Intense salt mobility in the Late Cretaceous marked the initial stage of regional inversion of the Mid-Polish Trough (Wagner, 1994; Dadlez *et al.*, 1997), which resulted in the Mid-Polish Swell ultimately being uplifted at the boundary of Cretaceous and Palaeogene. The uplift resulted in the inversion of local, tectonic zones, such as the Drawno–Człopa–Szamotuły Zone (Leszczyński, 2002; Krzywiec, 2006b). Post-Maastrichtian erosion of Jurassic to Cretaceous strata (Dadlez, 2000) contributed to the formation of the presently known salt structures (Krzywiec 2000, 2009). The inversion process reactivated pre-existing faults, the mobility of which triggered the growth of salt structures and controlled their geometry (Dadlez *et al.*, 1998, Krzywiec 2000, 2009).

In the seismic section analysed (Fig. 2), there are three salt structures, probably related genetically (Wagner, 2012): (1) the small Obrzycko Salt Pillow, the evolution of which was halted by faults, bordering the Szamotuły Zone; (2) the Szamotuły Zone, which is part of Mesozoic synsedimentary grabens and half-grabens, developed during the early Keuper to Early Jurassic, in response to subsidence of the Mid-Polish Trough (Kwolek, 2000); and (3) the Rogoźno Salt Pillow, located in the NE part of the transect, with a salt horizon, almost entirely squeezed out in a SW direction.

SEISMIC MODELLING

The seismic modelling was performed, using Divestco's *Outrider* software, based on seismic ray theory, and calculated 2-D seismic profiles, both as field records and stacked data. The software can be used for ray tracing and calculating the travel times of reflected, compressional (PP) and converted waves (PSV), as well as direct (in the case of modelling VSP data) and diffracted waves, using the 'diffraction' function (algorithm placing source points on seismic reflectors). Multiple waves can not be modelled with software. The full Zoeppritz equations were used for calculating reflection and conversion coefficients. Thus simulation of amplitude variation with offset was possible.

The modelling firstly was done, using a zero-offset method that aimed at (1) resolving the variability in seismic image of the Rotliegend strata, in relation to the Zechstein overburden, and (2) reliable interpretation of the Szamotuły Salt Diapir structure. The following modelling by means of offset methods was carried out to test the potential for imaging the pre-Zechstein strata, using the survey methodology, proposed for the acquisition of the regional Obrzycko-1–Zabartowo-1–Zabartowo-2 profile (Górecki, 2010).

The structure of the Permo-Mesozoic succession, imaged by a seismic profile, reveals from SW to NE an almost

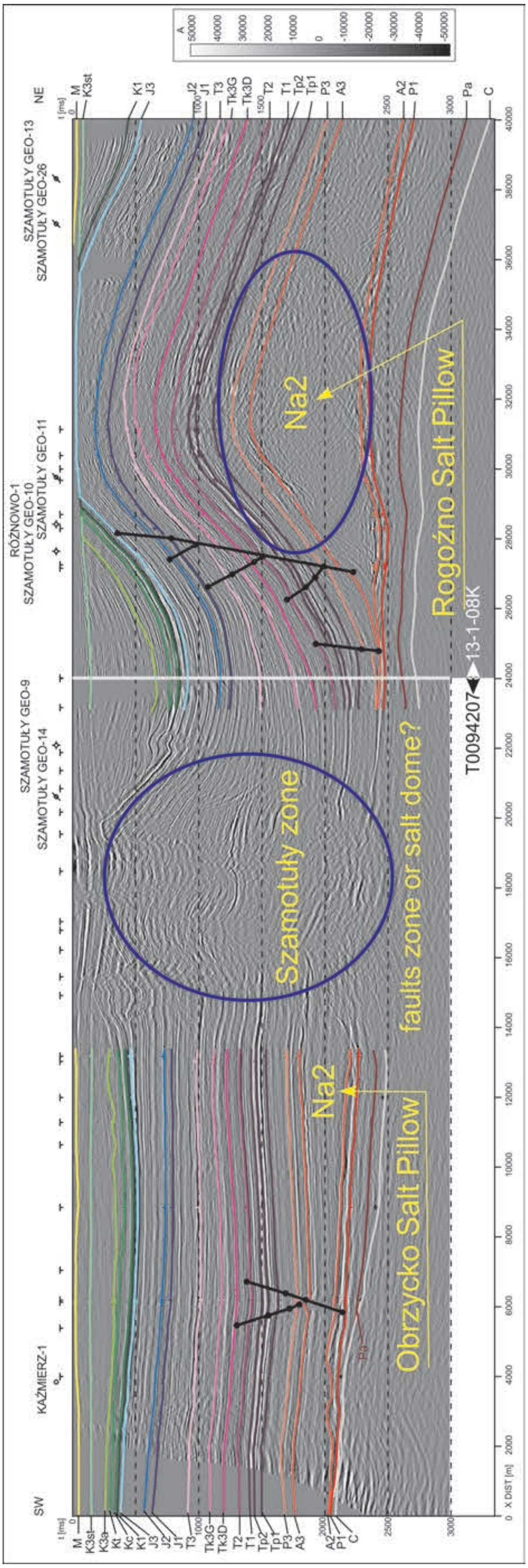

Fig. 2. Interpreted seismic transect T0094207–13-1-08K after migration (Pietsch *et al.*, 2010, 2012). Seismic boundaries: M – top Miocene, K3st – top Upper Cretaceous, K3a – Santonian, Kt – Turonian, Kc – Cenomanian, K1 – Lower Cretaceous; J3 –Malm, J2 – Dogger, J1 – Lias; T3 – Rhaetian, Tk3G – Upper Keuper (Upper Gypsum Series), Tk3D – Lower Keuper (Lower Gypsum Series), T2 – Muschelkalk, T1 – Roethian, Tp2 – Middle Buntsandstein, Tp1 – Lower Buntsandstein, P3 – Zechstein, A3 – Leine anhydrite, A2 – Stassfurt anhydrite, P1 – Rotliegend (Saxonian), Pa – Rotliegend (Autunian); C – top Carboniferous

flat-parallel configuration of beds, with the small Obrzycko Salt Pillow, the complex Szamotuły Zone (mostly reverse faults and large squeeze out of salt), and finally the large Rogoźno Salt Pillow (Fig. 2). The basic, seismic-geological model was built, using the interpreted, seismic transect (Fig. 2), except for the Szamotuły Zone (Pietsch *et al.*, 2010, 2012). The disrupted layout of seismic boundaries, observed in this zone, precludes any definitive, geological interpretation of the seismic record. For this reason, several models for the Szamotuły Zone were proposed and a layer-block structure of the Szamotuły Zone was assumed in the basic model (Fig. 3).

For the succession starting from the top of the Upper Keuper (Tk3G) and continuing to the top of the Zechstein (P3), the velocity model was constructed, using a depth-dependent velocity gradient (Wilk, 2010; Pietsch *et al.*, 2012). Seismic velocities for the remaining, geological successions, i.e. the Cretaceous, Jurassic, Rheatian and Permian (P2 and P1), were determined from seismic inversion (Pietsch *et al.*, 2010, 2012). Barely visible boundaries below the Zechstain beds have been interpreted, using available, geological information (Bujak, 2010). The basic, seismic-geological model in a depth domain, which was calculated on the basis of the data described above, is presented in Figure 4.

ZERO-OFFSET MODELLING

The aim of zero-offset modelling was mainly to describe the variability in a seismic wave field, in relation to different models of the Zechstein salt structures. During the subsequent iterations, changes to the seismic-geological model were introduced, which resulted in models ranging from a stratified (Fig. 4A) to a diapiric salt structure (Figs 5A–8A). A theoretical wave field was calculated, using Ricker-type wavelets of 26 Hz frequency (best approximating recorded signal) with 20 m distances between traces (Pietsch *et al.*, 2010). Calculations utilised the diffraction method (exploding reflector algorithm). The synthetic seismic wave field simulates the stacked, unmigrated, seismic section with wave diffractions. To construct the theoretical profiles, the finite-difference post-stack migration was used. The parameters for FD migration were: maximum dips of 45°–65° and an RMS velocity field in the range 50–100% (Słonka, 2013).

