Annales Societatis Geologorum Poloniae (2008), vol. 78: 135–149.

TOPOGRAPHY OF THE MAGURA FLOOR THRUST AND MORPHOTECTONICS OF THE OUTER WEST CARPATHIANS IN POLAND

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Zuchiewicz, W. & Oszczypko, N., 2008. Topography of the Magura floor thrust and morphotectonics of the Outer West Carpathians in Poland. *Annales Societatis Geologorum Poloniae*, 78: 135–149.

Abstract: Neotectonic (Pliocene–Quaternary) elevations and depressions detected on maps of subenvelope surfaces of the topography of the Outer West Carpathians of Poland are, to a certain extent, portrayed on the map showing topography of the Magura floor thrust, particularly in the western segment of the study area. The floor thrust of the Magura Nappe is highly uneven, its position changing from 725 m a.s.l. to more than 7,000 m b.s.l. The most prominent depression is located in the medial (S of Dunajec and Poprad confluence) segment of the Polish Outer Carpathians (2–7 km b.s.l.), and its axis trends NW–SE from the eastern margin of the Mszana Dolna tectonic window to the Poprad River valley. Another, much more shallower, Jordanów depression (2 km b.s.l.) is to be found NW of the Mszana Dolna tectonic window, shortly north of the Skawa River valley. Elevated structures, in turn, include the Mszana Dolna tectonic window, Sól–Skomielna (on the west), and Limanowa (on the east) elevations of subparallel orientation. Still farther to the east, a longitudinal elevation extending between the Klêczany–Pisarzowa and Œwi¹tkowa tectonic windows is to be seen some 10–15 km south of the Magura frontal thrust. South of this area, the Magura floor thrust slopes steeply down to more than 4 km b.s.l. A comparison between the pattern of elevated and subsided structures of the Magura floor thrust and subenvelope surfaces of different orders shows that in the western part of the Polish Outer Carpathians the highest-elevated neotectonic structures (in the southern portion of that area) coincide with depressions of the Magura thrust, whereas farther north a reverse pattern becomes dominant: neotectonic elevations coincide either with the Magura frontal thrust or with elevations of its surface. This is particularly true for an area comprised between 20° and 20°30’E meridians. The origin of such relationships is difficult to explain. We infer that one of possible factors could be Pliocene–Quaternary reactivation of faults cutting the Magura floor thrust, and particularly that one, which appears to separate the western-medial segment of the Outer Carpathians from their more eastern portion.

Key words: morphotectonics, neotectonics, Pliocene–Quaternary, Magura thrust, Outer Carpathians, Poland.

Manuscript received 1 September 2008, accepted 9 October 2008

INTRODUCTION

The aim of this paper is to discuss mutual relationships between the pattern of uplifted and subsided neotectonic structures in the Polish Outer Carpathians with highly changeable topography of floor thrust of the Magura Nappe, the most extensive nappe of that region. In the Pliocene and Quaternary, the Outer Carpathians have been subject to differential vertical and remnant horizontal movements resulting in the formation of several neotectonic elevations and depressions (Klimaszewski, 1966; Zuchiewicz, 1991; Zuchiewicz *et al.*, 2002). The apparent amount of Late Neogene–Quaternary uplift of the medial segment of the studied area, coinciding with the greatest width of the Magura Nappe, has ranged from 150–430 m in the south and 360–900 m in the medial sector, to 180–310 m in the north. The size of purely Quaternary uplift of the southern part of the Magura Nappe has been estimated for some 150 m (cf. Zuchiewicz, 1984, 1991).

GEOLOGICAL SETTING

The Outer West Carpathians of Poland represent a typical fold-and-thrust belt (Figs 1, 2), which is composed of a number of nappes piled one upon another during the Middle to Late Miocene (Ksi¹¿kiewicz, 1977).

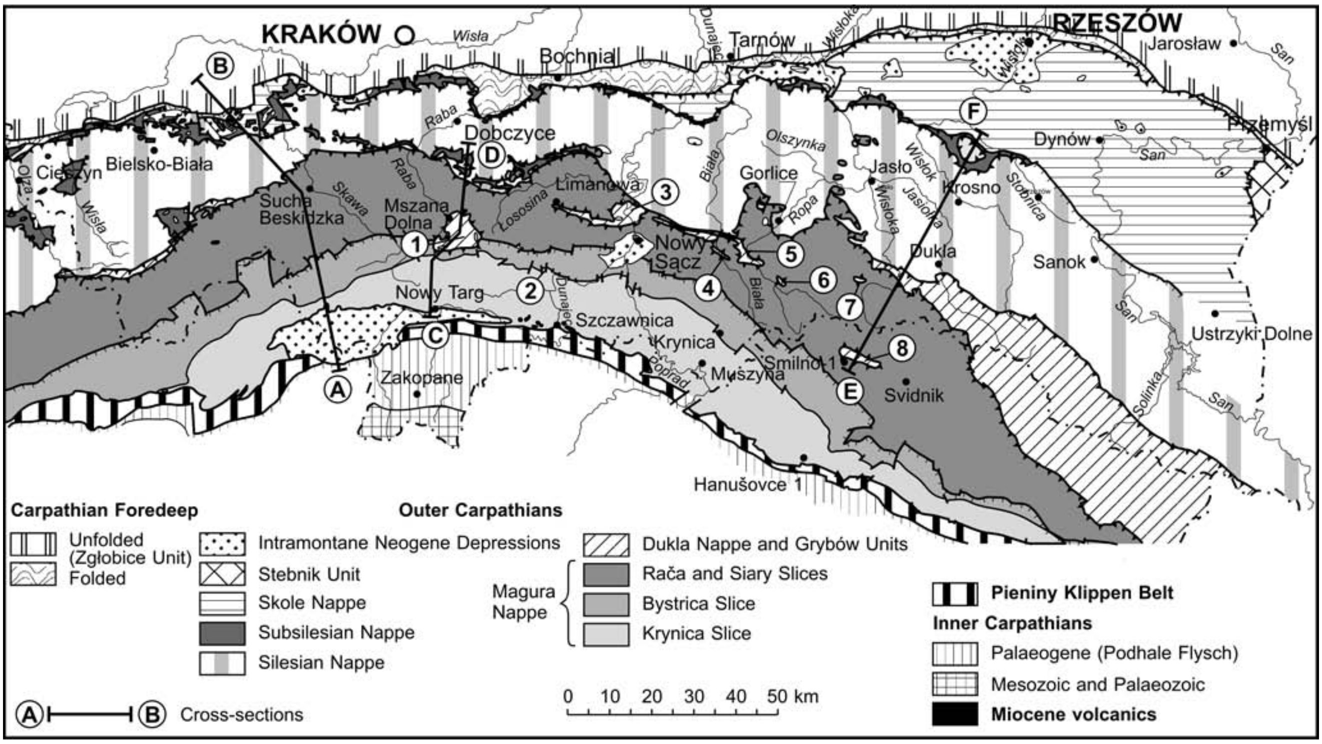

Fig. 1. Tectonic sketch of the Outer West Carpathians (based on Żytko *et al.*, 1989; simplified). Tectonic windows: 1 – Mszana Dolna, 2 – Szczawa, 3 – Klęczany–Pisarzowa, 4 – Grybów, 5 – Ropa, 6 – Uście Gorlickie, 7 – Świątkowa, 8 – Smilno

The Outer Carpathian flysch belt was formed as an accretionary prism during the southward-directed subduction of the European plate under ALCAPA (Pescatore & Ślączka, 1984; Tomek & Hall, 1993; Zoetemeijer *et al.*, 1999, and references therein), resulting in the NW-directed shortening, followed by major rotation of either the regional stress field (Aleksandrowski, 1985; Decker *et al.*, 1997) or the belt itself (Márton *et al.*, 1999; Zuchiewicz *et al.*, 2002). This rotation gave rise to the NE-directed shortening (Decker *et al.*, 1999) and was postdated in Late Neogene times by regional collapse accompanied by normal faulting (Decker *et al.*, 1997; Zuchiewicz *et al.*, 2002).

