Acta Geodyn. Geomater., Vol. 6, No. 3 (155), 291-308, 2009

NEOTECTONICS OF THE POLISH CARPATHIANS IN THE LIGHT OF GEOMORPHIC STUDIES: A STATE OF THE ART

Witold ZUCHIEWICZ

Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology, A. Mickiewicza 30, 30-059 Kraków, Poland
**Corresponding author's e-mail:* witoldzuchiewicz@geol.agh.edu.pl

(*Received* January 2009, *accepted* March 2009)

ABSTRACT
Neotectonics of the Carpathians used to be studied extensively, particular attention being paid to the effects of large-scale domal uplifts and open folding above marginal zones of thrusts and imbricated map-scale folds, and rarely to the characteristics of young faulting. Neotectonic faults tend to be associated with the margins of the Orava-Nowy Targ Basin, superposed on the boundary between the Inner and Outer Western Carpathians, as well as with some regions within the Outer Carpathians. The size of Quaternary tilting of the Tatra Mts. on the sub-Tatric fault were estimated at 100 to 300 m, and recent vertical crustal movements of this area detected by repeated precise levelling are in the range of 0.4-1.0 mm/yr in rate. Minor vertical block movements of oscillatory character (0.5-1 mm/yr) were detected along faults cutting the Pieniny Klippen Belt owing to repeated geodetic measurements performed on the Pieniny geodynamic test area. In the western part of the Western Outer Carpathians, middle and late Pleistocene reactivation of early Neogene thrust surfaces was suggested. Differentiated mobility of reactivated as normal Miocene faults (oriented (N-S to NNW-SSE and NNE-SSW) in the medial portion of the Dunajec River drainage basin appears to be indicated by the results of long-profile analyses of deformed straths, usually of early and middle Pleistocene age. Quaternary uplift of the marginal part of the Beskid Niski (Lower Beskidy) Mts. (W-E to WNW-ESE), in the mid-eastern part of the Outer Western Carpathians of Poland, was estimated at 100-150 m, including no more than 40 m of uplift after the Elsterian stage. The state of research into young faulting of the Outer Carpathians of Poland is still far from sufficient.

KEYWORDS: neotectonics, morphotectonics, recent stress field, Quaternary, Carpathians, Poland

INTRODUCTION

Neotectonics of the Outer Western Carpathians (OWC) used to be studied extensively, with particular attention focused on the effects of large-scale domal uplifts and open folding above marginal zones of thrusts and imbricated map-scale folds, and rarely to the characteristics of young faulting. Classic geomorphic studies aiming at the reconstruction of long-term landform development in the Polish Carpathians have been a favourite topic of numerous geomorphologists and some geologists for nearly a century. Gross features of the topography, including ridge and valley patterns, the number, origin and age of erosion surfaces, history of fluvial changes, aided by more and more detailed palaeogeographic reconstructions performed with the help of different techniques, should be listed as the most frequently discussed subjects.

The aim of this paper is to review several pieces of evidence pointing to the Pliocene and Quaternary tectonic mobility of this area.

GEOLOGICAL SETTING

The Outer Carpathians are a thrust-and-fold-belt, north-verging in the Polish segment (Figs. 1, 2). The belt, composed largely of Lower Cretaceous to Lower Miocene flysch strata, comprises several nappes. The innermost and largest of the nappes is the Magura Nappe. This nappe is subdivided by north-verging reverse faults into four slices which are termed (from south to north) Krynica, Bystrica, Rača and Siary slices. To the north, the Outer Carpathian nappe pile is thrust over the Carpathian Foredeep, whereas to the south the Magura Nappe contacts along steep faults with the Pieniny Klippen Belt, a narrow shear zone separating the Inner and Outer Carpathians and affected by Late Cretaceous and Neogene tectonic deformation. South of the belt, the Central Carpathian Palaeogene Basin occurs, which belongs to the Inner Carpathians, a continuation of the Northern Calcareous Alps. The intramontane Orava-Nowy Targ Basin, filled with Late Cenozoic fresh-water molasses, is superimposed upon all these units.

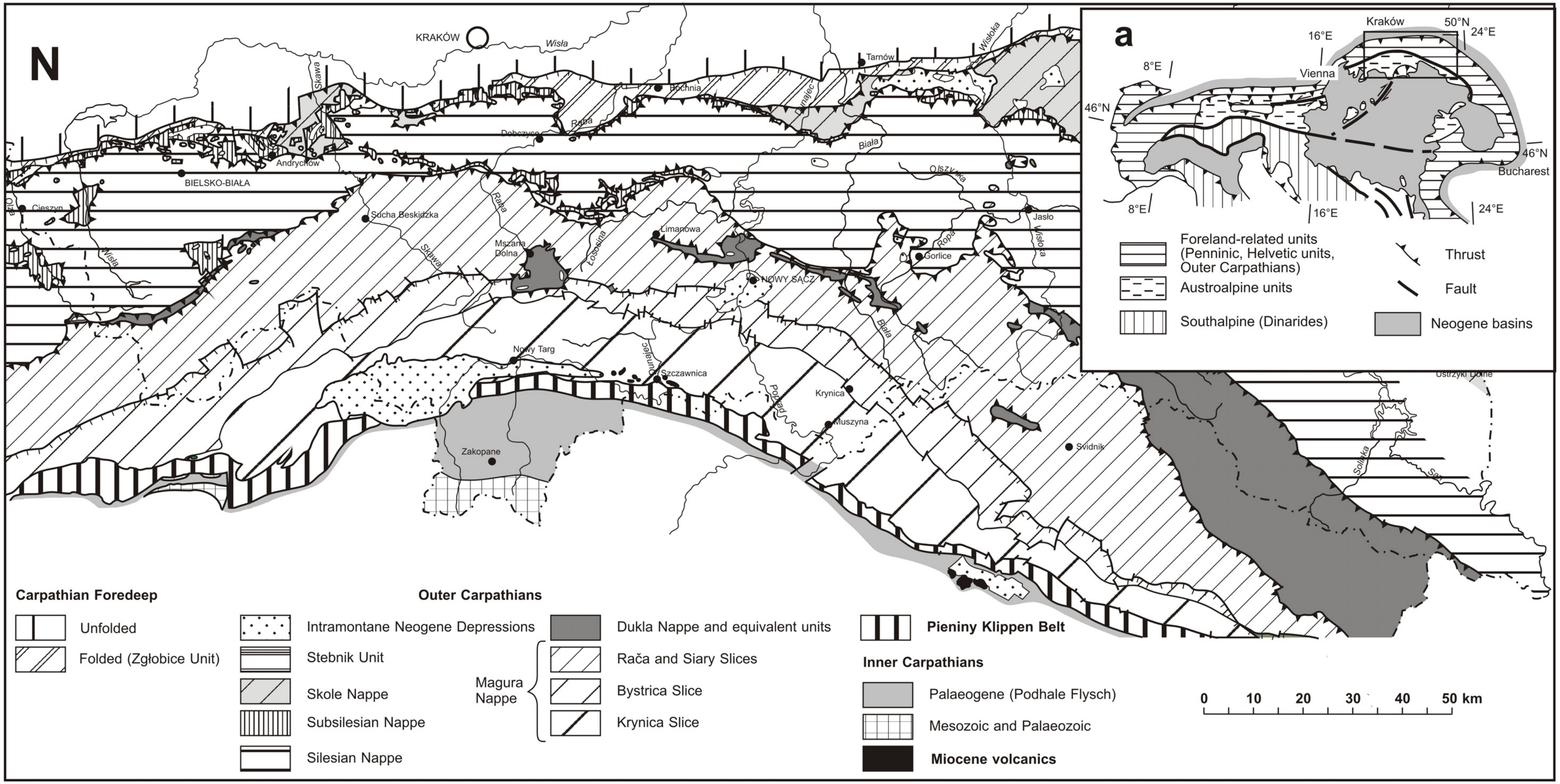


Fig. 1 Geological sketch-map of the Polish segment of the Outer Western Carpathians (based on Żytko et al., 1989; modified), (a) Inset map showing structural sketch of the Carpatho-Pannonian region (based on Neubauer et al., 1997; modified).

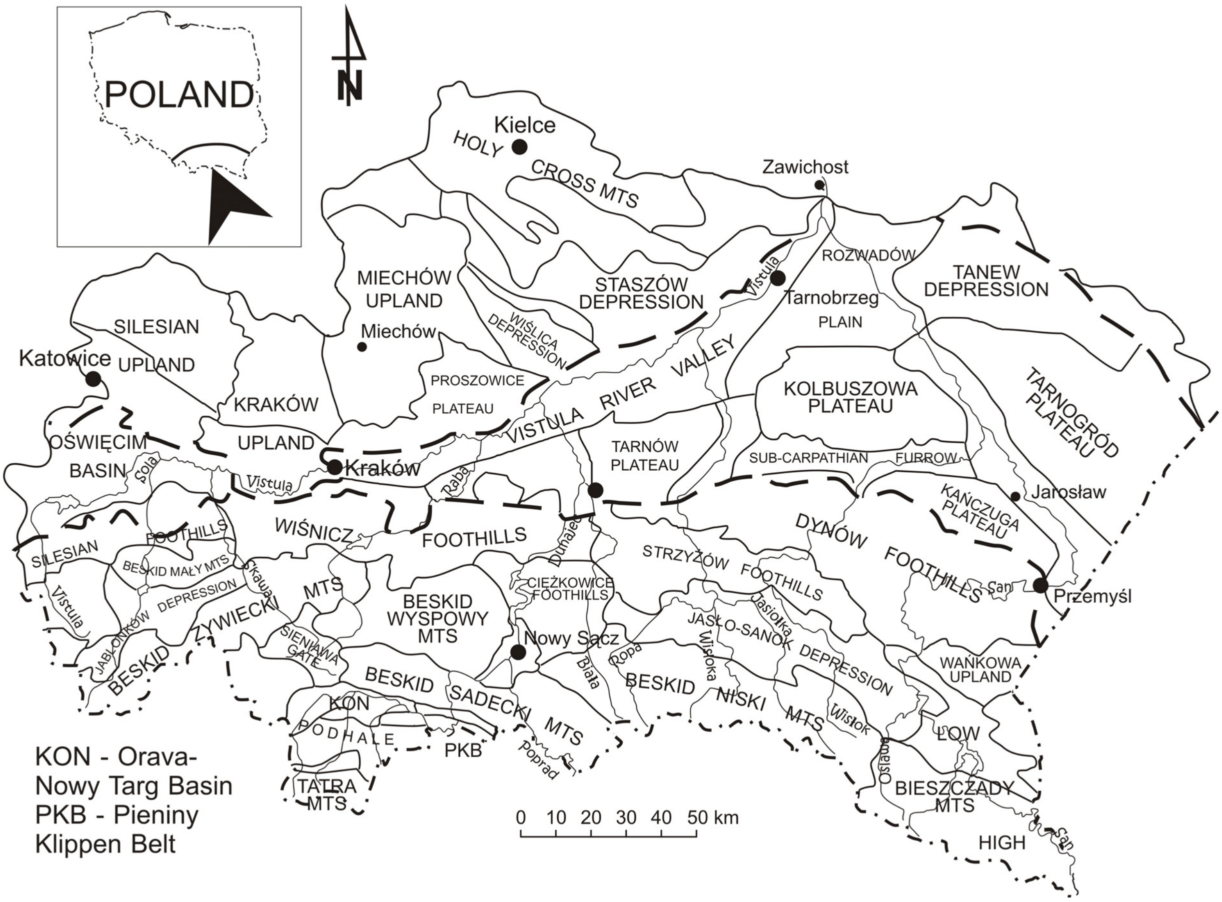


Fig. 2 Geomorphic units of the Polish Carpathians and their foreland (based on Starkel, 1991; modified).

Principal structural elements of the Outer Carpathians fold-and-thrust belt were shaped in the Palaeogene and Neogene, when the study area represented an accretionary prism associated with the south-directed subduction of the European Platform under the ALCAPA block (Tomek and Hall, 1993; Oszczypko, 1998, 2001; Fodor et al., 1999). Synsedimentary shortening of the Carpathian basins started in the Eocene in the inner part of the Magura Nappe, and continued until the Badenian-Sarmatian in the outermost part of the belt (Oszczypko, 1998, 2004; Świerczewska and Tokarski, 1998; Zoetemeijer et al., 1999). The last episode of thrusting of the Carpathian margin probably occurred after the Pannonian (Wójcik et al., 1999). Following subduction and collision, structural development of the Polish Outer Carpathians proceeded mainly in an extensional regime. Within intramontane basins, this extension survived until the Late Quaternary (see discussion in Zuchiewicz et al., 2002).