The initial, seismic, geological model (Fig. 4A), imaged in the depth domain, is based on the assumption that the inter-fault zone is associated with the stratified architecture of both the

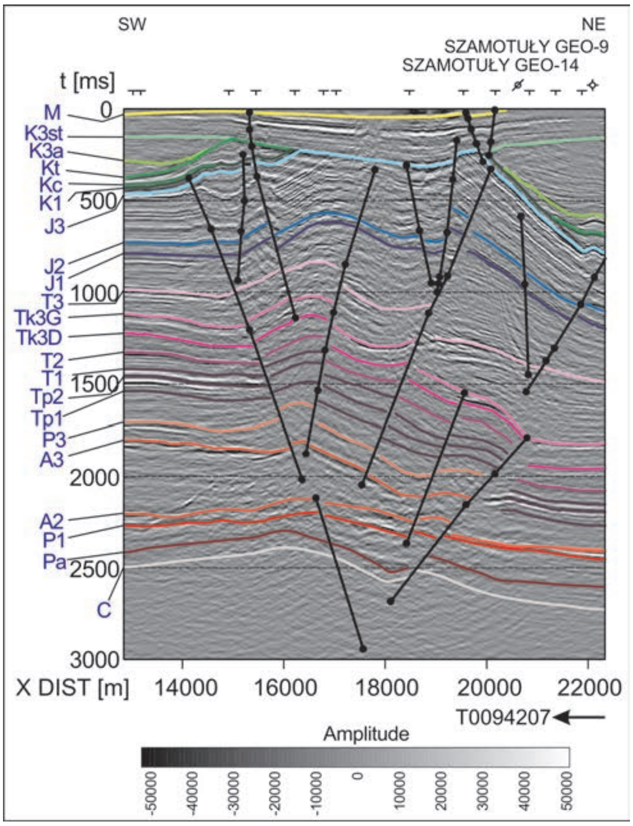

Fig. 3. Part of seismic transect, in which layer-block structure Szamotuły Zone (model I) was established. Seismic boundaries as in Fig. 2

Rotliegend succession (model I) and the overlying strata (including salt). The synthetic, seismic wave field, calculated for this model, is shown in Figure 4B.

The following models assume that a salt diapir grew between marginal, Palaeozoic-rooted faults of the Szamotuły Zone. In model II (Fig. 5A), the rock salt penetrates the Lower Keuper and the Bunter Sandstone strata in the SW and NE parts of the Szamotuły Zone, respectively. The postulated salt structure correlates in the analysed transect with domains of unclear or partly missing reflections (Fig. 2). The wave field, calculated for this model, using the diffraction method and after the migration procedure, is shown in panels B and C respectively of Figure 5. The same outline is used for models, shown in Figures 6–8.

Model III assumes a salt diapir, rising up to the Middle Jurassic in the SW part of the Szamotuły Zone (Fig. 6A). In model IV, a salt diapir penetrates the Upper Jurassic and has two overhangs (Fig. 7A). The top of the dome is cut by small faults, which terminate within the salt body. A gypsum-anhydrite cap rock was simulated by increasing the seismic velocity, associated with the uppermost part of the salt diapir.

The last model analysed (model V) was constructed on the basis of the petrophysical parameters, estimated for the initial seismic-geological model (Fig. 3A), although the geometry of seismic reflectors in the inter-fault zone was modified. A large salt diapir with two overhangs was tested in this model with a shape, resembling that of the Szamotuły Salt Diapir as interpreted by Krzywiec (2006a), on the seismic line, located to the NW of the transect analysed (Fig. 8A).

A comparison of the synthetic, seismic records, generated for the models analysed (Figs 4B, 5B, 6B, 7B, 8B), shows the difference between the seismic wave fields, associated with the assumed salt structure. This difference is related to the higher velocity contrast between laterally adjacent lithologies. In the initial, stratified model I, the pattern of reflection events related to the pre-Zechstein strata is generally similar in the depth (Fig. 4A) and time (Fig. 4B) sections. If a salt structure does not pierce the top Muschelkalk (Middle Triassic), it causes no significant distortion in the imaging of the pre-Zechstein boundaries. This is related to the small velocity contrast between the salt bodies and the Lower and Middle Triassic formations (Fig. 4A). In the subsequent models, assuming the development of a salt diapir (Figs 5A, 6A, 7A, 8A), the increase in the thickness of the salt results in a clear pull-up of the seismic reflection events, the top Rotliegend and Carboniferous, below the salt body (Figs 5B, 6B, 7B, 8B). This is associated with much higher, seismic velocities in a salt body, compared to the surrounding strata. In such a case, an anticlinal pattern of reflection events is displayed in the time section for the Rotliegend succession. The diffraction energy of waves, originating at points where the salt diapir pierces the overlying seismic reflectors, is also increased, owing to higher velocity contrasts. This results in higher energy dissipation and also in reduction of the energy of waves, reaching the pre-Zechstein strata. A comparison of the synthetic, seismic wave fields, calculated for model IV (Fig. 7A, B) and model V (Fig. 8A, B), proves an important role of faults in generating strong diffraction waves. Since the modelled salt diapirs were assumed to be isotropic bodies, there are no diffraction waves in the synthetic, seismic sections that can originate within them.

The theoretical wave fields, calculated for various, seismic-geological models, afterwards were used in the geological interpretation of the Szamotuły Salt Diapir. The wave fields, calculated for the models with large salt diapirs (Figs 7, 8), are significantly different from the wave field recorded (Fig. 2). In the theoretical field, the zones without reflections reach the top of the Jurassic formation (Figs. 7, 8). However, in the seismic data the extent of these zones is smaller. A seismic record from the Szamotuły Zone (Fig. 2) indicates the possible presence of a small, double salt diapir. Figures 5A, C, and 6A, C show seismic-geological models and calculated wave fields for the possible salt structure. The seismic boundaries from both models, reduced to the time domain, were overlaid onto the registered wave field (Fig. 9A, B). Model II (Fig. 9A) shows a better match of the boundaries with the registered events, compared to model III. For example, the magnitude of the pull-up effect within the pre-Zechstein strata in the modelled and registered fields is comparable (Fig. 9A). In the case of model III, the modelled pull-up effect is significantly larger than in the recorded field (Fig. 9B). A higher pull-up effect is caused by the lateral gradient increase of average velocity, when the salt diapir pierced formations with lower velocities (Fig. 6A).