The Magura Nappe is the innermost tectonic unit of the Outer Western Carpathians and it is linked with the Rheno-Danubian flysch of the Eastern Alps. The oldest, Jurassic–Lower Cretaceous strata are only known from the Grajcarek thrust-sheet in front of the Pieniny Klippen Belt, the southern margin of the Mszana Dolna tectonic window (Oszczypko, 2001, Oszczypko *et al.*, 2005a,b), and from the Moravian sector of the Magura Nappe (Švabenická *et al.*, 1997;

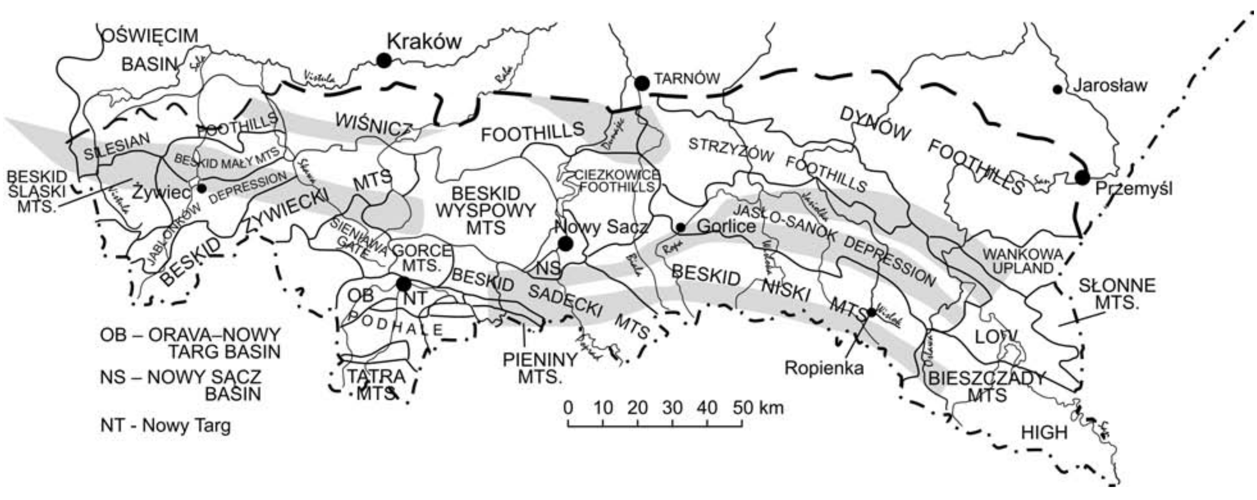

Fig. 2. Physiographic units of the Polish segment of the Carpathians showing place names mentioned in the text (based on Starkel, 1991; modified), as well as the zones of Quaternary uplift, marked by abnormally high river bed gradients (modified from Zuchiewicz, 1998, 1999)

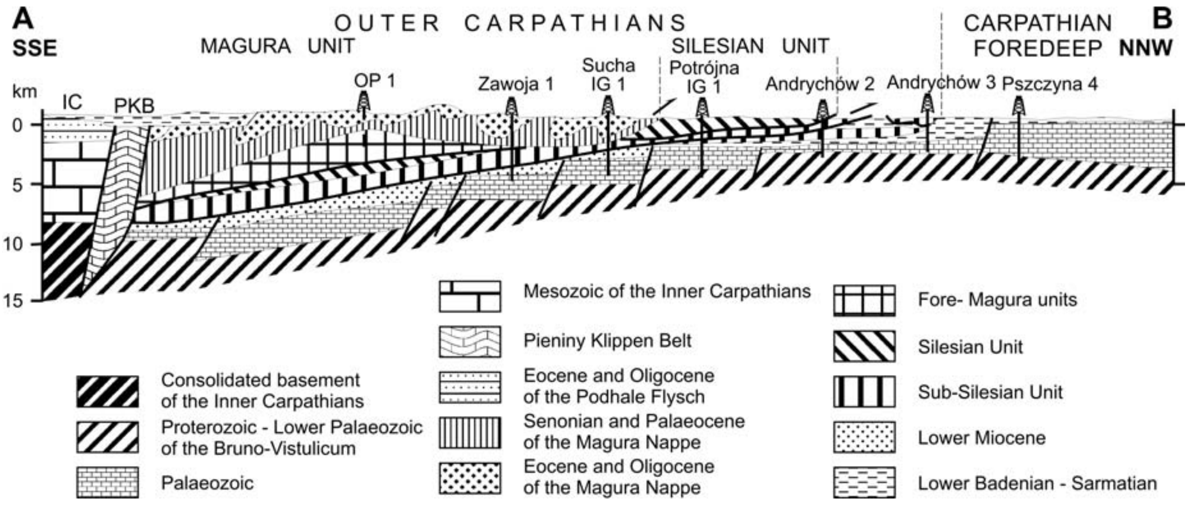

Fig. 3. Geological cross-section through the western portion of the Magura Nappe (based on Oszczypko *et al.*, 2006). For location see Fig 1. IC – Inner Carpathians, PKB – Pieniny Klippen Belt, OP 1 – Oravska Polhora 1 borehole

Œ¹czka *et al.*, 2006). On the basis of facies differentiation with respect to the Palaeogene deposits, the Magura Nappe has been subdivided into four facies-tectonic subunits, namely the Krynica, Bystrica, Raèa and Siary subunits (Fig. 1; see also Koszarski *et al.*, 1974).

Stratigraphy

The Upper Cretaceous deposits begin with Cenomanian/ Turonian variegated, hemipelagic mudstones with intercalations of thin-bedded turbidites. In the Raèa and Bystrica subunits, sedimentation of variegated clays was finished at the Santonian/ Campanian boundary, whereas in the Krynica subunit it still continued in the Maastrichtian (Oszczypko *et al.*, 2005a). The variegated shales pass upwards into thin-bedded turbidites with sporadic intercalations of thick-bedded sandstones. Higher up in the section, some thin-to medium-bedded turbidites, up to 50 m thick, appear. These turbidites contain numerous, 5–7 cm to 30 cm thick intercalations of turbiditic limestones. These deposits pass upwards into thick-bedded sandstones and conglomerates, which are up to 100–400 m thick. The youngest strata of this complex are of Palaeocene age. These deposits are overlain by a 20–50 m thick complex of variegated shales of Early to Middle Eocene age. The variegated shales pass upwards into thin-bedded turbidites, some few hundred metres thick (Oszczypko, 1991; Oszczypko *et al.*, 1999). In the Krynica, Bystrica and Raèa subunits, the youngest deposits of the Eocene to Oligocene complex belong to the Magura Sandstone Fm., which is of ? Early Eocene to Oligocene age. The thickness of this formation ranges from 1,200–1,400 m in the the Krynica, through 800–2,000 m in the Bystrica, to 1,000 – 2000 m in the Raèa subunits (Ksi¹¿kiewicz, 1971; Golonka & Wójcik, 1978; Birkenmajer & Oszczypko, 1989; Oszczypko, 1991). The Magura Fm. is locally overlain by the Globigerina marls (Upper Eocene–Lower Oligocene), bituminous shales, and thin-bedded calcareous flysch (Upper Oligocene). In the northernmost part of the Magura Nappe (Siary subunit), the Middle/Upper Eocene variegated shales pass upwards into marls and thin-bedded flysch with intercalations of Globigerina marls (Upper Eocene–Lower Oligocene), thick-bedded glauconitic sandstones (W¹tkowa Sandstones) of Early Oligocene age, and finally into marls with intercalations of glauconitic sandstones (Oligocene; see Oszczypko-Clowes, 2001). In the vicinity of Nowy S¹cz and close to the Pieniny Klippen Belt (Fig. 1), the Lower Miocene flysch strata of the Magura Nappe have recently been discovered (Cieszkowski, 1992; Oszczypko *et al.*, 1999; Oszczypko-Clowes, 2001; Oszczypko and Oszczypko-Clowes, 2002, Oszczypko *et al.*, 2005b).

Tectonics

In our tectonic and morphotectonic considerations we accept traditional shape of the front of the Magura Nappe in the Gorlice area, together with £u¿na and Harklowa salients (“peninsulas") (Figs 1,6, 7). This idea has recently been questioned by Jankowski *et al.* (2004), who interpreted these salients and “Magura erosional ouliers” near the Jas³o as chaotic complexes. In other interpretations these deposits are regarded as fragments of the Fore-Magura tectonic units (see Oszczypko *et al.* , 2008).

