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Neogene activity of the Outer Carpathians recorded by thrust-top basin deposits – an example from the Rzeszów area, Poland

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ABSTRACT:

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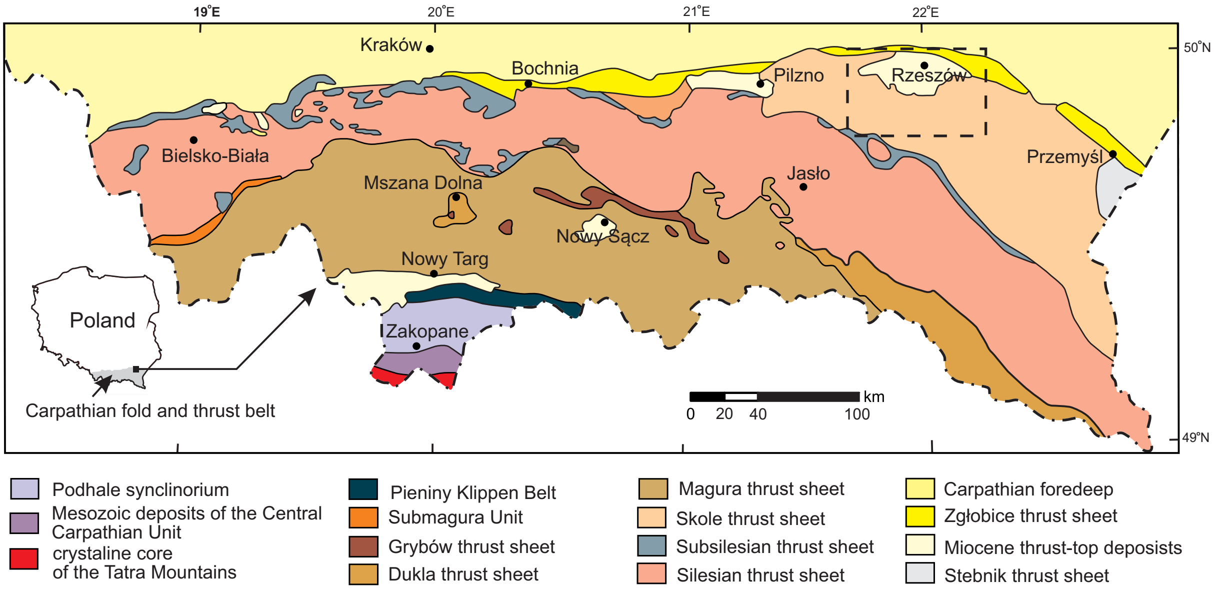
The Rzeszów thrust-top basin was formed on the active Skole thrust sheet of the Outer Carpathian fold-and-thrust belt and filled with Miocene syntectonic sediments. New seismic 3D, well and field data were used to define the relationship between sedimentation and tectonic activity and to establish the synkinematic context of the Rzeszów basin-fill architecture. The basin evolution was controlled by the activity of the Carpathian frontal thrust and hinterland thrusts developed in the forelimbs of folds in the Skole thrust sheet, bounding the basin from the north and south, respectively. The activity of the frontal thrust resulted in hinterland-directed depocentre migration and tilting of the syntectonic stratigraphic sequence. Balanced cross-sections have indicated that during the last compressive stage of deformation, the syntectonic deposits filling the basin were shortened by c. 5%, which resulted in the formation of folds and contractional faults. The architecture of the syntectonic deposits and the development of contractional structures reflect the activity of thrusts bounding the basin during compressive deformation of the Carpathian orogenic belt.

Key words: Skole thrust sheet; Foreland and hinterland thrusts; Outer Carpathian fold-and-thrust belt; Basin inversion; depocentre migration, syntectonic sedimentation.

INTRODUCTION

Thrust-top basins form on active thrust sheets belonging to fold-and-thrust belts (e.g., Butler and Grasso 1993; Bonini *et al.* 1999). These basins are parts of a foreland basin system developed within a wedge-top depozone (DeCelles and Giles 1996). The latter belongs to an orogenic wedge, experiencing progressive deformation. Syntectonic deposits formed on active orogenic belts constrain the relative time of deformation of thrust-top basins controlled by the activity of individual foreland and hinterland thrusts (Roure *et al.* 1991; Suppe *et al.* 1992; Zoetemeijer and Sassi 1992; Hardy and Poblet 1994; Bonini *et al.* 1999). The activity of the underlying thrust sheets results in a characteristic basin-fill architecture, i.e., angular unconformities, onlaps, and syntectonic progressive unconformities (Riba 1976; Zapata and Allmendinger 1996; Poblet *et al.* 1997; Bonini *et al.* 1999). Progress in sedimentary basin analysis puts constraints on the timing of progressive deformations developing synchronously with sedimentation in the foreland basins of many fold-and-thrust belts (e.g., Ori and Friend 1984; Ricci-Lucchi 1986; Roure *et al.* 1991; Butler and Grasso 1993; Hippolyte *et al.* 1994, Zapata and Allmendinger 1996; Bonini *et al.* 1999; Duerto *et al.* 2006; Casciello *et al.* 2013).

The aim of this paper is to describe the Rzeszów basin as a thrust-top basin structure formed during the Miocene on the active Skole thrust sheet (Text-



Text-fig. 1. Simplified geological map of the Polish part of the Carpathians based on Oszczypko *et al.* (2008), modified. The dashed box shows the study area

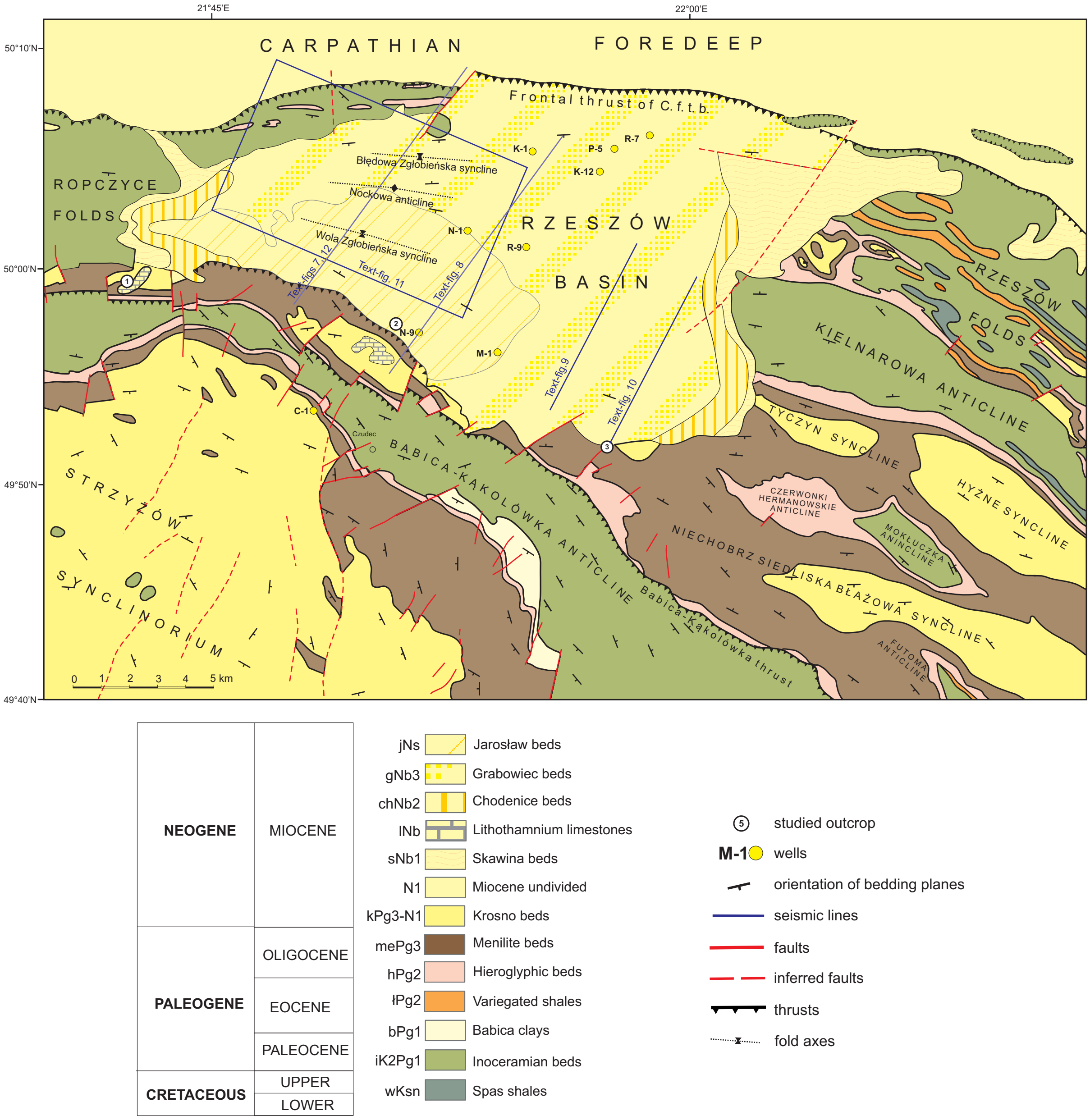
figs 1, 2) and to define the activity of the thrusts bounding the basin. These issues play a significant role in understanding the orogen evolution. The structure of the Rzeszów basin was modified as a result of subsequent contractional deformations. In this paper, regional stage names (Dziadzio *et al.* 2006) are used when assigning stratigraphic ages to formations. Deformations in the Outer Carpathians began in the early Oligocene (see Pescatore and Ślączka 1984; Nemčok *et al.* 2006). Thrusting in the external Carpathian flysch units, such as the Skole thrust sheet, commenced in the early Miocene (see Książkiewicz 1972; Oszczypko 1998; Bada 1999 with references therein), whereas sedimentation in the Rzeszów basin took place simultaneously with the late deformations of the Carpathian orogen in the middle Miocene on an already shaped orogen. Changes in its geometry due to progressive shortening allow for defining its present structure as a synclinorium, earlier named as 'embayment'. The presence of marine sedimentation in the Rzeszów basin gives the possibility of providing data that allow for determining the activity of geological structures as in other similar thrust-top basins (e.g., Butler and Lickorish 1997). Because of the lack of high-resolution stratigraphic data in the Rzeszów basin, determination of the age of the strata should be based on their geometry and mutual relationships between particular sedimentary units.

