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

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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).
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 (Zábek et al., 1993; Czarnecki et al., 2005). Repeated precise
Numerous pieces of evidence pointing to nearly permanent Neogene mobility of the OWC thrust sheets (cf. Oszczypko and Słączka, 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 (Glazek, 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 (Kuśmierczuk, 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 Miocene 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-Wysoczanska, 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-Wysoczanska, 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; Bagier, 1989, 1993; Zięta, 1991; Poprawa and Rączkowska, 1996; Wójcik and Zimmel, 1996; Margilewski, 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 (Jakubiska, 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 represents 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, shorty west of Tarnów (Polowicz, 1974), southern and central parts of the Jasło-Sanok Depression (Zuchiewicz, 1987; Wójcik, 1999, 2003), and the south-western (Niedziałkowska and Szczezanek, 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, 1999b). The axial part of the Beskid Sądecki Mts. underwent the most intensive uplift (Fig. 6). The Pliocene deposits occurring at the foot of the Luban 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
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 (Roźnów 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 Śadecki 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 deep 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 Tatraproduced (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 solifluxion within glacial stages. All Pleistocene fluvial covers interfinger with solifluxion tongues, those dated to the last and penultimate glacial stages being also overlain by slopewash and/or solifluxion-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.
NEOTECTONICS OF THE POLISH CARPATHIANS IN THE LIGHT ...

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 Jaslo-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 Jaslo-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 Jaslo-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 Rymanski 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 Jaslo-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-Wislok 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 antecedent?) water-gap of the Wislok 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-Wislok 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 Jaslo-Sanok Depression (cf. Koszarski, 1985).

A SW-NE oriented cross-section through BN and the Jaslo-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. Further 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 imbricate 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 geomorphologic 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.

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REFERENCES

Baumgart-Kotarba, M.: 1983, Kształcenie kory 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-
Birkenmajer, K.: 1976, Pleistocene sedimentation and hydrographic changes and sedimentary records of fault reactivation during successive Quaternary tectonic deformations at Szaflarach na Podhalu (Pleistocene tectonic deformations at Szaflary, West Carpathians, Poland), Rocznik Polskiego Towarzystwa Geologicznego, 46, 309–324.
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.
forms on Pogórze Gubalowskiej), Folia Geographica, series geographica-physica, 17, 5–17.


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.


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


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


Pomianowski, P.: 1995, Te ktonika Kotliny Orawsko-Nowotarskiej - wyniki kompleksowej analizy danych gravimetrycznych 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.


Starkel, L.: 1965, Rozwój rzeczy 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.: 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.


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.


W. Zuchiewicz


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.


