QUATERNARY TECTONICS OF THE POLISH OUTER CARPATHIANS

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Abstract: Results of geomorphological mapping in the Polish Outer Carpathians, combined with an analysis of morphometric indices, maps of envelopping surfaces and topolineaments identified on digital elevation models and dense contour maps indicate the presence of long and narrow zones, aligned subparallel to the structural grain of the area and showing alternately uplifting and subsiding tendencies in the Pliocene and Quaternary.

Key words: neotectonics, morphotectonics, Pliocene-Quaternary, Polish Outer Carpathians

The Outer Carpathians of Poland represent a typical fold-and-thrust belt that was affected by postorogenic uplift coupled with relaxation of some remnant horizontal stresses. Recent studies indicate that the generally modest Bouguer gravity anomalies point to nonisostatic processes causing the postflexural uplift, ranging from 250 m to 550 m (Zoetemeijer et al. 1999). Recent thrust activity causing local uplift has also been documented in the westernmost part of the West Carpathian foredeep.Numerous lines of evidence provided, *i. a.* by well-bore breakouts, deformation of oil industry well cores, structural data and geomorphic studies, all indicate Late Cenozoic tectonic activity of the Polish Outer Carpathians. The Pliocene-Quaternary ("neotectonic") activity resulted in deformation of geomorphic surfaces of the early Pliocene, late Pliocene and early Quaternary ages, as well as in upwarping, downwarping and/or faulting of straths of Quaternary fluvial terraces (cf. review papers by Zuchiewicz 1998, Zuchiewicz et al. 2000).

The late Palaeogene to Miocene history of the Carpathians is related to the change from collision to strike-slip faulting, surface uplift and sedimentary basin formation. The Outer Carpathian belt was formed as an accretionary prism during the southward-directed subduction of the European plate under Alcapa (Zoetemeijer et al. 1999; and references cited therein), resulting in the NW-directed shortening, followed by major rotation of either the regional stress field or the belt itself (Zuchiewicz et al. 2000).

The study area is composed of a number of imbricated thrust sheets, emplaced between the late Oligocene and the end of the Sarmatian (Oszczypko 1996; and references therein). These sheets are composed of Lower Cretaceous through Miocene flysch strata of variable thickness and competence. Thin-bedded turbidites are strongly deformed by tight folds and are included into a number of imbricated slices locally forming antiformal stacks, whereas thick-bedded turbidites are less deformed and are accreted in slightly imbricated thrust sheets.

Traditional geomorphological and structural-geomorphological studies in the Carpathians were aimed at the reconstruction of long-term landform development, by means of mapping the ridge and valley patterns, planation surfaces and fluvial terraces. These reconstructions are recently becoming more and more supplemented by palaeoclimatic, palaeohydrological, palaeontological, palaeoecological, archaeological, minero-petrographic and geophysical techniques.

The studies focusing on deformations of planation surfaces and fluvial terraces make it possible to distinguish a number of elevated and subsided structures, of relatively small widths (15-20 km) and subparallel arrangement with respect to the strike of principal thrusts and imbricated folds, which suggests that they originated due to Pliocene-Quaternary relaxation of remnant horizontal movements within the flysch nappes (Zuchiewicz 1998). Analysis of rates of fluvial downcutting helps to understand landscape evolution which is controlled by both climatic and tectonic factors. Differentiation in downcutting of a river along its long profile enables one to reconstruct the spatial distribution of young uplifted structures. Fluvial erosion depends principally on climatic changes in successive glacial/interglacial cycles, river hydraulics and geometry, sea-level changes and other factors, although its spatial variability is also controlled by tectonic tendencies.

Main valleys of the Outer Carpathians in Poland bear remnants of 5 to 9 Quaternary terrace steps (Zuchiewicz 1998, Zuchiewicz et al. 2000). Most of Pleistocene terraces are strath or complex-response terraces, whereas the last glacial and Holocene ones are cut-and-fill terraces, except for those that are located in axial zones of young uplifted areas. Longitudinal profiles of individual straths frequently show convergence, divergence or tilting, pointing to tectonic control. Moreover, both the amount and rate of downcutting of straths of comparable age are different for different morphotectonic units, despite regionally consistent Quaternary climatic conditions throughout the Outer Carpathians and more or less uniform bedrock resistance to erosion. Holocene terraces contain straths only in axial zones of neotectonically uplifted structures, and the highest rates of their incision are to be observed in some areas only. Increased rates of fluvial downcutting are characteristic for those segments of the Outer Carpathian rivers which dissect structures elevated in Plio-Quaternary times. These include in the western segment of the Polish Carpathians river gorges of So³a in the Beskid Ma³y Mts., Skawa and Raba in the Beskid ¯ywiecki Mts., Dunajec and Poprad in the Beskid S¹decki Mts., Bia³a Dunajcowa in the Ciê¿kowice Foothills, and - in the eastern portion of the Outer Carpathians of Poland - Wis³oka in the Strzy¿ów Foothills, Wis³ok in the northern Beskid Niski Mts., as well as of San in the Low Bieszczady Mts. Long-term rates of fluvial downcutting of successive Quaternary straths tended to increase in the periods of 800-472 ka, 130-90 ka, and 15-0 ka, ranging from 0.18 to 0.40 mm/yr. Rates calculated for individual Quaternary stages have varied from 0.04 to 2.00 mm/yr, being different for neighbouring morphotectonic units (Zuchiewicz 1998). The late Pleistocene increased rates of fluvial incision into solid bedrock are particularly well noticeable in frontal parts of some nappes and slices, both in the western (Raèa slice of the Magura nappe, Silesian nappe), and eastern segments of the Polish Carpathians (Dukla Nappe). Rates of incision in mountaineous regions are, of course, driven by both climatic and tectonic factors. The former are particularly well documented for the Vistulian Late Glacial and Holocene times.