Changes of the basin-fill architecture are discussed in the context of the activity of the Carpathian orogenic front and hinterland thrusts intersecting folds within the Skole thrust sheet (Text-fig. 3). Variations in the Rzeszów basin deposits above structures within the Skole thrust sheet suggest that these strata are syntectonic in origin, documenting the timing and activity of local structures.

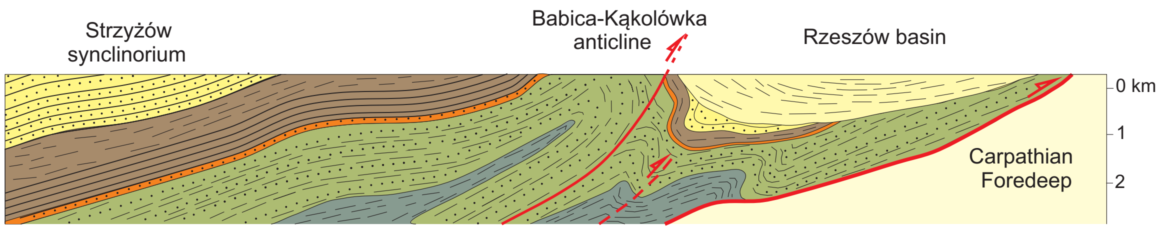
THRUST-TOP SEDIMENTATION

Thrust-top basin sediments play a significant role in understanding orogenic activity. Many conceptual and analogue models of thrust-top basin sedimentation exist (e.g., Roure *et al.* 1991 – Text-fig. 4A; Suppe *et al.* 1992; Hardy and Poblet 1994; Bonini *et al.* 1999). The geometry of syntectonic deposits depending on the sedimentation rate and shape of folds that developed on active faults was analysed by Suppe *et al.* (1992). Hardy and Poblet (1994) discussed the relations between growth strata and progressive limb rotation.

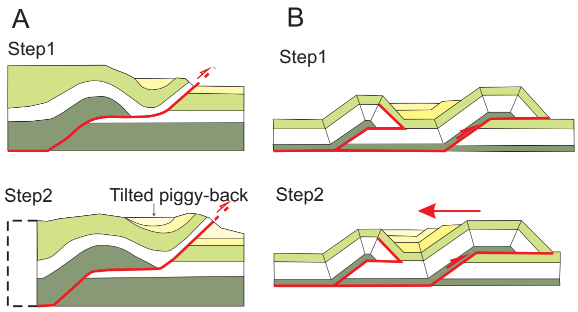
The preservation of thrust-top basin sediments within the orogen allows for the reconstruction of the fold activity (Butler and Lickorish 1997). To achieve this, detailed analysis of the depositional architecture in the basin, coupled with high resolution stratigraphy, is required.



Text-fig. 2. Simplified geological map of the study area (author's own investigations and based on Gucik *et al.* 1979; Jurkiewicz and Woiński 1979; Woiński 1988; Nescieruk *et al.* 1992; Malata 2009a). Location of outcrops: 1 – Olimpów, 2 – Niechobrz, 3 – Siedliska-Broniakówka; wells: C-1 – Czudec-1, M-1 – Mognielnice-1, N-1 – Nosówka-1, N-9 – Nosówka 9, R-9 – Racławówka 9, R-7 – Rzeszów 7, K-1 – Kielanówka 1, K-12 – Kielanówka 12, P-5 – Przybyszówka 5; C. f. t.b. – Carpathian fold and thrust belt



Text-fig. 3. Simplified schematic geological cross-section of the Skole thrust sheet and Rzeszów basin, based on Nescieruk *et al.* (1992), modified. See Text-fig. 2 for explanations



Text-fig. 4. Models of thrust-top basin sedimentation. A – Roure *et al*. (1991); B – Bonini *et al.* (1999)

The models proposed by Bonini *et al.* (1999) – Text-fig. 4B, show that symmetrical basins are formed when thrust activity is equal. Other models by Bonini *et al*. (1999) referring to the formation of asymmetric basins imply depocentre migration in the same sense as thrust propagation or in a direction opposite to the thrusting direction. In the former models, the hinterland thrusts are faster than the frontal thrust or the frontal thrust is inactive.

GEOLOGICAL SETTING

The Carpathian fold-and-thrust belt developed from late Oligocene to middle Miocene time (Burchfiel and Royden 1982; Kováč *et al.* 1998; Oszczypko 2004, 2006; Nemčok *et al.* 2006) as a result of rifting of the European sector of Pangea in the late Miocene forming a north-vergent thrust system (e.g., Książkiewicz 1972; Oszczypko 1998 and references therein). The present structure of the Outer Carpathians developed due to a combination of the effect of the initial architecture of the sedimentary basins and the deformations of the accretionary wedge (Oszczypko 1998; Gągała *et al.* 2012).

The research area is situated in the north-eastern Outer Carpathians, at the boundary between the fold-and-thrust belt and the Carpathian Foredeep (Text-figs 2, 3). The Rzeszów basin is one of the basins, referred to as 'embayments', formed during the Miocene in the frontal part of the Outer Carpathian fold-and-thrust belt as part of the Carpathian foreland basin system (Text-fig. 1; e.g., Oszczypko and Tomaś 1985; Krzywiec *et al.* 2004, 2012, 2014). These basins are located above the Outer Carpathian fold-and-thrust belt in a piggyback position (Krzywiec *et al*. 2014; Głuszyński and Aleksandrowski 2016). They developed south of a narrow zone of deformed Miocene deposits variably named as the Zgłobice Unit (Kotlarczyk 1985) or Stebnice Unit (Ney 1965; Książkiewicz 1972), belonging to the Carpathian Foredeep basin (e.g., Książkiewicz 1972; Oszczypko and Tomaś 1985; Krzywiec 2001; Oszczypko 2006). Various contractional structures including wedge structures, backthrusts, triangle zones and crocodile structures, causing significant changes of deposition, have been recognised in the frontal part of the Carpathian orogen (e.g., Krzywiec 2004; Krzywiec and Verges 2007; Sieniawska *et al.* 2010; Krzywiec *et al.* 2012, 2014; Głuszyński and Aleksandrowski 2017).

The stratigraphic succession within the basins of the frontal part of the Carpathian fold-and-thrust belt records the relationship between deposition and deformation stages. Syntectonic deposition in a wedge-top depozone was for instance documented in detail in the Pilzno basin (Sieniawska *et al.* 2010; Głuszyński and Aleksandrowski 2016). Deposits in the basins were deformed during the final stages of development of the Carpathian fold-and-thrust belt (Gągała *et al.* 2012; Krzywiec *et al.* 2012).