The Magura Nappe is flatly thrust over its foreland which is built up of the Fore-Magura group of units and partly by the Silesian Unit (Fig. 1). The amplitude of the overthrust is up to 50 km (Figs 1, 3, 4), and the post-Middle Badenian thrust displacement is more than 12 km (Oszczypko & Zuchiewicz, 2000; Oszczypko, 2001, 2006) The northern limit of the nappe is an erosional one, whereas the southern limit coincides with a strike-slip fault along the northern boundary of the Pieniny Klippen Belt (Figs 3, 4). The thrust developed mainly within the ductile Upper Cretaceous variegated shales. The sub-thrust morphology of the Magura foreland is very distinctive (Figs 3–5). The shape of the northern limit of the Magura Nappe and the distribution of the tectonic windows inside the nappe are connected with the topography of the Magura basement. As a rule, the “em-

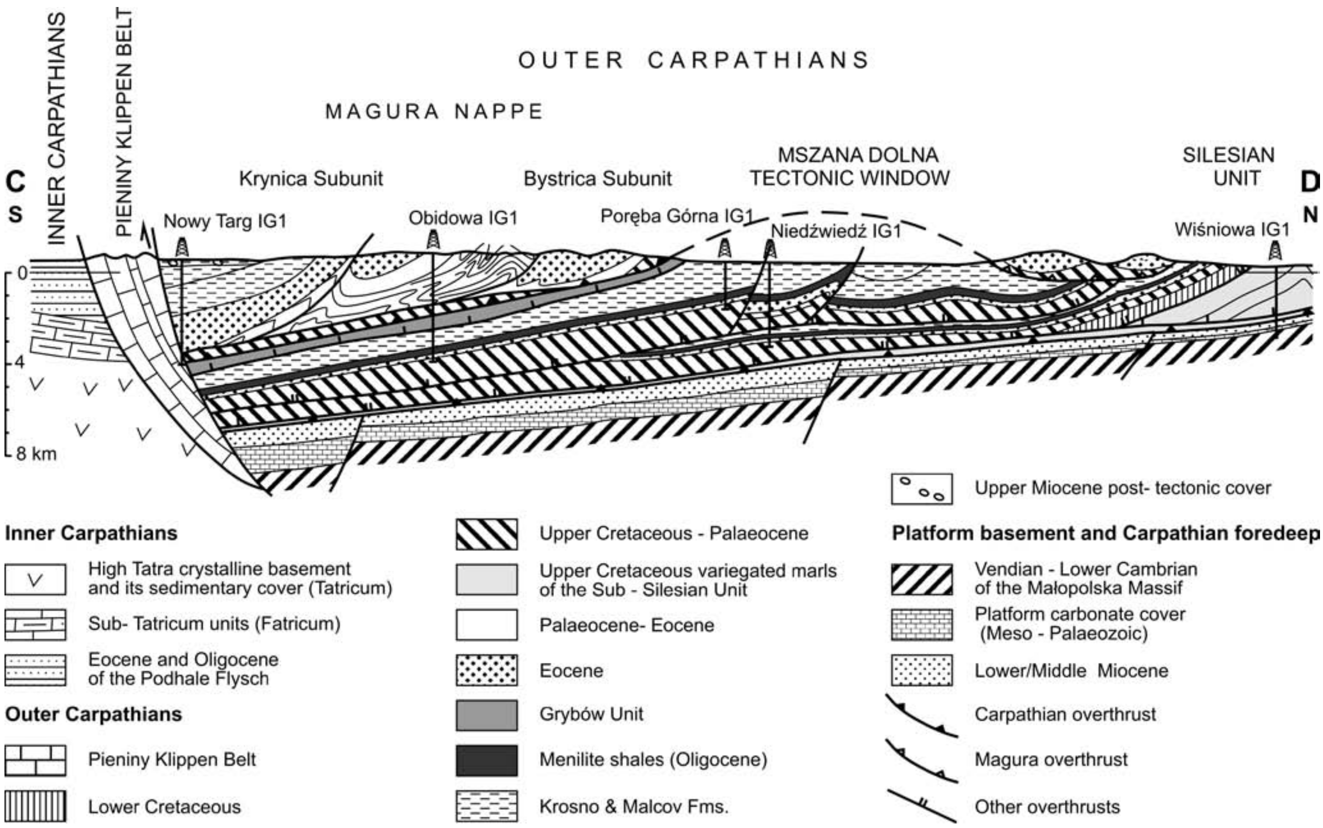

Fig. 4. Geological cross-section through the medial segment of the Magura Nappe (based on Oszczypko, 2006). For location see Fig. 1.

bayments" of the marginal thrust are related to transversal bulges in the Magura basement, whereas the salients are located upon the depressions (Oszczypko, 2001, 2006). At a distance of 10–15 km south of the northern limit of the nappe, the zone of tectonic windows connected with the uplifted Fore-Magura basement is located (*e.g.*, Mszana Dolna, Szczawa, Klêczany, Grybów, Ropa, Uœcie Gorlickie, and Œwi¹tkowa tectonic windows; cf. Fig. 1). The Magura Nappe is subdivided into four structural subunits (slices), namely: the Krynica, Bystrica (Nowy S¹cz), Raèa, and Siary (Fig. 1). The ? Lower Eocene to Oligocene flysch strata of the Raèa and Krynica subunits build broad, W–E trending synclines and narrow anticlines. The southern limbs of synclines are often reduced and overturned. In the Bystrica subunit, sub-vertical thrust-sheets are common. Both the northern limbs of anticlines and southern limbs of synclines are tectonically reduced and usually overturned. In the Krynica and Raèa subunits the youngest (Late Eocene–Early Oligocene), weakly deformed, deposits of the Magura Nappe rest uconformably upon the older Eocene flysch strata (Figs 3–5).

The Magura thrust has developed in several stages. The first episode of thrusting occurred in Late Oligocene times when the nappe, together with the Grybów Unit, was thrust over the Dukla Unit (Oszczypko-Clowes & Oszczypko, 2004). In the early Burdigalian, the frontal part of Magura Nappe was thrust northwards onto the terminal Krosno flysch basin. This was also accompanied by the formation of a piggy-back basin on the Magura Nappe, filled with the Lower Miocene synorogenic turbidites of the Zawada and Kremna formations (Oszczypko, 2006).

The subsequent episodes of thrusting took place in the Ottnangian and after the middle Badenian. The last episode, including some 12 km of thrusting, was that which controlled the present-day intersection of the thrust and was responsible for the strike-slip character of the contact between the Magura Nappe and the Pieniny Klippen Belt (cf. Oszczypko, 1998). The post-Badenian thrusting has finally shaped the duplex structure of the Mszana Dolna tectonic window (Oszczypko, 2001; Oszczypko-Clowes & Oszczypko, 2004), being postdated by normal faulting (Oszczypko & Zuchiewicz, 2000), controlling subsidence of the Late Badenian–Sarmatian troughs of the Orava–Nowy Targ and Nowy S¹cz basins.

BASE OF THE MAGURA NAPPE

The map of the base of the Magura Nappe (Fig. 6) was constructed by one of us (N. Oszczypko) basing on 90 well logs, as well as on the results of numerous exploration wells. Well-bore data from the western part of the nappe are unevenly distributed, most of them coming from the northern, marginal part of the nappe that coincides with the Raèa facies zone. This applies particularly to the Klêczany–Pisarzowa window and the Limanowa area. The region comprised between the Raba and So³a rivers has also been drilled extensively, whereas the southern part of the nappe,