NEOTECTONIC SETTING

From different definitions of the neotectonic period (see discussion in Zuchiewicz, 1995a), I am inclined to adopt that suggested by Şengör et al. (1985), where "neotectonics" is described as ..."*the time that elapsed since the last major whole-scale tectonic reorganization*".

Analysis of deformed longitudinal profiles of terraces of the main Carpathian rivers points to the presence of several elevated and subsided zones, the strike of which is nearly parallel to that of principal thrusts. The maximum of Quaternary uplift (150 m) was found to characterize the southern part of the Polish segment of the OWC (Starkel, 1972; Zuchiewicz, 1984b,c, 1998); an area showing a relatively high amount of erosional dissection. Episodes of intense erosional dissection of straths, largely induced by surface uplift, occurred in the following intervals: 800-470 ka (0.15-0.21 mm/yr), 130-90 ka (0.18-0.40 mm/yr), and 15-0 ka (0.2-2.0 mm/yr; cf. Zuchiewicz, 1991). The only dated example of Holocene dextral reactivation concerns the Dunajec Fault, crossing both the Magura Nappe and Pieniny Klippen Belt. The last episode of fault activity occurred 6.5-2.5 ka (Jurewicz et al., 2007).

The rates of recent vertical crustal motions in the Polish Outer Carpathians range between 0 mm/yr in the western and medial segment to ca. +1 mm/yr in the east (Wyrzykowski, 1985), whereas those in the Pieniny Klippen Belt do not exceed 0.5 mm/yr (Ząbek et al., 1993; Czarnecki et al., 2005). Repeated precise levelling surveys in the area (Makowska and Jaroszewski, 1987; Makowska, 2003) point to diversified uplift of the Tatra Mts., Pieniny Klippen Belt and the southern portion of Magura Nappe, and variable subsidence of the Orava-Nowy Targ Basin. Recently obtained results of PSInSAR (*Persistent Scatterers SAR interferometry*) processing of 51 ERS-1/2 SAR scenes, covering a period of 1992-2000 years, showed relative 1 mm/year uplift of the Zakopane area in respect to Nowy Targ, and suggested recent activity of some faults (cf. Perski, 2008). The results of recent GPS campaigns (Hefty, 2007) and borehole breakout analyses (Jarosiński, 1998, 2006) point, in turn, to NNE-directed horizontal motions throughout the area.

Recent seismicity concentrates along the southern marginal fault of the Pieniny Klippen Belt and along some normal and strike-slip faults, transverse to the former (Prochazková et al., 1978; Guterch et al., 2005; Guterch, 2006). Local magnitudes do not exceed 4.5 on the Richter scale, averaging between 2.5 and 3.4 (Pagaczewski, 1972; Prochazková et al., 1978; Guterch et al., 2005).

PLIOCENE TECTONICS IN THE LIGHT OF GEOMORPHIC STUDIES

The last decade witnessed a profound change in interest of structural geomorphologists. The studies of planation surfaces and types of relief, so popular in the 1960s and the 1970s (*cf.* Starkel, 1972, 1980; Henkiel, 1977; Jahn, 1992), gave way to detailed reconstructions of fluvial processes controlled by both climatic and tectonics factors, more or less sophisticated morphometric and statistical analyses of various topographic indices, including mutual relationships between bedrock resistance and various aspects of the topography, factors controlling types, distribution and frequency of occurrence of structural landslides, as well as to studies of long- and short-term evolution of landforms in different young-tectonic settings.

A concept of several planation surfaces, preserved upon bedrock of variable resistance and deformed during a few "orogenic phases", has been dealt with by numerous authors until the late 1980s (Figs. 3, 4). Four surfaces in the OWC and 4 to 6 in the Inner Western Carpathians (IWC) have been distinguished (*cf.* Starkel, 1972; Baumgart-Kotarba, 1983; Zuchiewicz, 1984a; Gilewska, 1987; Klimaszewski, 1988, and discussion therein), although the lack of correlative deposits makes the precise dating of planation episodes impossible. That was the reason why the subject has largely been abandoned, following the last published discussion between adherents of the two opposite views on the age of planation (Klimaszewski, 1987; Starkel, 1988). Few conjectural papers from the IWC area are the only exception (*i.a.* Kukulak, 1991, 1993; Bac-Moszaszwili, 1993, 1995).

Numerous pieces of evidence pointing to nearly permanent Neogene mobility of the OWC thrust sheets (*cf.* Oszczypko and Ślączka, 1985; Oszczypko, 1998, 2004) cast serious doubt on the possibility of uninterrupted development of planation surfaces during prolonged periods of tectonic "quiescence". The thrusting proceeded continuously, although with variable intensity, between Middle Burdigalian and Serravallian times, at rates ranging from 7.7 to 12.3, and even 20 mm/a (Oszczypko, 1998). The minimum size of post-tectonic, isostatic uplift during the past 10 to 11 million years has been calculated for *ca*. 1 km in the West Beskidy Mts. to some 260-360 m in the Carpathian Foothills, the maximum rate of uplift being 0.1 mm/yr (Oszczypko, 1996). The estimates of the size of uplift of the Tatra Mts. crystalline core, inferred for the last 15 Ma from fission-track studies, range from 4 to 6 km (Burchart, 1972). According to recent speleothem datings, the oldest denudation surfaces in the Tatras cannot predate the latest Miocene (Głazek, 1996). Reconstructions of the hypothetical position of palaeo-summit surface in the Eastern Outer Carpathians lead to high, although variable estimates of the size of denudation during the post-tectonic inversion (Kuśmierek, 1990). The role of compaction of Miocene molasses underlying the overthrust flysch nappes should also be taken into account, since these figures range from 200-300 m to 500 m, respectively, from the early Pliocene and the early Sarmatian onwards (Oszczypko et al., 1993). Nevertheless, the rates of uplift, approximated by those of downcutting of planation surfaces or inferred from different estimates of Neogene denudation, appear to be poorly constrained (Malarz, 1992; Zuchiewicz, 1995b).

INDICATORS OF QUATERNARY TECTONICS

Morphological manifestations of Quaternary tectonic activity include, *i. a.*, disturbed longitudinal profiles of strath terraces (Starkel, 1972; Zuchiewicz, 1991, 1995b), incomplete sequences of alluvia (Starkel, 1985), convex-upward slope profiles in some regions (Starkel, 1972), young changes in the drainage pattern (Gerlach et al., 1985; Zuchiewicz, 1987; Laskowska-Wysoczańska, 1995), tilting of Upper Pleistocene lacustrine sediments (Koszarski and Koszarski, 1985), and some examples of young subsidence in intramontane (Baumgart-Kotarba, 1991-92, 1996, 1997) and Carpathian Foredeep basins (Starkel, 1972; Laskowska-Wysoczańska, 1995).

Numerous studies of structural landslides document the importance of lithological contrasts, attitude of beds, as well as of the presence of transversal fault zones and joints, apart from suitable climatic, morphological and hydrogeological factors (Bober, 1984; Kotarba, 1986; Bajgier, 1989, 1993; Ziętara, 1991; Poprawa and Rączkowski, 1996; Wójcik and Zimnal, 1996; Margielewski, 2002, 2006). The largest landslides are usually confined either to fault zones or frontal thrusts of nappes and slices

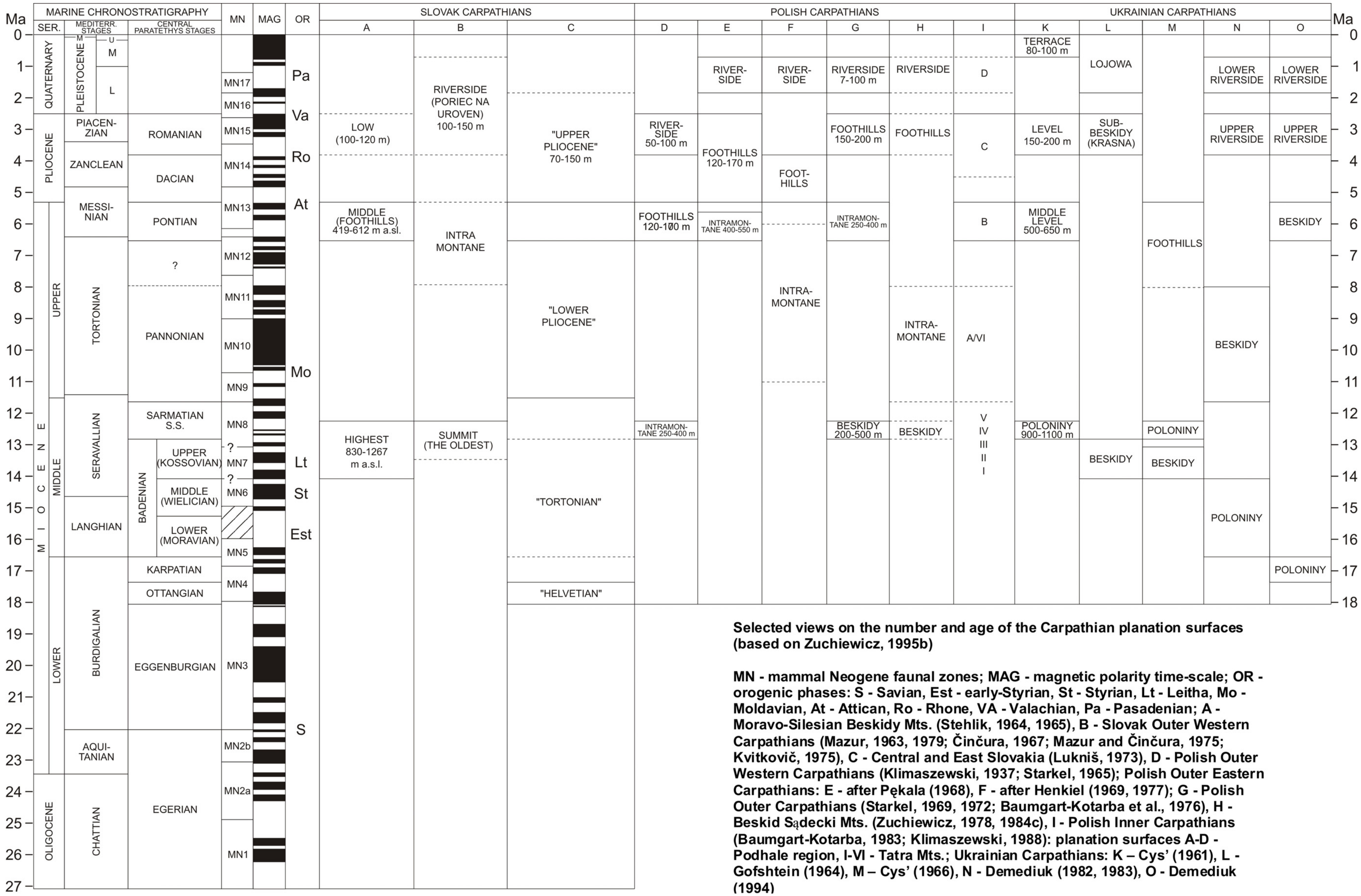


Fig. 3 Views on the number and age of planation surfaces in the Outer Carpathians (modified from Zuchiewicz, 1995b; supplemented).