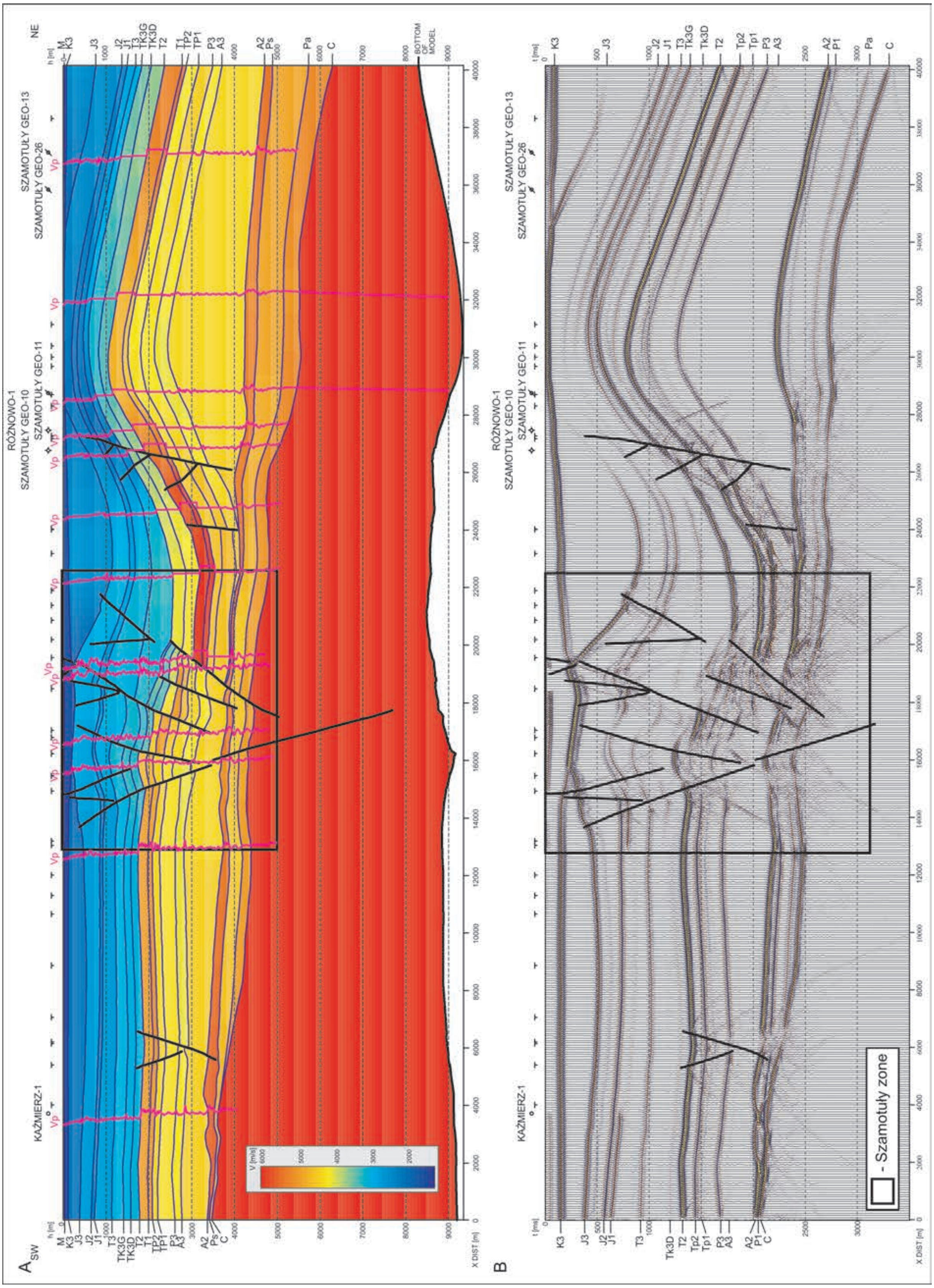

Fig. 4. Seismic-geological depth model (I) along seismic transect (**A**); zero-offset synthetic section (calculated in version: 'diffraction') (**B**) Seismic boundaries as in Fig. 2

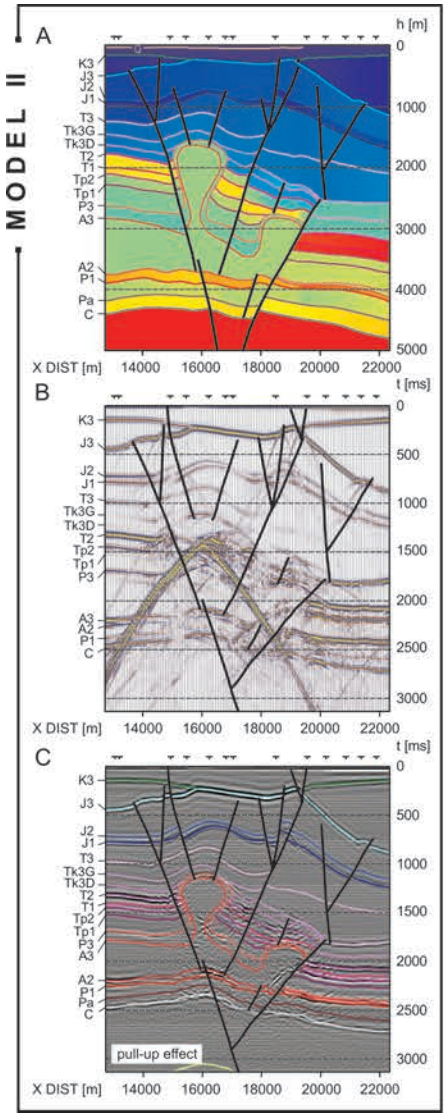

Fig. 5. Seismic-geological depth model (II), with salt jammed in inter-fault zone (**A**); zero-offset synthetic section, calculated in version: 'diffraction' (**B**); seismic profile after migration FD (**C**). Seismic boundaries as in Fig. 2

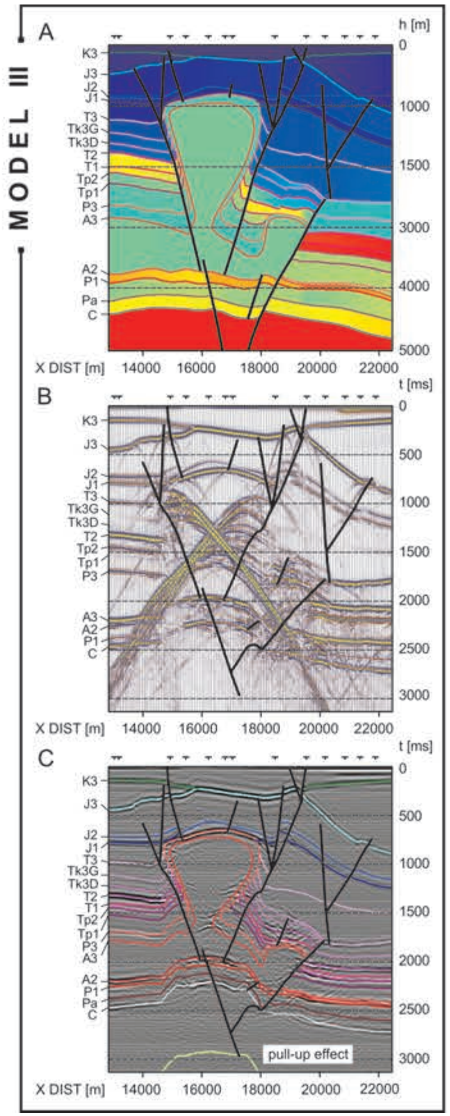

Fig. 6. Seismic-geological depth model (III), with two-part salt diapir (**A**). **B** and **C** as in Fig. 5, seismic boundaries as in Fig. 2

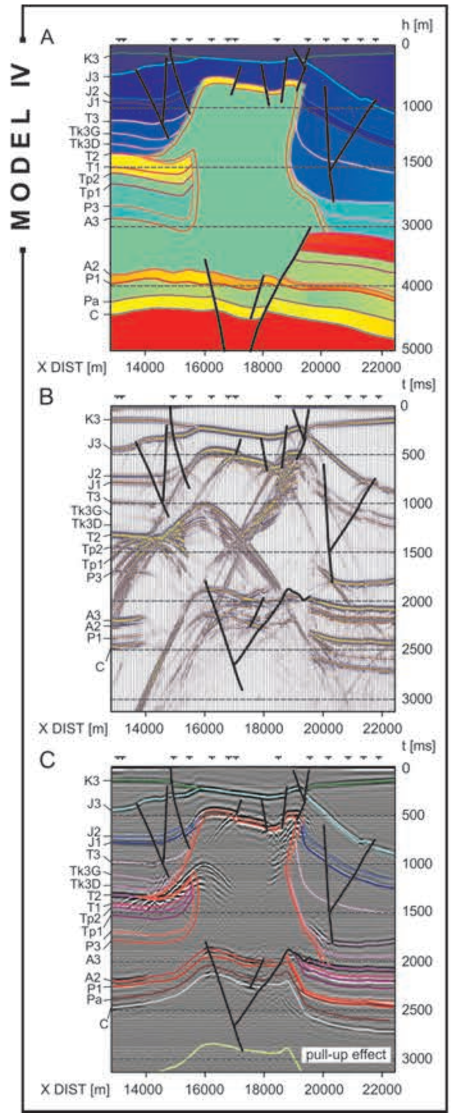

Fig. 7. Seismic-geological depth model (IV) with salt diapir with a corniche and overhang (**A**). **B** and **C** as in Fig. 5, seismic boundaries as in Fig. 2

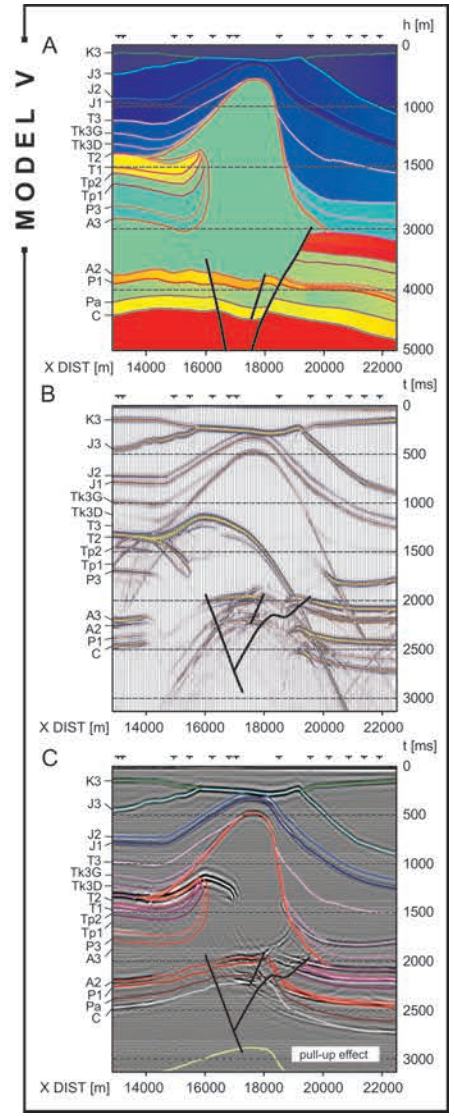

Fig. 8. Seismic-geological model (V) with Szamotuły Salt Diapir (**A**). **B** and **C** as in Fig. 5, seismic boundaries as in Fig. 2