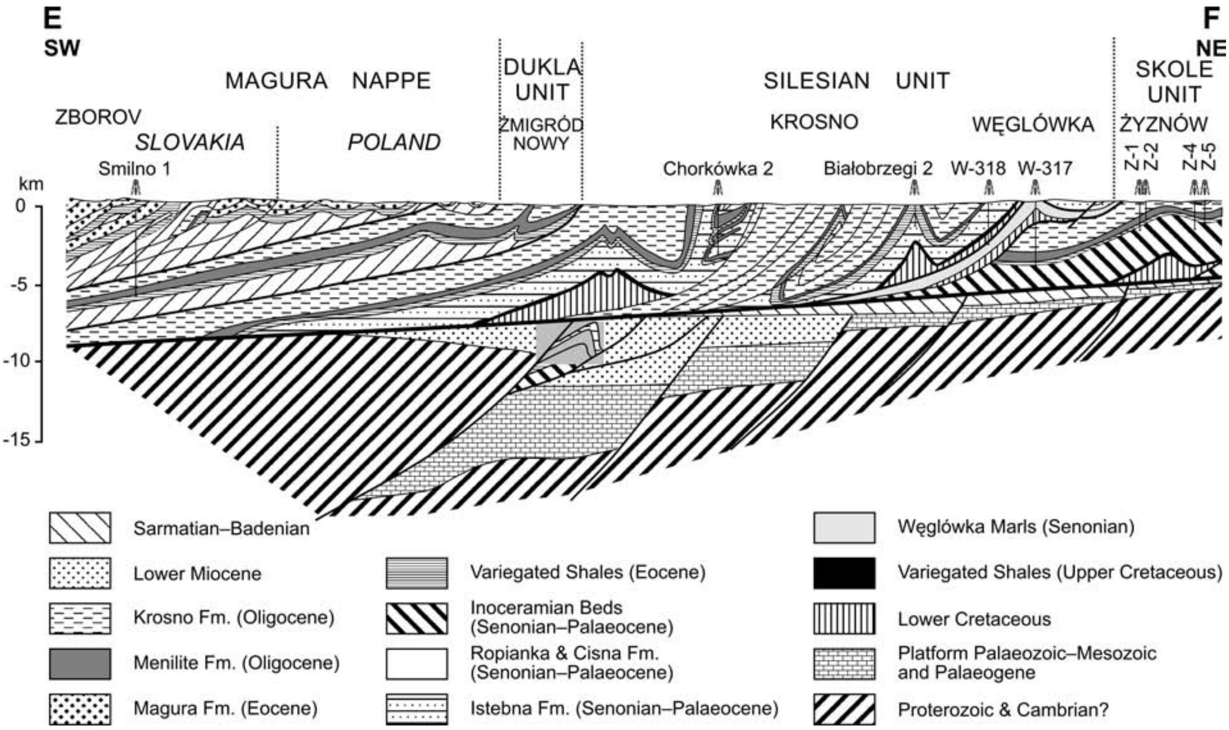

Fig. 5. Geological cross-section through the eastern portion of the Magura Nappe (based on Oszczypko *et al.*, 1998; modified). For location see Fig. 1

namely the Krynica facies zone, still remains to be studied. The only well from that area, located near Nowy Targ (Figs 1, 2; cf. Paul & Poprawa, 1992), did not produce unequivocal results, although it did document that the thickness of the Magura Nappe exceeds here 3.8 km. To the east of the Dunajec River, well-bore data are relatively scarce, being concentrated near Gorlice, within the Siary and northern part of Raèa zones. The remaining facies zones between the Dunajec–Poprad and Ropa rivers (southern Raèa, Bystrica, and Krynica zones) have not been drilled yet.

To the west of the Dunajec River (Figs 3, 6), the Magura Nappe is relatively steeply thrust over its foreland, *i.e*. the Silesian Nappe, and west of the So³a River also over the Fore-Magura thrust-sheets. The Grybów Unit builds the base of the Magura Nappe within the Klêczany–Pisarzowa, Mszana Dolna, and Szczawa tectonic windows (Figs 4, 6). The Grybów Unit has also been drilled by numerous wells near Limanowa (cf. Po³towicz, 1985), where it forms three slices composed of the Krosno, Menilite, Grybów, sub-Grybów, and Klêczany beds. The thickness of this unit changes from a few hundred metres to a few kilometres, whereas shortly south of the Mszana Dolna tectonic window its thickness is reduced to some 100 m only. Views on the origin of more outer units are strongly differentiated. It is generally accepted that immediately below the Grybów Unit, the Dukla Unit is to be found. The latter unit has been described from a few wells (Figs 1, 4). The affinity of Lower Cretaceous strata, mostly the Lgota beds, drilled by a few wells south of Limanowa (Fig. 1) is not clear.

In the western part of the Outer Carpathians, the topography of the Magura basal thrust is dominated by the Mszana Dolna elevation and the Nowy S¹cz and Orawa–Nowy Targ basins (Figs 3, 4, 6, 7). The Mszana Dolna elevation extends 20 km N–S and 25 km E–W (Figs 1, 6). This elevation contains two culminations, which are coincident with the Mszana Dolna and Szczawa tectonic windows. The former shows an isometric shape and is *ca*. 10 km across. In the middle part of the window, strata belonging to the Dukla–Grybów Unit are exposed at 725 m a.s.l. A small tectonic window of Szczawa is situated on the eastern slope of the elevation (Figs 1, 6). It is only 1 km across, and in its highest-elevated part the Grybów Unit deposits are exposed at 550 m a.s.l. The Mszana Dolna elevation builds a duplex structure. Outside the elevation, the Magura basal thrust dips at ca. 25° in all directions, except to the north. To the south, near Nowy Targ, and east (close to Nowy S¹cz), the thrust surface slopes down to ca. 4 km b.s.l.

The Mszana Dolna elevation (Figs 6, 7) is linked through narrow passages with two other elevations of Sól–Skomielna and Limanowa. The Sól–Skomielna elevation, extending across the Oravska Polhora region, is up to 5 km wide and strikes roughly E–W (Fig. 7). The Limanowa elevation, in turn, is separated from the Mszana Dolna elevation by a transversal (NNW–SSE) S³opnice–Leœniówka zone of rapid thickness change, also 5 km wide (Po³towicz, 1985). The Klêczany–Pisarzowa tectonic window builds a culmination of the Limanowa zone. Strata of the Grybów Unit near Klêczany are elevated as high as 500 m a.s.l.

The Limanowa, Mszana Dolna, and Sól–Skomielna belt of elevations is surrounded on the north and south by depressions (Fig. 7). The northern ones are represented by: Jaworzna (–1,209 m b.s.l.), Jordanów (–2,470 m b.s.l.), and

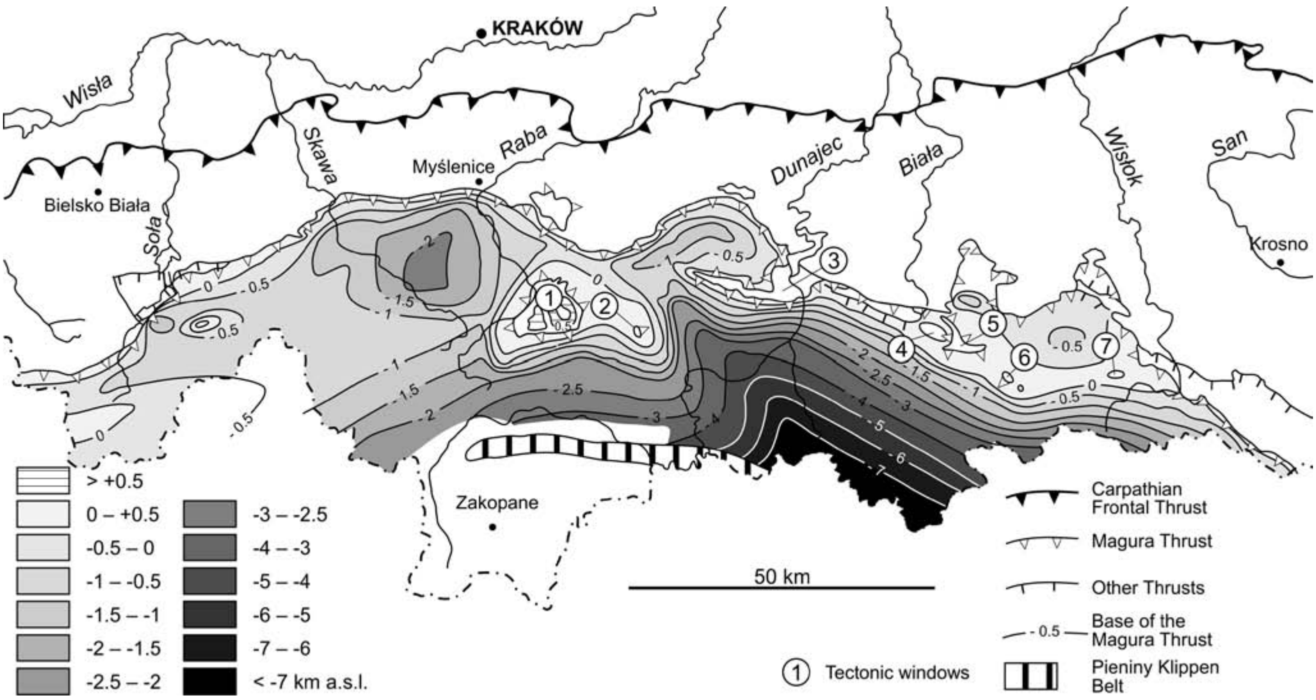

Fig. 6. Topography of the Magura floor thrust. Numbers refer to tectonic windows shown in Fig. 1. Different shades of grey indicate distance between the Magura floor thrust and sea level

