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On different approaches to neotectonics: A Polish Carpathians example

The Carpathian Mountains of central Europe show differential neotectonic behavior that is dependent upon crustal thicknesses and isostatic anomalies. Studies of erosional dissection of rock socles of fluvial terraces compared to the morphometry may help to determine the neotectonic activity of the region. Rates of uplift recorded in the Polish Carpathians differ very little from those calculated for other Alpine regions of Europe.

Introduction

The term "neotectonics" denotes post-Miocene vertical and horizontal structural activity on both global and local scales, which may be studied by geological, geomorphological, geodetic, seismic, and volcanological methods (Morner, 1978; Winslow, 1986; Vita-Finzi, 1986; Pavlides, 1989). The earliest time boundary for neotectonic activity usually is related to the time of origin of the present plate configuration or stress field of a region (Hancock and Williams, 1986).

The Carpathian mountain system (fig. 1) along the southern border of Poland contains two principal tectonic units, the Inner and Outer Carpathians, which are separated by a deeply penetrating suture zone called the Pieniny Klippen Belt (fig. 2). The Inner Carpathian units, composed mostly of Mesozoic to early Tertiary sedimentary sequences superposed upon crystalline basement, were folded during Late Cretaceous time and were uplifted in the middle Miocene (Książkiewicz, 1977). The Outer Carpathians, in turn, represent a leading imbricated fan (see Boyer and Elliott, 1982), consisting of a series of thrust sheets piled one upon another and composed chiefly of Upper Jurassic through lower Miocene flysch deposits. The main episode of folding took place early in the Styrian orogeny during late Burdigalian time (Kotłarczyk, 1985). The subsequent thrusting, associated with oblique subduction of the East European Platform under the Pannonian microplate (Oszczypko and Slaczka, 1989), proceeded from west to east diachronously from the late Burdigalian through the middle to late Serravallian (Oszczypko and Tomas, 1985).

The amplitudes of Neogene vertical movements in the Polish Carpathians range from 300 to 1,000 m, but the amount of Quaternary uplift does not exceed 170 m (Zuchiewicz, 1984, 1987). Recent vertical crustal movements recorded in this region change from -1 to $+2$ mm a^{-1} (Joo and others, 1981). These movements are controlled mainly by variable crustal thicknesses and the distribution of isostatic anomalies (Zuchiewicz, 1989). Rates of present-day horizontal movements are 7–10 mm a^{-1} (extension) in the West Carpathians and 9–15 mm a^{-1} (compression) in the East Carpathians. Seismic intensities of the Polish Carpathian earthquakes range from IV to VII+ on the Mercalli scale, whereas their magnitudes do not exceed 5 on the Richter scale.

Figure 1.—The Carpathian-Balkan region showing structural features and geographic divisions (based on Royden and others, 1983). **Explanation:** 1, molasse; 2, Outer Carpathians; 3, Inner Carpathians; 4, area of Polish Carpathians shown in figure 2; BM, Bohemian Massif; E, East European Platform; EA, Eastern Alps; SA, Southern Alps; PA, Peri-Adriatic Line; WC, West Carpathians; EC, East Carpathians; SC, South Carpathians; Vr, Vrancea region; A, Apuseni Mountains; M, Moesia microplate; PB, Pannonian microplate; DA, Dinarides mountain belt; V, Vardar zone.

Neotectonic studies in the Carpathians have been of three general types: (1) the application of classical geologic and geomorphic methods of mapping and interpretation, (2) the construction of various morphometric maps based on mathematical transformation of the present-day topography, and (3) the use of a wide range of mathematical techniques to model the theoretical longitudinal river profiles and the valley network, as well as to process statistically the drainage-basin parameters. In this paper, I will concentrate chiefly on the Polish Carpathians (figs. 2 and 3), where numerous geomorphic studies of all three general types have been conducted.