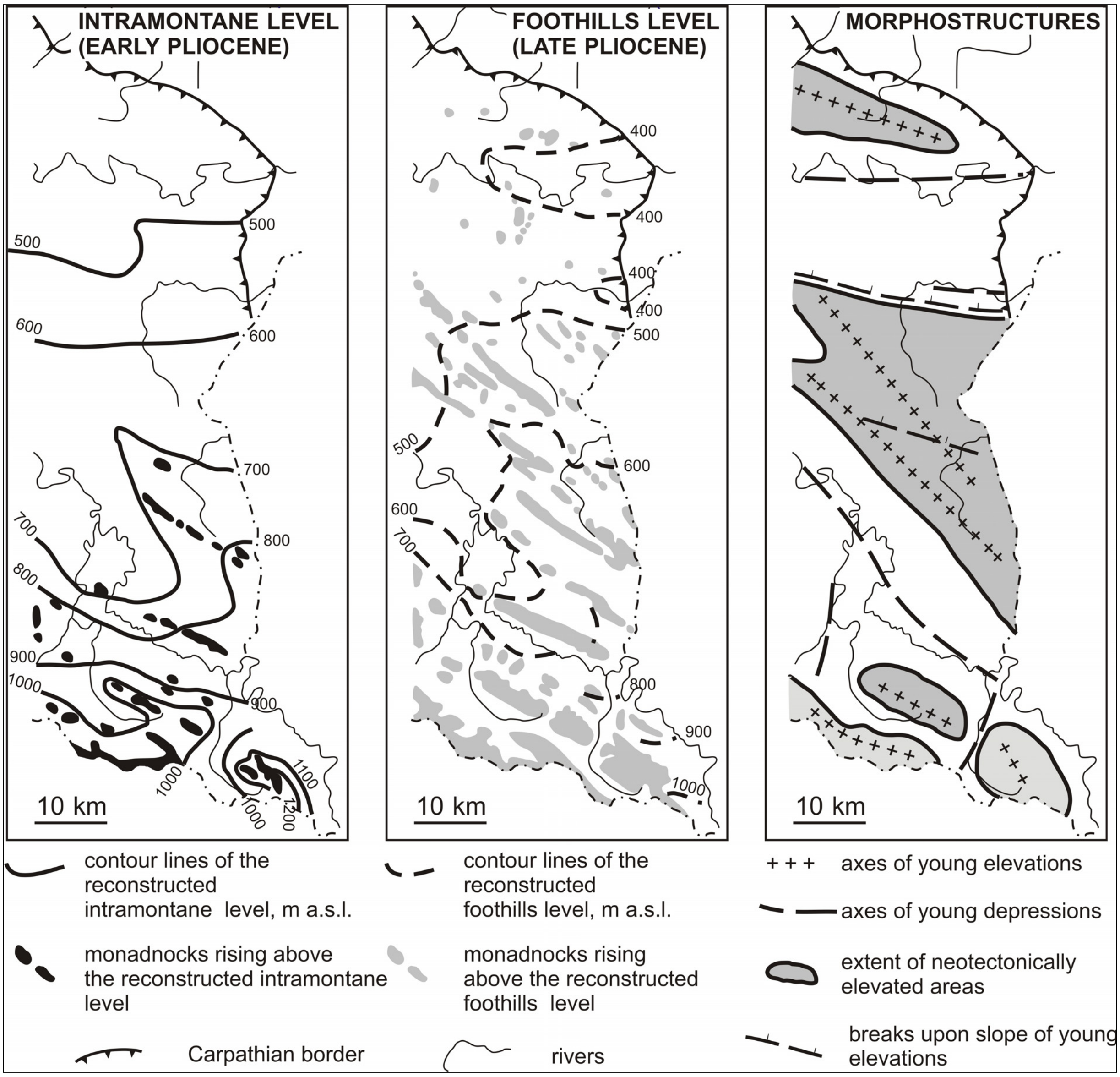


Fig. 4 Reconstructed topography of the Pliocene planation surfaces in the eastern segment of the Polish Carpathians (modified after Henkiel, 1977).

(Ziętara, 1991; Bajgier, 1993; Wójcik, 1997) throughout the OWC. In the western part, the most landslide-prone slopes are those developed upon thick-bedded sandstones (Wójcik, 1997). Recent reactivation of fault zones (Kukulak, 1988; Bajgier, 1989, 1993) and/or seismic control have frequently been suggested (Bober, 1984; Michalik, 1989; Bajgier, 1993; Wójcik, 1997; Poprawa and Rączkowski, 2003), without giving convincing evidence.

Rates of river incision are one of necessary tools for understanding rates of erosion, landform evolution, and tectonic uplift (Young and McDougall, 1993). Variations in downcutting rates along the valley's profile help to reconstruct the spatial pattern of uplift (Burbank et al., 1996; Granger et al., 1997; Wobus et al., 2006).

Valleys of the Outer Carpathians bear 8 to 9 terrace steps of Quaternary age. Most of Pleistocene terraces are strath or complex-response terraces (*cf.* Bull, 1990); the Weichselian and Holocene steps are usually cut-and-fill terraces, except those located in the neotectonically elevated structures, characterized by the presence of young straths.

Longitudinal profiles of individual strath terraces frequently show divergence, convergence or tilting that can be indicative of young tectonic control (Zuchiewicz, 1987, 1991, 1995b; Henkiel et al., 1988; Wójcik, 1989; Kukulak, 1993). Moreover, the size and rate of dissection of straths of comparable age are different in different morphotectonic units; a feature pointing to variable pattern of Quaternary uplift. Rates of river downcutting result mainly from climatic changes throughout the glacial-interglacial cycles (*cf.* discussion in Starkel, 1985, 1996 and Zuchiewicz, 1995), but their spatial differentiation appears to be influenced by tectonic factors as well. These figures differ from unit to unit.

The increasing need for quantitative analysis of landforms resulted in several purely descriptive papers dealing with both static and dynamic control exerted by the structure upon geomorphic development of different physiographic units.

Simple correlation analysis has been applied to mutual relationships among morphometric parameters, like slope inclination, drainage density, river-bed gradients or relief energy and the bedrock lithology (Malarz, 1983) and attitude of beds (Malarz, 1986). Taxonomic analysis of the links between structure and the character of valleys, ridges and landslide niches completed the picture in the Outer West Carpathians (Jakubska, 1987, 1995), indicating young age of those ridge and valley patterns which are independent of bedrock structures. Detailed maps of relief energy and summit surfaces clearly show zones of increased resistance to erosion, as well as those associated with uplifted morphostructures (Zuchiewicz, 1995b, 1998).

Another approach represent more or less successful attempts at digital processing of some morphometric parameters of small drainage basins (*cf.* Zuchiewicz, 1987, 1991) and time-series analysis of river-bed gradients or the valley floor width/valley height ratios (Zuchiewicz, 1995b). The zones of abnormally high and low values of the first and second parameter, respectively, are aligned subparallel to the structural grain of the OWC, their number increasing from the west to the east. They also coincide, to a large extent, with the axes of neotectonically uplifted structures detected on geomorphic maps. Such an arrangement of these zones, treated as indicative of young uplift tendencies, led Zuchiewicz (1995b) to hypothesize about Plio-Quaternary relaxation of remnant horizontal stresses, built up during the Late Neogene thrusting. Reactivation of frontal thrusts of nappes has already been suggested by Zuchiewicz (1987) and Wójcik (1989). The present-day orientation of maximum horizontal stresses indirectly supports such a view.

QUATERNARY FAULTING

Evidence for Quaternary faulting in the Polish Carpathians is far from sufficient. Few examples have been documented, more or less convincingly, from the Orava-Nowy Targ Basin (*cf.* Baumgart-Kotarba, 1983, 1997; Pomianowski, 1995, 2003), Podhale region (Kukulak, 1985; Szczęsny, 1987), Pieniny Klippen Belt (Czarnecka, 1986), Jeleśnia Basin in the Beskid Żywiecki Mts. (Wójcik, 1989), NW margin of the Nowy Sącz Basin (Tokarski, 1978), Dunajec River Valley in the foothills area, shortly west of Tarnów (Połtowicz, 1974), southern and central parts of the Jasło-Sanok Depression (Zuchiewicz, 1987; Wójcik, 1999, 2003), and the south-western (Niedziałkowska and Szczepanek, 1993-94) and south-eastern segments of the Carpathian Foredeep (Laskowska-Wysoczańska, 1995; see Figure 2 for location).

Quaternary grabens within the Orava-Nowy Targ Basin, oriented E-W, reveal throws of up to 120 m (cf. Baumgart-Kotarba, 2001). Orientation of these grabens points to N-S-oriented extension during the last episode of neotectonic mobility of the area. Reactivation of the northern boundary fault of the Pieniny Klippen Belt was shown to have occurred as late as in the Holsteinian (Birkenmajer, 1976; Birkenmajer et al., 2008). Minor vertical block movements of oscillatory character (0.5-1 mm/yr) were detected along faults cutting the Pieniny Klippen Belt owing to repeated geodetic measurements performed on the Pieniny geodynamic test area (Czarnecki, 2004). The rates of such motions, however, usually fall into error limits.

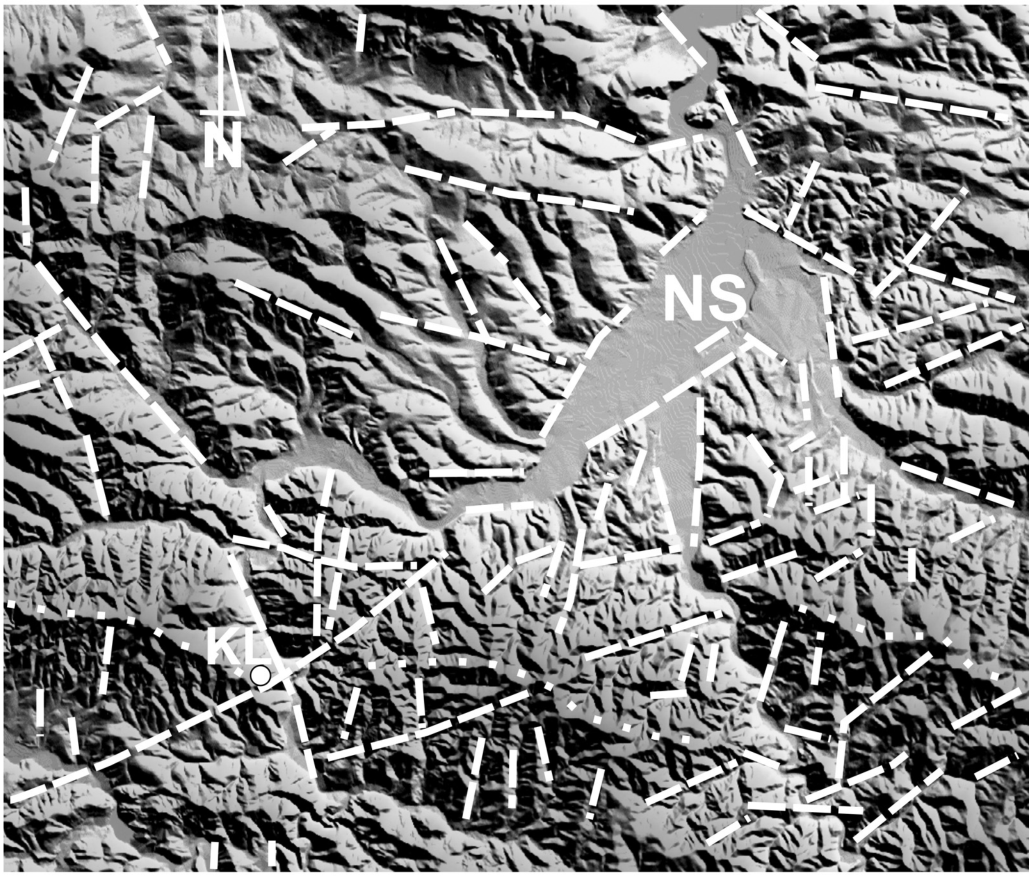
In the western portion of the OWC, middle and late Pleistocene reactivation of early Neogene thrust surfaces was postulated for the Jeleśnia Basin (Wójcik, 1989). Differentiated mobility of reactivated as normal Miocene faults (oriented (N-S to NNW-SSE and NNE-SSW) in the medial portion of the Dunajec River drainage basin appears to be indicated by the results of long-profile analyses of deformed straths, usually of early and middle Pleistocene age (cf. Zuchiewicz, 1984b, 1998). A small normal, seismogenic fault on the NW margin of the Nowy Sącz Basin probably originated in Eemian times (Tokarski, 1978).

CASE STUDIES

MEDIAL PORTION OF THE PIENINY KLIPPEN BELT AND MAGURA NAPPE CUT BY THE DUNAJEC RIVER

The central part of the Dunajec River drainage basin (Fig. 5), medial sector of the Polish Outer Carpathians, comprises several structural-geomorphic units of contrasting neotectonic behaviour (Klimaszewski, 1937; Starkel, 1972; Zuchiewicz, 1978, 1984a,b).

