Annales Societatis Geologorum Poloniae (2012), vol. 82: 263–277.

THE INFLUENCE OF SEISMIC VELOCITY DISTRIBUTION ON THE DEPTH IMAGING OF THE SUB-ZECHSTEIN HORIZONS IN AREAS AFFECTED BY SALT TECTONICS: A CASE STUDY OF NW POLAND

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Pietsch, K., Marzec, P., Niepsuj, M. & Krzywiec, P., 2012. The influence of seismic velocity distribution on the depth imaging of the sub-Zechstein horizons in areas affected by salt tectonics: a case study of NW Poland. *Annales Societatis Geologorum Poloniae*, 82: 263–277.

Abstract: Lateral changes in the thickness of strata and petrophysical parameters within the Zechstein succession (salt pillows and domes) can cause many problems in seismic exploration of the aeolian Rotliegend formations, which are prospective for hydrocarbons.

An assessment of the influence of halokinesis on the seismic imaging of the sub-Zechstein strata in NW Poland (Obrzycko–Szamotuły area, to the SW of the Mid-Polish Swell) utilised time-to-depth conversion with different, seismic-geological models. Various, seismic velocities were used in models for the Zechstein and the Mesozoic successions, namely velocities, dependent on the thickness of particular rock successions, on their depths, and velocities, determined from seismic inversion. The results show opposite reflection patterns for the seismic section imaged in the time and depth domains. The synclinal arrangement of the strata boundaries in the depth model is represented by convex-upwards reflection events on the seismic section. The pull-up of reflection events, associated with the sub-Zechstein strata, observed on the seismic sections, is mainly a result of both the greater thickness of the Zechstein salt within the salt structures (pillows, diapirs) and the increase in velocity contrast between the salt body and the Mesozoic strata.

Key words: seismic imaging of sub-Zechstein boundaries, velocity models for Zechstein and Mesozoic successions, halokinesis, Mid-Polish Swell

Manuscript received 25 April 2012, accepted 20 December 2012

INTRODUCTION

Improving the effectiveness of seismic exploration for gas reservoirs, underlying the Zechstein succession in the area of depressions, located to the SW of the Mid-Polish Swell, is one of the most important objectives of seismic studies in Poland. The key issue is locating reliably the base of the Zechstein and the boundaries of the Rotliegend strata.

Seismic imaging of the aeolian Rotliegend deposits is significantly affected, both by the uniform character of the petrophysical parameters of the Lower Permian and the Carboniferous, as well as tectonic deformation of the Zechstein and Mesozoic overburden (fault zones, salt diapirs and pillows) and the high variability, both lateral and vertical, of the elastic parameters, associated with these successions (for example, salt: $v \approx 4{,}500$ m/s, $\rho \approx 2.1$ g/cm^3, anhydrite: $v \approx 6{,}000$ m/s, $\rho \approx 2.8$ g/cm^3). Thus, seismic imaging of the Rotliegend formations is often problematic.

In such settings, seismic interpretation of the sub-Zechstein strata boundaries should include the reliable recognition of tectonic elements, particularly those related to salt tectonics, as well as the preparation of a seismic velocity model for the overlying Zechstein and Mesozoic successions. Such features have a significant influence on the formation and distribution of the hydrocarbon traps in the Rotliegend succession, as well as on their seismic imaging. However, seismic imaging of the overlying Zechstein and Mesozoic successions is also problematic.

A method, which can support the seismic interpretation of such data, is seismic modelling. Synthetic, seismic data, generated for seismic-geological models, can be used to correlate individual elements of such models with their seismic response. Thus they not only aid in developing criteria for the seismic interpretation of recorded seismic data (Ko-

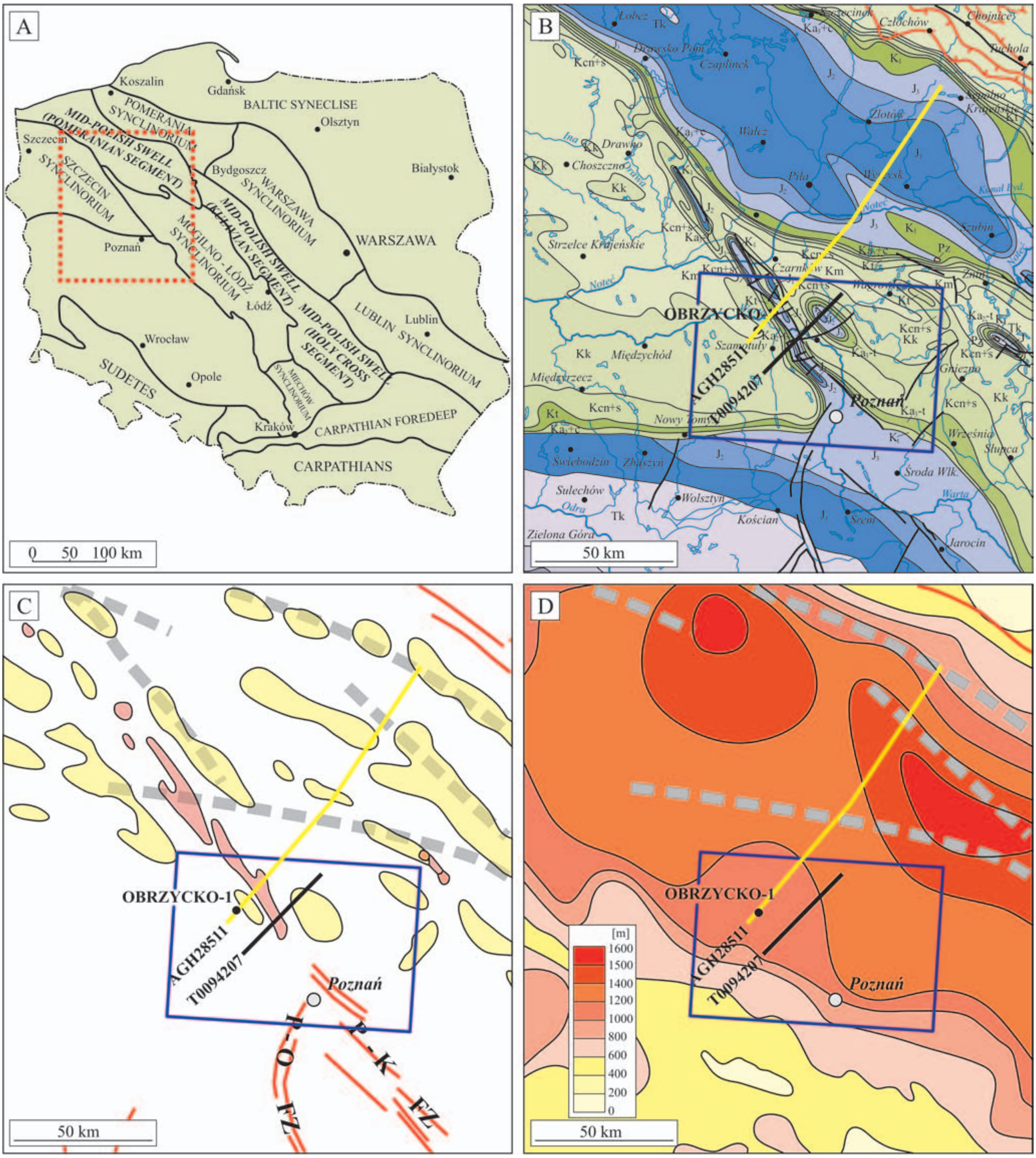

Fig. 1. Outline of geology of study area. **A** – Location of study area and major structural units of Poland; **B –** Geology of study area below Cenozoic cover (Dadlez *et al.*, 2000). Location of study area (navy blue rectangle), seismic lines, used in structural interpretation (black line) and experimental regional seismic line Obrzycko-1 – Zabartowo-1 – Zabartowo-2 (yellow line); Green colours – Cretaceous; blue colours – Jurassic; pink colours – Triassic; see Dadlez *et al.* (2000) for further explanation. Regional, structural grain of Permo-Mesozoic basin of Poland is expressed by so-called Mid-Polish Swell, formed above Teisseyre–Tornquist Zone, as a result of Late Cretaceous – Early Paleogene inversion of Mid-Polish Trough. Mid-Polish Swell can be divided into three segments (Pomeranian, Kuiavian and Holy Cross) that reflect deeper, crustal control on basin evolution (cf. Krzywiec *et al.*, 2006); **C** – map of salt structures and main faults (red lines) within Mesozoic cover of Mid-Polish Trough (Dadlez and Marek, 1998, modified). Thick grey, dashed lines: hypothetical sub-Zechstein fault zones, responsible for regional subsidence and inversion of Mid-Polish Trough (cf. Krzywiec *et al.*, 2006); obliquely hatched area: Mid-Polish Swell, defined by sub-Cenozoic subcrops of Lower Cretaceous and older deposits (cf. Fig. 1B). Yellow: salt pillows, pink: partly pierced salt diapirs, orange: fully pierced salt diapirs. P-K FZ: Poznań – Kalisz fault zone, P-O FZ: Poznań – Oleśnica fault zone; **D** – map of Zechstein paleothickness (after Wagner, 1998). Thick grey, dashed lines: sub-Zechstein fault zones, responsible for regional subsidence and inversion of Mid-Polish Trough (cf. Krzywiec *et al.*, 2006)

bylarski *et al.*, 2007, 2008; Pietsch *et al.*, 2007a, b), but also support the choice of methodology and optimum processing sequence for a seismic survey (Pietsch *et al.*, 2010).