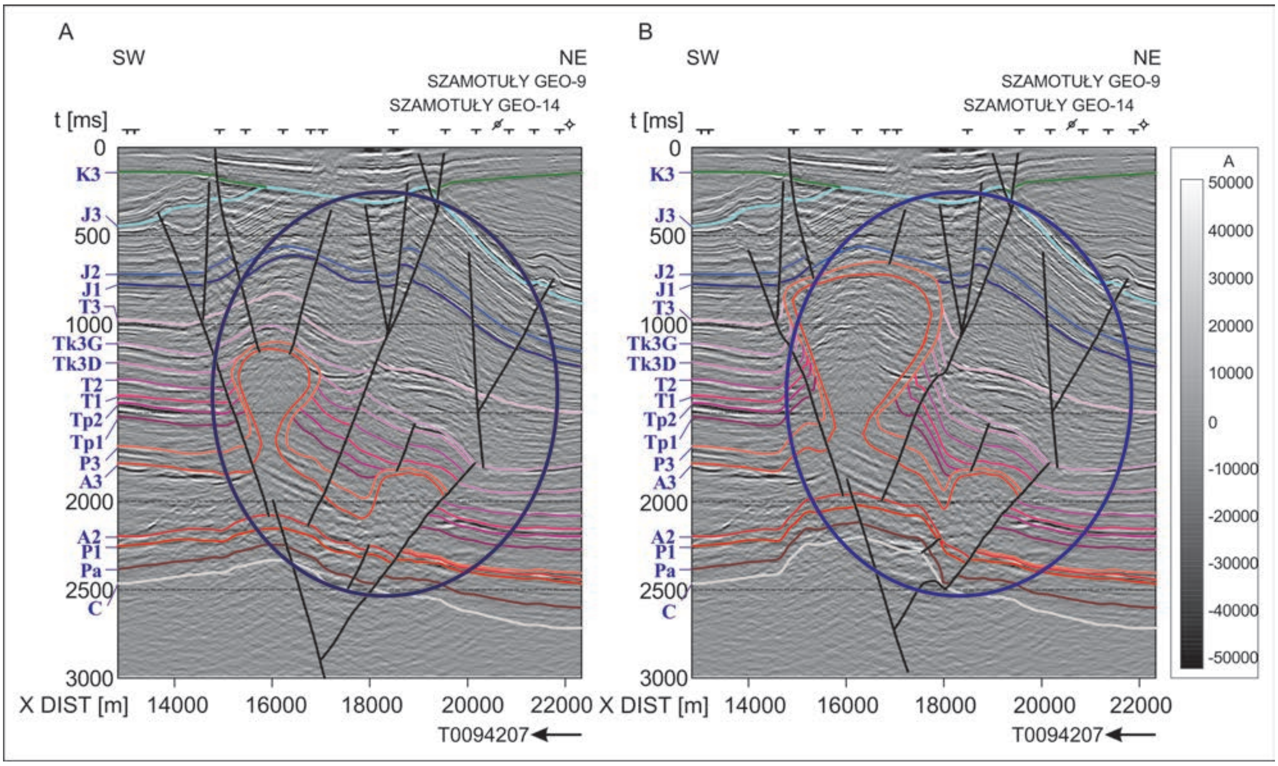

Fig. 9. Structural interpretation of Szamotuły Zone, using seismic boundaries distribution for model II (Fig. 5A) (**A**) and model III (Fig. 6A) (**B**). Seismic boundaries as in Fig. 2

OFFSET MODELLING

The main objective of the offset modelling was to assess the potential for imaging the pre-Zechstein strata boundaries with the survey methodology, originally proposed for the acquisition of the regional-scale test profile Obrzycko-1–Zabartowo-1–Zabartowo-2 (Górecki, 2010). The results of offset modelling are presented as seismic ray paths, generated for the set of source points, and common-shot gathers, which present the calculated travel-time curves, convolved with the source signal. The relationship between the amplitude and the angle of incidence of seismic rays was included in the calculations. The results can be used, both for designing the survey methodology and for planning and optimising the seismic data processing.

Offset modelling was carried out for the same seismic-geological models as described above, i.e., ranging from the stratified model (Fig. 4A) to the model, resembling the Szamotuły Salt Diapir (model V, Fig. 8A). The ray paths for model I (Fig. 4A) were generated for two sources at PS 32000 and PS 17000. Point PS 32000 was located above the salt pillow, while point PS 17000 lied above the fault zone. Consequently, they were located in the positions with the greatest impact on the seismic image of the pre-Zechstein strata. The distribution of seismic ray paths, generated at point PS 32000, is presented in Figure 10A, while Figure 10B shows part of a seismic-geological model, with the seismic reflectors identified by seismic rays. The analysis of both figures proves that if the proposed, seismic spreads of 4500-0-4500 [m] and 6500-0-6500 [m] are used for acquisition of the regional-scale, seismic line (Górecki, 2010), the majority of seismic ray paths, reflected from the pre-Zechstein interfaces, should be recorded. The synthetic common-shot gather, generated for the proposed seismic spreads, is shown in Figure 10C. The theoretical travel-time curves, marked with colours, which correspond to the colours indicating the respective seismic reflectors in the models, show that the Zechstein and Rotliegend reflectors also can be imaged, using a seismic spread with longer offsets (extensions of the travel-time curves, estimated for the seismic spread 4500-0-4500 [m]). The arrangement of ray paths, generated at point PS 17000, located above the fault zone, is shown in Figure 11A, while the synthetic common-shot gather for this source is presented in Figure 11B.

A similar approach was used for modelling of the salt dome, which resembles the Szamotuły Salt Diapir (model V in Fig. 8A). The seismic ray paths, generated for the source located above the top part of the salt diapir (PS 17000), are shown in Figure 12A, while the common-shot gather, calculated for this point, is presented in Figure 12B. Additionally, ray paths were calculated for model IV (Fig. 8A), i.e., the large salt diapir with two overhangs (Fig. 13). The pattern of seismic ray paths, associated with such a complex seismic-geological model, as well as the calculated travel-time curves, indicate potential problems, associated with the interpretation of deeper reflectors. The analysis of the calculated records, which was carried out in order to evaluate the potential for imaging of the pre-Zechstein strata, shows that the least reliable results can be recorded with receivers, which are adjacent to a source point, located above the salt diapir. This is because the ray paths, which are vertical, encounter steeply inclined, seismic boundaries (fault planes,