The Rzeszów basin is filled with c. 600 m thick Miocene evaporites and marine deposits (Text-fig. 2). The Miocene deposits of the Rzeszów basin represent shallow-water sediments that were formed within the southernmost part of the Carpathian Foredeep basin (Oszczypko 1998). The thickness of the Miocene in the Rzeszów basin is very variable and ranges from 200 m in the northern part of the basin to 1000 m in the south-east (Wdowiarz 1976). The sediments were deposited on previously deformed rocks of the Skole thrust sheet, in the southernmost part of the Carpathian Foredeep basin (Text-fig. 3; Wdowiarz 1976; Urbaniak 1986; Połtowicz and Turska-Pawica 1993). The tectonic position of the Rzeszów basin within the wedge-top depozone above an orogenic prism (DeCelles and Giles 1996) is comparable to that of a thrust-top basin (Ricci-Lucchi 1986; Butler and Grasso 1993) or a piggyback basin (Ori and Friend 1984) that was formed along the northern part of the Carpathian orogenic wedge (Krzywiec 2004). Therefore, it is essential to resolve whether the Rzeszów basin had formed during thrust activity so that sedimentation was synkinematic in origin, or are the sediments postkinematic in origin, simply draping the underlying structures.

The west- to east-trending Rzeszów basin, about 24 km long and 12 km wide, is located above the section of the Outer Carpathian fold-and-thrust belt, which includes folds belonging to the Skole thrust sheet (Text-figs 2, 3). In the direct contact zone of the

Skole thrust sheet with the basement of the Rzeszów basin there is a zone of folds with narrow fold hinges that are termed the Ropczyce and Rzeszów folds, respectively (Text-fig. 2; Książkiewicz 1972). South of this fold zone occur folds with distinctly larger interlimb angles: Kielnarowa anticline, Hyżne syncline prolongating to the west as the Tyczyn syncline, Mokłuczka–Czerwonki Hermanowskie anticline, Niechborz–Siedliska–Błażowa syncline and Futoma anticline (Nescieruk *et al.* 1992). The zone of these open folds is limited from the south by the Babica–Kąkolówka thrust (Text-fig. 2). The Miocene deposits of the Rzeszów basin were subject to several successive deformations (Text-fig. 2). Synsedimentary structuration of the Rzeszów basin has already been suggested by Połtowicz and Turska-Pawica (1993) based on the analysis of gravity anomalies, in contrast to earlier models suggesting a simple structure of the Rzeszów 'embayment' (Ney 1965; Wdowiarz 1976).

The Rzeszów basin is bounded to the north by the Skole frontal thrust corresponding to the front of the Carpathian orogenic belt (Text-fig. 2). The basin is thrust over folded Miocene rocks belonging to the Carpathian Foredeep (representing the Zgłobice Unit) and the underlying autochthonous Miocene sediments of the foredeep (Text-fig. 2; Ney 1965; Czernicki 1977). The southern limit of the central part of the basin corresponds to thrusts intersecting the forelimbs of folds in the Skole thrust sheet: Niechobrz–Siedliska–Błażowa syncline and Babica–Kąkolówka anticline (Text-fig. 2). The Skole thrust sheet was thrust over the Miocene of the Rzeszów basin by c. 1 km (Text-fig. 2). Overthrusting of the Skole thrust sheet on the Rzeszów basin sediments was earlier suggested by Gonera (1980).

STRATIGRAPHY OF THE SKOLE UNIT AND THE RZESZÓW BASIN

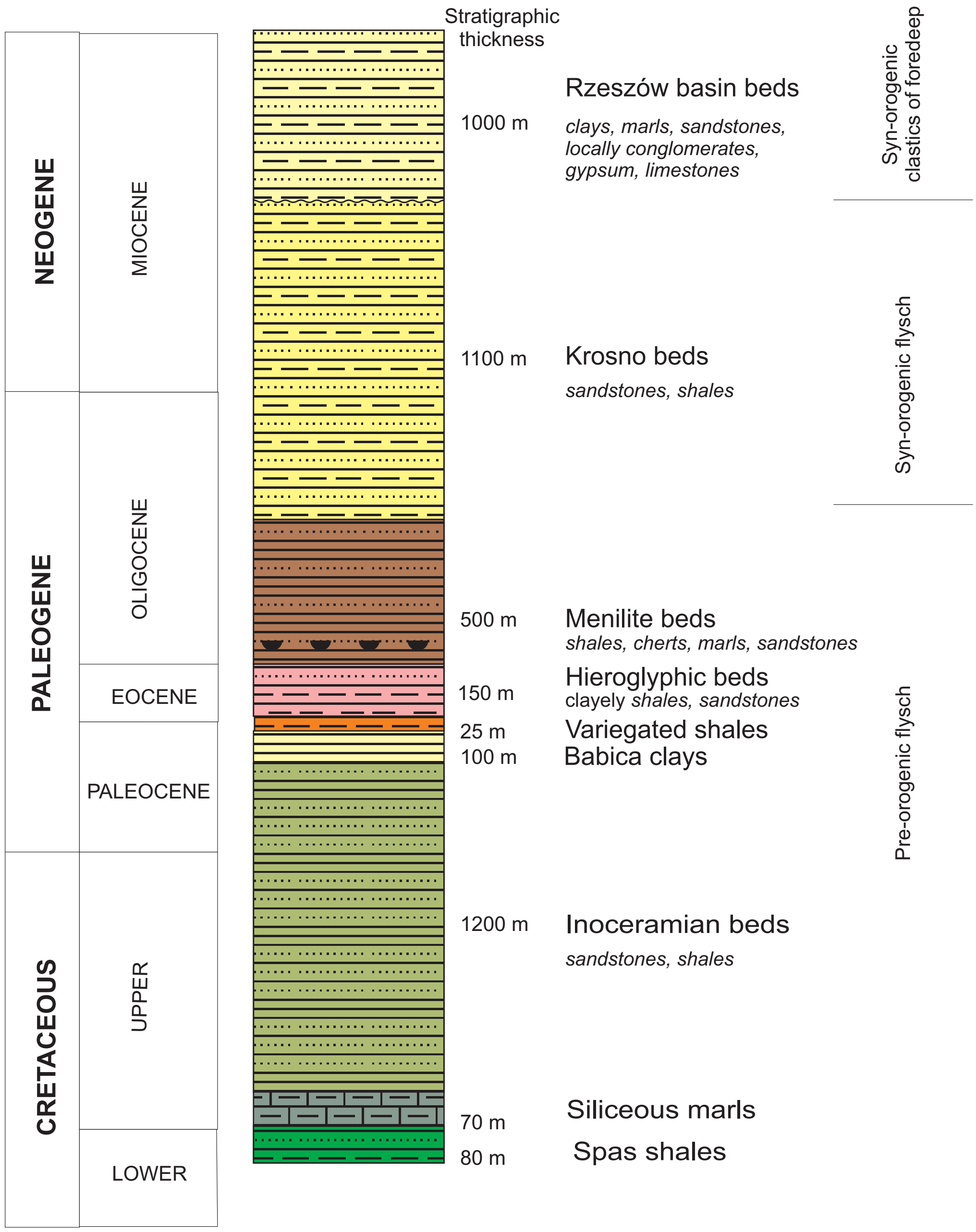
Skole unit – underfilled basin stage

The Skole unit deposits represent hemipelagic and deep-water turbiditic flysch sequences representing the underfilled basin stage (Oszczypko *et al.* 2008). The oldest deposits of this unit are the Spas shales and siliceous marls, representing the Barremian–Albian (Text-fig. 5; Nescieruk *et al.* 1996). The shales and marls reach a thickness of about 150 m. The Inoceramian beds occurring above form the hinges of anticlines within the Skole nappe; they consist of sandstones and shales and are Coniacian to Santonian in age. The upper part of the Inoceramian beds, dated to the Maastrichtian–Palaeocene, is developed as calcareous sandstones. The thickness of the Inoceramian beds is estimated at around 1200 m (Malata 2009b). The overlying Babica clays (Palaeocene) and Variegated shales (lower Eocene) attain a thickness of about 25 m. The dominant lithofacies of the middle Eocene in the Skole unit are the Hieroglyphic beds, comprising clayey shales, less often marly shales interbedded with sandstones. Their thickness ranges from 130 to 180 m (Malata 2009b). The Oligocene is composed of Menilite beds and consists of cherts, marls and shales interbedded with sandstones. The thickness of the Menilite beds is estimated at approximately 500 m. The youngest rocks within the Skole nappe are the Krosno beds comprising thick-bedded calcareous sandstones, being overlain by thin-bedded sandstones and shales (Nescieruk *et al.* 1996), these beds represent a syntectonic sequence (e.g., Gągała *et al.* 2012) and were deposited at shallower water depths than the underlying sequences (Olszewska 1984). Sedimentation of the Krosno beds lasted from the late Oligocene until the early Miocene and their total thickness exceeds 1100 m (Malata 2009b).