Owing to the problems with interpretation of seismic data recorded for the Zechstein and Mesozoic successions, a critical issue is making a suitable geometrical velocity model for subsurface strata. This is the subject of this article.

A depth–velocity model of the Permo-Mesozoic succession was prepared, on the basis of seismic data (Fig. 1 – seismic line T0094207 – black line) and well-log data from the area, located to the north-west of Poznań.

GEOLOGY OF STUDY AREA – AN OVERVIEW

The study area is located in the NW part of the Permo-Mesozoic basin, in Poland (Fig. 1A). This formed the E part of the epicontinental, sedimentary basins of Western and Central Europe (Ziegler, 1990; Pharaoh *et al.*, 2010). The Permian and Mesozoic sedimentary cover, deposited in the axial part of this basin, called the Mid-Polish Trough, attained a total thickness of several kilometres. The Mid-Polish Trough was inverted in the Late Cretaceous–Paleogene and, as a result, a regional inversion structure, called the Mid-Polish Swell, was formed (Fig. 1; see e.g. Marek and Pajchlowa, 1997; Scheck-Wenderoth *et al.*, 2008 for a more detailed description and additional references).

The evolution of the Pomeranian and Kuiavian segments of the Mid-Polish Trough was strongly influenced by salt tectonics (for more details and further references, see Krzywiec, 2004, 2006a, b, 2009, 2012). Both during basin extension and subsidence, as well as during its compression and inversion, the presence of thick ductile Zechstein evaporites at the base of the sedimentary infill resulted in a regional, mechanical decoupling between the supra-salt Mesozoic cover and sub-salt Rotligend and the older substratum. Sub-salt faulting and regional extension and compression led to the formation of salt structures, such as salt pillows and salt diapirs (e.g. Krzywiec, 2006a, b; Krzywiec *et al.*, 2006).

The analysed seismic transect that was used as a starting point for the seismic modelling, described below, is located on the SW edge of the Mid-Polish Swell (Fig. 1B). In this area, a system of salt diapirs, located generally to the N of Poznań (Drawno, Dzwonowo, Człopa and Szamotuły salt diapirs – see Krzywiec, 2006b), is replaced by a system of tectonic grabens, bounded by faults, generally detached within the Zechstein evaporites (the so-called Poznań – Oleśnica and the Poznań – Kalisz fault zones; Fig. 1C; cf. Kwolek, 2000).

Both the systems of salt structures, mentioned above, as well as graben / fault structures, are located obliquely to the reconstructed Zechstein palaeothickness and to the hypothetical basement fault zones, responsible for basin subsidence and subsequent inversion (Fig. 1D). The seismic transect is located in the transitional zone that was characterized by a total thickness of the Zechstein evaporites of approximately 1000–1300 m. As a result, salt structures in this area are of a complex, character, transitional between the fully developed salt diapirs, located to the NW, and the graben and half-graben structures, located to the SE.

SEISMIC DEPTH MODEL

2-D seismic surveys have been carried out in the Obrzycko–Szamotuły area since 1976. The most recent 2-D data include the lines Obrzycko–Szamotuły (2001 and 2007), acquired by the Geofizyka Toruń Ltd. and the line Murowana–Goślino–Kłecko (2008), acquired by the Geofizyka Kraków Ltd. (Fig. 2). The seismic-geological model is primarily based on a seismic transect, stretching in a SW–NE direction between seismic lines T0094207 and 13-1-08K (Figs. 2 and 3). The seismic transect was calibrated with well data and interpreted structurally.

When analysed from the SW to NE, i.e. the direction of the palaeoslope inclination, the seismic image of the Permo-Mesozoic succession shows near-horizontal strata, with a small salt pillow. Further to the NE, there is a structurally complex zone (mainly reverse faults, probably related to a compressionally reactivated salt structure and significant upward movement of the salt), while in the NE part of the section, there is a large salt pillow at Rogoźno.

In the study area, there are several tens of wells, from which a large variety of geophysical and geological data was collected. Adjacent to the seismic transect (Fig. 2), acoustic velocity logging, which is the most important for seismic surveys, has only been carried out in the Obrzycko-1, Objezierze IG-1 and Kaźmierz-1 wells, while mean velocity data have been collected in the Obrzycko-1, Objezierze IG-1, Szamotuły GEO-10 and Szamotuły GEO-13 wells. The remaining wells provided only stratigraphic data (Fig. 2).

Synthetic seismograms (LogM software of GeoGraphix, *Landmark Graphics Corporation*) were calculated, in order to correlate the seismic records with the well data. The Kaźmierz-1 well is the only one, which is located along the seismic transect and offers velocity data. The data from this well were used for correlation with the SW part of the transect (Fig. 3), which is located to the SW of the small salt pillow. Lithology and thickness of strata, similar to those of the zone associated with the salt pillow, were found in the Obrzycko-1 well, which is located on profile T0470180, oriented orthogonally to the transect. Thus, the geological data, available from the Obrzycko-1 well, were correlated with seismic data from the area, located on the SW margin of the tectonically deformed zone, i.e. the area of the first salt pillow. Data from the Objezierze IG-1 well, which was located on profile T0520177, oriented orthogonally to the transect, were correlated with seismic reflectors on the NE side of this zone (Fig. 2).

Normal, synthetic seismograms, calculated from the logs of the Kaźmierz-1 (Fig. 4A) and Objezierze IG-1 wells (Fig. 4B), were compared with the fragments of seismic transects, located near the wells and with geophysical well data (gamma ray, interval transit time from a sonic log). Additionally, a velocity curve was added, and represented mean velocity values for the lithostratigraphic successions identified (velocities of selected lithostratigraphic successions). Thus, it can be treated as a 1-D seismic-geological