The amount of uplift of this area during the early Tortonian reached 200-350 m, and during the subsequent episodes of tectonic mobility in Messinian and Zanclean time it varied from 75 to 300 m. Younger episodes of tectonic activity resulted in an uplift of 25-120 m (Pliocene/early Pleistocene) and 15-100 m (early Pleistocene; cf. Zuchiewicz, 1995b). The axial part of the Beskid Sądecki Mts. underwent the most intensive uplift (Fig. 6). The Pliocene deposits occurring at the foot of the Lubań Range were redeposited from previously higher situated sites as a result of tectonic movements which subsided the border zone between the Pieniny Klippen Belt and



NS - Nowy Sącz Basin, KL - site Kłodne

Fig. 5 Digital elevation model based on SRTM level 2 data of the medial segment of the Polish Carpathians, dissected by the Dunajec River valley. Dashed lines mark the most prominent topolineaments; dotted line denotes axis of the Beskid Sądecki neotectonic elevation.

the Magura Nappe. The antecedent Dunajec water-gaps (Niedzica, Pieniny, Beskid Sądecki), as well as the captured Poprad valley in the Beskid Sądecki Mts., were formed mainly during the earliest Quaternary. The total amount of Quaternary uplift of the Dunajec drainage basin varies from 100-110 m in the Nowy Sącz Basin and the Spiš Pieniny Mts. to 150-170 m within other regions.

Detailed geomorphic studies of fluvial terraces along the Dunajec River, crossing different morphotectonic units, helped to reconstruct the neotectonic behaviour of the region (Figs. 7, 8). All the morphotectonic units display different patterns of terraces, each of them showing peculiar neotectonic disturbances. The morphostructures include, in a meridional orientation from south to north, a subsiding intramontane depression (Nowy Targ Basin), an uplifted range of low mountains (Pieniny Mts.), an higher uplifted mountain range belonging to one of longitudinal neotectonic elevations (Beskid Sądecki Mts.), and a foothills region showing diversified, young tectonic activity that probably is related to reactivation of the coinciding Miocene fault zones (Łącko-Podegrodzie Foothills). Progressively onward to the north, the following units occur: another intramontane basin of moderate subsidence (Nowy Sącz Basin), a range of mountains of medium elevation showing evidence of uplift (Beskid Wyspowy Mts.), and a region of highly elevated foothills, cut on their northern rim by a recently formed neotectonic escarpment (Rożnów Foothills; Fig. 8).

The rates of Quaternary uplift can be approximated by rates of fluvial incision into Quaternary straths within individual morphostructures of the Dunajec drainage basin. The highest figures are confined to the Beskid Sądecki Mts. and the Łącko-Podegrodzie Foothills, whereas the youngest episode of uplift (10-0 ka) is recorded on the northern margin of the Nowy Targ Basin, in the Pieniny Mts. and, less clearly, in the Beskid Sądecki Mts. The highest differentiation in uplift trends and scale can be observed throughout the periods of 440-195 ka and 130-90 ka, during which reactivation of older

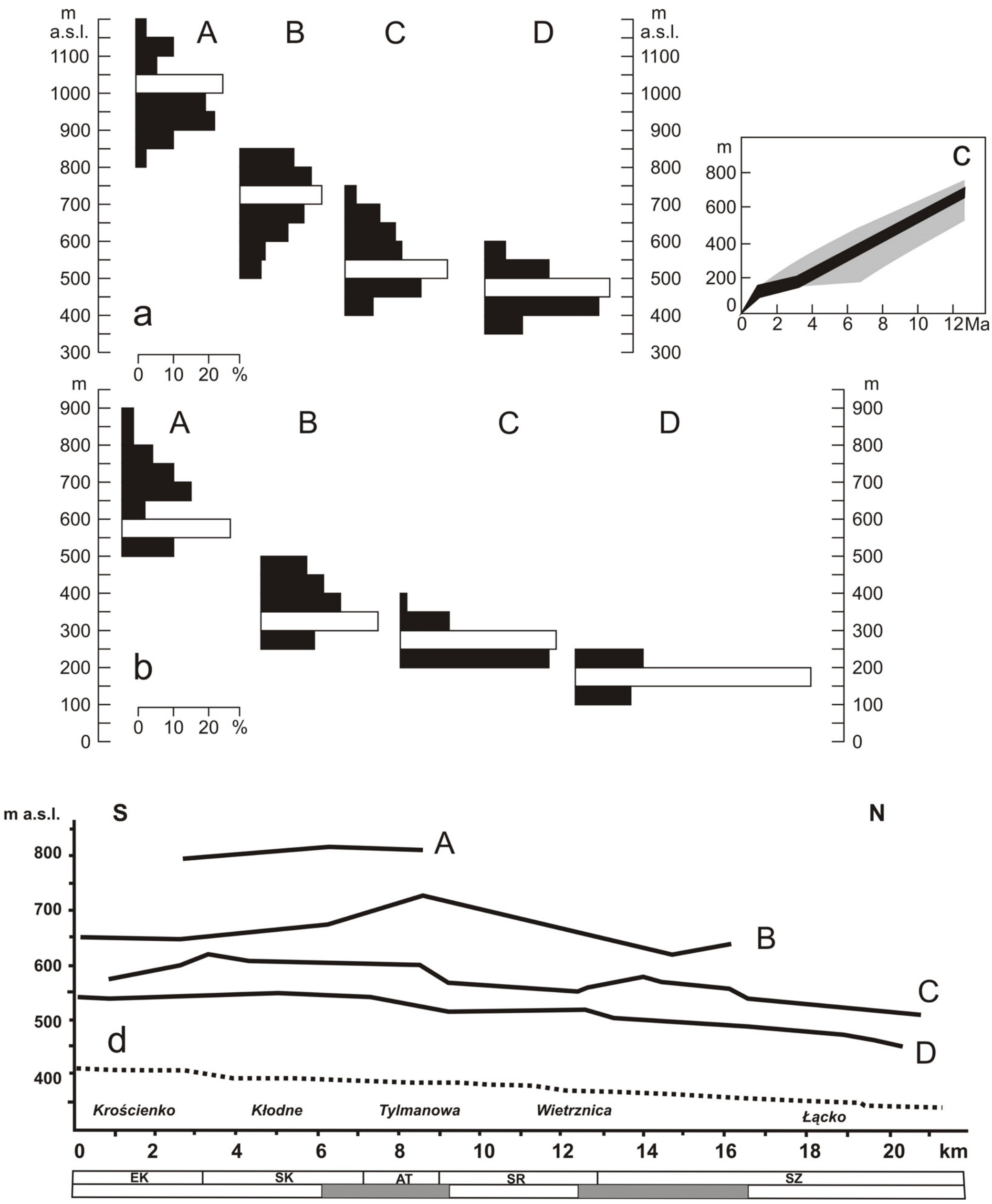


Fig. 6 Diagrams showing elevation of preserved fragments of planation surfaces in the central part of the Dunajec River drainage basin (based on Zuchiewicz, 1995b; modified and supplemented). Planation surfaces: A – "Beskidy" level (middle – late Serravallian), B – "intramontane" level (early – middle Tortonian), C – "foothills" level (Piacenzian), D – "riverside" level (Early Pleistocene). (a) Elevation above sea level; (b) elevation above present-day river bed; (c) rates of erosional dissection with confidence intervals shown in grey; (d) long profiles in the Dunajec River gorge segment in the Beskid Sądecki Mts. Tectonic units (based on Tokarski, 1975): EK – Krościenko Elevation, SK – Kłodne syncline, AT – Tylmanowa anticline, SR – Rzeka syncline, SZ – Sobel-Zabrzeż anticline. Shaded bars mark zones of disturbance within long profiles of planation surfaces.

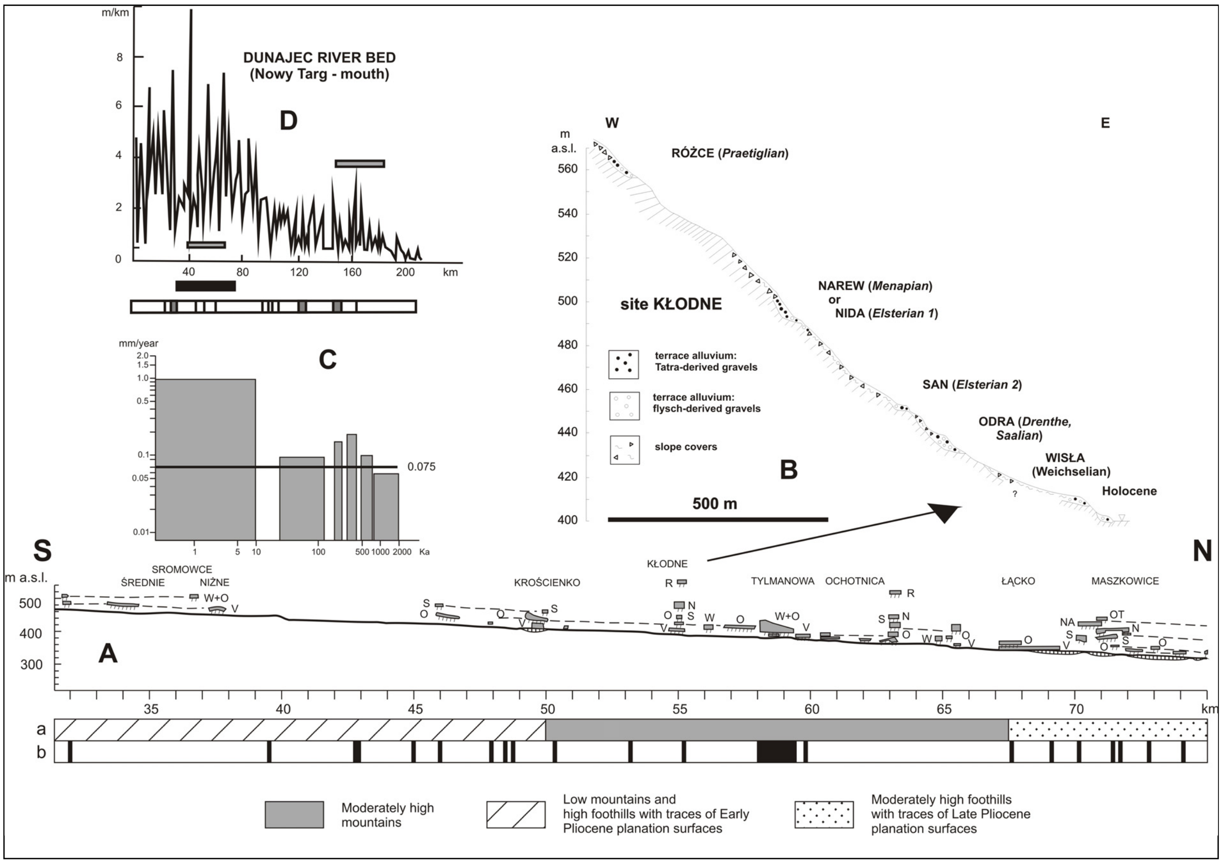


Fig. 7 Fluvial terraces in the Dunajec River valley: (A) Long profile of terraces between Pieniny Mts. and Beskid Wyspowy Mts. Shaded areas denote alluvium, barbed lines – position of straths. Age of terraces (Polish climatostratigraphic stages and their West European equivalents): R – Różce (Praetiglian), OT – Otwock (Eburonian), NA – Narew (Menapian), N – Nida (Elsterian-1), S – San (Elsterian-2), O – Odra (Saalian/Drenthe), W – Warta (Saalian/Warthe), V – Wisła (Weichselian). Thick black bar marks the extent of gorge segment in the Beskid Sądecki Mts.; a – types of landscape, b – location of bedrock fault zones cut by the river; (B) cross-section through the Dunajec River straths at site Kłodne, within a meander loop dissecting the highest elevated zone in the Polish Outer Carpathians; (C) rates of dissection of straths portrayed in (B); (D) slope of the Dunajec River bed between Nowy Targ and mouth. Shaded bars mark segments of abnormally high gradients with respect to the surrounding reaches; black bar indicates river bed segment shown in (A). The lower bar shows location of principal fault zones in the bedrock.

fault zones is likely to have occurred, especially in the Łącko-Podegrodzie Foothills and the Beskid Wyspowy Mts. This type of alternation of morphostructures, which shows varying rates of neotectonic movements, may reflect either concurrent isostatic adjustment or Quaternary remnant folding (Zuchiewicz, 1991).