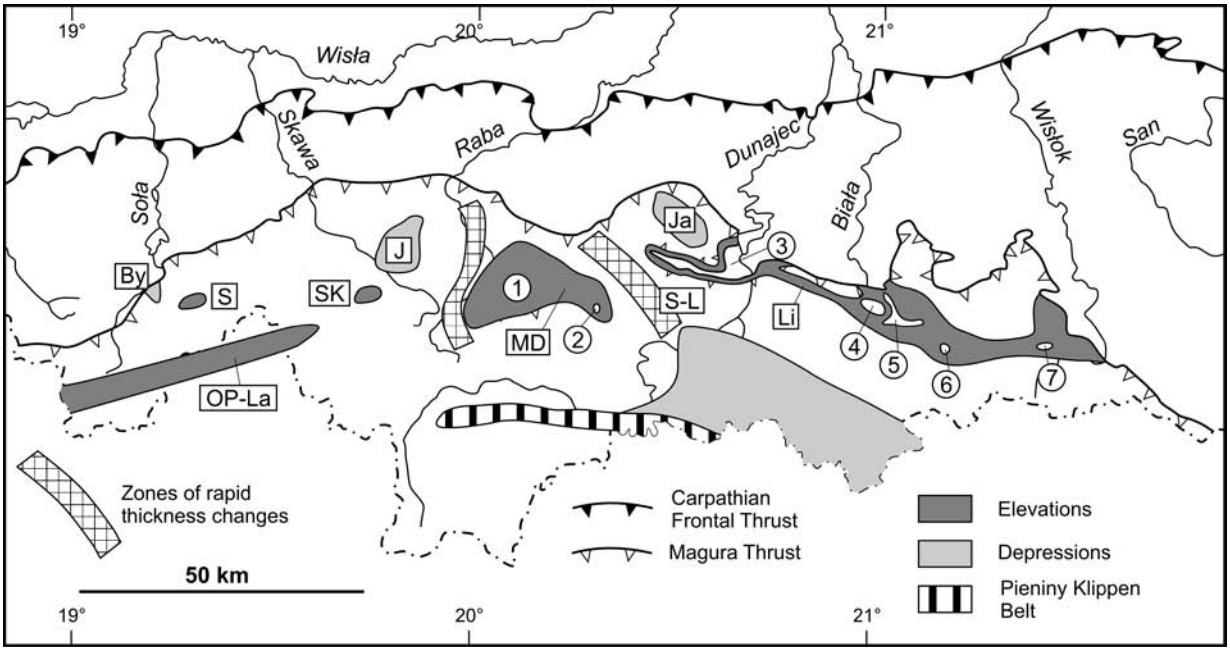

Fig. 7. Elevations and depressions in the base of the Magura Nappe. Numbers refer to tectonic windows shown in Fig. 1. Elevations: S – Sól, Sk – Skomielna, OP-La – Oravska Polhora – Lachowice, MD – Mszana Dolna, Li – Limanowa; Depressions: By – Bystra, J – Jordanów, Ja – Jaworzna; S-L – S³opnice – Leœniówka zone

Bystra (–1,148 m b.s.l.) depressions. Between the Jordanów and Bystra depressions, the transversal Oravska Polhora–Lachowice elevation (–230–550 m b.s.l.) occurs. Particularly high relief of the base of Magura thrust is to be observed between the Mszana Dolna elevation and Jordanów depression, where the base of the Magura Nappe slopes by more than 3 km at a distance of 20 km. The southern belt of depressions is poorly recognized. The only data come from two deep wells (Hanušovce-1, Nowy Targ IG-1), which did not drilled the entire Magura Nappe (Figs 1, 2). The borehole Nowy Targ IG-1 probably reached the back-thrust of the Magura Nappe onto Grajcarek thrust-sheet, at a depth of 3,853 m. It can be conluded that the base of the Magura Nappe at the contact with the Pieniny Klippen Belt is placed at ca. –6 km b.s.l. in Eastern Slovakia, and at around –4 km b.s.l. near Nowy Targ. The problem of depth differentiation of the base of Magura Nappe can only be solved by new seismic soundings.

The topography of the base of the Magura Nappe influences as well the strike of its frontal thrust. Elevated portions of the Magura Nappe are marked at the surface by concave towards the south, bay-like curves of the frontal thrust, whereas the depressions are reflected by “peninsulas” of this nappe. Such a relationship, however, is not so well-marked as in the eastern part of the Outer Carpathians.

To the east of the Dunajec River, the Magura Nappe is flatly thrust over its foreland, which is composed of the Silesian Nappe and Dukla–Grybów Unit (Figs 5–7). Morphological differentiation of the base of the Magura Nappe is well marked in the strike of its frontal thrust, forming characteristic “embayments” and salients. The “embayments” are related to uplifted parts of the foreland, the salients coincide with transversal depressions. Elevation differences between the “embayments” and salients do not exceed 250 m. To the east, the dip of the Magura frontal thrust increases markedly, as documented by wells drilled near Ropianka.

Some 10–15 km south of the Magura frontal thrust, a belt of tectonic windows located upon a longitudinal basement elevation is to be found. This zone, 4–6 km wide, begins on the west in the Klêczany–Pisarzowa window, and continues farther east through a half-window north of Nowy S¹cz, and the Grybów–Ropa–Uœcie Gorlickie and Œwi¹tkowa windows (Figs 1, 6, 7). To the south of the Uœcie Gorlickie and Œwi¹tkowa tectonic windows, the base of the Magura Nappe rapidly slopes down to 4,200 m b.s.l. in Smilno-1 well in Slovakia. This well has documented that the position of the Smilno tectonic window is probably different from those near Gorlice. South of Gorlice, the tectonic windows are clearly associated with basement highs, whereas the Smilno window is detached from its basement and embedded into one of the Magura slices. South of Smilno, the base of the Magura Nappe has not been drilled yet. One can suppose that this base near Pieniny Klippen Belt can be placed at depths ranging from 7 to 10 km. This hypothesis is confirmed in part by the results of the Hanušovce-1 well (6,003 m deep) in Eastern Slovakia, wherein the Pieniny Klippen Belt has been drilled through at a depth of 4 km b.s.l., whereas the Magura Nappe has not been drilled down to its base. We infer, therefore, that also in the SE part of the Magura Nappe in Poland, its base is probably placed at depths of 4 to 7 km. In the Nowy S¹cz Basin, in turn, where the thickness of Miocene molasses is up to 600 m, the base of the Magura Nappe must be located at a depth of at least 3–3.5 km.

To summarise, the floor thrust of the Magura Nappe is highly uneven, its position changing from 725 m a.s.l. to more than 7,000 m b.s.l. (Figs 6, 7). The most prominent depression is located in the medial segment of the Polish Outer Carpathians (2–7 km b.s.l.), and its axis trends NW–SE from the eastern margin of the Mszana Dolna tectonic window to the Poprad River valley. Another, much more shallower, Jordanów depression (2 km b.s.l.) is to be found NW of the Mszana Dolna tectonic window, shortly north of the Skawa River valley. Elevated structures, in turn, include the Mszana Dolna tectonic window, Sól–Skomielna (on the west), and Limanowa (on the east) elevations of subparallel orientation. Still farther to the east, a longitudinal elevation extending between the Klêczany–Pisarzowa and Œwi¹tkowa tectonic windows is to be seen some 10–15 km south of the Magura frontal thrust. South of this area, the Magura floor thrust slopes steeply down to more than 4 km b.s.l.

MORPHOTECTONIC PATTERN OF THE OUTER CARPATHIANS

The studies focusing on deformation of planation surfaces of Late Miocene, Early and Late Pliocene and Early Quaternary age, as well as Quaternary fluvial terraces have made it possible to distinguish a number of elevated and subsided structures of relatively small widths (15–20 km) and subparallel arrangement with respect to the strike of principal thrusts and imbricated folds. These structures probably originated due to Plio-Quaternary relaxation of horizontal movements within the flysch nappes, leading to the steepening of frontal thrusts and open folding above terminal thrust planes (cf. Zuchiewicz, 1998; Zuchiewicz *et al.*, 2002). The maximum size of Quaternary uplift has been from 150 m in the Beskid S¹decki Mts. to 50–100 m in the other regions (Zuchiewicz, 1984, 1995), whereas the overall, minimum amplitude of post-tectonic uplift during the past 10 to 11 million years has been calculated for some 1 km in the West Beskidy Mts. to 260–360 m in the Carpathian Foothills (Oszczypko, 1996; Zuchiewicz *et al.*, 2002). The distribution of Bouguer gravity anomalies points to generally non-isostatic processes causing this uplift, ranging from 250 m to 550 m (Zoetemeijer *et al.*, 1999).

The rates of recent vertical crustal motions in the Polish Outer Carpathians range between 0 mm/yr in the western and medial segments to ca. +1 mm/yr in the east (Wyrzykowski, 1985), while those in the Pieniny Klippen Belt do not exceed 0.5 mm/yr (cf. Czarnecki, 2004). The results of recent GPS campaigns (Hefty, 2007) as well as borehole breakout analyses (Jarosiñski, 1998, 2005) point, in turn, to NNE-directed horizontal motions throughout the area.