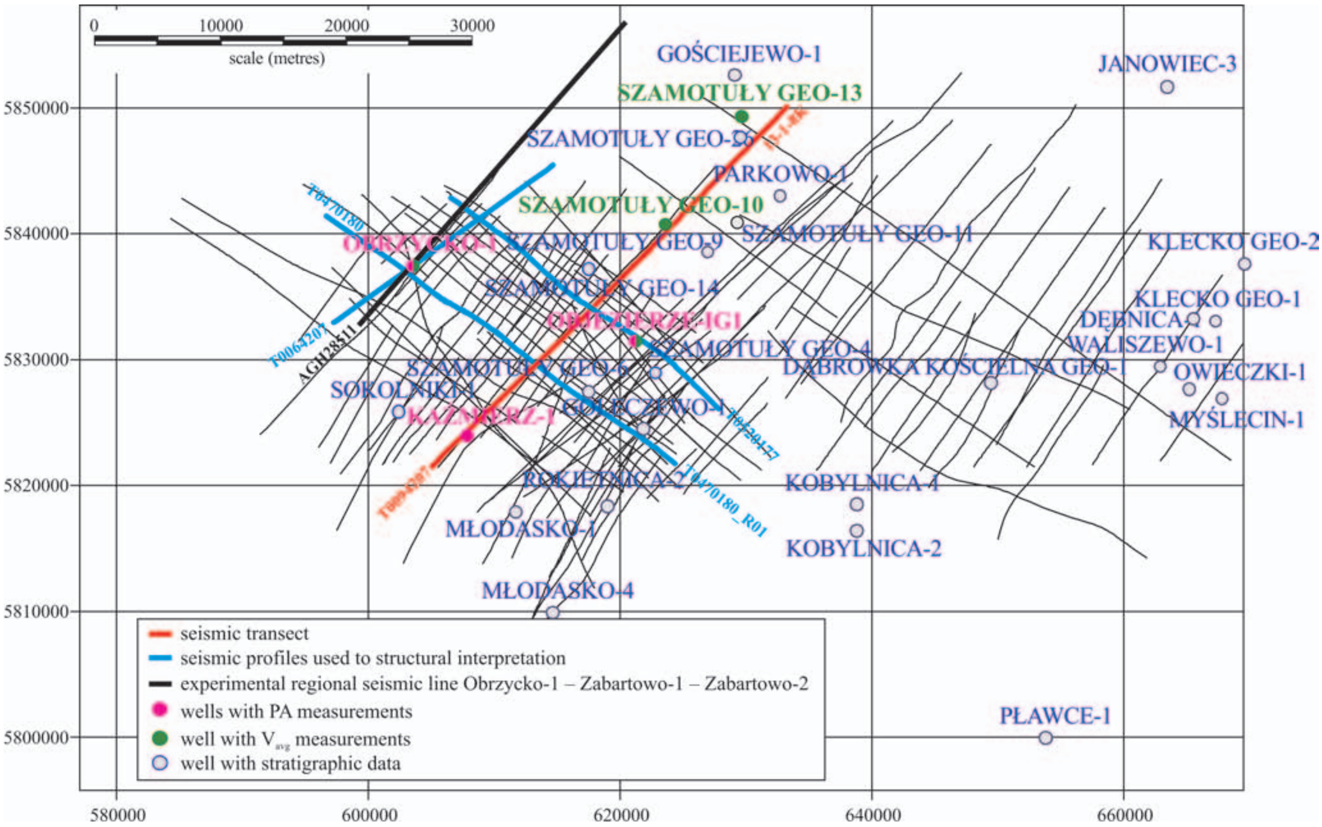

Fig. 2. Location map for seismic and borehole data. 1 – seismic transect; 2 – seismic profiles used for structural interpretation; 3 – experimental regional seismic line Obrzycko-1 – Zabartowo-1 – Zabartowo-2, 4 – wells with PA measurements, 5 – well with V_{avg} measurements, 6 – well with stratigraphic data

model from the location of the well. The synthetic seismograms were generated, using the 26 Hz frequency Ricker signal extracted from the seismic traces (Pietsch *et al.*, 2010).

A comparison of the synthetic seismogram, generated from the logs of the Kaźmierz-1 well (Fig. 4A), with the recorded seismic traces showed good correlation, which indicated that the main, lithostratigraphic boundaries were recorded in the seismic data. The correlation of the recorded, seismic data with the synthetic data from the Objezierze-IG well was slightly worse (Fig. 4B). As the well was located in the E margin of the tectonically deformed zone, the poorer correlation was associated with the steep inclination of the strata. It was also a result of the large distance (over 4 km) between the Objezierze IG-1 well and the seismic transect. Shallow wells, located above the salt pillow, were also used to correlate the boundaries of the strata. These wells, however, did not reach even the Triassic formations (the NE part of the transect).

Correlation of the geological and geophysical data, described above, was necessary for identification of the reflectors along the seismic survey lines, i.e. to construct the geological model (geometrical model).

Figure 3 presents the geological interpretation of the seismic transect. The SW part of the section (profile T0094 207) shows near-horizontal, lithostratigraphic units, which start with the Cretaceous and extend to the base of the Zechstein. The Cretaceous seismic reflectors (green) are associated with reflection events of low amplitude. The first, well defined reflection event is associated with the top of the Jurassic (J3), i.e. the boundary between the Cretaceous succession (Cenomanian and the Lower Cretaceous) and the Upper Jurassic carbonates (blue boundaries). The next, strong reflection events are within the Triassic successions (pink and violet boundaries). They are associated with gypsum-anhydrite and carbonate series, which occur both within the Keuper (T3) and the Muschelkalk (T1).

The Bunter Sandstone is associated with a distinctive pattern in the seismic record. This is a thick succession with no apparent reflection events (Tp1-P3). The lower part of the section is associated with a number of strong-amplitude reflection events, which represent anhydrite strata, i.e. P3 (top of the Zechstein), A3 and A2. Between these strata, salt horizons occur, and there are no significant reflection events within them. The last, clearly defined boundary in the seismic record is associated with the base of the Zechstein (P1). The Kaźmierz-1 well penetrated the base of the Zechstein into the Carboniferous strata (C). Low-amplitude reflection events, which may be associated with the top of the Carboniferous, are inclined to the NE. The probable location of this boundary was identified, on the basis of other, interpreted, seismic sections (Pietsch *et al.*, 2010).

The central part of the transect (north-eastern part of profile T0094207) is associated with a completely different, geological structure. Here, the subsurface is divided by a series of faults. The strata of the basement (Carboniferous, Rotliegend and base of the Zechstein) are cut by two faults, i.e. from the SW by a normal fault, which terminates in the Older Halite horizon (Na2), and from the NE by a reverse fault, which extends up to the Middle Triassic succession. The seismic records indicate that the faults are associated with conjugate faults. These are usually reverse faults, which start in the Zechstein succession and continue up to the Miocene strata. They surround the zone of strong, tectonic deformation and the sediments, overlying it, have been uplifted and partly eroded. Within the zone between the faults, the Jurassic and Upper Triassic boundaries can be interpreted in a relatively unambiguous way. However, in the deeper part of the profiles, which stretch down to the base of the Zechstein, the reflection events are only partly recognisable or cannot be distinguished at all. Thus, the reflection-free zone stretches between the Jurassic boundaries and the base of the Zechstein succession. This is possibly a result of intrusion of the salt from the Older Halite stratum (Na2), or alternatively the Younger Halite (Na3), into the overlying strata. During the phase of seismic modelling, three different scenarios of halokinesis were taken into account (Pietsch *et al.*, 2010). The marginal fault on the SW side of the zone is a normal fault of small displacement, hence the thicknesses of sediments on both sides of the fault are similar. The opposite situation occurs on the NE side of the zone, where a reverse fault terminates in the Lower Keuper. This large fault significantly changes the geometry of seismic reflectors on the NE side of the deformed zone where the Zechstein strata (Werra sequence of small thickness) are pinched out against the top Rotliegend. The thicknesses of strata on both sides of the fault are fundamentally different. The lack of Zechstein deposits on the SE side is compensated by the increased thicknesses of the Upper Keuper (Tk3G), Rhaetian (T3) and Upper Cretaceous deposits, which fill the drag fold beneath the fault. The Objezierze IG-1 well (Fig. 4B) is located within the same tectonic zone, although further towards the SE (see Fig. 2). The well penetrated the Triassic sandstones (Tp), overlying the thin Werra sequence. Above that, the fault was recorded in the well. Above the fault are the PZ2 and PZ3 units, which are conformably overlain by the Bunsandstein formation. This interpretation was based on the sequence of strata from the Objezierze IG-1 well, although the similarity between the seismic facies, associated with the Older Halite (Na2 strata) in the SW part and the Tp2 unit in the NE part of the section, could suggest a different interpretation.

The NE part of the transect (Fig. 3), profile 13-1-08K, shows the Rogoźno salt pillow, which is built from the Older Halite (Na2). Despite the poor quality of the data, particularly in the NE part of the profile, the concentric pattern of the seismic reflectors is apparent. Their geological interpretation was based on data from the shallow wells, located on both sides of the pillow. However, the image of the deeper reflectors in the transect is rather poor, as it is in other profiles, collected in the area of the large salt pillow. Thus, the interpretation of the top and base of the Werra sequence, as well as the boundary, correlated with the top of the Carboniferous, is not entirely certain.