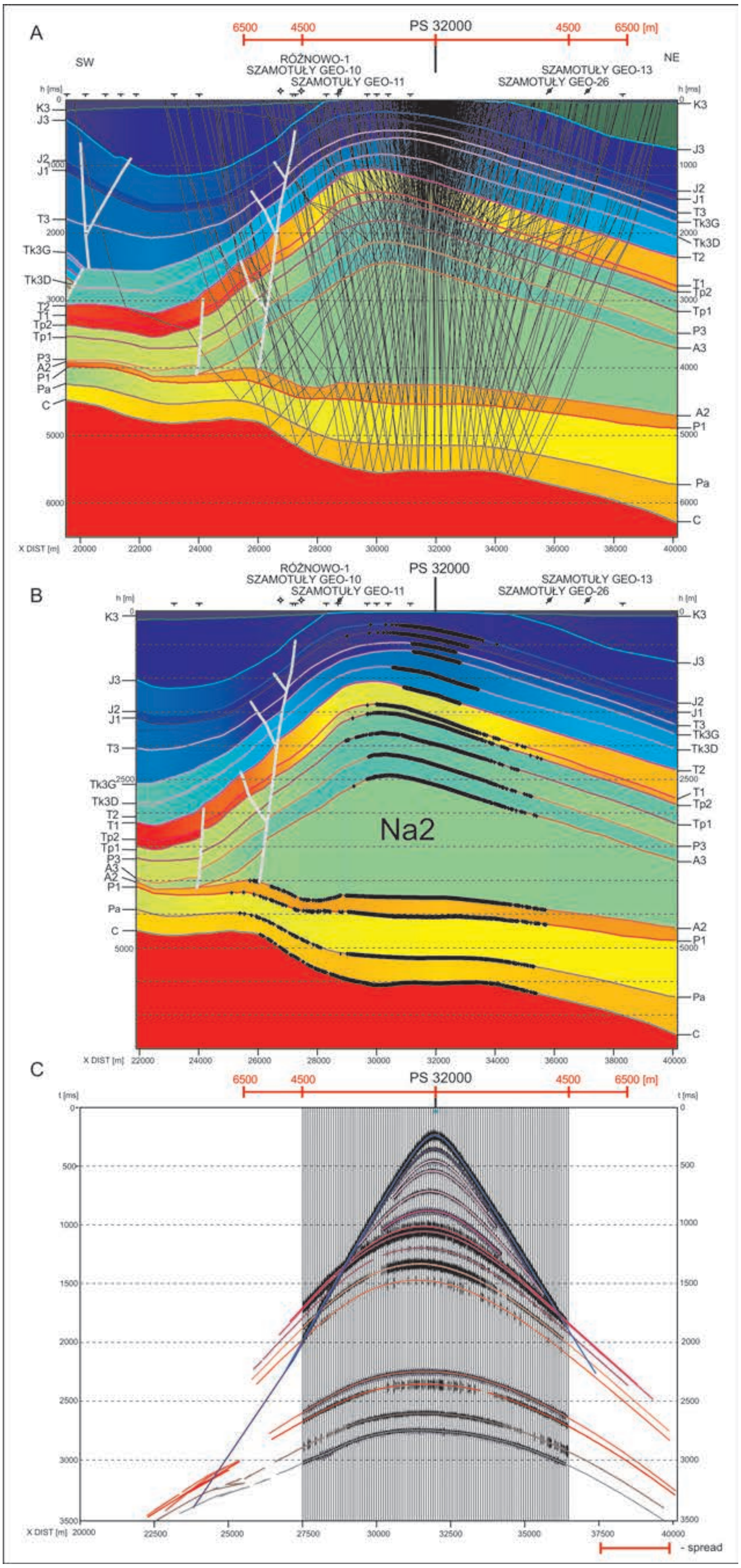

Fig. 10. Offset modelling: part of basic, seismic-geological model I (Rogoźno Salt Pillow), PS 32000. **A** – Seismic ray trajectories; **B** – "Lighting" boundaries seismic rays; **C** – Seismic record. Hodographs of reflection waves, marked with colours: Jurassic boundaries – blue; Triassic boundaries – violet; Zechstein boundaries– orange; inside Rotliegend boundary – brown, and bottom of Carboniferous – black

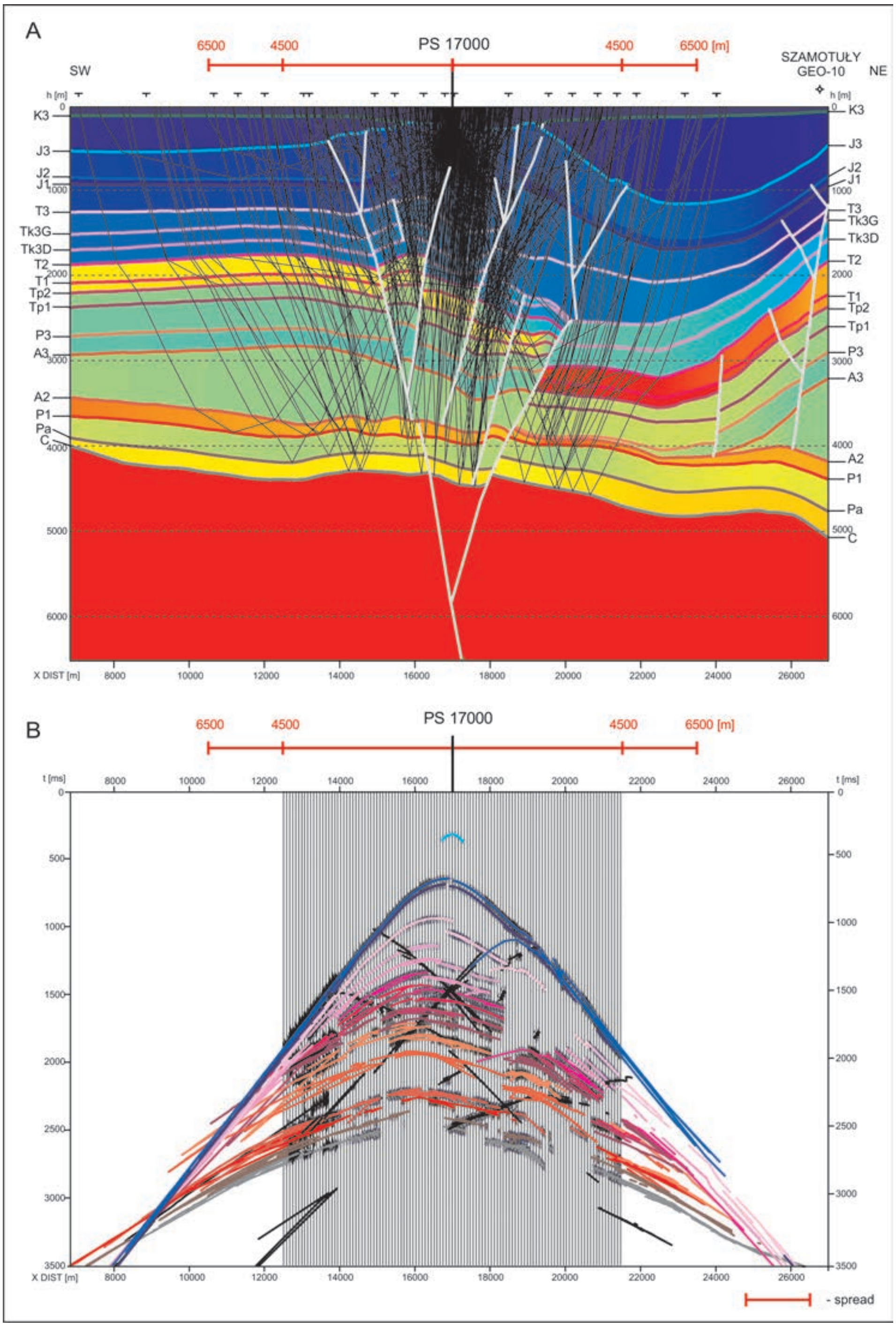

Fig. 11. Offset modelling: part of basic, seismic-geological model I (Szamotuły Zone), Ps 17000. **A** – Seismic ray trajectories; **B** – Seismic record. Colours marked as in Fig. 10C

slopes of the dome), which they reach at a large angle. Thus, they may be refracted easily (large velocity contrasts), without being transmitted into the underlying strata. The algorithm simulates this phenomenon by omitting such ray paths. The ray paths, generated for longer offsets, even longer than the range of seismic spread, indicate the potential for imaging of the deep reflections (see Figs 11B, 12B, 13).

The analysis of seismic illumination of the deeper reflectors with waves, generated in the central part of the deformed zone (PS 17000), was carried out for each of the seismic-geological models. It shows that the poorest coverage of the bottom reflectors in the models is associated with the stratified model (model I; Fig. 11A). This results from the presence of a large number of faults, which transect all stratigraphic units. Because a seismic signal is reflected from the fault planes, it does not reach the deepest reflectors. Slightly better seismic illumination of the deep reflectors is apparent in model IV, which assumes that the salt diapir is associated with two overhangs (Fig. 13). In this model, the deep, seismic reflectors are much better imaged,