Classical geomorphic methods

Most papers published on neotectonic studies in the Carpathians have attempted to reconstruct the neotectonic influence upon geomorphological development. The drainage pattern and distribution of the main geomorphic units have been associated with transversal and longitudinal undulations of the orogen, and a structural control for the orographic network has been emphasized strongly. Numerous authors have dealt with the spatial distribution, origin, and age of planation surfaces, the mutual relationships between tectonic elevations and depressions, and the deformation as recorded in the topography of planation levels.

Morphological manifestations of Quaternary tectonic activity include the disturbances that can be seen in longitudinal profiles of river terraces, the diversified rates of erosional dissection, the lack of sections showing complete sequences of alluvial deposits in the Carpathian valleys, and the presence of slopes displaying convex-upward profiles. The Pleistocene hydrographic changes enable one to interpret local subsidence or warping of fold structures, whereas

oscillations in the erosional base level appear to be the primary evidence for differentiation of morphogenetic processes during consecutive Quaternary stages. Geological studies on Carpathian landslides provide evidence for seismic triggering of some of these features.

Examples of Quaternary subsidence of the Carpathian foredeep include the presence of thick lower Quaternary conglomerates, the

Figure 2.—Tectonic units of the Polish Carpathians (based on Książkiewicz, 1977). Explanation: 1, Carpathian frontal thrust; 2, subordinate thrusts; 3, faults; 4, Pieniny Klippen Belt; 5, Miocene molasse resting on eroded flysch deposits; 6, axis of the regional gravimetric low. Inner Carpathians: T, Tatra units; FC, Podhale Flysch (Eocene-Oligocene). Outer Carpathian thrust sheets: MA, Magura; DU, Dukla; SL, Silesian; SSI, sub-Silesian; SK, Skole.

Figure 3.—Principal physiographic units of the Polish Carpathians, including: ONT, Orava-Nowy Targ Basin; LPF, Lacko-Podegrodzie Foothills; KSB, Kotlina Sadecka (Nowy Sącz) Basin; ZD, Zakliczyn Depression and Roznow Foothills. Abbreviation: MTS., Mountains. Sawtoothed line represents Carpathian frontal thrust.

alternation of several series of bedload- and overbank-facies deposits in the Vistula alluvial fan that was deposited in front of the rising Carpathians, the encroachment of Holocene alluvium upon older denudational and eolian landforms, and the persistent tendency for some main rivers to migrate laterally along the subsidence axis.

Main valleys of the Polish Carpathians bear traces of eight or nine terrace steps dating from the Pleistocene and two to four, from the Holocene. Most are either rock-cut or erosion-accumulational terraces; however, the Last Glacial (Vistulian) and the Holocene terraces are cut-and-fill depositional landforms, except for some that are located in neotectonically elevated morphostructures. The altitudes of terrace rock socles and the variable amount of their dissection during consecutive Quaternary stages may reflect, to some extent, the rate of recent tectonic uplift of individual drainage basins. Even though numerous attempts have been made to correlate and date these terraces stratigraphically, their age is still debated. A tentative climatic and morphostratigraphic chronology of the Polish Carpathian terrace system seems to correlate with the northwest-European (Koster and Castel, 1980; Sibrava, 1986) and north-Polish-lowland (Rozycki, 1978; Lindner, 1981) climatostratigraphic subdivisions in the following way (compare Zuchiewicz, 1987): T_1 , Praetiglian-earliest Quaternary; T_2 , Eburonian-Otrock stage; T_3 , Menapian-Narewian; T_4 , Elsterian 1-Nidanian; T_5 , Elsterian 2-Sanian; T_6 , Saalian-Odranian; T_7 , Warthe-Wartanian; T_8 , Weichsel-Vistulian; T_9 , Late Glacial (late Vistulian=15–10 ka) erosional step; and T_{10-13} , Holocene terrace steps.