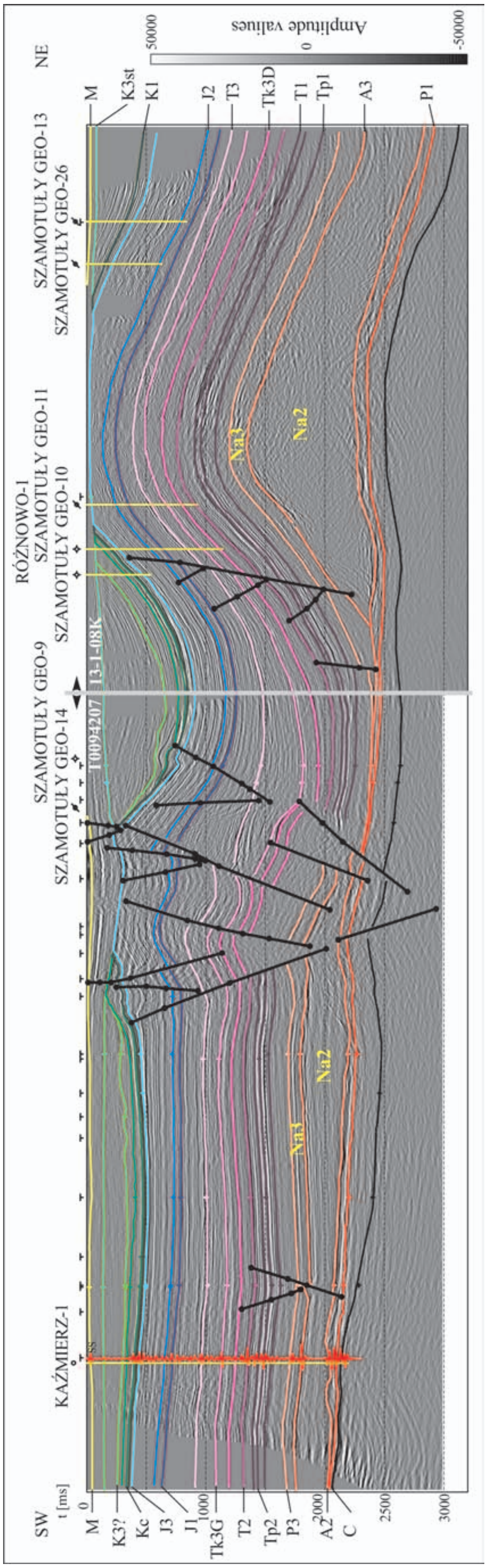

Fig. 3. Seismic transect (T0094207 and 13-1-08K profiles). Seismic boundaries: Miocene top: M; Cretaceous: K3st, K3?, Kt, Kc, K1; Jurassic: J3, J2, J1; Triassic: T3, Tk3G, Tk3D, T2, T1, Tp2, Tp1; Permian: P3, A3, A2, P1; Carboniferous top: C

The seismic transect that was structurally interpreted and calibrated with the well data (Fig. 3) revealed the geometrical pattern of the seismic reflectors, which became the basis for the seismic-geological model. The model was used later in seismic modelling, which aimed to assess the influence of the salt structures on the seismic representation of the basement strata (Pietsch *et al.*, 2010).

The velocity model, which was essential for developing the seismic-geological model, was prepared on the basis of acoustic velocity logs from the deep Kaźmierz-1, Obrzycko-1 and Objezierze IG-1 wells, mean velocity data from the shallow GEO-10 and -13 wells and stratigraphic information (depths to seismic markers) from the Szamotuły GEO-9, -11, -14, -26 and Różnowo-1 wells. Owing to the small number of wells with available velocity data and the non-uniform distribution of wells along the seismic survey line (Fig. 2), the model, which was based only on strata velocities from these wells (e.g. Fig. 4), was very general. Such a model, which, because of the complex geology of the area, is definitely different from the real seismic-velocity distribution in the subsurface, was used for the initial assessment of the influence of the salt structures on the seismic imaging of the basement strata.

Development of the seismic-geological model utilised modules LogM and Struct of the GeoGraphix software.

The entry data include (1) seismic reflectors, established along the seismic transect (Fig. 3) and (2) velocity values, based on geophysical data from wells. The seismic-geological model in time is shown in Figure 5A. The seismic-depth model, the result of time-to-depth conversion, is shown in Figure 5B. It approximates the actual shape of the geological boundaries in the subsurface.

REPRESENTATION OF STRATA BOUNDARIES IN SEISMIC RECORD

A comparison of the time model (Fig. 5A) and the depth model (Fig. 5B), based on velocity data, revealed differences in configuration of the boundaries in these two models.

In the SW part of the transect, the boundaries of the lithostratigraphic successions form a flat-lying, parallel pattern. The patterns, associated with seismic reflectors in the depth model and the time model, are very similar. A contrasting situation is in the NE part of the profile, i.e. in the zone of the large salt pillow. Here, in the depth model (Fig. 5B), the strata, underlying the salt pillow (strata of the lower Zechstein, Rotliegend and top of the Carboniferous) are inclined to the NE, thus forming a syncline in the zone of the largest thickness of the pillow. However, in the time model (Fig. 5A), as in the seismic transect (Fig. 3), only the strata in the marginal part of the profile are inclined to the NE, while in the zone of the largest thickness of the pillow, the strata are uplifted, forming a distinct convex-upwards pattern. The reverse shapes of the reflection events are also apparent in the zone between the salt pillow and the deformed zone. Here, however, the basement strata form an anticline in the depth model (Fig. 5B), which in the seismic section (Fig. 5A) is represented by a concave-upwards shape.

The range of changes in the shape of the basement strata, which, because of the velocity variations in the overlying strata, are introduced into the seismic image, are well demonstrated by the morphology of the base, is indicated as 'the bottom of the model' (Fig. 5B). This is the base of the velocity model at 3.20 s (Fig. 5A).

Analysis of the shape of the boundary showed that on the seismic section in time, the largest changes in the shape of the base strata were introduced in the areas of the salt pillows or a potential dome. Such variability is not present in strata, which overlie the Zechstein succession (Fig. 5A, B). Thus, the analysis indicated the fundamental influence of the presence of salt structures on the seismic imaging of the subsurface.

In the zones, where the salt structures are present, the shape of reflections, representing the boundaries of the sub-Zechstein strata, is strikingly different on the seismic images shown in the time and depth domains. The differences in the geometry (the convex-upwards shape of the sub-Zechstein reflection events on the time section and their concave-upwards pattern in the depth model) are related to the presence of salt structures, associated with velocities, which are higher than those of the surrounding rocks. This leads to a reduction in the time travel of seismic waves, which is demonstrated by the pull-up of reflection events on the seismic sections with respect to time.

ALTERNATIVE VELOCITY MODELS AND THEIR INFLUENCE ON SHAPE OF REFLECTION EVENTS

The velocity model used for the time-to-depth conversion (Fig. 5A) was developed, using a small amount of velocity data from the wells.

The pull-up of the reflection events, associated with the sub-Zechstein boundaries (Fig. 5A), is related to the large, vertical and lateral changes in seismic velocity and to the variable thicknesses of the salt structures, as well as to the thicknesses of the Triassic, Jurassic and Cretaceous strata, surrounding them. Thus, the velocity influence on the depth imaging of the sub-Zechstein strata boundaries was analysed in two stages: the first involved applying different velocity models to the Mesozoic succession, while the second involved applying them to the Zechstein succession.

The analysis of the influence of velocity within the Mesozoic successions on the seismic imaging was carried out with three separate velocity models. The velocity models use (1) complex velocities, defined for the lithostratigraphic successions as a function of their thickness, (2) complex velocities, defined as a function of their depth, and (3) velocities determined, using the seismic inversion process.

In order to determine the distribution of the velocity of the strata, overlying the Zechstein, defined as a function of the thickness of lithostratigraphic successions, the mean velocity data from the wells, located in the study area, were analysed. The analysis was carried out for the lithostratigraphic successions of the Quaternary and Tertiary (Q+Tr), Cretaceous (Cr), Upper Jurassic (J3), Middle Jurassic (J2), Lower Jurassic (J1), Rhaetian (T3-Tk3G); Upper Keuper – Upper Gypsum series (Tk3G-Tk3D), Lower Keuper – Lower