A Miocene angular unconformity separates deposits of the Skole unit and the Rzeszów basin. The unconformity incorporates a hiatus in the lower Miocene succession and is related to a contractional stage that began in the Skole unit in the early Miocene (Nemčok *et al.* 2006) and deformed pre-existing sedimentary units. Erosion of these previous successions is indicated by the presence of clasts of flysch rocks within the Rzeszów basin (Nescieruk 1996).

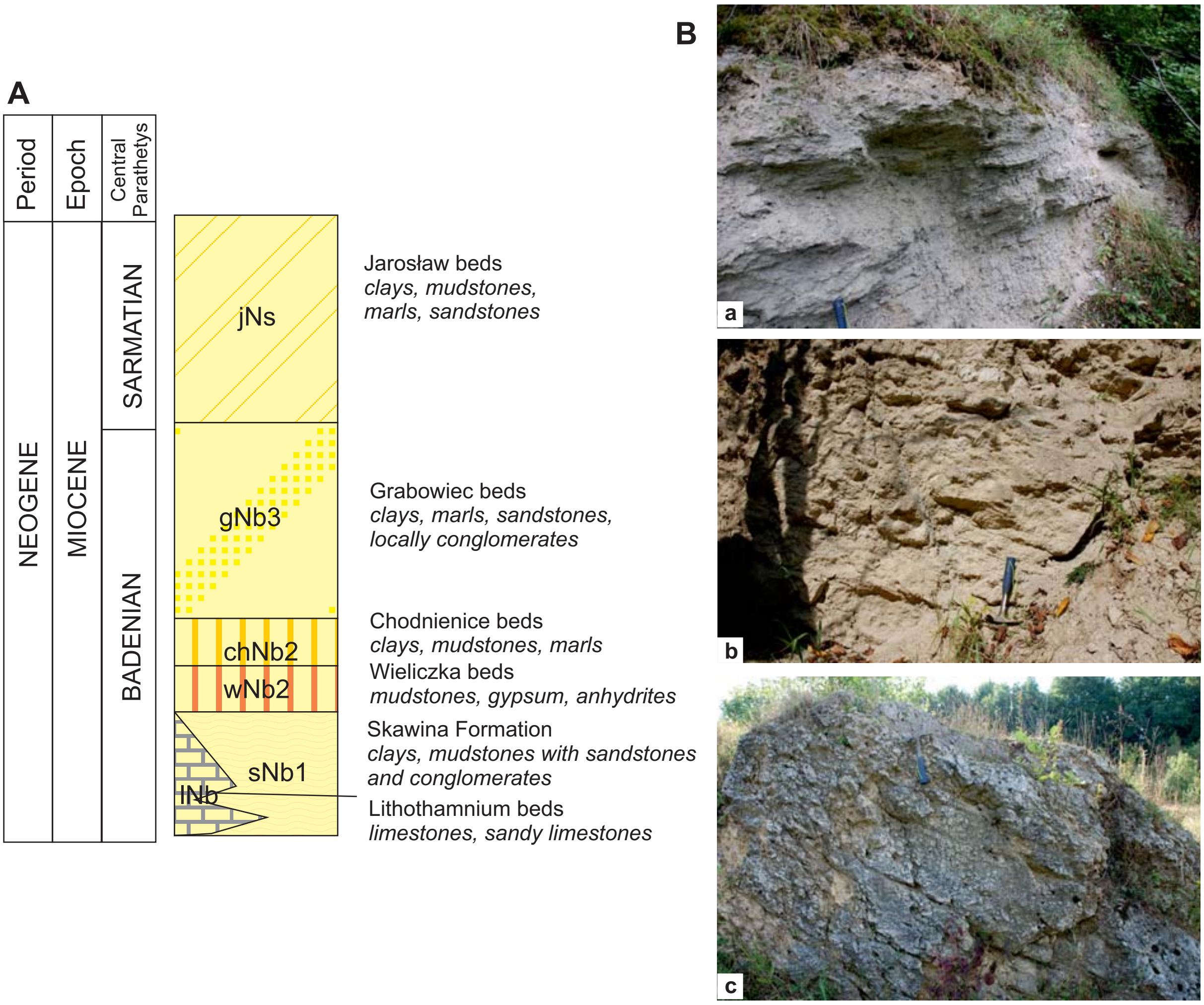
Rzeszów basin

The lowermost part of the Miocene succession in the Rzeszów basin comprises the Skawina beds, representing Early/Middle Badenian claystones and mudstones with sandstone interbeddings (Text-fig. 6) (Czernicki 1977; Gonera 1980). The thickness of these beds reaches a maximum of about 200 m. Age correlatives of the Skawina beds are Lithothamnium limestones comprising blue-grey, yellow-grey and grey limestones and sandy limestones (Nescieruk 1996), pointing to shallow marine conditions and attaining a total thickness of up to 50 m (Urbaniak 1986). The Lithothamnium limestones represent shallow-marine facies, deposited in the southern, marginal part of the basin. Above the Skawina beds there occurs an evaporitic complex developed as sulphate facies corresponding in age to the Wieliczka Formation from the Carpathian Foredeep basin. The lower part of the formation consists of claystones and mustones



Text-fig. 5. Simplified litostratigraphic column of the study area (based on Gucik *et al.* 1979; Jurkiewicz and Woiński 1979; Woiński 1988; Nescieruk *et al.* 1996; Gągała 2012)

with variable components of anhydrite and gypsum with a combined thickness, in the Rzeszów basin of 25–35 m. Their age is defined as Late Badenian. The overlying Chodenice beds consist of a thick complex of grey clays and claystones, and gypsum. Their thickness reaches 25 to 35 m (Nescieruk *et al.* 1996). The Chodenice beds are succeeded by the Grabowiec beds, which including Late Badenian grey-blue sandy clays, weakly compacted, with sandstones at the base (Czernicki 1977). Sometimes sands prevail (Grabowiec sands) in the upper part of the Grabowiec beds. These beds reach thicknesses of 250–350 m. The youngest rocks occurring in the Rzeszów basin are the Jarosław beds comprising Sarmatian sand-shale complex (Nescieruk *et al.* 1996) that reaches a thickness of up to 350 m.



Text-fig. 6. Deposits of the Rzeszów basin. A – Simplified litostratigraphic column. Based on Gucik *et al.* (1979), Jurkiewicz and Woiński (1979), Woiński (1988), Nescieruk *et al*. (1996), Dziadzio *et al*. (2006). B – Examples of the Rzeszów basin strata cropping out in study area. Explanations: a – gypsum – Siedliska–Broniakówka, b – Lithothamnium limestones – Niechobrz Quarry, c – Lithothamnium limestones – Olimpów Quarry. See Text-fig. 2 for location