In the most strongly uplifted part of the area, the Dunajec River valley forms two antecedent water-gaps, dissecting the Pieniny Klippen Belt in the south and the Krynica and southern part of Bystrica slices of the Magura Nappe in the north. The latter water-gap is cut into the Beskid Sądecki Mts. range, rising above 1,200 m a.s.l. The "Beskid Sądecki" water-gap includes two deeply cut meanders which are separated by a rectilinear valley, parallel to a fault line. This area is situated at a place of intersection of NNW, NE, and N-S striking topolineaments. The gorge is 15 km long and up to 700 m deep, its width changing from 75-100 m within the meanders to 450-500 m in other segments. The river-bed is cut into solid bedrock and its long profile is ungraded and of exceptionally high gradient, compared to the upstream and downstream valley reaches. The eastern valley sides are steep and dissected by a network of short and high-gradient minor tributary valleys and ravines. Outlets of tributary valleys are usually hanging above the present-day river bed, up to 10-15 m. Headwater parts of some of these tributaries represent hour-glass valleys. The surrounding ridges bear traces of four pre-Quaternary planated surfaces that rise 900 m, 770-830 m, 500-590 m, and 450-500 m a.s.l. The eastern valley sides are mantled by weathering debris and loams, while the western ones are dominated by a flight of straths and complex-response terraces, the alluvial covers of which were deposited during

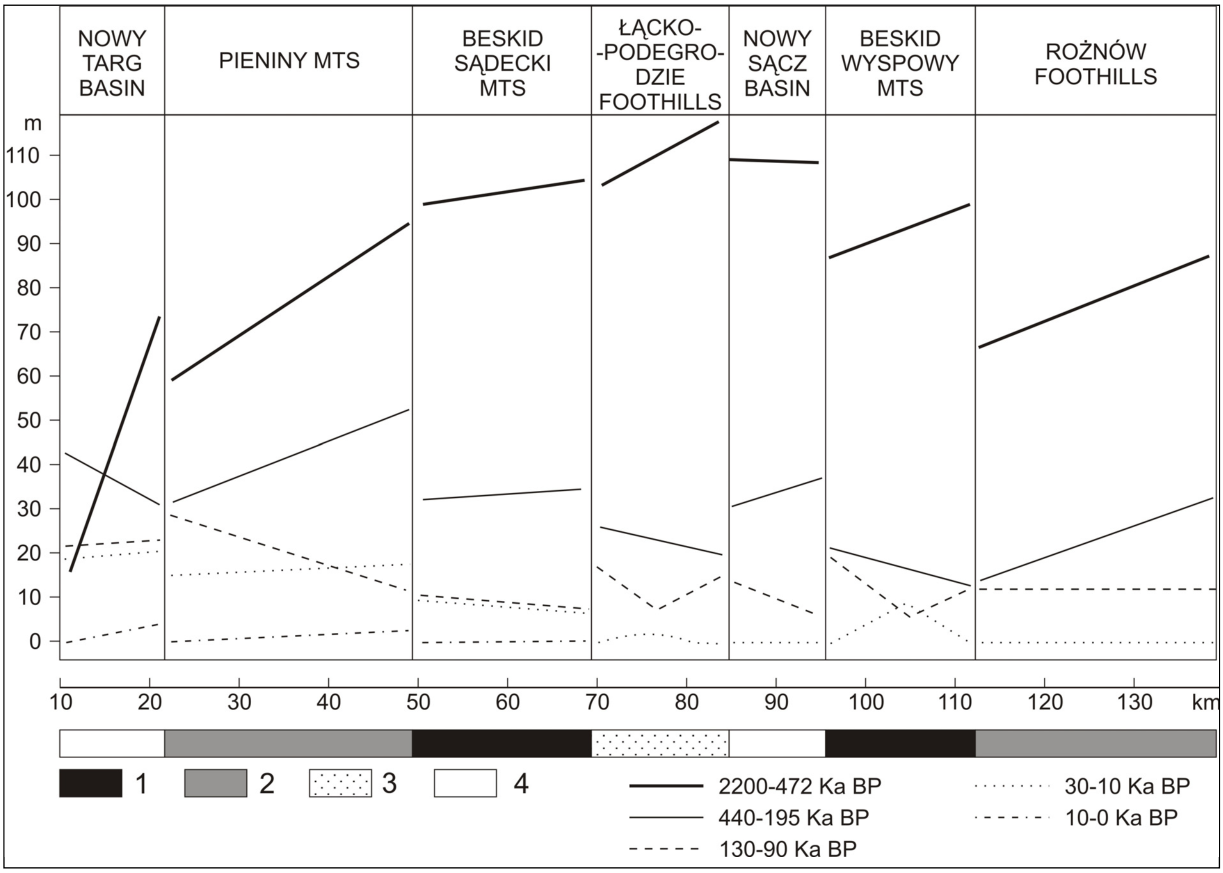


Fig. 8 Amounts of Quaternary erosion for different time intervals within morphostructures dissected by the Dunajec River valley (modified after Zuchiewicz, 1995b). Relief types: 1 – moderately high mountains, 2 – low mountains and high foothills with traces of early Pliocene planation surfaces, 3 – moderately high foothills with traces of late Pliocene planation surfaces, 4 – low foothills and intramontane basins with traces of early Pleistocene planation surfaces.

the Pleistocene glacial stages: Praetiglian (150-155 m to 154-161 m), Menapian or Elsterian-1 (75-84 m to 78-96 m), Elsterian-2 (51-55 m to 52-65 m), Saalian (26-41 m to 29-41 m), Wartanian (17-24 m to 20-31 m), and Weichselian (10-11 m to 16-18 m), as well as in the Holocene (6-10 m, 4-5 m, 2-3 m). The thickness of terrace alluvium is between 3-4 m and 10-14 m (cf. Zuchiewicz, 1984c, 1995b, and references therein). These covers are composed of poorly rounded and poorly sorted, both OWC flysch (sandstones, siltstones, rare conglomerates) and Tatra-derived (granites, quartzites) gravels and cobbles. Limestones shed from the Pieniny Klippen Belt can only be found within the youngest, i.e. Weichselian and Holocene alluvium; limestone clasts of older fluvial series became completely dissolved. The Early and Middle Pleistocene covers include a large proportion of angular clasts, pointing to the role of intensive solifluction within glacial stages. All Pleistocene fluvial covers interfinger with solifluction tongues, those dated to the last and penultimate glacial stages being also overlain by slopewash and/or solifluction-slopewash sediments, which are 3-8 m thick. Such interfingering enables for relative dating of the preserved terrace covers, i.e. their assignment to individual glacial stages.

Long-profiles of Pleistocene straths (Fig. 7) clearly show increased relative heights of the latter within meander loops. These heights are greatest within the entire Polish segment of the Outer Carpathians; straths of equivalent age within the remaining Dunajec River valley reaches, and those of other Carpathian river valleys are lower even by 30 m in case of the oldest Pleistocene straths (cf. Zuchiewicz, 1998 and references therein). Deformations of Pleistocene straths combined with intense erosional downcutting appear to indicate Pleistocene surface uplift of the axial part of the Beskid Sądecki Mts., part of the most strongly elevated neotectonic structure in the Polish OWC (cf. Starkel, 1972; Zuchiewicz, 1995b). The lack of fluvial covers from the Eburonian and – possibly – also Menapian stages points to intense, tectonically-controlled, erosion before the Elsterian; the equivalent-age terrace covers are to be found immediately north of the gorge.

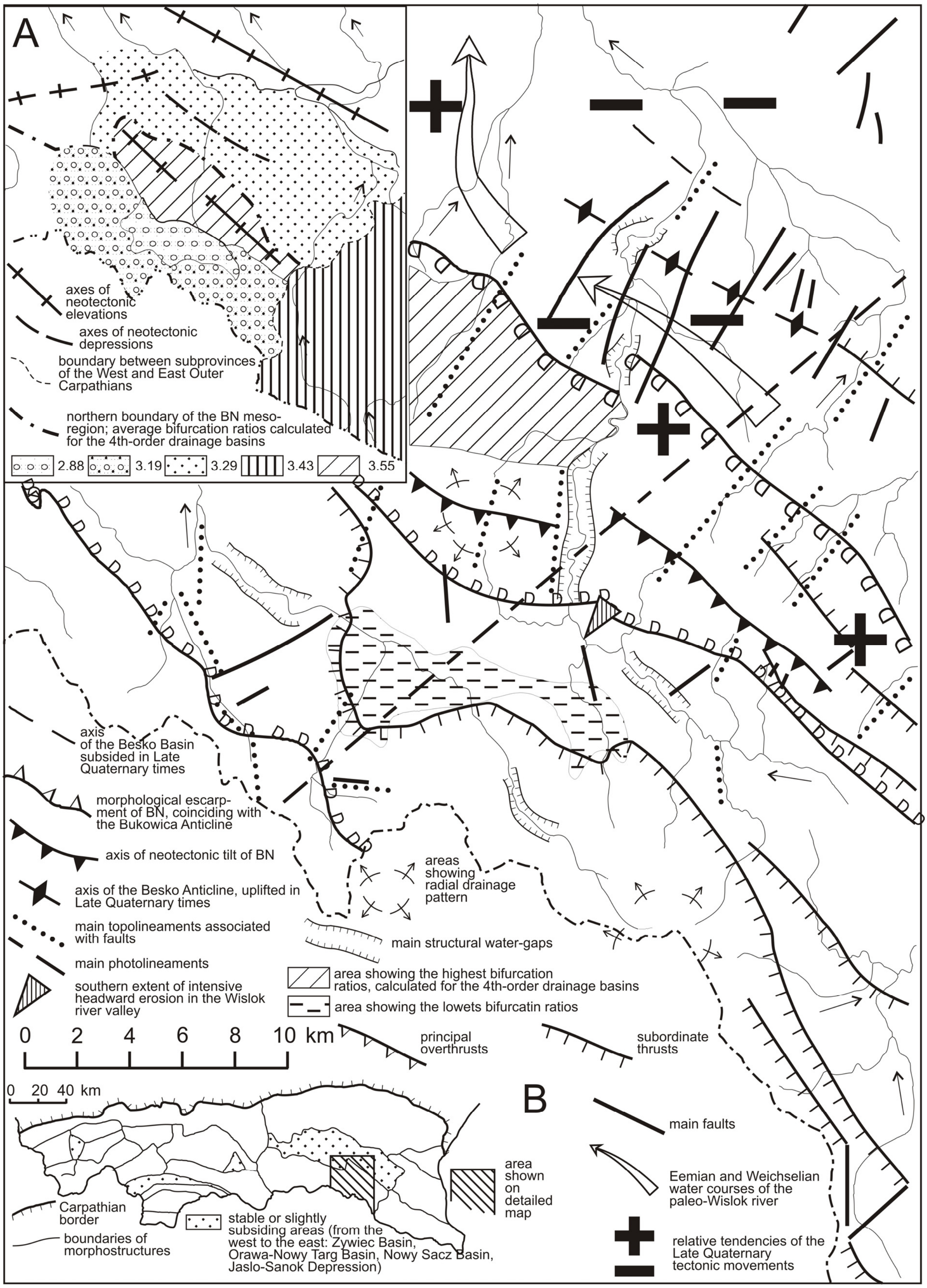


Fig. 9 Morphotectonic sketch of the eastern Beskid Niski Mts., eastern part of the Polish Outer Carpathians (modified after Zuchiewicz, 1988, 1989); A - morphostructures of the Beskid Niski Mts. active in Late Quaternary times; B – morphostructures of the Polish Carpathians with location of the study area.

BESKID NISKI MTS.: A PECULIAR MORPHOSTRUCTURE IN THE POLISH OUTER CARPATHIANS

The analyses of erosional dissection of planation surfaces and Quaternary straths reveal an unique position of the Beskid Niski (Lower Beskid) Mts. (BN), compared to the other OWC morphostructures (Fig. 9). The total amount of Plio-Quaternary dissection of the northern part of BN attains 350-380 m, whereas in its southern part it does not exceed 180-200 m (Fig. 9; Zuchiewicz, 1988, 1989).