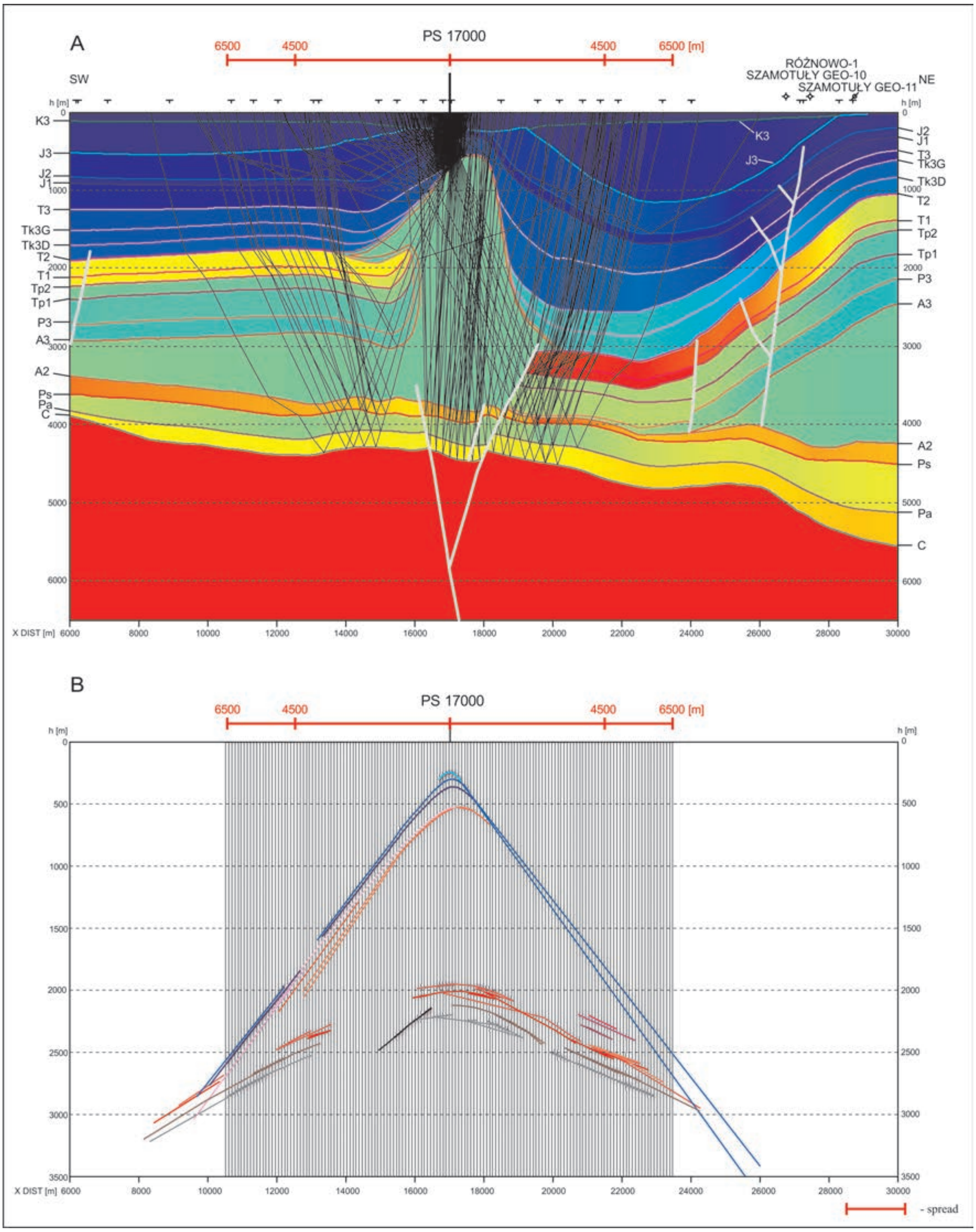

Fig. 12. Offset modelling: Szamotuły Salt Diapir model (V), PS 17000. **A** – Seismic ray trajectories; **B** – Seismic record. Colours marked as in Fig. 10C

particularly on the NE side of the salt diapir. The lack of reflections on the SW side of the salt structure is mainly due to the presence of a large salt overhang, intruding into the Triassic. Because of the large velocity contrast, the ray paths incident on the top of the overhang, are deflected and reach the ground surface beyond the extent of the seismic spread. The best, seismic illumination of the deep reflectors is undoubtedly in model V, which resembles the Szamotuły Salt Diapir (Fig. 12A). This is clearly because there are no large faults in the model, which would otherwise disperse the seismic rays. However, the presence of the salt overhang casts a "shadow" on the Lower Zechstein and deeper reflectors.

However, not only the seismic illumination of reflectors is important for the effectiveness of the seismic method. The geometry of ray paths is also important. The analysis of the ray paths, reaching the seismic spread, indicates that the ray trajectories are in many cases very complex. Because of this, common-depth-point (CDP) stacking definitely will be more problematic. Correct data stacking will require an individual approach to all processing steps, in order to con-

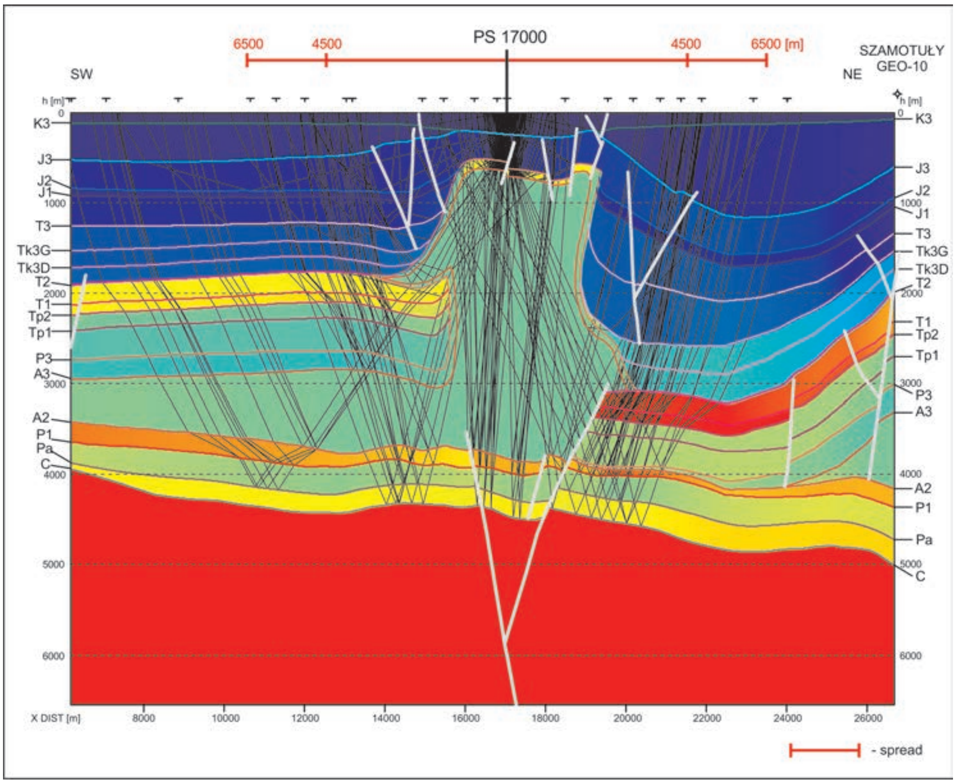

Fig. 13. Offset modelling: salt diapir, with two overhangs model (IV), PS 17000: Seismic ray trajectories

struct seismic time profiles. Processing algorithms, such as DMO and Kirchhoff pre-stack depth migration (PreSDM) or, better yet, the most modern methods such as wave equation migration (Farmer *et al.*,1996), reverse time migration (Jones, 2008) and beam migration (Farmer, 2006) will have to be applied.

Some problems that may occur, when processing data from areas of halokinesis, are illustrated by the comparison of the seismic ray paths, generated at points above both sides of the Szamotuły Salt Diapir, with the ray paths, simulating CDP gather data. The modelling utilised the program *Outrider*, which does not simulate CDP gathers, although it can be used to simulate diffraction ray paths. Thus, diffraction rays were simulated, in order to approximate the CDP gathers. Figures 14 and 15 show the seismic ray paths, generated on both sides of the salt diapirs, at points PS 15000 (SW side of the salt structure) and PS 20000 (NE side). In both cases, the salt overhang formed a distinct obstacle for the propagation of seismic waves. The distribution of seismic rays, obtained in the way discussed above, obviously differs from the real ray paths. *Outrider* cannot be used to simulate rays, reflected multiple times, but only rays reflected a number of times from the steep boundaries of the salt diapir and the surrounding strata on its return path to the surface. Such problems are not expected in areas, underlain by salt pillows. Simulations of seismic ray propagation from point PS 30000 (Fig. 16A), described by coordinate 30000 and located on top of the Rotliegend (diffraction rays, Fig. 16B), showed a fairly regular distribution of both the incident and diffracted rays, which approximate the CDP gather. In such a case, CDP stacking should not cause any difficulties. The distortions, which are apparent around the point, described by coordinate 25000, resulted from the presence of faults which reach the Lower Zechstein. These conclusions are confirmed by modelling, done for points PS 5000, 10000, 25000 and 30000 (Pietsch *et al.*, 2010).