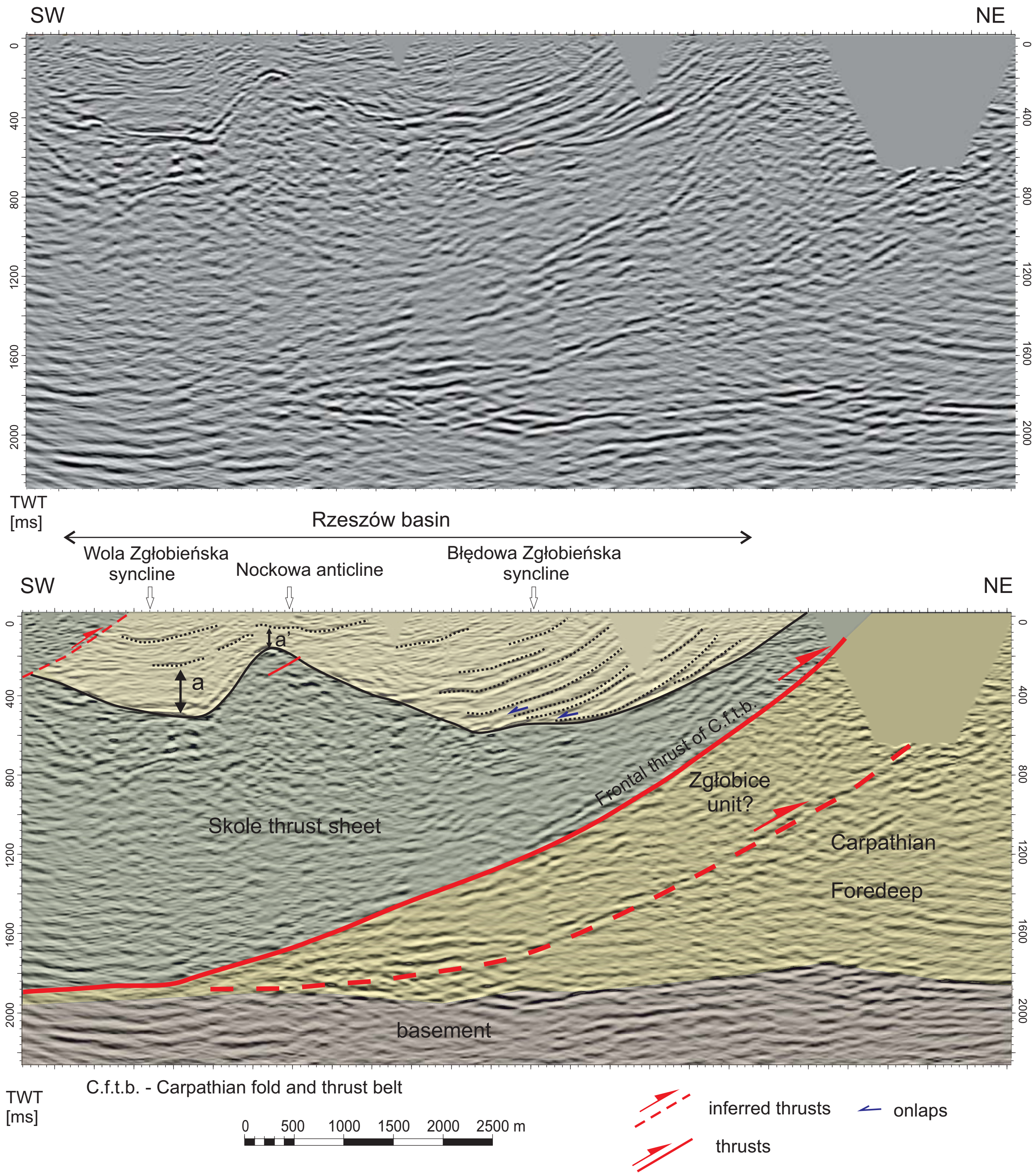
DATA AND METHODS

This paper uses 2D and 3D seismic data provided in TWT by the Polish Oil and Gas Company. Accurate stratigraphic calibration is based on the Nosówka-9, Nosówka-1, Racławówka-1 and Mogielnice-1 deep wells (located on Text-fig. 2). To ensure an accurate link between well data (depth domain) and seismic data (time domain), synthetic seismograms were calculated. Well-to-seismic correlation was achieved using synthetic seismograms, preceded by statistical seismic wavelets using Petrel Seismic Well Tie software. Key stratigraphy boundaries (e.g., unconformity between the Skole thrust sheet and the Rzeszów basin) were identified and mapped in seismic reflection data.

Time-to-depth conversion was calculated using formation tops from boreholes in Petex Move software. A 2D model of the Rzeszów basin was constructed and restored according to the balancing principles in Petex Move software with simple shear and fault-parallel-flow algorithms. Due to the poor quality of seismic data within the Carpathian orogen, the structures within the Skole thrust sheet are represented schematically.

SEISMIC INTERPRETATION

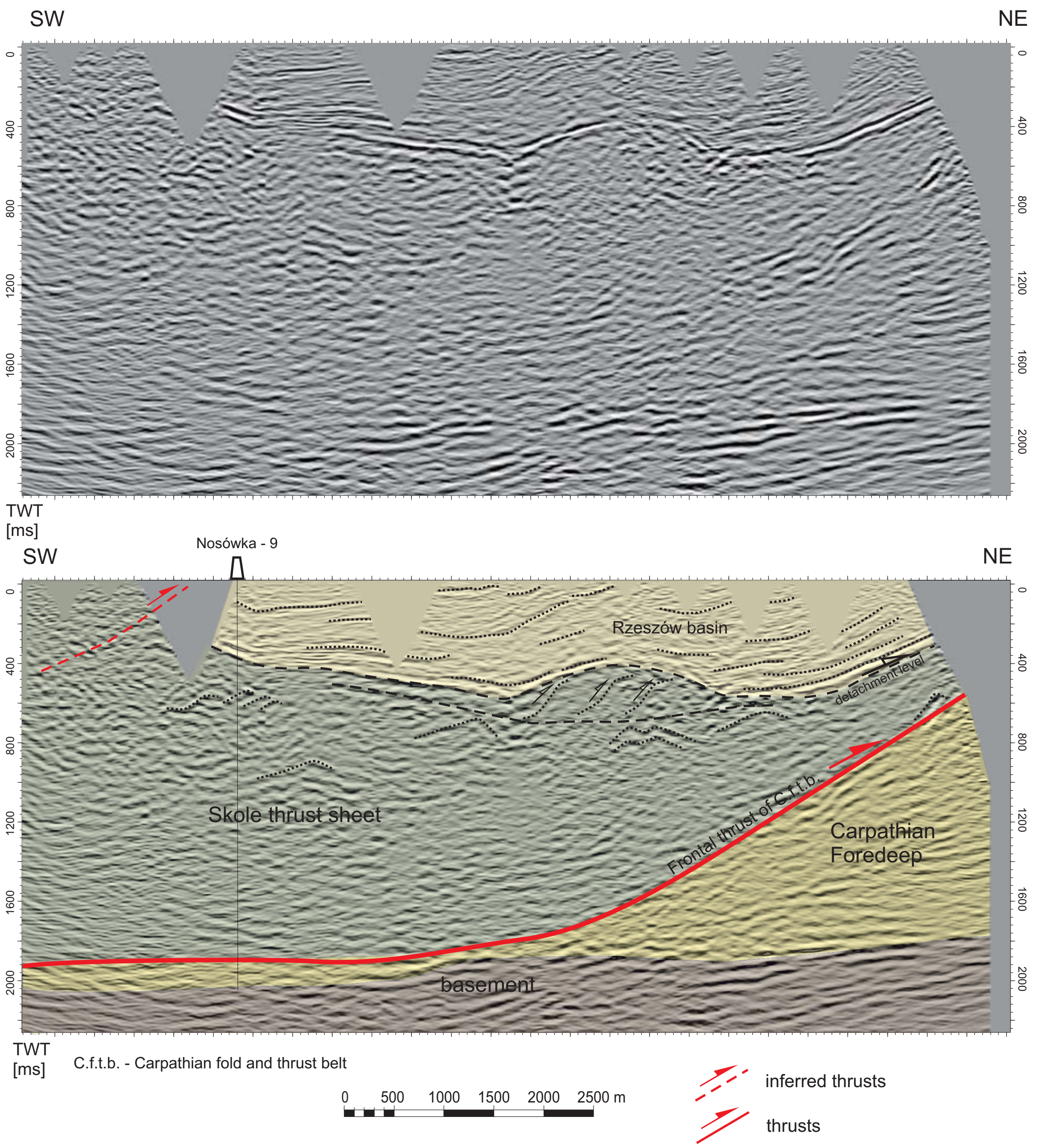
2D and 3D seismic data were interpreted using Schlumberger Petrel software. Four seismic sections



Text-fig. 7. Seismic images of syntectonic sediments of the Rzeszów basin above the Nockowa anticline (visible thickness difference between a and a'). In the northern part of the Rzeszów basin sediments are tilted. Onlaps and angular unconformities between the Skole thrust sheet and Rzeszów basin sediments are also visible. See Text-fig. 2 for location

from different sectors of the Rzeszów Basin are discussed to characterise the shape, structure and evolution of the basin. Sections are described in turn, from west to east.