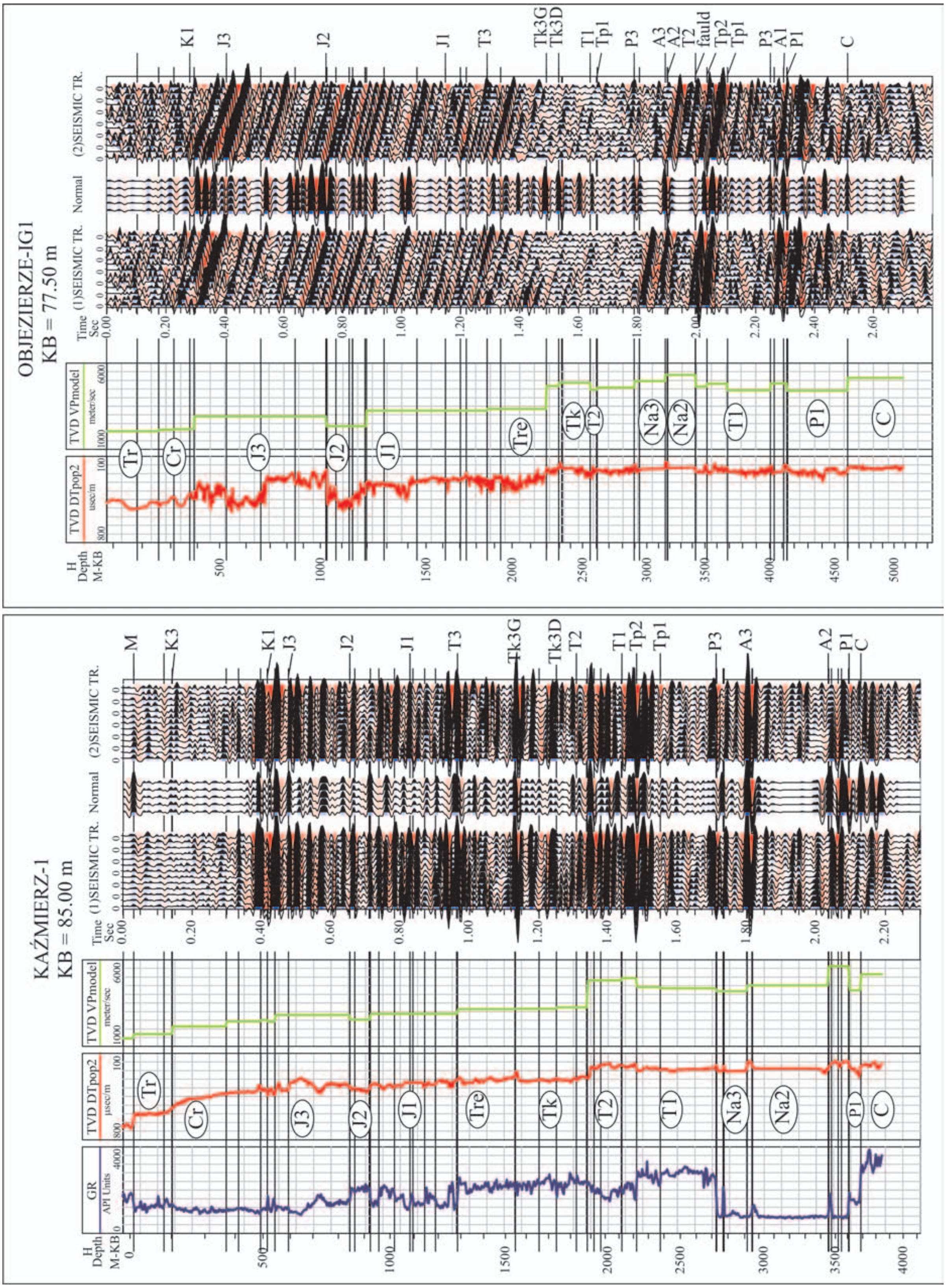

Fig. 4. Synthetic seismograms with 0-phase signal application. A – Kaźmierz-1 well; B – Objezierze IG-1 well; *GR* – gamma ray; *TVD DTpop2* –transit interval time from sonic log; *TVD VPmodel* – velocities of selected litho-stratigraphic complex ; KB – kelly bushing elevation. Seismic boundaries as in Fig. 3

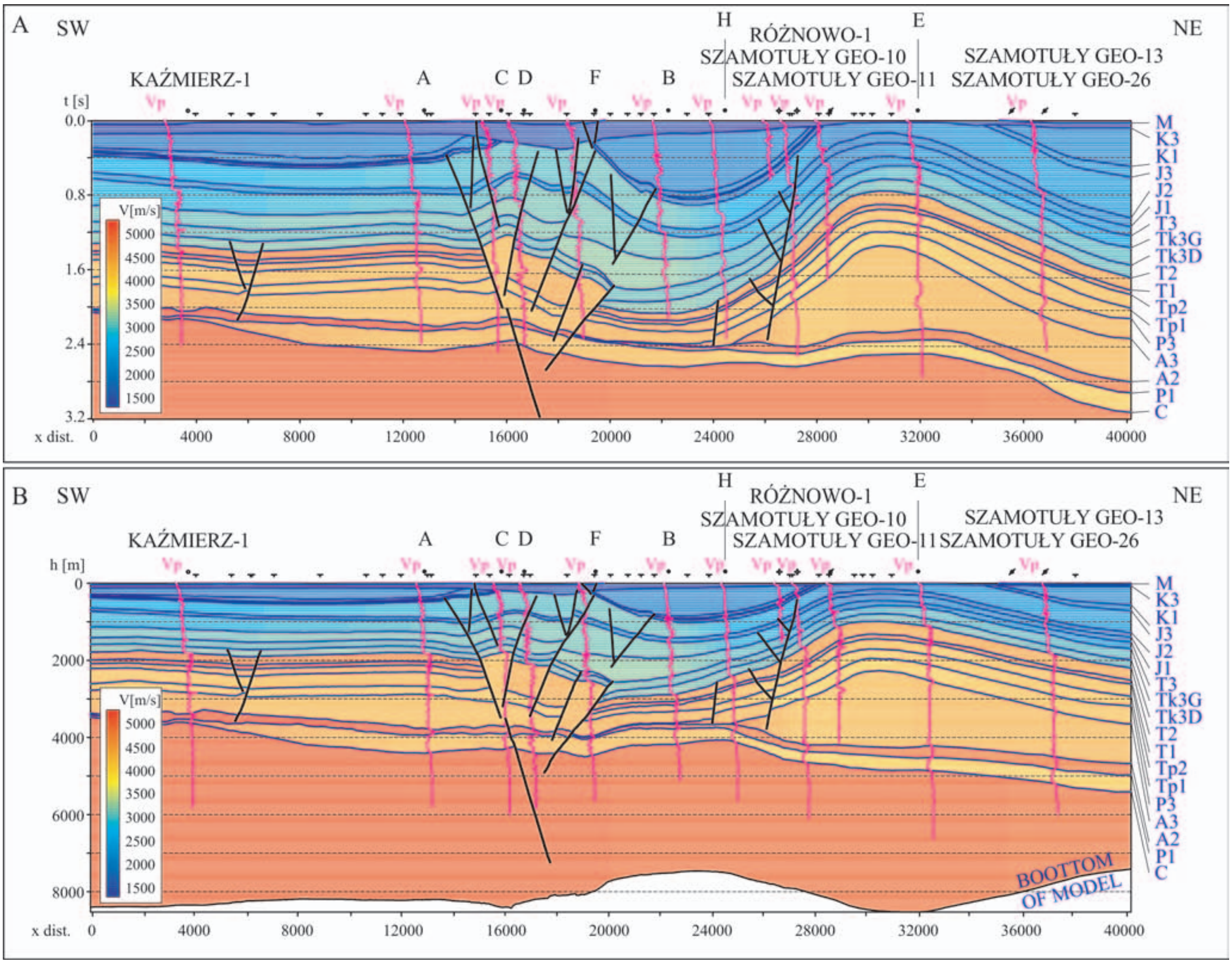

Fig. 5. Seismogeological model along seismic transect. **A** – time model; **B** – depth model. Seismic boundaries as in Fig. 3

Gypsum series (Tk3D-T2), Middle Triassic – Muschelkalk (T2), Rhaetian (T1-Tp2), Middle Buntsandstein (Tp2-Tp1) and Lower Buntsandstein to the top of the Zechstein (Tp1-P3).

The mean velocity of the Cretaceous succession, which is the most variable, in terms of thickness (ranging between 0 and 1,000 m), was analysed on the basis of data from the Młodasko-1, Rokietnica-26, Kaźmierz-1, Obrzycko-1, Szamotuły GEO-10, -13, -15 and -21 wells. For the remaining successions, data from the Objezierze-IG1, Obrzycko-1, Goleczewo-1, Kobylnica-1 and -2 wells were used.

The change of mean velocity, in relation to the changing thickness of a stratum, was analysed through cross-correlation of the data, using a coordinate system, expressing the relationship between the thickness of the strata in metres (ΔH), and time-thickness (Δt) in milliseconds. For the data approximation, the following relation was used:

$$\Delta H = a \cdot \Delta t^{b}$$

where ΔH is the thickness of a stratum in m, Δt is time-related thickness [ms], while a and b are coefficients which describe the shape of the curve.

The inclination of the curves (Fig. 6) defined the relationship between velocity and change in the thickness of the strata, overlying the Zechstein deposits. In all cases, there was a high correlation coefficient (R2) of over 0.9, which expressed the correlation between the trend line and the points, representing the recorded data.

The linear relationship for nearly all of the successions analyzed (Fig. 6) indicated constant velocities within individual, lithostratigraphic units (Pietsch *et al.*, 2010). Only the Cretaceous succession, which reached a total thickness of 1,000 m within the zone of the drag fold adjacent to the reverse fault, was associated with increasing velocity with depth. The velocity, associated with the Jurassic formations, was also constant, with the exception of the Objezierze IG-1 well. The Jurassic strata encountered in this well were cut across by a fault (thus lower velocity values were recorded; Fig. 6, the O–IG1 well).

The relationship, established by Wilk (2010), was used to develop the velocity model, in which seismic velocities were defined by as a function of depth to the Mesozoic successions. Entry data for the analysis were mean velocity values from 26 wells.

The relationship proposed by Wilk (2010) assumes that with increasing depth, the signal velocity changes exponentially and is expressed as

$$H = H_0 (e^{Bt} - 1),$$

where H is the depth to a lithostratigraphic unit [m], t is the two-way-travel time, and H_0 and B are coefficients, which describe the shape of the curve.