The size of uplift during Pliocene times (120-140 m) in the Beskid Niski Mts. did not differ much from that described in other areas. This may indicate a relatively uniform rate of uplift of the Outer Carpathians in Pliocene times. Such a pattern changed drastically in the Quaternary. The lowermost planation surface ("riverside level") in BN was developing uninterruptedly up to the Elsterian stage, whereas in the surrounding regions its development terminated by the end of the Pliocene. The relief of the riverside level increases northwards from 30-40 m to 100-120 m, suggesting tectonic reactivation of the southern margin of the Jasło-Sanok Depression. The rates of Quaternary dissection in Middle Pleistocene times were insignificant, accelerating only in the Weichselian and Holocene (Zuchiewicz, 1988). This is indicated by a northward-proceeding increase in dissection of the Weichselian strath, from 8-10 m to 30-35 m. The last figure appears to be exceptional throughout the Polish Outer Carpathians.

The size of Quaternary erosion in BN has been considerably smaller, as compared to that of the Beskid Sądecki on the west and Bieszczady Mts. on the east. However, the deep incision during the last glacial-interglacial cycle may suggest reactivation of tectonic subsidence in the Besko Basin (southern part of the Jasło-Sanok Depression) and/or uplift of the northern part of BN.

The Beskid Niski morphostructure revealed only two distinct stages of tectonic activity in the late Cainozoic: at the end of the Pliocene and during Early Quaternary times, as well as in the Weichselian and Holocene. Neotectonic episodes described from the OWC (Zuchiewicz, 1984c) were much more weaker and embraced the southern part of the Jasło-Sanok Depression, leading to changes in the drainage pattern. The results of morphometric and geomorphic studies enable one to distinguish several morphostructural units within the eastern Beskid Niski Mts. and their foreland. These units conform very well to structural and physiographic subdivisions of that area. The northern morphostructure (Beskid Rymanowski Mts.) is characterized by increased bifurcation ratios and high amount of 1st-order valleys, increased stream gradients, as well as rapid erosional dissection during the Late Weichselian and Holocene. The total amount of erosional dissection is 350-380 m, that of Middle-Late Quaternary being 100-120 m. The southern unit (Beskid Dukielski Mts.), in turn, reveals lower values of erosional deepening (180-220 m; including 30-50 m in the Quaternary), smaller stream gradients and the overall predominance of morphology typical for not rejuvenated interfluve areas. The SE part of the Jasło-Sanok Depression consists of several subordinate morphostructural units, showing different neotectonic tendencies. These units relate to fold structures reactivated during the last glacial-interglacial cycle (Sieniawa syncline, Besko anticline). The Besko anticline has undergone uplift leading to subsequent changes in the drainage pattern. Alluvial fans shed by the palaeo-Wisłok river migrated in time from the west to the east. The remaining morphostructures reveal slight subsidence or show no traces of neotectonic activity whatsoever. A lowering of the Besko Basin during the Late Weichselian and Holocene led to the formation of a regressional (partly antecendent?) water-gap of the Wisłok River, and favoured intensive headward erosion in its valley. The above units are bounded on the west by a meridional fracture zone, the reactivation of which controlled changes of the palaeo-Wisłok River course from WNW-ESE to NNE-SSW in the Late Pleistocene (Fig. 9). The mobility of fault zones is responsible for the termination of longitudinal drainage pattern within subsequent basins in this part of the Jasło-Sanok Depression (*cf.* Koszarski, 1985).

A SW-NE oriented cross-section through BN and the Jasło-Sanok Depression reveals a peculiar succession of morphostructural units. To the north of the stable Beskid Dukielski Mts. an uplifted structure occurs, following the axis of an anticline which, in turn, is bounded from the north by the Sieniawa Depression, the uplifted Wysoczany Ridge and the subsided Besko Basin. Farther to the north, the Strzyżów Beskid Mts. follow, known to have been uplifted during the Middle through Late Pleistocene (Koszarski and Koszarski, 1985). Such an alternation of elevated and subsided structures could be an effect of the Late Quaternary remnant folding, the wavelength of which attains a dozen or so kilometres. These movements manifest themselves in uplifting frontal parts of nappes and subordinate imbricated thrust sheets, and result from the relaxation of horizontal stresses accumulated during the Middle to Late Miocene thrusting.

FINAL REMARKS

The Pliocene-Quaternary tectonic mobility of the Polish segment of the Carpathian arc has been relatively weak. The amount of Quaternary uplift did not exceed 150 m. Neotectonic mobility resulted in minor uplift, subsidence, and faulting recorded in deformations of erosion surfaces, fluvial terraces, as well as in changes of the drainage pattern. Recent vertical crustal movements change from -1 to +2 mm/yr, being controlled mainly by variable crustal thicknesses, whereas the earthquake magnitudes do not exceed 5 on the Richter scale.

The results of classical geomorphic and morphometric-statistical studies suggest that the main driving forces leading to young tectonic deformations are those which result from the relaxation of remnant horizontal stresses, built up during the Late Neogene thrusting.

This abridged and far from complete review of structural and morphotectonic studies conducted so far in the Polish Carpathians reveals many hypotheses, not always sufficiently supported by facts. Future research should focus on showing the actual, and not only apparent or inferred, relationships between short- and long-term landform development and the climatic/tectonic factors. Well-dated evidence for hydrographic changes and sedimentary records of fault reactivation during successive Quaternary stages would be particularly welcome. Moreover, recently initiated studies of fractured clasts within Pleistocene and Holocene fluvial series (Tokarski and Świerczewska, 2005; Tokarski et al., 2007) will certainly provide new constraints regarding seismotectonic activity of some reactivated thrusts and strike-slip faults.

ACKNOWLEDGEMENTS

This research was supported statutory funds (project 11.11.140.560) of the Faculty of Geology, Geophysics and Environmental Protection, AGH University of Science and Technology in Kraków. Two anonymous Referees are thanked for their helpful remarks.

REFERENCES

Bac-Moszaszwili, M.: 1993, Struktura zachodniego zakończenia masywu tatrzańskiego (Structure of the western termination of the Tatra massif), Annales Societatis Geologorum Poloniae, 63, 167–193.

Bac-Moszaszwili, M.: 1995, Diversity of Neogene and Quaternary tectonic movements in the Tatra Mountains, Folia Quaternaria, 66, 131–144.

Bajgier, M.: 1989, Wpływ morfostruktury na rozwój głębokich osuwisk na stokach Skrzycznego w Beskidzie Śląskim (Influence of morphostructure on development of deep landslides on Skrzyczne slopes in the Beskid Śląski), Folia Geographica, series geographica-physica, 21, 61–77.

Bajgier, M.: 1993, Rola struktury geologicznej w ewolucji rzeźby wschodniego skłonu Beskidu Śląskiego i zachodniej części Kotliny Żywieckiej (The role of geological structure in relief evolution on the eastern slopes of the Silesian Beskid and in the western part of Żywiec Basin), Zeszyty Naukowe AGH, 1523, kwart. Geologia, 19, 1, 1–69.

Baumgart-Kotarba, M.: 1983, Kształtowanie koryt i teras rzecznych w warunkach zróżnicowanych ruchów tektonicznych (na przykładzie wschodniego Podhala) (Channel and terrace formation due to differential tectonic movements (with the eastern Podhale Basin as example)), Prace Geograficzne Instytutu Geografii i Przestrzennego Zagospodarowania PAN, 145, 1–133.

Baumgart-Kotarba, M.: 1991-92, Rozwój geomorfologiczny Kotliny Orawskiej w warunkach ruchów neo-tektonicznych (The geomorphological evolution of the intramontane Orawa Basin associated with neotectonic movements, Polish Carpathians), Studia Geomorphologica Carpatho-Balcanica, 25-26, 3–28.

Baumgart-Kotarba, M.: 1996. On origin and age of the Orawa Basin, West Carpathians, Studia Geomorphologica Carpatho-Balcanica, 30, 101–116.

Baumgart-Kotarba, M.: 1997, Tectonic evolution of the Orava Basin in the light of geomorphological and geophysical studies tested by earthquake of 11 September 1995, Przegląd Geologiczny, 45, 10, 1067–1068.

Baumgart-Kotarba M.: 2001, Continuous tectonic evolution of the Orava Basin (Northern Carpathians) from Late Badenian to the present-day? Geol. Carpathica, 52, 103–110.

Baumgart-Kotarba, M., Gilewska, S. and Starkel, L.: 1976, Planation surfaces in the light of the 1: 300 000 geomorphological map of Poland, Geographia Polonica, 33, 5–22.

Birkenmajer, K.: 1976, Plejstoceńskie deformacje tektoniczne w Szaflarach na Podhalu (Pleistocene tectonic deformations at Szaflary, West Carpathians, Poland), Rocznik Polskiego Towarzystwa Geologicznego, 46, 309–324.

Birkenmajer, K., Derkacz, M., Lindner, L. and Stuchlik, L.: 2008, Stanowisko 1: Szaflary Wapiennik – żwiry wodnolodowcowe zlodowacenia Mindel i starsze osady organiczne (in Polish), in: Rączkowski, W., Derkacz, M. and Przasnyska, J. (eds.), Plejstocen Tatr i Podhala – zlodowacenia tatrzańskie. XV Konferencja „Stratygrafia Plejstocenu Polski", Zakopane 1-5 września 2008. Materiały konferencyjne, Państwowy Instytut Geologiczny, Warszawa, 149–154.

Bober, L.: 1984, Rejony osuwiskowe w polskich Karpatach fliszowych i ich związek z budową geologiczną regionu (Landslide areas in the Polish Flysch Carpathians and their connection with the geological structure of the region), Biuletyn Instytutu Geologicznego, 340, 115–162.

Bull, W.B.: 1990, Stream-terrace genesis: implications for soil development, Geomorphology, 3, 351–367.

Burbank, D.W., Leland, J., Fielding, E., Anderson, R.S., Brozovic, N., Reid, M. R. and Duncan, C.: 1996, Bedrock incision, rock uplift, and threshold hillslopes in the northwestern Himalayas, Nature, 379, 505–510.

Burchart, J.: 1972, Fission-track age determinations of accessory apatite from the Tatra Mts., Poland, Earth Planet. Sci. Lettr., 15, 418–422.

Cys', P.N.: 1961, Glacial history and some problems of Quaternary tectonics of the Soviet Carpathians, VI INQUA Congress, Poland 1961, Abstracts of Papers, Łódź, 45.

Cys', P.N.: 1966, Obzor osnovnykh problem morfogenezisa Ukrainskikh Karpat, in: Geomorphological Problems of Carpathians, vol. 2, Instytut Geografii PAN, Warszawa, 37–49.

Czarnecka, K.: 1986, Uwarunkowania strukturalne współczesnych ruchów tektonicznych pienińskiego pasa skałkowego w rejonie Czorsztyna (Recent tectonic movements in relation to geological structure of the Czorsztyn region, Pieniny Klippen Belt), Przegląd Geologiczny, 34, 10, 556–560.