Differentiated values of morphometric parameters characterizing the present-day topography provide indirect evidence in favour of diversified neotectonic tendencies. Analysis of river-bed gradients, Hortonian indices, hypsometric curves and hypsometric integrals, drainage basin asymmetry, valley floor width to valley height ratios, mountain front sinuosity, and other parameters proved helpful in identification of uplifted and subsided zones in the Polish segment of the Outer Carpathians (cf. Zuchiewicz, 1995, 1999; and references therein).

In 1965, Klimaszewski published a map showing generalized topography of the Outer Carpathian drainage pattern by plotting contours of the main river valley bottoms. This pattern suggested differentiated Pliocene–Quaternary uplift of the Outer West Carpathians, since the elevations of valley bottoms rose from 200 m a.s.l. in the foothills area up to 400–500 m a.s.l. in the Beskidy Mts. A similar technique was applied by Jahn (1992) to the East Carpathians.

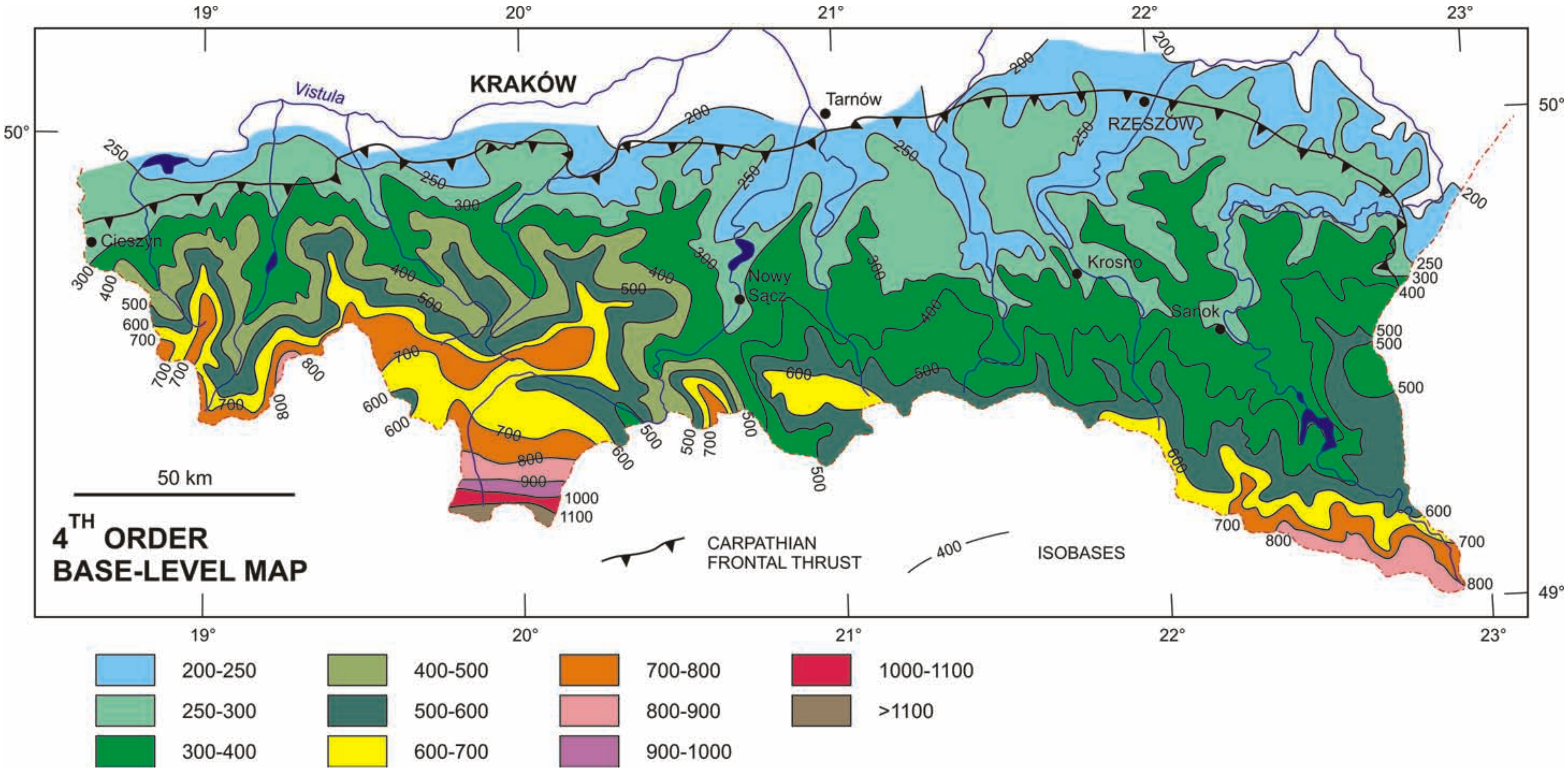

Fig. 8. Subenvelope map of the 4th-order of the Polish Outer Carpathians (modified from R¹czkowski *et al.*, 1984)

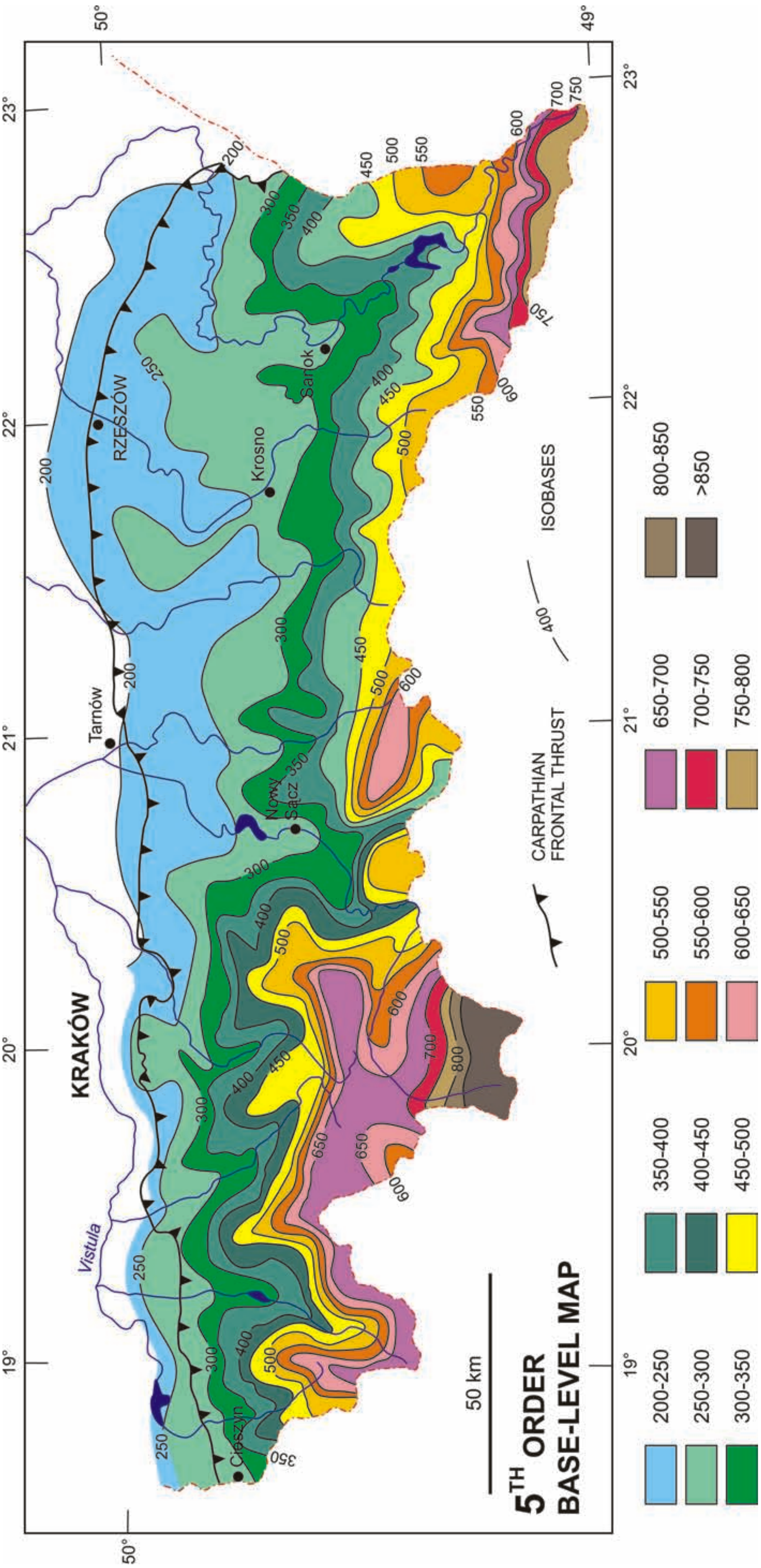

Fig. 9. Subenvelope map of the 5th-order of the Polish Outer Carpathians (modified from Rączkowski *et al.*, 1984)