The relationship was established for the following lithostratigraphic successions: the Cenozoic, with a velocity of about 2,000 m/s, Cretaceous Cr (to the top of the Turonian) (Fig. 7A), the succession between the top of the Turonian and the top of the Malm (Crt–J3), the Malm (J3–J2), the Dogger, Lias and Rhaetian deposits (J2–Tk), the Keuper (Tk), the succession of the Muschelkalk (T2) (Fig. 7B) and the Buntsandstein to the top of the Zechstein (T1) (Wilk, 2010).

The third model of the velocity distribution in the Mesozoic formations was based on velocity data from wells, supplemented with velocity distribution data, established from the seismic inversion process. This allowed the velocity distribution to be reconstructed, on the basis of the recorded seismic sections. The Hampson-Russell STRATA software was used for the model-based inversion process. In order to carry out such an inversion, the entry geological model was employed, and the synthetic, seismic data were generated, on the basis of this model. As the next stage, the model was gradually modified, by applying a method of trial and error, until the synthetic section, created from this model, was consistent with the section, recorded in the field.

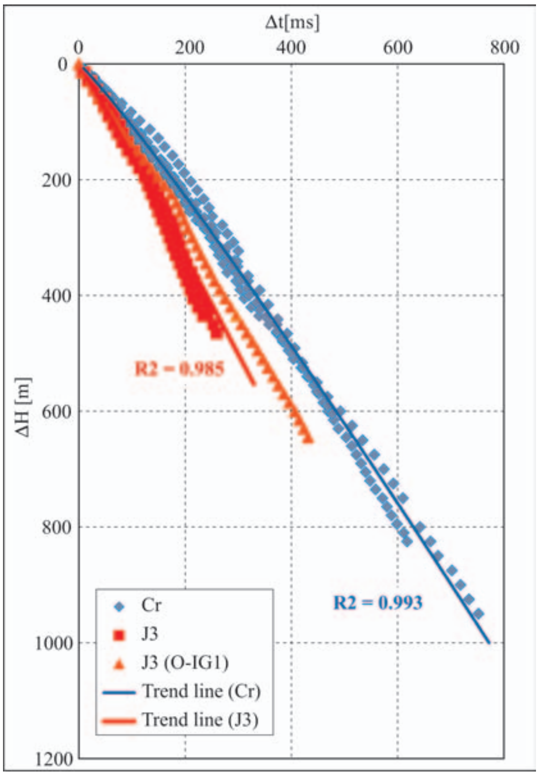

Fig. 6. Complex velocities as a function of complex thickness for Cretaceous and Upper Jurassic formation. ΔH – thickness formation [m]; Δt – two-way travel time thickness [ms]; R – correlation coefficient

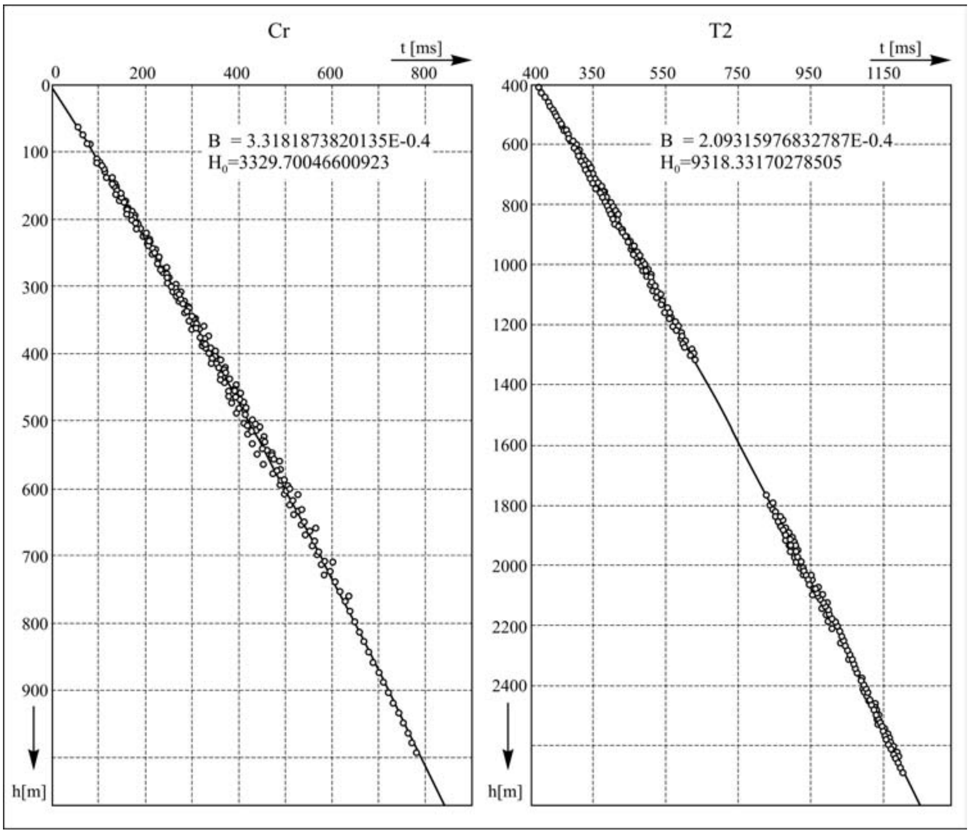

Fig. 7. Complex velocities as a function of depth of burial for the Cretaceous (Cr), and Muschelkalk (T2) (after Wilk, 2010). H – depth [m]; t – two-way travel time [ms]; H_0 and B – coefficient of curve form determinative

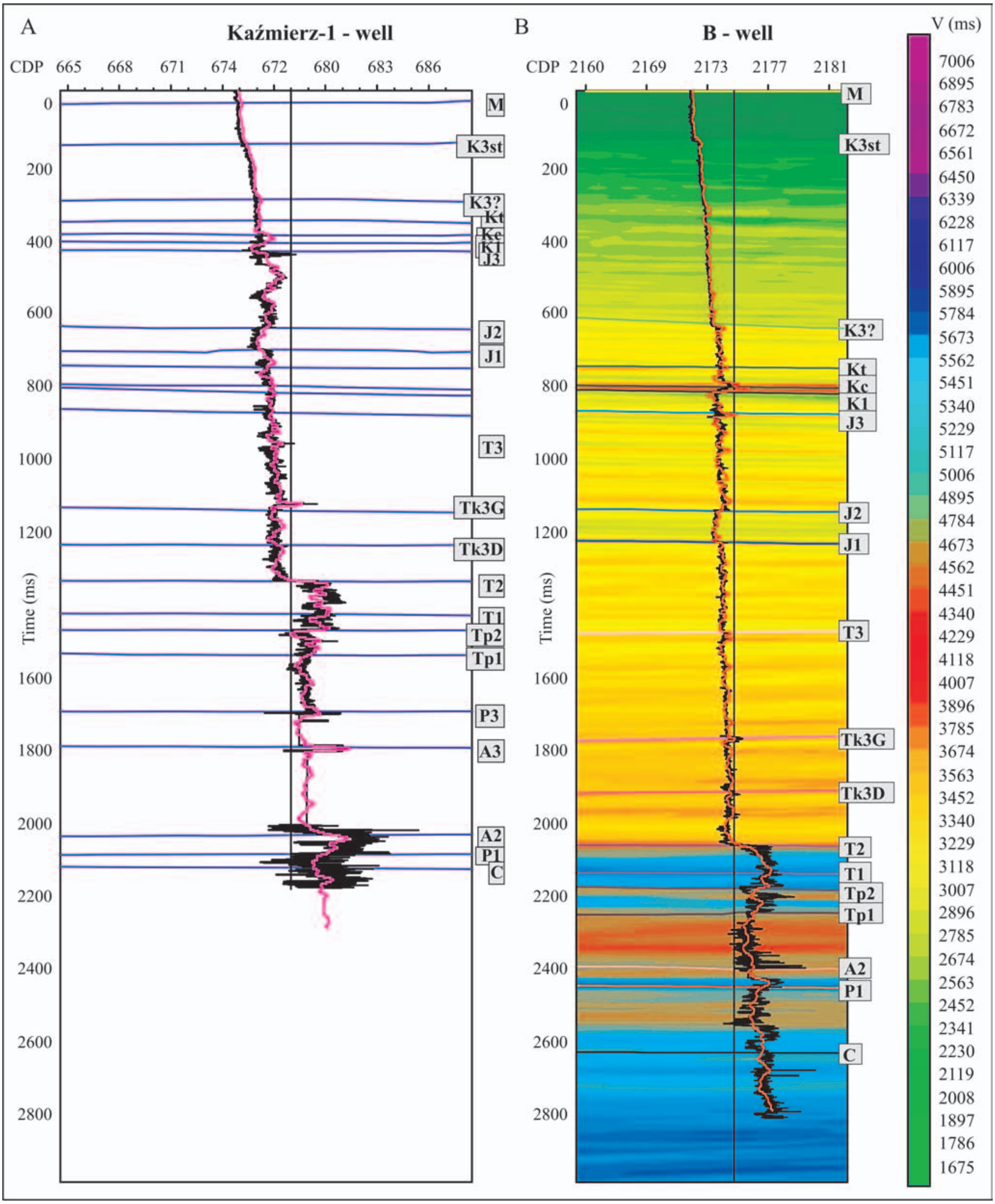

Fig. 8. Velocities from seismic inversion. **A** – Kaźmierz-1 well; **B** – theoretical well at location B in the seismogeological model; velocities from well log data – black curve; velocities from seismic inversion – red curve. Seismic boundaries as Fig. 3