Another problem may be associated with a signal of insufficient energy, reaching the pre-Zechstein strata. Owing to the high positive reflection coefficient (approximately 0.3) of the shallow erosional boundary underlying the Tertiary succession, the critical angle associated with this reflector is low (approximately 30°). This means that only a small part of the wavefront can be transmitted deeper. This is apparent in the common-shot gather data, computed for points PS 17 000 (Figs 11B, 12B) and PS 32000 (Fig. 10C). The figures present a very big difference between the range of maximum offset of waves, reflected at angles lower than a critical angle from the Tertiary/Jurassic (light blue travel-time curve) boundary, and the range of maximum offset of waves, reflected from the Upper/Middle Jurassic reflector (dark blue travel-time curve).

SUMMARY

Zero-offset modelling and offset seismic modelling, which tested different geometries of the subsurface, were carried out, using seismic ray theory. Such modelling can be very helpful in assessing the survey methodology for the proposed regional-scale seismic test line, Obrzycko-1–Za-

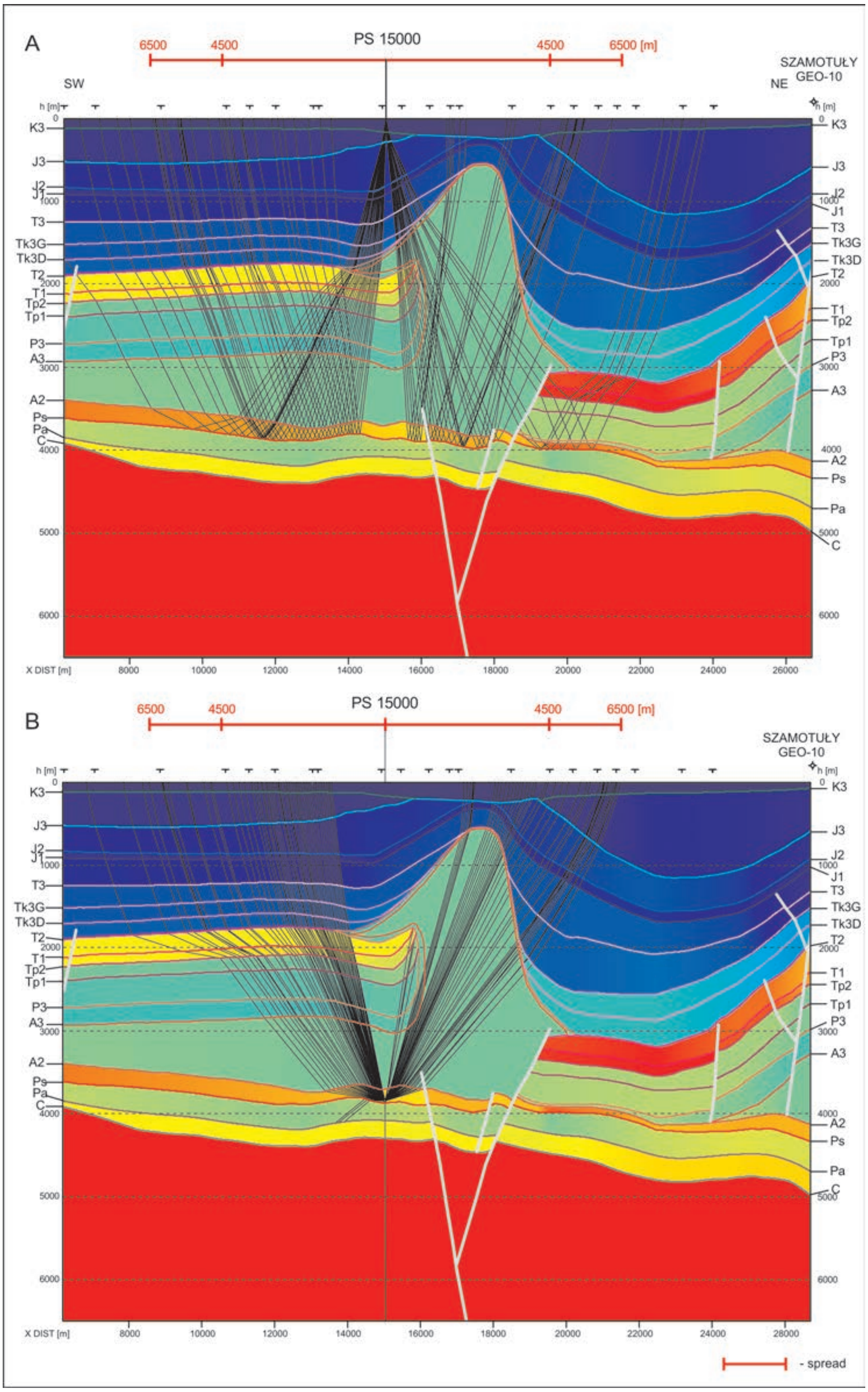

Fig. 14. Seismic ray trajectories, Szamotuły Salt Diapir model (V), PS 15000. **A** – shot record simulation **B** – diffraction point (CDP gather simulation)

bartowo-1–Zabartowo-2 (Górecki, 2010), designing the approach for data processing and developing criteria for the seismic interpretation of recorded wave field.

The conclusions with regards to the survey methodology are mainly based on the analysis of seismic ray paths, calculated for the seismic-geological models, which show the subsequent stages in the development of the salt structure. The distribution of ray paths and the seismic illumination of reflectors show that it should be possible to record a seismic signal, reflected from the Rotliegend strata, both when salt pillows overlie them and when simple-shaped salt diapirs are present. Significant limitations are expected,

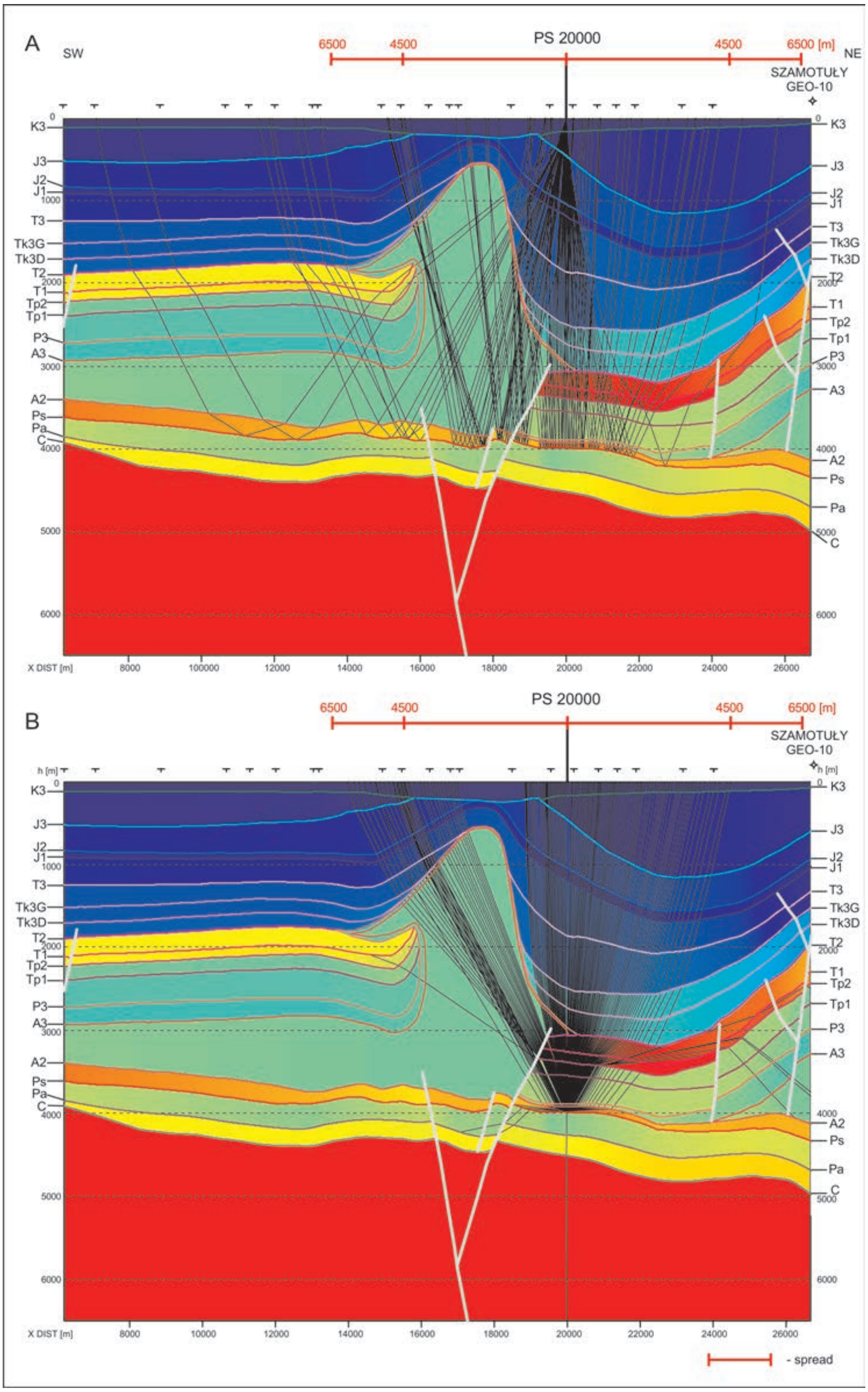

Fig. 15. Seismic ray trajectories, Szamotuły Salt Diapir model (V), PS 20000. **A** – shot record simulation; **B** – diffraction point (CDP gather simulation)