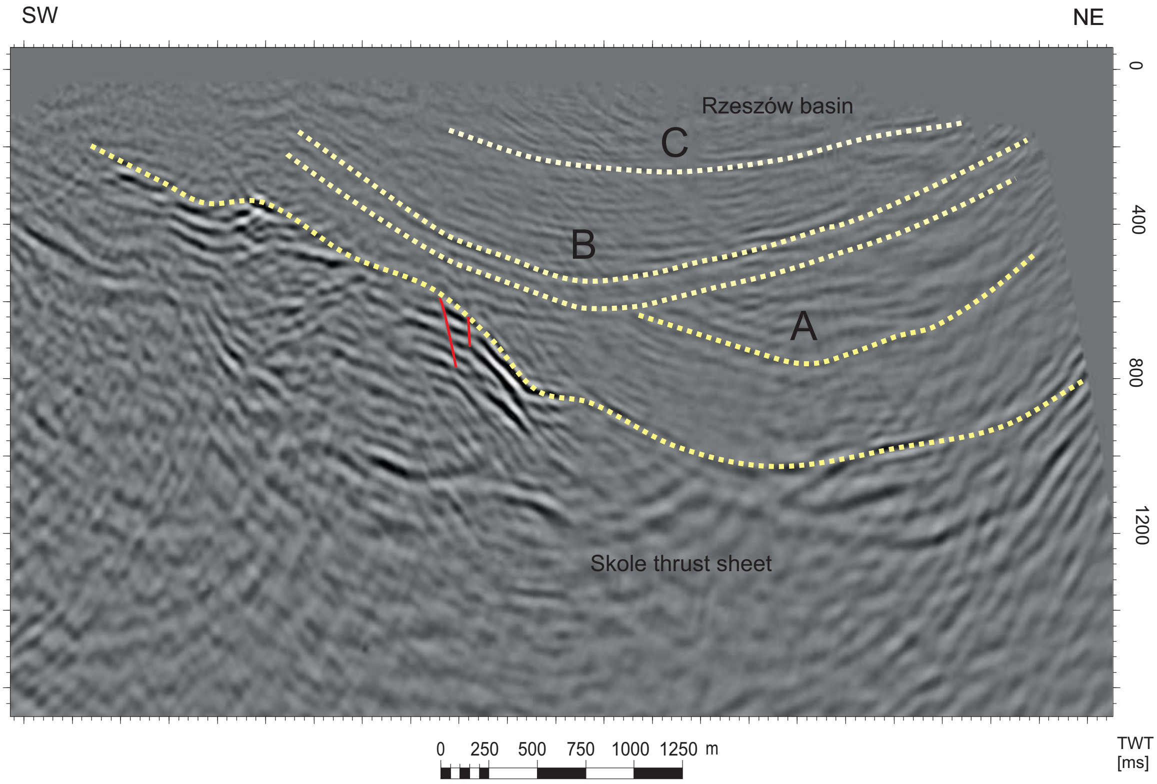
The westernmost section (Text-fig. 7) shows a variable basement morphology of the Rzeszów basin. Deposits of the Rzeszów basin are folded into W–E-trending structures. The shortening resulted in the de-



Text-fig. 8. Seismic profile showing thrusts at the base of the Rzeszów basin. Passive-roof duplex is visible in the Skole thrust sheet. See Text-fig. 2 for location

velopment of a synclinorium (Text-fig. 7), consisting of two map-scale synclines being separated by a map-scale anticline (Text-figs 2, 7). Thus, the south-western limb of the synclinorium forms the Wola Zgłobieńska syncline, its central part – the Nockowa anticline, whereas the north-eastern limb corresponds to the Błędowa Zgłobieńska syncline (Text-fig. 7).

The seismic data for the western section reveal distinct tectonostratigraphic packages that can be related to various folds. The core of the Nockowa anticline is filled with rocks of the Skole unit; an angular unconformity between rocks of the Skole unit and deposits of the Rzeszów basin is distinctly visible on the seismic sections. The limbs of the Nockowa



Text-fig. 9. Seismic profile across the Rzeszów basin (trace in Text-fig. 2). Seismic interpretation shows depocentre migration to the south in response to the activity of the Carpathian frontal thrust. Angular unconformity between A and B unit in the Rzeszów basin is visible. The youngest sediments are least deformed

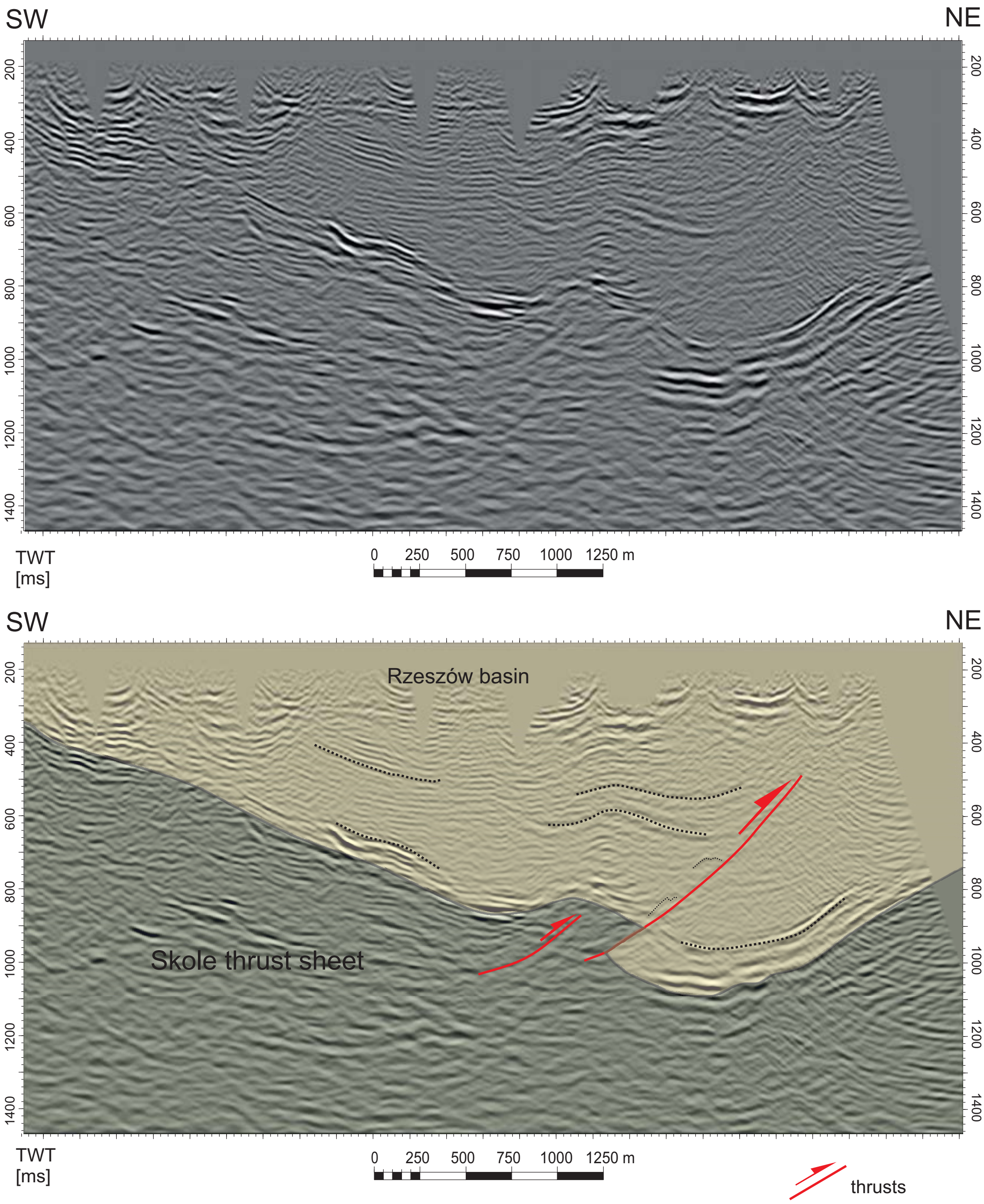
anticline are dissected by a few sets of contractional forelimb shear thrusts (Text-fig. 7). The tectonic tilt of Rzeszów basin deposits is recorded by variations in dip of growth strata. Over the Nockowa anticline, the thickness of the youngest strata of the Rzeszów basin changes in comparison to both adjacent synclines (Text-fig. 7). The thickness is smaller over the hinge of the anticline and larger in the hinges of the synclines (Text-fig. 7, thicknesses marked as: a-a').

The Błędowa Zgłobieńska syncline is composed of the Chodenice and Grabowiec beds (Text-fig. 6). The Wola Zgłobieńska syncline occurs in the southern part of the Rzeszów synclinorium (Text-figs 2, 7). This syncline comprises the Chodenice and Grabowiec beds, and the youngest strata of the Rzeszów basin, i.e., the Jarosław beds (Text-fig. 2). The thickness of the rocks in this part of the Rzeszów basin is greater than in the area located further north, over the Nockowa anticline (Text-fig. 7).

As with the western section, adjacent areas (Text-fig. 8) show distinctive strata relationships indicative of basin infill and tilting of the strata. Here, the hinge of the Nockowa anticline is probably composed of duplexes consisting of rocks of the Skole thrust sheet (Text-fig. 8), often observed within the Carpathian fold and thrust belt (e.g., Konon 2001). The horses form a duplex, the roof thrust of which coincides with the main detachment horizon of the Rzeszów basin (Text-fig. 8). In the upper part, where the hinge of the Nockowa anticline comprises the Miocene rocks of the Rzeszów basin, the fold profile is m-shaped and consists of a second-order anticline with two subsidiary synclines (Text-fig. 8).

Continuing east, the structure changes so that the infill of the Rzeszów basin contains angular unconformities and depocentre migration (Text-figs 9, 10). Thickness changes of particular rock units point to sedimentation within an active orogen. The thrust on the easternmost section, cutting rocks of the Skole nappe and the Rzeszów basin, is distinct, whereas the folds ceased amplifying in the Rzeszów basin (Text-fig. 10).