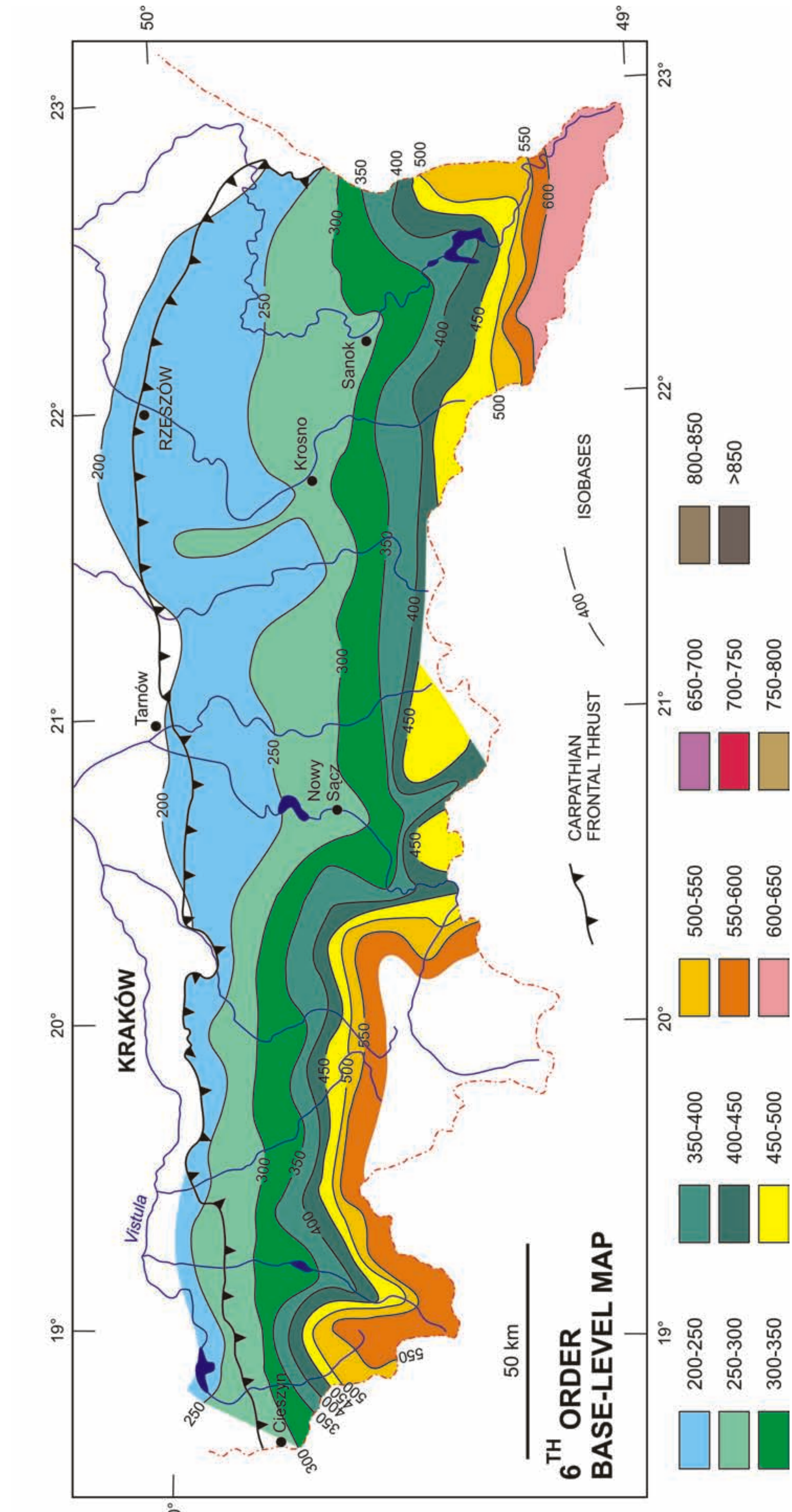

Fig. 10. Subenvelope map of the 6th-order of the Polish Outer Carpathians (modified from R¹czkowski *et al.*, 1984)

Another cartometric approach to morphological manifestations of young tectonic activity is represented by construction of envelope and subenvelope maps (Dury, 1951; Filosofov, 1960; Pannekoek, 1967; Rączkowski *et al.*, 1984; Keller & Pinter, 1996; and references therein). The former portray the highest elevations of terrain, the latter reconstruct the level to which the streams have eroded by connecting points of equal elevation between the streams. A series of such subenvelope maps produced for drainage networks, classified according to the Horton-Strahler hierarchy and called base-level surface maps, makes it possible to compute maps of residuals between individual surfaces of different orders and to hypothesize about either uplift or subsidence tendencies, indicated by dense or sparse pattern of isobases and increased or decreased relief portrayed on residual maps (cf. Rączkowski *et al.*, 1984; Zuchiewicz & Oaks, 1993). Reliable interpretation of such maps, however, is impossible without knowledge about the number and age of geomorphic cycles that affected the study area. Therefore, both envelope and subenvelope maps should complement traditional geomorphic mapping (see, for instance, arguments listed by Starkel, 1985).

The 4th-order subenvelope (base-level) map, originally constructed at the scale of 1:100,000, shows several areas of high isobase concentration, including the uplifted Beskid Żywiecki, Tatra, Pieniny, Gorce, Beskid Sądecki, and Bieszczady Mts. (Figs 2, 8). Broadly-spaced isobases within intramontane depressions are indicative of subsiding tendencies. The 5th-order map, in turn, displays two regions of contrasting isobase pattern (Fig. 9). In the western area isobases of 250 to 850 m a.s.l. run close to one another; the eastern area is characterized by low isobase density and lower elevations (200–700 m a.s.l.). Slightly higher elevations (650–750 m a.s.l.) occur only in the axial part of the Bieszczady Mts. The 6th-order map shows a distinct boundary between the West and East Carpathians (Fig. 10). In the western part, a southern region encircled by the 550 m a.s.l. isobase, is well pronounced. Farther to the north, base-level values diminish to 250 m a.s.l. Isobases are broadly spaced within the intramontane depressions of Żywiec and Nowy Sącz. The general E–W trending pattern of isobases is disturbed by “depressions” associated with transversal, deeply-cut valleys of Soła (NNE–SSW), Dunajec (NNE– SSW), and San (NW–SE) rivers.

Base-level surfaces of different orders are very difficult to date: in many cases they represent different fragments of a mature landscape, formed during different time-spans (like, for instance, upper valley reaches within watershed areas), although being assigned to one base-level surface. One can only infer that the 6th-order subenvelope (base-level) map portrays, roughly, the Late Miocene/Early Pliocene topography of the studied area (cf. Rączkowski *et al.*, 1984). Differences among base-level maps of different orders appear to reflect both lithological control and young tectonic processes. The uplifted regions are marked on maps of residuals as longitudinal elevations (Beskid Żywiecki, Tatra, Beskid Sądecki, Słonne Mts.) or block/dome-like uplifts (Gorce Mts., western Bieszczady Mts., Beskid Śląski Mts.).

Summing up, the hitherto-published geomorphological maps of the Polish Carpathians feature a few longitudinal elevated areas (Starkel, 1980; Rączkowski *et al.*, 1984; Zuchiewicz, 1995). More prominent subsiding structures are located along the Soła River course, in the Orava–Nowy Targ Basin, in the Jasło–Sanok Depression, and following the lower course of the San River valley in the eastern portion of the Outer Carpathians.

MORPHOTECTONIC STRUCTURES VERSUS MAGURA FLOOR THRUST

The present-day differentiated morphology of the Magura Nappe floor thrust strongly contrasts with very regular, SE deepening, Middle/Late Miocene floor thrust of the Polish Outer Carpathians (see Oszczypko & Tomaś, 1985; Behrmann *et al.*, 2000). In the western part of the Outer West Carpathians, the base of the Magura Nappe displays strongly differentiated and thrust upon ramp-flat morphology of the basement (cf. Nemčok *et al.*, 2000). The nappe is underlain here by a strongly reduced in thickness equivalent of the Dukla Unit, which, in its more eastern part, is represented by relatively thick rock complex of undifferentiated, smooth top surface (Behrmann *et al.*, 2000). This suggests multi-stage development of the Magura Nappe floor thrust. The process of overthrusting was initiated during the Late Oligocene when the front of the Magura Nappe reached, under submarine conditions, the Dukla–Grybów sedimentary area (Oszczypko-Clowes & Oszczypko, 2004). During the Eggenburgian, the front of the Magura Nappe reached the southern part of the Silesian Basin (Oszczypko *et al.*, 1999; Oszczypko & Oszczypko-Clowes, 2002).