Nevertheless, average rates of fluvial downcutting for the whole of Quaternary (0.06 to 0.22 mm/yr) are compatible with those of isostatic uplift of that area during the last 10 million years, which has been from 0.03 to 0.11 mm/yr, or from *ca.* 200 to nearly

1000 m in the Carpathian Foredeep and the Outer Carpathians, respectively (Oszczypko 1996, Zuchiewicz 1998). Such estimates, based on comparative analysis of compaction curves across the basin and on extrapolation of erosionally truncated seismic horizons, have been made for several tens of wells which pierce through Miocene molasses, either underlying the overthrust flysch nappes or filling the Carpathian Foredeep.

The hitherto-published geomorphological maps of the Polish Carpathians feature a few longitudinal elevated areas, including the Beskid Œl¹ski, Beskid ¯ywiecki and Beskid S¹decki Mts., Ro¿nów Foothills - Grybów Mts. - Beskid Niski - High Bieszczady Mts., Low Bieszczady Mts., and Wañkowa Highland areas (R¹czkowski et al. 1984). More prominent subsided structures are to be located along the So³a river course, in the Orava - Nowy Targ Basin, in the Jas³o-Sanok Depression and following the lower course of the San river valley in the Przemyœl Carpathians.

The photolineament pattern shows some resemblance to that of topolineaments, interpreted from shaded-relief topographic maps. This applies particularly to the Carpathian Foredeep and Roztocze areas, whereas in the Outer Carpathians such coincidence is barely recognizable. In the latter case, topolineaments visible on digital elevation models appear to follow some rectilinear river bed stretches and, in the southern part, zones of increased density of joints. Therefore, any “neotectonic” significance of such a picture is difficult to assess, since the sole coincidence of the existent zone of weakness (increased fracture density) with a topolineament does not necessarily mean its young tectonic reactivation. North of the Carpathian frontal thrust, however, well-pronounced topolineaments coincide very well with the escarpment zone of Roztocze, as well as with the trace of the Subcarpathian furrow and linear zones that bound on the NE and NW the uplifted Kolbuszowa Plateau. One of the most prominent E-W trending linear features visible on digital elevation models, air photographs and MSS (Landsat Multi Spectral Scanner) images is that following the Subcarpathian furrow in the autochthonous foredeep basin, and called sometimes the Wis³ok fault line (cf. also Chorowicz et al. 1999).

The pattern of different types of relief, together with spatial distribution of topolineaments and some photolineaments in the Polish Outer Carpathians has been shaped due to mutual interactions between climatic, lithological and tectonic factors.

Lithology is important as far as small-scale landforms are concerned and controls the state of preservation of individual planation surfaces, particularly in higher elevated regions, but appears to have reduced influence upon the orientation of zones of deformed planation surfaces, distribution of zones of abnormally increased river bed gradients or some morphometric parametres, like those portraying relationship between valley floor width and relief energy. A notable example is the Central Carpathian Depression where NW-arranged array of morphological depressions are located upon exposures of relatively resistant, thick-bedded sandstone complexes. On the other hand, differences in the amount and rate of fluvial incision observed throughout relatively small area, i.e. developing under comparable, regionally consistent climatic conditions, point to young tectonic control. Well-pronounced topolineaments either follow fault-related zones of weakness, provided one side of the fault is composed of strongly resistant rocks, are associated with dense network of extensional cross-fold joints, or indicate recent reactivation of some faults and/or joint sets.

The presence of long and narrow zones that show alternately uplifting and subsiding tendencies in the eastern segment of the Outer Carpathians of Poland and are aligned subparallel to or crossing under small angles the structural grain of the region appears to exclude their purely isostatic origin. Localised uplift of frontal thrusts and larger slices could have resulted from recent relaxation of horizontal stresses accumulated within the overthrust nappes. Such a mechanism explains: (a) manifestations of localised young uplift occurring along frontal thrusts of some imbricated slices, (b) the present-day configuration of S_{hmax} recorded by breakouts in wells that pierce through the flysch nappes and their substratum (cf. Jarosiñski 1998), and revealed by focal mechanisms of the 1992-1993 Krynica earthquakes (Wiejacz 1994), as well as (c) the orientation of maximal compressive stress interpreted from joint pattern in late Neogene molasses that rest unconformably upon eroded flysch units (Zuchiewicz et al. 2000).

Sublongitudinal zones of localised uplift started to form during postorogenic collapse of the Outer Carpathian belt, most probably in late Miocene-Pliocene times. This uplift is considered to be a byproduct of relaxation of remnant horizontal stresses accumulated during the Late Neogene thrusting.

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