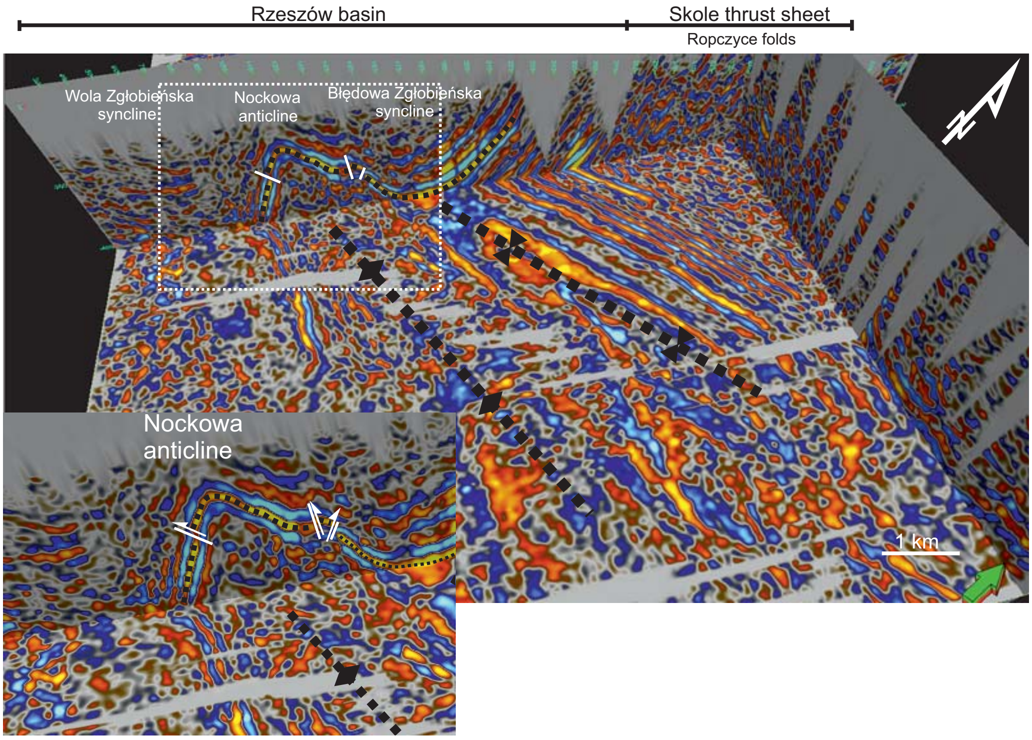
Analysis of seismic data indicate that the Rzeszów basin-fill architecture is characterised by numerous



Text-fig. 10. Seismic profile showing thrusts cutting the SE part of the Rzeszów basin. See Text-fig. 2 for location

onlaps, angular unconformities, thickness changes, and migration of depocentres (Text-figs 7–10). The depocentres formed above older, already tilted strata of the basin infill (Text-fig. 7). Onlaps and angular unconformities prevail especially in the northern part of the basin, near its basement (Text-fig. 7).

All map-scale folds are clearly visible within the Rzeszów basin in its western part, and gradually lose amplitude to the east (Text-figs 2, 11). The folds extend over a distance of about 5 km and their axes are W–E-oriented (measurements based on 3D seismic data, Text-fig. 11).



Text-fig. 11. 3D visualization of seismic data with the W-E trending fold hinges in the Rzeszów basin. Fold accommodation faults (forelimb shear thrusts) visible in fold limbs. See Text-fig. 2 for location

MODEL OF THE RZESZÓW BASIN EVOLUTION

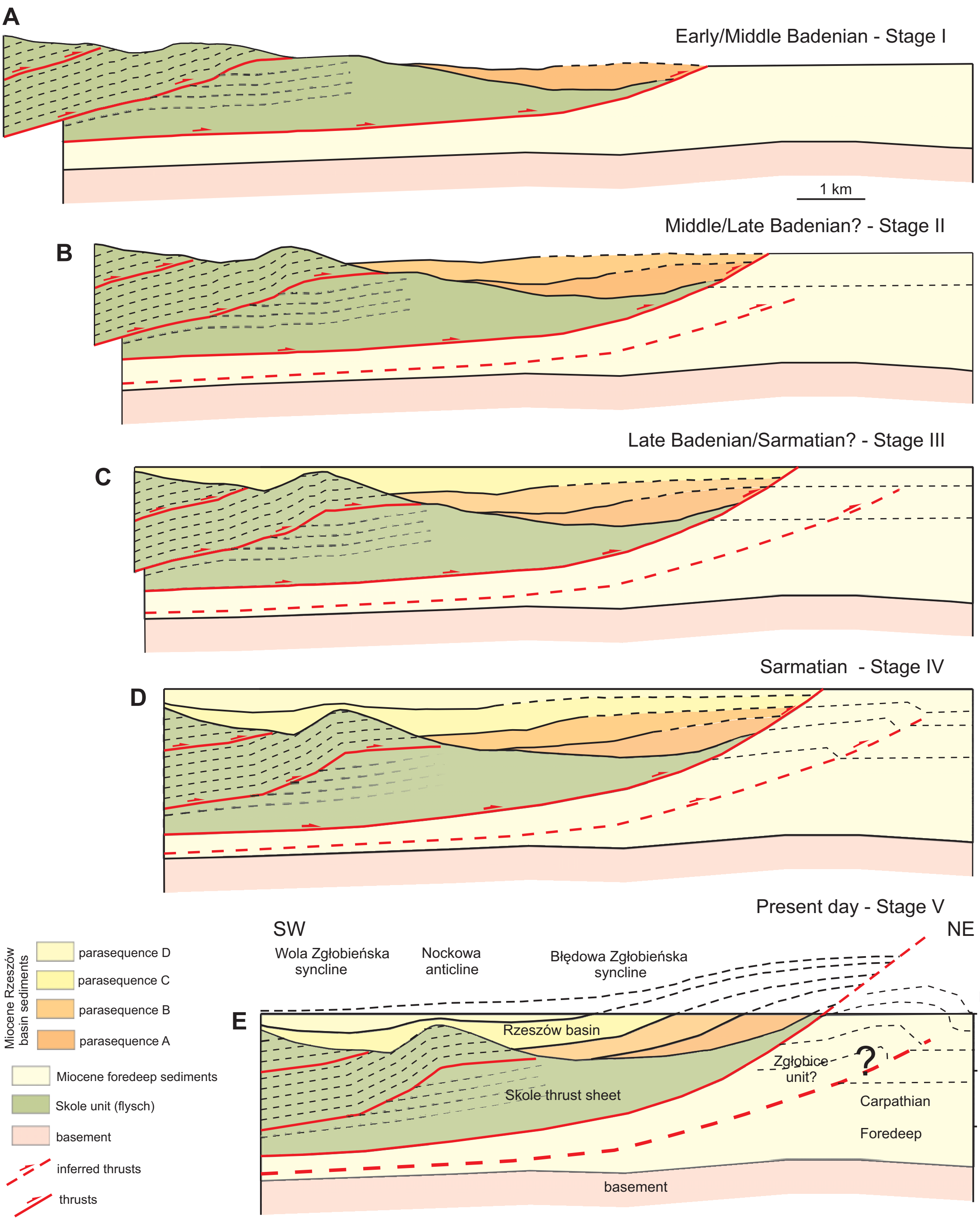
The progressive evolution of the Rzeszów basin is studied along the restored NE–SW-oriented cross-section across the Nockowa anticline (Text-fig. 12) based on the seismic section shown in Text-fig. 7. The model documents the geometric evolution of the basin corresponding to the activity of the thrusts within the Skole thrust sheet. Part of the cross-section intersecting the Carpathian foredeep and the Zgłobice unit has not been balanced, and the structures within them are shown schematically.

During stage I (Early/Middle Badenian) (Text-fig. 12A), the oldest strata of the Rzeszów basin infill were deposited in its northern part on the partly formed Carpathian orogen. The Nockowa anticline had a relatively low amplitude. At this stage, both the frontal and hinterland thrusts were active. Tilting of the sequence in the Rzeszów basin began during stage II (Text-fig. 12B), as a result of frontal thrust activity. The Nockowa anticline was further formed with the sedimentation of the Rzeszów basin infill. During stage III, sedimentation in the Rzeszów basin had a wider lateral range, covering the partly developed Nockowa anticline. At the same time, the frontal thrust caused tilting of parasequences A and B in the Rzeszów basin (Text-fig. 12C).

At stage IV the activity of the hinterland thrust slowly diminished, whereas the frontal thrust caused further rotation of strata, resulting in distinct tilting of the oldest sequences, maximally 20º to the south in the north-eastern part of the basin (Text-figs 7, 12D). The present-day structure was shaped by the youngest deformations of the Carpathian orogen, due to which the Rzeszów basin succession was shortened by approximately 470 m (c. 5%) (Text-fig. 12E). The youngest thrust was probably located within the Miocene deposits of the Carpathian Foredeep, but its activity is beyond the scope of this paper.