To develop the geological base model along the analysed transect (Fig. 3), the geometry of the seismic reflectors and the complex velocity values were used. The strata thicknesses were based on data from the Kaźmierz-1 well; the Objezierze-IG-1 well, which was transposed in accordance with the structural pattern of the strata (well G); and the Obrzycko-1 well, in which the thicknesses of the Mesozoic successions were similar to the interpreted pattern of

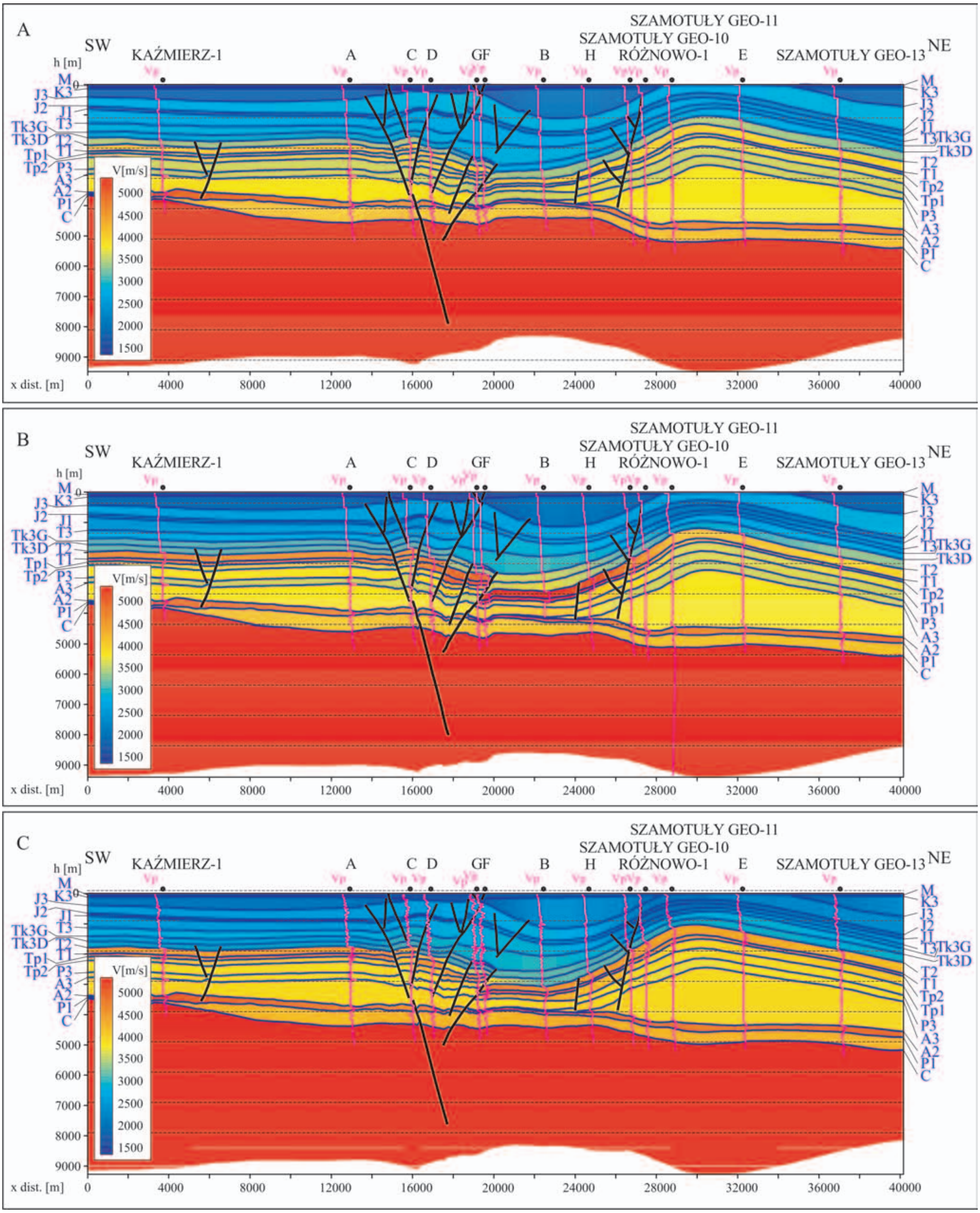

Fig. 9. Depth seismogeological model – change of velocity in Mesozoic formation when using: **A** – velocities as a function of complex thickness; **B** – velocities as a function of depth of burial of rock complexes; **C** – velocities from seismic inversion; Vp – P-wave velocity curve. Seismic boundaries as Fig. 3

seismic reflectors in the area of well B. Additionally, the mean velocity data from shallow Szamotuły GEO-10 and -13 wells were used for developing the model. Where data were missing, stratigraphic boundaries, correlated with the corresponding seismic horizons on the interpreted seismic section (Fig. 3), were used. The aim of the inversion process was to establish the vertical velocity distribution at locations A, C, D, G, H, and K, which were important for developing the seismic-geological model. Figure 8 presents examples of seismic inversion results, i.e. the vertical distribution of the velocities, compared with the well velocity curves (black) and with the velocity curves established, using the inversion process. The good correlation of the results showed that the velocity model, constructed in the inversion process, was reliable.

The seismic depth models (Fig. 9) were calculated, using the LogM and Struct modules of the GeoGraphix software. The entry data included the geometry of seismic reflectors, consistent with the distribution of reflection events on the interpreted seismic transect (Fig. 3), as well as the three velocity models, described above. The depth models present both the pattern, associated with the seismic reflectors, and the velocity model, used for the time-to-depth conversion.

Seismic depth model A (Fig. 9A) was developed with the seismic velocities, defined by the thicknesses of the strata. The shapes of the reflectors, presented in this model, are very similar to the shapes in the base model (Fig. 5B), which is justified by the velocity model used.

The velocity analyses revealed that the velocity is constant within the individual, lithostratigraphic successions. An exception is the insignificant increase in velocity with increasing thickness of the Cretaceous succession (Fig. 6A). The increase in velocity is apparent in the Cretaceous strata, which fill the trough near the fault, on the SW side of the salt pillow (Fig. 9A).

The seismic depth model B (Fig. 9B) was developed, using the velocity model, which was prepared, on the assumption that the velocity changes depend on depth to the lithostratigraphic successions (Wilk, 2010). The largest velocity changes are observed in the Jurassic and Triassic deposits. The lowest velocity values are associated with the Middle and Lower Jurassic strata (2,000–2,300 m/s) above the salt pillow, in the zone of its greatest thickness. The seismic velocity within the Triassic strata increases to a value of above 5,500 m/s in the Muschelkalk and Rhaetian formations in the zones of greatest depth, i.e. within the near-fault trough on the SW side of the salt pillow (Fig. 7B). Owing to the reduction in velocity above the salt pillow and the increase in velocity in the zone surrounding the pillow, the lateral velocity changes are balanced. This is reflected in the shape of the geological boundaries beneath the Zechstein, which in the depth model are nearly horizontal in the zone, where the salt pillow is thickest.

The third seismic depth model C (Fig. 9C) was developed, by means of velocity values that were calculated, using the seismic inversion process (Fig. 8). The characteristic feature of this velocity model is the significant reduction of velocity in the Jurassic succession above the salt pillow. Such velocity reduction is also observed on the SW margin of the pillow. An insignificant increase in the velocity is associated with the bottom strata of the Muschelkalk and Rhaetian formations. This increase, however, is definitely smaller than in the second model (model B), where there is a significant velocity increase with depth. The pattern of the reflection events, associated with the sub-Zechstein boundaries, is very similar to the pattern, associated with the model, based on velocities, depending on the depth to the lithostratigraphic successions.