Rates of Quaternary erosional dissection of rock socles of fluvial terraces (fig. 4) in the Polish Carpathian valleys range from 0.02 to 2 mm a^{-1} and increased in the late Pleistocene and the Holocene. Intensive dissection during the latest Pleistocene and the Holocene

was restricted, however, to certain regions, including the longitudinal elevations truncated by the Raba, Dunajec, and San valleys (fig. 3). In the middle Pleistocene (440–195 ka), the rate of dissection dropped significantly. A general diminishing of the absolute amount of erosional downcutting is indicated during consecutive Quaternary ages, and the total value of dissection of terrace rock socles generally decreased from west to east (fig. 5). For example, downcutting during the period 2,200–900 ka ranged from 70 to 110 m in the Sola valley and from 30 to 40 m in the San valley, whereas in the timespan of 130–90 ka, downcutting was about 10 m in the Sola valley and ranged from 10 to 30 m in the San valley. The Beskid Sadecki Mountains, the Pieniny Mountains, and an area along the northern margin of the Beskid Niski Mountains (fig. 3) are the only places where dissection penetrated into solid rocks during the latest Pleistocene and the Holocene. Average rates of Quaternary incision into these solid rocks are more or less uniform and only changed from 0.05 to 0.08 mm a^{-1} . However, at least three episodes of increased erosional activity can be traced in nearly all the main drainage basins. These episodes include, roughly, the Cromerian-Elster 1 to Elster 1/2 (800–472 ka), the Eemian and early Vistulian (130–90 ka), and the latest Pleistocene and Holocene (15–0 ka) (fig. 4). During these episodes, the highest rates of dissection were in the west, middle, and east Polish Carpathians, respectively: 0.18, 0.21, and 0.15; 0.30, 0.18, and 0.40; and 0.33, 0.20, and 2.00 mm a^{-1} . The times that show considerably lowered fluvial activity, in contrast, include the Tiglian-Eburonian-Waalian (2,200–900 ka) and Holsteinian *sensu lato*-Drenthe-Treene (440–195 ka); these are characterized by rates of fluvial erosion equal to 0.05, 0.02, and 0.02; and 0.12, 0.15, and 0.08 mm a^{-1} , respectively.

Figure 4.—Rates of Quaternary erosional dissection of rock socles of terraces within the main valleys of Polish Carpathian rivers.

All the dissection rates stated above are comparable with the rates of Quaternary uplift that have been calculated for the neotectonically uplifted Rhenish Massif (compare Bibus, 1983; Semmel, 1983), which is dissected by the middle Rhine River (0.01 to 1.0 mm a⁻¹), and with the rates of uplift that have been inferred for the Iller-Lech Platte region of the Bavarian Alps (compare Brunnacker and others, 1982) (fig. 6). These uplift rates are, in turn, at least 1 to 2 orders of magnitude lower than middle and late Quaternary uplift rates that have been recorded in the Karakoram Range of India and Pakistan and the Himalayas of eastern Nepal (compare Kalvoda, 1988) (fig. 7).

Detailed geomorphic studies of fluvial terraces along a river that dissects different morphotectonic units may help in reconstructing the neotectonic behavior of a region. The best opportunity for such studies in the Polish Carpathians is provided by the Dunajec River (figs. 3 and 8), which cuts across different morphostructures that belong to the Inner and Outer Carpathians. All the morphotectonic units display different patterns of terraces, each of which shows peculiar neotectonic disturbances (fig. 8). 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 Mountains), a higher uplifted mountain range belonging to one of longitudinal neotectonic elevations (Beskid Sadecki Mountains), and a foothills region showing diversified, young tectonic evidence that probably is related to reactivation of the coinciding Miocene fault zones (Lacko-Podogrodzie Foothills). Pro-

gressively onward to the north are another intramontane basin of moderate subsidence (Nowy Sacz Basin), a range of mountains of medium elevation showing evidence of uplift (Beskid Wyspowy Mountains), and a region of highly elevated foothills, cut on their northern rim by a recently formed neotectonic escarpment (Roznow Foothills). Figure 9 shows the rates of Quaternary uplift approximated by rates of fluvial incision into terrace rock socles within individual morphostructures of the Dunajec drainage basin. The highest figures are confined to the Beskid Sadecki Mountains and the Lacko-Podogrodzie Foothills, whereas the youngest episode of uplift (10–0 ka) is recorded on the northern margin of the Nowy Targ Basin, in the Pieniny Mountains, and, less clearly, in the Beskid Sadecki Mountains. 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 fault zones is likely to have occurred, especially in the Lacko-Podogrodzie Foothills and the Beskid Wyspowy Mountains. This type of alternation of morphostructures, which shows varying rates of neotectonic movements, may reflect either Quaternary remnant folding or, more probably, concurrent isostatic adjustment.