DISCUSSION: DEFORMATION OF THE RZESZÓW BASIN IN RESPONSE TO THE ACTIVITY OF THE CARPATHIAN FRONTAL THRUST

The Rzeszów basin, filled with Badenian to Sarmatian syntectonic deposits, was formed in the



Text-fig. 12. Sequential kinematic restoration of the cross-section across the Rzeszów basin starting from the present day (stage V) to the beginning of the Rzeszów basin strata sedimentation in Early/Middle Badenian (stage I). The Carpathian Foredeep was not restored. See Text-fig. 2 for location

hanging-wall of the Skole frontal thrust, which coincides with the front of the Carpathian orogenic belt (Text-figs 2, 3). The basin developed as a thrust-top basin between the frontal thrust and the hinterland thrusts bounding the Niechobrz–Siedliska–Błażowa syncline and the Babica–Kąkolówka anticline (Text-figs 2, 3). During thrusting of the Skole thrust sheet over the foreland of the Babica–Kąkolówka anticline, simultaneous subsidence continued at the rear of the thrust, which is manifested by significant increase in deposit thickness in the southern part of the Rzeszów basin (Text-fig. 7).

Deposition in the Rzeszów basin is documented by onlaps, tilting of layers, syntectonic angular unconformities, migration of depocentres through time, and differences in deposit thickness between different parts of the basin. Such features as syntectonic angular unconformities and migration of depocentres through time are consistent with observations from basins of the Spanish Pyrenees (Riba 1976), the Bermejo foreland basin near the thrust zone of the Precordillera fold-and-thrust belt in central Argentina (Zapata and Allmendinger 1996), or the Velona basin in the Northern Apennines in Italy (Bonini *et al.* 1999). Collectively these stratigraphic features in the Rzeszów basin are indicative of sedimentation occurring during progressive deformation,, hence the deposits can be termed as syntectonic.

The strata relationships interpreted for the Rzeszów basin can be compared with those proposed for other thrust-top basins. In the model proposed by Bonini *et al.* (1999), a thrust-top basin lying between two active thrusts with differential displacement that controls the geometry of the basin fill is shown. For the Rzeszów basin there is no evidence of a backthrust in the forelimb of the more internal (hinterlandward) anticline, as in the Bonini *et al.* (1999) model. Therefore, a scenario similar to that proposed by Roure *et al.* (1991) is preferred.

In the case of the Rzeszów basin, hinterlandward depocentre migration in a direction opposite to the direction of the Carpathian frontal thrust should be considered (Text-fig. 9). Taking into account such a direction of depocentre migration, the models by Bonini *et al.* (1999) imply the hinterland thrust propagating faster than the foreland thrust, leading to strong shortening of the basin, or activity of the foreland thrust at the time when the hinterland thrust was not active (Text-fig. 12).

The much larger thickness of the Upper Badenian and Sarmatian deposits, including the youngest strata, i.e., the Jarosław beds, in the southern part of the Rzeszów basin, compared to the northern part demonstrates that the basin developed asymmmetrically (Text-figs 7, 8). Moreover, regional subsidence caused by thrusting of particular slices could be superposed on the local basin geometry.

The results obtained suggest that the original geometry of the Miocene Rzeszów basin was modified by subsequent shortening (Text-fig. 7), which led to the formation of the Rzeszów synclinorium comprising several map-scale folds (Text-figs 7, 11). The Błędowa Zgłobieńska and Wola Zgłobieńska synclines separated by the Nockowa anticline formed during shortening stages I–IV (Text-fig. 12A–E). The orientation of the axial planes of folds of Miocene strata within the Rzeszów basin indicates horizontal NNE-SSW to NE-SW shortening, which was suggested for the Outer Carpathians by numerous authors (e.g., Kováč *et al.* 1998; Mastella and Konon 2002; Szczęsny 2003).

The presence of evaporites in the lower part of the Rzeszów basin-fill could favour fold formation within the basin as detachment folds (slickensides in e.g., the Rzeszów 7 well, at the boundary of rocks of the Skole nappe and the Rzeszów basin units). Moreover, the unconformity surface commonly becomes a decollement surface (Alonso *et al.* 2011). The much larger thickness of the Upper Badenian and Sarmatian deposits in the hinge of the Wola Zgłobieńska syncline in comparison to their thickness in the hinge of the Nockowa anticline suggests that fold development in the Rzeszów basin was coeval with sedimentation in the Late Badenian and Sarmatian (Text-fig. 12A–E). At the same time, other contractional structures such as reverse faults and thrusts, dissecting the basal parts of the Rzeszów basin, developed owing to shortening of the Carpathian orogen (Text-fig. 7). During the shortening of the Rzeszów basin its sedimentary fill was overthrust northwards on the top of the Outer Carpathian nappes. The displacement magnitude of the Outer Carpathians margin in the final phase of deformation was estimated at c. 30 km by Oszczypko (1998).

The activity of the frontal thrust is confirmed by the hinterland-directed depocentre migration, formation of angular unconformities and progressive tilting of strata towards the south within the northern part of the Rzeszów basin (Text-figs 7, 12). These features are consistent with the passive rotation of the northern limb of the Rzeszów basin in accordance with the models by Roure *et al.* (1991) and Bonini *et al.* (1999; Text-fig. 4). Displacement along the hinterland thrusts that intersect the forelimbs of the Niechobrz–Siedliska–Błażowa syncline and the Babica–Kąkolówka anticline can be estimated at c. 1 km, using the top of the youngest deposits as a reference horizon (Text-fig. 2).

Tilting of the syntectonic stratigraphic sequence in the northern part of the basin took place during the beginning of deformation in the Badenian (Text-fig. 12B). During the Late Badenian and Early Sarmatian, depocentres located above the older, previously tilted strata migrated towards the south, in a direction opposite to the direction of thrusting along the frontal Carpathian orogenic belt, which is represented by local unconformity (Text-fig. 9).

The presented scenario for the evolution of the Rzeszów basin is consistent with the model linking the shortening of the Skole thrust sheet and Rzeszów basin with the advance of previously initiated thrusts. According to Książkiewicz (1972), the Carpathian thrust sheets moved northward and were initiated in a break-forward sequence. Each new thrust formed on the foreland side of the previous one according to the piggyback propagation model (Butler 1982; Nemčok *et al.* 1998). Consequently, the youngest thrust in the study area is the frontal thrust of the Outer Carpathians, partly covered with the thrust-top sediments of the Rzeszów basin (Text-figs 2, 7). The hinterland thrust was active during the Rzeszów basin strata deposition; however, the frontal thrust was active longer and propagated much faster than the hinterland thrust (Text-fig. 12). This interpretation indicates that different thrust structures within the orogen could be active simultaneously as postulated by Butler and Lickorish (1997), but not in a strict sequence as proposed in general (Boyer and Elliott 1982) and for the Carpathians (Nemčok *et al.* 1998). The study of Butler and Lickorish (1997) shows that thrusts were active simultaneously, something that is now is increasingly recognised for emergent systems (Butler 2019; Butler *et al.* 2019). Thrusts within the Rzeszów basin, distinct in the seismic sections (Text-fig. 10), are rarely exposed at the surface, which indicates that at a certain depth thrusts terminate upwards passing into folds, something that is common in thrust belts (e.g., Jamison 1992; Butler and Lickorish 1997). The fold limbs show protracted rotational histories recorded by growth strata. Any kink-band models for fold-thrust structures as proposed by Suppe (1983) involve hinge migration and instantaneous limb rotation. Similar geometries have been described from growth strata at other emergent systems (e.g., Jamison 1992; Butler and Lickorish 1997; Butler *et al.* 2019).

The possibility of using high-resolution stratigraphy would have enriched knowledge of the Rzeszów basin, giving precise dating of particular stages in its development. However this is a subject for future studies.

CONCLUSIONS

Integrated seismic and well data has resolved the relationships between the Miocene stratigraphy of the Rzeszów basin. Deposition in the basin was controlled by the relative activity of thrust-related folds, within a broad area of regional subsidence. Individual folds (e.g., Nockowa anticline) show protracted amplification histories. Folds were active together but the more hinterlandward ones became inactive earlier so that the thrust front remained active longest.

These interpretations show that this segment of the Carpathians was folded jointly in the last contractional stage of the orogenic deformation with significant influence of synkinematic sedimentation. The presented model suggests that tilting of the Rzeszów basin strata took place during several stages from the middle to the late Miocene. In common with other emergent thrust systems, the structures of this sector of the Carpathians did not form in a strict sequence but were active together.

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