Analysis of the influence of seismic velocity in salt strata on the shape of reflection events was carried out in the NE part of the seismic transect, i.e. in seismic section 13-1-08K, where the large salt pillow is present. In the SW part of the transect, where no lateral changes in the thickness of the lithostratigraphic succession occur, analysis of the influence of velocity on the seismic record within the salt structures is not relevant.

The majority of works on seismic velocity, based on well data, assumed that the velocity was constant and depended on the amount of anhydrite within the salt body (Jarzyna *et al.*, 2012a). For the analysis of the influence of salt velocity on the imaging of the sub-Zechstein boundaries by Jarzyna *et al.* (2012b), velocities, characteristic of the Older Halite Na2, which forms the salt pillow, were used. The velocity values, which were given by Jarzyna *et al.* (2010), were 4,200 m/s (the lowest velocity), 4,500 m/s (the medium velocity) and 5,000 m/s (the highest velocity). Lower velocity values of 100 m/s were assumed for the Younger Halite Na3. This stratum surrounds the older deposits and its total thickness is constant. The velocity model for the strata above the salt body, stretching up to the Tk3G boundary, was based on velocity changes as a function of depth (Wilk, 2010). Above that boundary, a model, based on seismic inversion (tied to stratigraphic information from shallow wells), was used.

The depths of seismic reflectors, based on the different salt velocities, are shown in Figure 10A, B, and C. With a higher salt velocity, a larger bend-down of the sub-Zechstein strata is observed. The pull-up effect in the sub-Zechstein strata, similar to that on the time section, would only be possible with a velocity below 3,400 m/s (Pietsch *et al.*, 2010). Such velocities, however, particularly at the depth of the Older Halite strata, are not acceptable.

IMPACT OF SEISMIC VELOCITY MODELS ON SEISMIC IMAGING OF SUB-ZECHSTEIN HORIZONS: DISCUSSION

All of the velocity models analysed (Figs. 5, 9 and 10) were built on the basis of the surface seismic data and well logs (sonic logging, mean velocity measurements, stratigraphic data – Fig. 2), recorded in this area. These data formed a framework, which defined the acceptable variability of the velocity models, while the differences between them were a result of different methods, applied to constructing spatial (2D) velocity models.

The seismic velocity models, developed through iterative model-based updating, aimed to assess the influence of

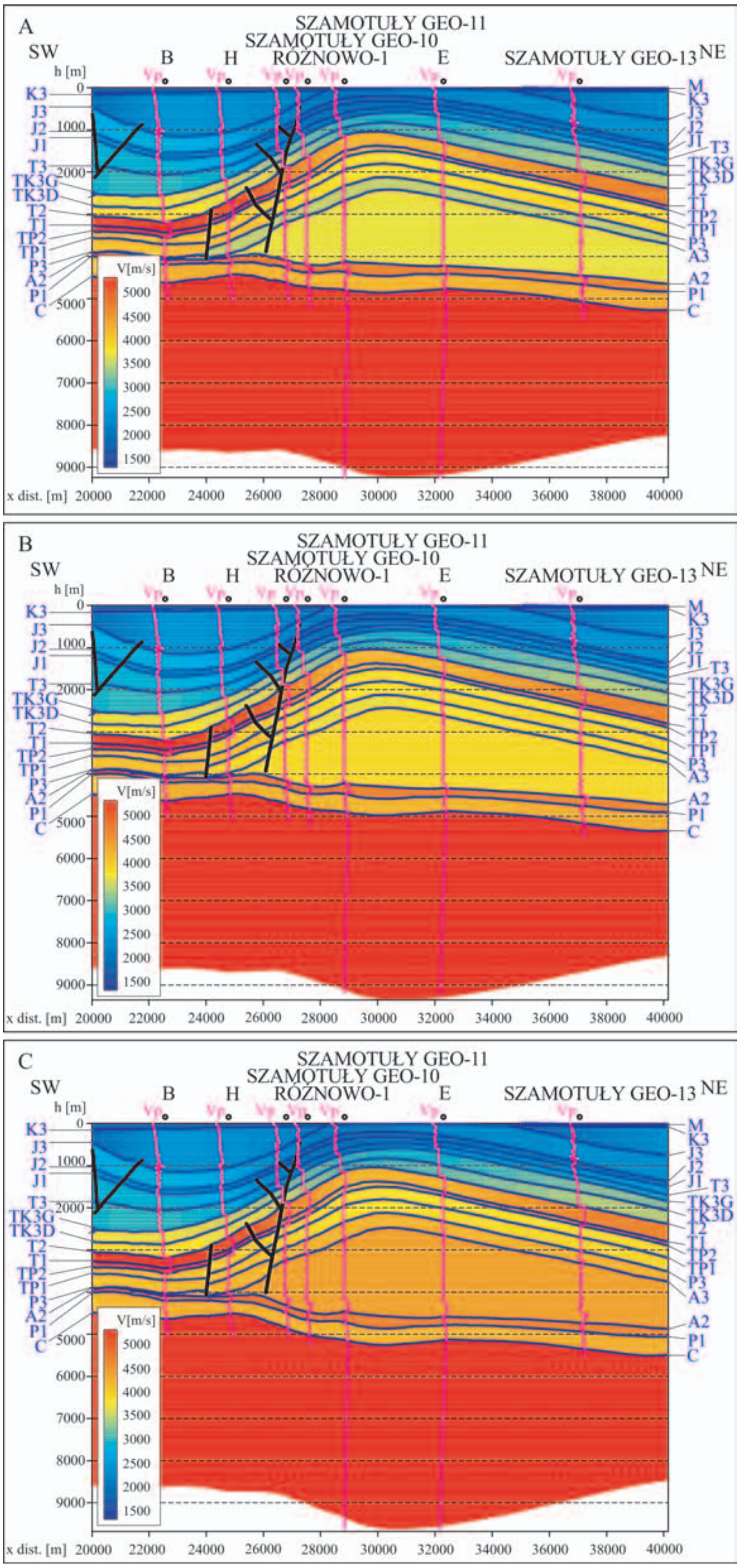

Fig. 10. Depth seismogeological model – change of velocity in salts. **A** – V = 4,200 m/s; **B** – V = 4,500 m/s; **C** – V = 5,000 m/s; Seismic boundaries as Fig. 3

halokinesis on the seismic representation of the sub-Zechstein strata. These models clearly revealed the opposite patterns of reflection events in the depth model and the seismic time record. The pull-up effect, observed on the seismic sections, is a result of high velocities in the salt structures. This leads to strong, horizontal-velocity contrast between the uplifted salt dome and the subsided Mesozoic successions of lower velocity.

CONCLUSIONS

Analysis of the depth models, developed by matching different velocity models, both with the Mesozoic and Zechstein structures, led to the following conclusions, regarding distortion of reflection events, associated with the sub-Zechstein geological boundaries:

– the pull-up effect becomes stronger with increasing thickness of the salt structures and with increasing velocity contrast between the salt and the Upper Triassic, Jurassic and the Cretaceous strata;

– the presence of the grabens, associated with the salt structures, results in increased thickness of the low-velocity Mesozoic strata, which increases the pull-up effect;

– where no tectonic deformation is present, the older Mesozoic strata, which underwent diagenesis and were uplifted to the level of the sub-Cenozoic surface, make the pull-up effect more apparent;

– the decrease in velocity, which is related to the increased, tectonic deformation within the apex of the fold above the salt pillow, reduces the pull-up effect;

– a similar effect is observed, where the strata, filling the zones between the salt structures, are associated with increased velocities (due to their subsidence and compaction);

– the presence above the salt structures of the troughs, which are filled with Cenozoic deposits above the salt structures, reduces the pull-up effect.

The results of seismic modelling show opposite patterns in the distribution of the sub-Zechstein seismic interfaces for the depth images and for seismic sections in time. However, the lack of well data in areas, underlain by salt structures, makes it difficult to answer the question: which velocity model approximates most precisely the subsurface strata analysed? Based on the results obtained, it seems plausible that the most accurate is the model using seismic inversion, where a change in velocity with depth in the overlying strata is assumed. The opposite patterns of the seismic event on time sections and seismic reflectors on depth sections show the necessity of applying seismic velocity models during the processing stage, for example, using velocity models for depth migration (PreSDM).

Acknowledgements

The paper was completed as part of a research grant No. MNiSW WND-POIG.01.01.02.00.122/09 (Improvement of the effectiveness of seismic survey for prospecting and exploration for natural gas deposits in Rotliegend formations) supervised by Wojciech Górecki (AGH University of Science and Technology). We are greatly indebted to the reviewers, Andrzej Kostecki (Oil and Gas Institute), Tadeusz Peryt (Polish Geological Institute) and Wacław Zuberek (University of Silesia), for their comments that helped to improve our work.

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