During the Middle Miocene thrusting, a large SW–NE trending duplex structure began to develop at the front of the Magura Nappe against its foreland (cf. Roca *et al.*, 1995; Behrmann *et al.*, 2000). This duplex zone, marked by a zone of tectonic windows within the Magura Nappe, is composed of imbricated horses of the Grybów Unit, developed between two thrust surfaces: the floor thrust surface formed along the frontal ramp of the Dukla Unit, and the roof thrust surface related to the Magura Nappe (Oszczypko-Clowes & Oszczypko, 2004). The same mechanism of the Magura Nappe thrusting was suggested by Mastella and Rubinkiewicz (1998) in the Świątkowa tectonic window. The last episode of progressive thrusting (about 10–15 km) of the Magura Nappe towards the north took place during the Late Miocene (Late Badenian /Sarmatian, 9–10 Ma), where the hinge zone of the duplex structure was pushed by the front of the Magura Nappe (see Cieszkowski *et al.*, 1988; Oszczypko, 1998). These movements probably resulted in the development of a sinistral, transpressional strike-slip-fault zone along the front of the Magura Nappe in its NW part (cf. Nemčok *et al.*, 2000).

In the West Carpathians, elevated morphotectonic structures reconstructed owing to analysis of geomorphic indices, like: abnormally high river bed gradients or valley floor width-valley height ratios, appear to correlate with the zone of tectonic windows, *i.e*. elevated structures at the base of the Magura thrust. This is also true for an area situated east of the Dunajec River, particularly in a region placed east of Gorlice (Figs 2, 7), although to a minor extent.

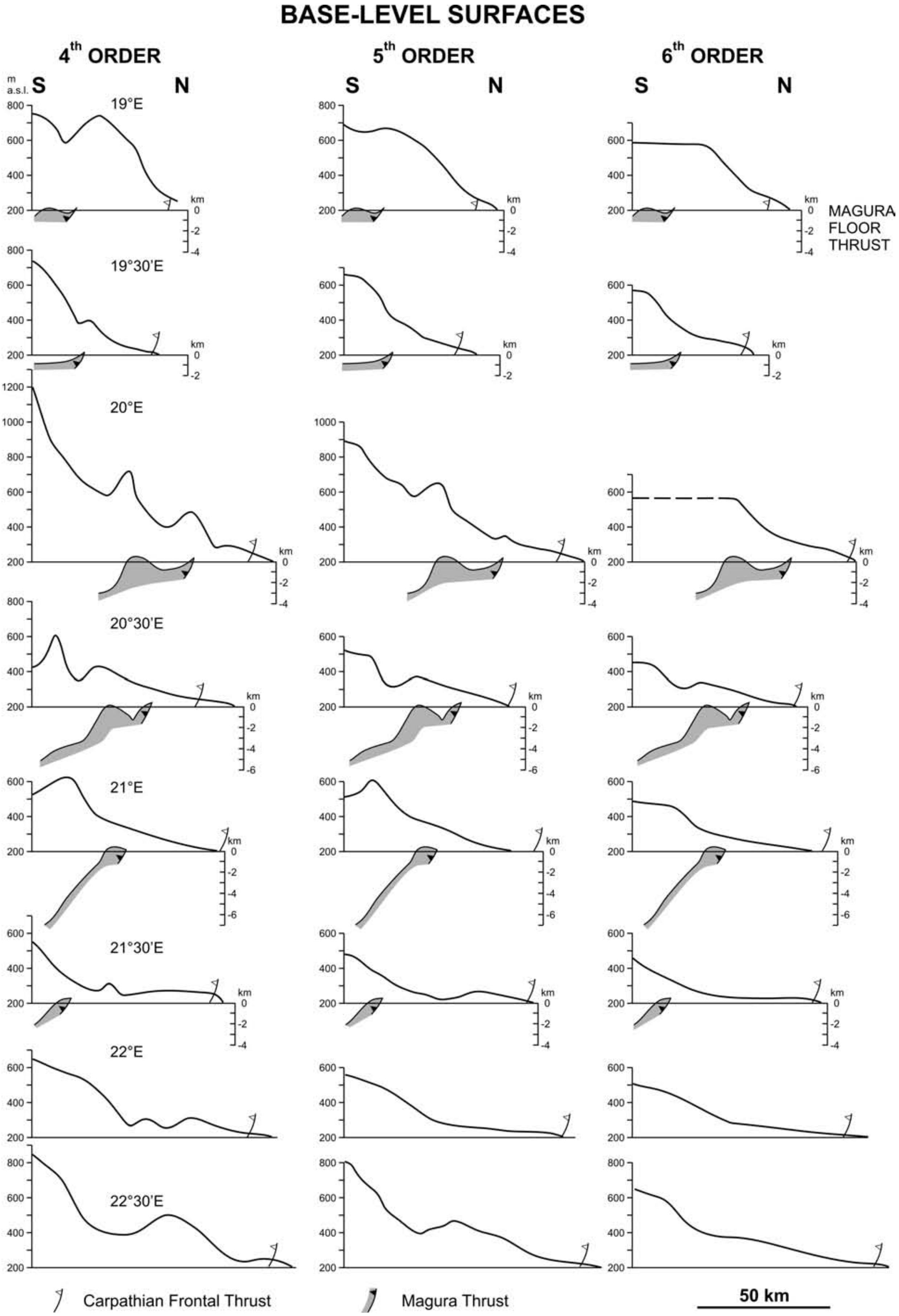

Fig. 11. Cross-sections through base-level (subenvelope) surfaces of different orders versus topography of the Magura floor thrust

On the other hand, a comparison between the pattern of elevated and subsided structures of the Magura floor thrust and subenvelope sufaces of different orders shows that in the western part of the Polish Outer Carpathians (Fig. 11) the highest-elevated neotectonic structures (in the southern portion of that area) coincide with depressions of the Magura thrust, whereas farther north a reverse pattern becomes dominant: neotectonic elevations coincide either with the Magura frontal thrust or with elevations of its surface. This is particularly true for an area comprised between 20° and 20°30’E meridians. Moreover, the strongly uplifted region in this part of the Outer Carpathians, *i.e*. the Gorce Mts., is situated shortly south of the main elevation of the Magura floor thrust, represented by the Mszana Dolna tectonic window. Farther to the east, no clear relationship between the discussed surfaces can be seen, except for that the highest orogen-parallel neotectonic structures appear to coincide with the greatest thicknesses of the Magura Nappe (Figs 6, 7, 11).

CONCLUSIONS

The origin of above-discussed relationships is difficult to explain. We infer that one of possible factors could be Pliocene–Quaternary reactivation of faults cutting the Magura floor thrust, as well as the basal thrust of the Outer Carpathians, and particularly that which appears to separate the western-medial segment of the Outer Carpathians from the more eastern portion. This zone, probably marking the boundary between the Upper Silesian and Ma³opolska blocks in the Carpathian basement and roughly coincident with the Dunajec fault (cf. Birkenmajer, 1979; Jurewicz *et al.*, 2007), strikes NW–SE between Limanowa and the Poprad River valley, dividing regions showing contrasting pattern of both subenvelope surfaces and the Magura floor thrust. A similar conclusion has been proposed by Zuchiewicz *et al.* (2002) when analysing morphometric parameters of uplifted neotectonic structures in the western and eastern portions of the Outer West Carpathians, whose en echelon arrangement is different on either side of a reactivated, probably dextral deep fault zone located beneath the overthrust nappes. The zone in question is called sometimes the Kraków–Lubliniec fault zone (¯aba, 1999), being responsible for entirely different structural style of the Upper Silesian and Ma³opolska blocks underlying the overthrust Carpathians, and which has been reactivated in late Cainozoic times, up to the Holocene (cf. Jurewicz *et al.*, 2007).

Acknowledgements

We would like to express our gratitude to Profs. Marek Cieszkowski and Jan Golonka for their critical comments, which improved this paper. The paper was financed from statutory funds (project 11.11.140.560) of the Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology (to WZ), and by the Polish Ministry of Science and High Education (Grant 1997/PO1/2006) to (NO).

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