where salt diapirs with large overhangs or fault zones are present above the strata. In such a situation, due to the signal being reflected from the additional, seismic interfaces, which are usually associated with strong contrasts and are steeply inclined, the ray paths of the reflected waves reach the ground surface far beyond the survey stretch, while ray paths, associated with the refraction waves, are very easily refracted.

The results of the analysis of seismic ray paths, seismic records and synthetic wave fields also indicate that the processing of recorded, seismic data may be problematic. The non-uniform distribution of ray paths, which results in the

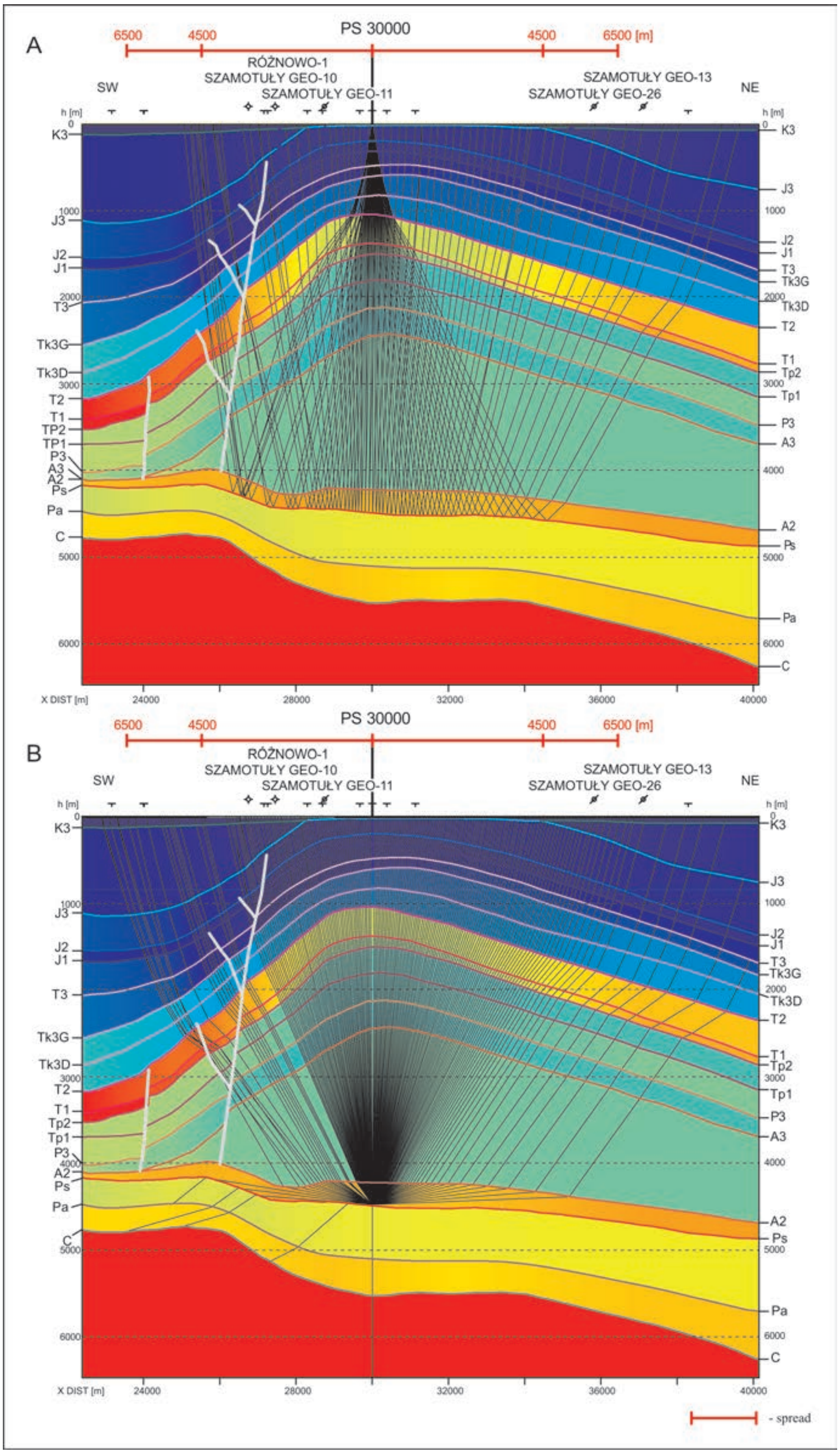

Fig. 16. Seismic ray trajectories, Salt Pillow Rogoźno, PS 32000. **A** – shot record simulation; **B** – diffraction point (CDP gather simulation)

non-hyperbolic shape of travel-time curves, in the curve discontinuity, apparent on the individual records, as well as in a complex wave field (such as a large number of diffracted waves), observed in tectonic zones, indicates that it will be necessary to apply the survey methodology and processing algorithms, developed for the seismic exploration of complex salt structures (Hale, 1991; Hill *et al.*, 1991; Cavalca and Lailly, 2005; Farmer and Jones, 2006; Buur and Kuhnel, 2008).

The synthetic wave fields, calculated for the subsequent, seismic-geological models, ranging from the stratified model to a salt diapir, resembling the Szamotuły Salt Diapir, indicate the following conclusions:

– the presence of small salt pillows does not significantly affect the image of the underlying strata. The distribution of seismic reflection events on time profiles resembles the distribution of seismic reflectors in the depth domain;

– when a large salt pillow is present, correct recording of reflected waves should not be problematic. However, in such a case, a reverse arrangement of seismic events in time sections and seismic reflectors in depth sections should be expected. Flat-lying or synclinal geologic boundaries may appear as anticlinal seismic events in time profiles. The pull-up effect will increase with increasing thickness of salt strata and with increasing seismic velo- city, associated with them;

– the presence of salt diapirs significantly complicates the seismic image of sub-salt structures. This is due to the shape of the salt diapir and the wave velocity contrast between a salt body and the surrounding strata. The presence of an irregularly shaped salt diapir and associated faults results in large numbers of additional seismic interfaces. In such a situation, the seismic signal is reflected in all directions, which significantly complicates accurate, seismic data processing and decreases the quality of the signal, reflected from the Rotliegend strata. The velocity contrast is particularly apparent, when a salt diapir penetrates the Muschelkalk strata, resulting in a clear increase in the pull-up effect;

– the modelling exercise performed demonstrates the effectiveness of multi-optional modelling in the geological interpretation of complex salt structures.

The modelling, using a method, based on seismic ray theory gives simplified ray paths and synthetic wave fields. Nevertheless, the modelling, presented here, shows the difficulties which may be encountered during seismic exploration of the pre-Zechstein successions in areas of salt tectonics. The modelling indicates that both high-velocity contrasts in zones, where salt diapirs reach the Cretaceous and Tertiary strata, and steep inclination of seismic reflectors, associated with large-displacement faults and the walls of diapirs, affect the seismic image of the pre-Zechstein successions.

The main conclusion of the present study is that the architecture of the eolian Rotliegend strata cannot be accurately recognised without a good understanding of the structure of the Zechstein succession. In order to gain a reliable picture of the Zechstein succession, it is necessary to adopt advanced methods of seismic data processing, suited to the imaging of steeply inclined, subsurface features, frequently cut by faults. Equally important is the construction of a reliable velocity model, since the model determines the effectiveness of the processing procedures (such as migration) and is also necessary for developing – using seismic modelling – the criteria for the seismic interpretation of recorded wave field.

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