Czarnecki, K.: 2004, Pieniński poligon geodynamiczny w rejonie Czorsztyna (in Polish), in: Czarnecki, K. (ed.), Badania geodynamiczne pienińskiego pasa

skałkowego w rejonie Czorsztyna. Monografia, Polit. Warsz., Wydz. Geod. i Kartogr., Inst. Geod. Wyższej i Astronomii Geod., Warszawa, 5–12.
Czarnecki, K., Barlik, M., Czarnecka, K., Olszak, T., Pachuta, A., Szpunar, R. and Walo, J.: 2005, Geodynamic studies of the Pieniny Klippen Belt In the Czorsztyn region in 2001-2003, Acta Geodyn. Geomater., 2, 3 (139), 33–41.
Činčura, J.: 1967, Ein Beitrag zum Alter des Flussniveaus in den Westkarpaten, Geografický Časopis, 19, 4, 316–326.
Demediuk, N.S.: 1982, Poverkhnosti vyravnivania Ukrainskikh Karpat, Geomorfologiya, 3, 36–44.
Demediuk, N.S.: 1983, Poverkhnosti vyravnivania Ukrainskikh Karpat i ikh predgorii (Planation surfaces in the Ukrainian Carpathians and in their promontories), Studia Geomorphologica Carpatho-Balcanica, 16, 3–14.
Demediuk, M.S.: 1994, Morfostruktury i morfoskulptury teritorii karpatskogo geodinamichnogo poligonu, in: Ostrovskiy, A. (ed.), Mizhnarodnyi sympozium "Geodinamika girskikh sistem Evropy" (tezy dopovidey), Lviv - Yaremche 10-17 IV 1994 r. Golovn. upravl. geod., kartogr. ta kadastru Ukrainy, Lviv, 17.
Fodor, L., Csontos, L., Bada, G., Györfi, I. and Benkovics, L.: 1999, Tertiary tectonic evolution of the Pannonian Basin system and neighbouring orogens: a new synthesis of palaeostress data, in: Durand, B., Jolivet, L., Horvath, F. and Seranne, M. (eds.), The Mediterranean Basins: Tertiary Extension within the Alpine Orogen, Geol. Soc. Spec. Publs., 156, 295–334.
Gerlach, T., Koszarski, L. and Koszarski, A.: 1985, Stop 23. Łężany-Jabłonica-Niebylec-Krasna-Węglówka. Selected problems of geomorphology and Quaternary along the Dukla Pass-Rzeszów transect, Guide to Exc. 5, XIIIth Congress Carpatho-Balkan Geol. Assoc., Cracow, Poland 1985, Geol. Inst., Kraków, 96–110.
Gilewska, S.: 1987, The Tertiary environment in Poland. Geographia Polonica, 53, 19–41.
Głazek, J.: 1996, Kras i jaskinie Tatr Polskich, stan i perspektywy badań (Karst and caves of the Polish Tatra Mountains, state of knowledge and perspectives), in: Kotarba, A. (ed.), Przyroda Tatrzańskiego Parku Narodowego a człowiek, 1, Nauki o Ziemi, TPN, PTPNoZ Oddz. Krak., Kraków – Zakopane, 31–44.
Gofshtein, I.D.: 1964, Neotektonika Karpat. Izd. AN USSR, Kiev, 183 pp.
Granger, D.E., Kirchner, J.W. and Finkel, R.C.: 1997, Quaternary downcutting rate of the New River, Virginia, measured from differential decay of cosmogenic ^{26}Al and ^{10}Be in cave-deposited alluvium, Geology, 25, 107-110.
Guterch B.: 2006, Seismic events in the Orava – Nowy Targ Basin, Western Carpathians, November 30, 2004 – December 2005, Acta Geodyn. Geomater., 3, 3 (143), 85–95.
Guterch, B., Lewandowska-Marciniak, H. and Niewiadomski, J.: 2005, Earthquakes recorded in Poland along the Pieniny Klippen Belt, Western Carpathians, Acta Geophysica Polonica, 53, 27-45.
Hefty, J.: 2007, Geo-kinematics of Central and South-East Europe resulting from combination of various regional GPS velocity fields, Acta Geodyn. Geomater., 4, 4 (148), 173–189.
Henkiel, A.: 1969, Ewolucja morfologiczna dorzecza Strwiąża (Morphologic evolution of the drainage basin of the Strwiąż river), Annales UMCS, Sec. B, 24, 99–140.
Henkiel, A.: 1977, Zależność rzeźby Karpat Zewnętrznych od budowy geologicznej jednostek fliszowych i ich głębokiego podłoża (na przykładzie wschodniej części Karpat polskich) (in Polish), Rozprawy habilitacyjne UMCS, Wydawnictwo UMCS, Lublin, 1–100.
Henkiel, A., Pękala, K. and Poprawa, D.: 1988, Wycieczka C. Geomorfologia, geologia czwartorzędu oraz wybrane zagadnienia z geologii inżynierskiej i hydrogeologii Karpat Przemyskich i Przedgórza (in Polish), in: Kotlarczyk, J. (ed.), Przewodnik LIX Zjazdu Polskiego Towarzystwa Geologicznego, Przemyśl, 16-18 IX 1988. Wyd. AGH, Kraków, 191–258.
Jahn, A.: 1992, Z morfologii Karpat Wschodnich (Geomorphology of the Eastern Carpathians), Acta Universitatis Wratislaviensis, Prace Geologiczno-Mineralogiczne, 27, 1–48.
Jakubska, O.: 1987, Związek między elementami strukturalnymi płaszczowiny magurskiej a morfologią górnej części dorzecza Skawy (Relations between the structural elements of the Magura Nappe and the morphology of the upper part of the Skawa River basin), Czasopismo Geograficzne, 58, 19–44.
Jakubska, O.: 1995, Tectonic features of young structural relief of the Western Carpathians, South Poland, Folia Quaternaria, 66, 123–130.
Jarosiński, M.: 1998, Contemporary stress field distortion in the Polish part of the Western Outer Carpathians and their basement, Tectonophysics, 297, 91–119.
Jarosiński, M.: 2006, Recent tectonic stress field investigations in Poland: a state of the art, Geological Quarterly, 50, 303–321.
Jurewicz, E., Hercman, H. and Nejbert, K.: 2007, Flowstone-like calcite in the andesite of Jarmuta Mt. – dating the Holocene tectonic activity in the vicinity of Szczawnica (Magura Nappe, Outer Carpathians, Poland), Acta Geologica Polonica, 57, 187–204.
Klimaszewski, M.: 1937, Morfologia i dyluwium doliny Dunajca od Pienin po ujście (Morphologie und Diluvium des Dunajec-Tales von den Pieninen bis zur Mündung), Prace Instytutu Geografii UJ, 18, 1–54.
Klimaszewski, M.: 1987, The geomorphological evolution of the Tatra Mountains of Poland. Zeitschr. Geomorph., N.F., Suppl. Bd. 65, 1–34.
Klimaszewski, M.: 1988, Rzeźba Tatr polskich (in Polish), PWN, Warszawa, 1–668.
Koszarski, A. and Koszarski, L.: 1985, Stop 39. Łężany. Tectonics of the Jasło-Sanok Depression and its relation to the Quaternary events, in: Geology of the Middle Carpathians and the Carpathian Foredeep. Guide to Exc. 3, XIIIth Congress Carpatho-Balkan Geol. Assoc., Geol. Inst., Kraków, 176–178.
Koszarski, L. (ed.): 1985, Geology of the Middle Carpathians and the Carpathian Foredeep. Guide to Exc. 3, XIIIth Congress, Carpatho-Balkan Geol. Assoc., Cracow, Poland 1985. Geological Institute, Kraków, 1–354.
Kotarba, A.:1986, The role of landslides in modelling of theBeskidian and Carpathian Foothills relief, Przegląd Geograficzny, 58, 119–129.
Kukulak, J.: 1985, Tektoniczne założenia form zboczowych na Pogórzu Gubałowskim (Tectonic base of slope

forms on Pogórze Gubałowskie), Folia Geographica, series geographica-physica, 17, 5–17.

Kukulak, J.: 1988, Powiązania morfostrukturalne w rozwoju osuwisk zachodniego Podhala (Morphostructural connections in development of landslides in the Western Podhale), Folia Geographica, series geographica-physica, 20, 33–49.

Kukulak, J.: 1991, Udział tektoniki w rozwoju poziomów grzbietowych Zachodniego Podhala (Influence of tectonics on ridge levels development in the Western Podhale), Folia Geographica, series geographica-physica, 22, 87–102.

Kukulak, J.: 1993, Przejawy aktywności ruchów pionowych w rzeźbie zachodniego Podhala (The reflection of vertical crustal movements in morphology of the Western Podhale region, South Poland), Folia Quaternaria, 64, 151–164.

Kuśmierek, J.: 1990, Zarys geodynamiki centralnokarpackiego basenu naftowego (Outline of geodynamics of Central Carpathian oil basin), Prace Geologiczne Komitetu Nauk Geologicznych PAN, Oddział w Krakowie, 135, 1–85.

Kvitkovič, J.: 1975, Movement tendencies of the West Carpathians in the Quaternary, Tectonophysics, 29, 369–375.

Laskowska-Wysoczańska, W.: 1995, Neotectonic and glacial control on geomorphic development of middle and eastern parts of the Sandomierz Basin and the Carpathian margin, Folia Quaternaria, 66, 105–122.

Lukniš, M.: 1973, Relief Vysokych Tatier a ich predpolia, Slov. Akad. Vied, Bratislava, 376 pp.

Makowska, A. and Jaroszewski, W.: 1987, O współczesnych ruchach pionowych w Tatrach i na Podhalu. On present vertical movements in Tatra Mts. and Podhale. Przegląd Geologiczny, 35, 10, 506–512.

Makowska, A.: 2003, Dynamika Tatr wyznaczana metodami geodezyjnymi (in Polish), Inst. Geod. Kartogr., Seria Monograficzna, 6, 1-201, Warszawa.

Malarz, R.: 1983, Relationships between relief and lithology exemplified by selected flysch rock series in the So≈a drainage basin, Studia Geomorphologica Carpatho-Balcanica, 16, 51–68.

Malarz, R.: 1986, Influence of lithology of the basement on slopes inclinations in the Beskidian part of the Sota catchment area, Folia Geographica, series geographica-physica, 18, 51–57.

Malarz, R.: 1992, Etap denudacyjny w polskich Karpatach fliszowych (in Polish), Prace Monograficzne WSP w Krakowie, 150, 1–158.

Margielewski, W.: 2002, Geological control on the rocky landslides in the Polish Flysch Carpathians, Folia Quaternaria, 73, 53-68.

Margielewski, W.: 2006, Structural control and types of movements of rock mass in anisotropic rocks: Case studies in the Polish Flysch Carpathians, Geomorphology, 77, 47–68.

Mazúr, E.: 1963, Žilinska Kotlina a prilahle pohoria (geomorfologia a kvarter) (The Žilina Basin and the adjacent mountains (geomorphology and Quaternary era)), Vyd. Slov. Akad. Vied, Bratislava, 186 pp.

Mazúr, E.: 1979, Morfoštruktúry Zapadných Karpát a ich vyvoj, Acta Facultatis Rerum Naturalium Universitatis Comenianae, Geographia, ČSK, 17, 21–34.

Mazúr, E. and Činčura, J.: 1975, Planation surfaces in the Western Carpathians, Studia Geomorphologica Carpatho-Balcanica, 9, 27–36.

Michalik, A.: 1989, Gravitationsdeformationen in Tatra Gebirge, in: Pinczes, Z. (ed.), Proceedings, Carpatho-Balkan Geomorphological Commission, Debrecen, 117–123.

Neubauer, F., Cloetingh, S., Dinu, C. and Mocanu, V.: 1997, Tectonics of the Alpine-Carpathian-Pannonian region: introduction, Tectonophysics, 272, 93–96.

Niedziałkowska, E. and Szczepanek, K.: 1993-94, Utwory pyłowe vistuliańskiego stożka Wisły w Kotlinie Oświęcimskiej (Vistulian silty sediments of the Vistula river fan in the Oświęcim Basin), Studia Geomorphologica Carpatho-Balcanica, 27–28, 29–44.

Oszczypko, N.: 1996, The Miocene dynamics of the Carpathian Foredeep in Poland, Przegląd Geologiczny, 10, 1007–1018.

Oszczypko, N.: 1998, The Western Carpathian Foredeep - development of the foreland basin in front of the accretionary wedge and its burial history (Poland), Geol. Carpathica, 49, 415–431.

Oszczypko, N.: 2001, Magura Unit. General geology, in: 12^{th} Meeting of the Association of European Geological Societies, 10-15 September 2-1, Kraków. Field trip guide “Carpathian palaeogeography and geodynamics: A multidisciplinary approach”, Państwowy Instytut Geologiczny, Kraków, 173–177.

Oszczypko, N.: 2004, The structural position and tectonosedimentary evolution of the Polish Outer Carpathians, Przegląd Geologiczny, 52, 780–791.

Oszczypko, N. and Ślączka, A.: 1985, An attempt to palinspastic reconstruction of Neogene basins in the Carpathian Foredeep, Annales Societatis Geologorum Poloniae, 55, 55–75.

Oszczypko, N., Tomaś, A. and Zuchiewicz, W.: 1993, Rola kompakcji w ocenie mobilności neotektonicznej pogórzy karpackich (Compaction of Miocene molasses and neotectonic mobility of the Polish Carpathian Foothills), Przegląd Geologiczny, 41, 6, 411–416.

Pagaczewski, J.: 1972, Catalogue of earthquakes in Poland in 1000-1970 years. Materiały i Prace Instytutu Geofizyki PAN, 51, 3–36.

Perski, Z.: 2008, Współczesna aktywność tektoniczna Tatr i Podhala w świetle wyników badań satelitarnej interferometrii radarowej InSAR i PSInSAR (Recent tectonic activity of the Tatra Mts. and Podhale (Poland) studied by InSAR and PSInSAR), Przegląd Geologiczny, 56, 12, 1082–1086.

Pękala, K.: 1968, Ewolucja reliktów rzeźby neogeńskiej w strefie wododzielnej (na przykładzie okolicy Cisowej - Karpaty Wschodnie) (Relicts of the Neogene relief: their evolution in the water-divide, an example from the Carpathians), Folia Societatis Scientiarum Lublinensis, Geographia, Sec. D, 7–8, 65–70.

Połtowicz, S.: 1974, Wgłębna tektonika brzegu Karpat w okolicy Tarnowa i Pilzna. Tectonic structures of the Carpathian border in the Tarnów and Pilzno area (Polish Middle Carpathians), Rocznik Polskiego Towarzystwa Geologicznego, 44, 491–514.

Pomianowski, P.: 1995, Budowa depresji orawskiej w świetle analizy wybranych materiałów geofizycznych (Structure of the Orava Basin in the light of selected geophysical data), Annales Societatis Geologorum Poloniae, 64, 67–80.

Pomianowski, P.: 2003, Tektonika Kotliny Orawsko-Nowotarskiej - wyniki kompleksowej analizy danych grawimetrycznych i geoelektrycznych (Tectonics of the Orava - Nowy Targ Basin - results of the combined analysis of the gravity and geoelectrical data), Przegląd Geologiczny, 51, 6, 498–506.

Poprawa, D. and Rączkowski, W.: 2003, Osuwiska Karpat (Carpathian landslides, southern Poland), Przegląd Geologiczny, 51, 8, 685–692.

Prochazková, D., Brouček, I., Guterch, B. and Lewandowska-Marciniak, H.: 1978, Map and list of the maximum observed macroseismic intensities in Czechoslovakia and Poland. Publs. Inst. Geophys., Pol. Acad. Sci., B-3, 122, 1–75.

Starkel, L.: 1965, Rozwój rzeźby polskiej części Karpat Wschodnich (na przykładzie dorzecza górnego Sanu) (Geomorphological development of the Polish Eastern Carpathians (upon the example of the Upper San basin)), Prace Geograficzne Instytutu Geografii PAN, 50, 1–160.

Starkel, L.: 1969, The age of the stages of development of the relief of the Polish Carpathians in the light of the most recent geological investigations, Studia Geomorphologica Carpatho-Balcanica, 3, 33–44.

Starkel, L.: 1972, Karpaty Zewnętrzne (in Polish), in: Klimaszewski, M. (ed.), Geomorfologia Polski, 1, PWN, Warszawa, 52–115.

Starkel, L. (ed.): 1980, Geomorphological map of Poland 1: 500 000. Instytut Geografii i Przestrzennego Zagospodarowania PAN, Warszawa.

Starkel, L.: 1985, Controversial opinions on the role of tectonic movements and climatic changes in the Quaternary evolution of the Polish Carpathians, Studia Geomorphologica Carpatho-Balcanica, 19, 45–60.

Starkel, L.: 1988, O genezie i wieku zrównań w polskich Karpatach (w odpowiedzi Profesorowi M. Klimaszewskiemu) (in Polish), Przegląd Geograficzny, 60, 401–408.

Starkel, L.: 1991. Rzeźba terenu (in Polish), in: Dynowska, I. and Maciejewski, M. (eds.), Dorzecze górnej Wisły. Część I, Publishing House Państwowe Wydawnictwo Naukowe, Warszawa-Kraków, 42–54.

Starkel, L.: 1996, Cykle glacjalno-interglacjalne w ewolucji systemu rzecznego Wisły (The glacial-interglacial cycle in the evolution of the Vistula River basin), in: Kostrzewski, A. (ed.), Geneza, litologia i stratygrafia utworów czwartorzędowych, 3, Geografia, 57, 297–305, UAM, Poznań.

Stehlik, O.: 1964, Prispevek k poznani tektoniky Beskydskeho hoskeho oblouku, Geografický Časopis, 16, 271–280.

Stehlik, O.: 1965, The Beskydy Mts. arc, in: Geomorphological Problems of Carpathians, 1, VEDA, Bratislava, 71–80.

Szczęsny, R.: 1987, Geologiczna interpretacja wybranego lineamentu z Podhala (Geologic interpretation of a lineament from Podhale), Biuletyn Geologiczny Uniwersytetu Warszawskiego, 31, 401–410.

Świerczewska, A. and Tokarski, A.K.: 1998, Deformation bands and the history of folding in the Magura nappe, Western Outer Carpathians (Poland), Tectonophysics, 297, 73-90.

Şengör, C.M.A., Görür, N. and Şaroglu, F.: 1985, Strike-slip faulting and related basin formation in zones of tectonic escape: Turkey as a case study, Spec. Publ. Soc. Econ. Paleont. Miner., 37, 227–264.

Tokarski, A. K.: 1975, Structural analysis of the Magura Unit between Krościenko and Zabrzeż (Polish Flysch Carpathians), Rocznik Polskiego Towarzystwa Geologicznego, 45, 327–359.

Tokarski, A.K.: 1978, O czwartorzędowym ciosie i uskoku w Kotlinie Sądeckiej (Zachodnie Karpaty Zewnętrzne) (On Quaternary fault and jointing in Nowy Sącz Basin, Outer Western Carpathians, Poland), Annales Societatis Geologorum Poloniae, 48, 509–516.

Tokarski, A.K. and Świerczewska, A.: 2005, Neofractures versus inherited fractures in structural analysis: a case study from Quaternary fluvial gravels (Outer Carpathians, Poland), Annales Societatis Geologorum Poloniae, 75, 95–104.

Tokarski, A.K., Świerczewska, A. and Zuchiewicz, W.: 2007, Fractured clasts in neotectonic reconstructions: an example from the Nowy Sącz Basin, Western Outer Carpathians, Poland, Studia Quaternaria, 24, 47–52.

Tomek, C. and Hall, J.: 1993, Subducted continental margin imaged in the Carpathians of Czechoslovakia, Geology, 21, 535–538.

Wobus, C., Whipple, K.X., Kirby, E., Snyder, N., Johnson, J., Spyropolou, K., Crosby, B. and Sheehan, D.: 2006, Tectonics from topography: procedure, promise, and pitfalls, in: Willett, S. D., Hovius, N., Brandon, M. T. and Fisher, D. M. (eds.), Tectonics, Climate, and Landscape Evolution, Geological Society of America Special Paper, 398, 55–74.

Wójcik, A.: 1989, Systemy teras rzecznych dorzecza Koszarawy w Beskidzie Żywieckim i ich związek z ruchami tektonicznymi (Terrace systems in the Koszarawa drainage basin and their relation to tectonic movements in the Beskid Żywiecki Mts.), Studia Geomorphologica Carpatho-Balcanica, 22 (1988), 21–45.

Wójcik, A.: 1997, Osuwiska w dorzeczu Koszarawy - strukturalne i geomorfologiczne ich uwarunkowania (Karpaty Zachodnie, Beskid Żywiecki) (Landslides in the Koszarawa drainage basin - structural and geomorphological control (Western Carpathians, Beskid Żywiecki Mts.)), Biuletyn Państwowego Instytutu Geologicznego, 376, 5–42.

Wójcik, A.: 1999, Tektoniczne deformacje utworów glacjalnych i limnoglacjalnych Karpat (Pogórze Dynowskie) (in Polish), Posiedzenia Naukowe Państwowego Instytutu Geologicznego, 55, 7, 113–115 (1998).

Wójcik, A.: 2003, Czwartorzęd zachodniej części Dołów Jasielsko-Sanockich (polskie Karpaty Zewnętrzne) (Quaternary of the western part of the Jasło-Sanok Depression, Polish Outer Carpathians), Prace Państwowego Instytutu Geologicznego, 178, 1–148.

Wójcik, A., Szydło, A., Marciniec, P. and Nescieruk, P.: 1999, The folded Miocene of the Andrychów region, Biuletyn Państwowego Instytutu Geologicznego, 387, 191–195.

Wójcik, A. and Zimnal, Z.: 1996, Landslides along the San valley between Bachórzec and Reczpol (the Carpathians, the Carpathian Foreland, Biuletyn Państwowego Instytutu Geologicznego, 374, 77–91.

Wyrzykowski, T.: 1985, Mapa prędkości współczesnych pionowych ruchów powierzchni skorupy ziemskiej na obszarze Polski (in Polish), Instytu Geodezji i Kartografii, Warszawa.

Young, R. and McDougall, I.: 1993, Long-term landscape evolution: Early Miocene and modern rivers in southern New South Wales, Australia, Jour. Geol., 101, 35–49.

Ząbek, Z., Barlik, M., Knap, T., Margański, S. and Pachuta, A.: 1993, Continuation of geodynamic investigations in the Pieniny Klippen Belt, Poland, from 1985 to 1990, Acta Geophysica Polonica, 41, 131–150.

Ziętara, T.: 1991, Influence of geological structure on landslide development in the eastern part of the flysch Carpathians, Folia Geographica, series geographica-physica, 22, 71–86.

Zoetemeijer, R., Tomek, Č. and Cloetingh, S.: 1999, Flexural expression of European continental lithosphere under the western outer Carpathians, Tectonics, 18, 5, 843–861.

Zuchiewicz, W.: 1978, Czwartorzędowe ruchy tektoniczne a rzeźba przełomu Dunajca przez Beskid Sądecki (Quaternary tectonics and the relief of the Dunajec river gorge in the Beskid Sądecki Mts., Polish Western Carpathians), Annales Societatis Geologorum Poloniae, 48, 517–532.

Zuchiewicz, W.: 1984a, Ewolucja poglądów na genezę i wiek karpackich powierzchni zrównania (Evolution of views on origin and age of Carpathian planation surfaces), Przegląd Geologiczny, 32, 8-9, 468–477.

Zuchiewicz, W.: 1984b, Neotectonic movements of the Polish West Carpathians, Catena, 11, 1, 1–12.

Zuchiewicz, W.: 1984c, The Late Neogene-Quaternary tectonic mobility of the Polish West Carpathians. A case study of the Dunajec drainage basin, Annales Societatis Geologorum Poloniae, 54, 133–189.

Zuchiewicz, W.: 1987, Tectonics and climate versus relief evolution: old controversy and new arguments, Studia Geomorphologica Carpatho-Balcanica, 21, 183–202.

Zuchiewicz, W.: 1988, Evolution of the eastern Beskid Niski Mts. and morphotectonics of the Polish Carpathians, Zeszyty Naukowe AGH, 1156, kwart. Geologia, 13 (1987), 3–4, 3–167.

Zuchiewicz, W.: 1989, Morphotectonic phenomena in the Polish Flysch Carpathians. A case study of the eastern Beskid Niski Mts., Quaestiones Geographicae, Spec. Issue, 2, 155–167.

Zuchiewicz, W.: 1991, On different approaches to neotectonics: A Polish Carpathians example, Episodes, 14, 2, 116–124.

Zuchiewicz, W.: 1995a, Neotectonics of Poland: a state-of-the-art review, Folia Quaternaria, 66, 7–37.

Zuchiewicz, W.: 1995b, Selected aspects of neotectonics of the Polish Carpathians, Folia Quaternaria, 66, 145–204.

Zuchiewicz, W.: 1998, Quaternary tectonics of the Outer West Carpathians, Poland. Tectonophysics, 297, 121–132.

Zuchiewicz, W., Tokarski, A.K., Jarosiński, M. and Márton, E.: 2002, Late Miocene to present day structural development of the Polish segment of the Outer Carpathians, EGU St. Mueller Spec. Publ. Series, 3, 185–202.

Żytko, K., Gucik, S., Ryłko, W., Oszczypko, N., Zając, R., Garlicka, I., Nemčok, J., Eliaš, M., Menčik, E., Dvorak, J., Stranik, Z., Rakus, M. and Matejovská, O.: 1989, Geological map of the Western Outer Carpathians and their foreland without Quaternary formations, in: Poprawa, D. and Nemčok, J. (eds.), Geological Atlas of the Western Outer Carpathians and their Foreland 1: 500,000, Państwowy Instytut Geologiczny, Warszawa.