Morphometric maps

A wide range of morphometric techniques may be used to interpret neotectonic impact upon the evolution of a landscape. Among these

Figure 5.—Amounts of Quaternary erosion for time intervals A through E within the main valleys of Polish Carpathian rivers.

Figure 6.—Rates of Quaternary uplift determined in the Iller-Lech Platte region of the Bavarian Alps and along the middle Rhine River, which dissects the Rhenish Massif, Western Europe (based on data published by Brunnacker and others, 1982; Bibus, 1983; and Semmel, 1983). Thick solid line is the average rate of uplift calculated for the Quaternary; dashed line is the cumulative rate.

Figure 7.—Rates of Quaternary uplift determined in the western Karakoram Range of India and Pakistan and the Himalayas of eastern Nepal (based on Kalvoda, 1988). Black areas denote the range of uplift rates.

techniques is the compilation of maps portraying relief energy, drainage density, valley gradients, summit levels, stream-line surfaces, generalized contours, base levels, and goniobases (see definition below). In the Polish Carpathians, summit-level, base-level, goniobase, and isolong maps (Raczkowski and others, 1984) have been used most extensively (fig. 10).

Base-level maps (Pannekoek, 1967; Filosofov, 1970) make it possible to construct sets of other maps that show differences between various surfaces, including the present-day topographic surface. Within uplifted areas, valley gradients increase, and hence, distances on isobases tend to be shorter. The reverse happens in areas of subsidence. Local anticlinal structures are characterized by short distances on isobases (Filosofov, 1970) and result in chainlike or horseshoelike patterns. Within homoclinal structures, isobases show

straight trends and parallel one another. For investigations of mountainous morphostructures, goniobase maps have been introduced (Filosofov, 1970), the construction of which consists in linking, by straight lines, the points at which individual thalwegs are crossed by given topographic contours.

The application of base-level or goniobase maps to the studies of neotectonic activity is, nonetheless, restricted to certain regions. These maps may be particularly helpful in analyzing the morphological evolution of areas that developed during one geomorphic cycle. Otherwise, one is confronted with landscapes that are situated at different altitudinal levels and were formed by diversified processes during various evolutionary cycles. Such areas should, therefore, be dealt with separately and should not be included on one base-level surface. This applies especially to mountainous topography. Base-

Figure 8.—Amounts of Quaternary incision of the Dunajec River within different morphotectonic units of the Polish Carpathians. Explanation: 1, moderately high mountains; 2, low mountains and high foothills bearing traces of early Pliocene planation surfaces; 3, moderately high foothills bearing traces of late Pliocene planation surfaces; 4, low foothills and intramontane basins bearing traces of early Quaternary planation surfaces; MTS., Mountains.

Figure 9.—Rates of Quaternary uplift approximated by rates of erosional incision into rock socles of terraces as recorded in some Polish Carpathian morphostructures of the Dunajec drainage basin.

level maps should be constructed, if at all, for plain and upland regions only. Results obtained from young orogenic belts sometimes may be deceptive (Raczkowski and others, 1984; Baumgart-Kotarba, 1986; Starkel, 1985).

Maps of isolongs (Gvin, 1965; Zuchiewicz, 1981) facilitate the estimation of the relationships between structure and valley growth. On these maps, isolines, expressing equal lengths of valley sectors, are marked with respect to valley order. Lengths of individual valley links are assigned to centers of the measured stretches and then are connected by smooth curves. The highest figures usually coincide with narrow tectonic troughs, whereas the lowest ones usually characterize tectonic uplifts. The isolong pattern also reflects buried, uplifted structures. These maps have been applied successfully to the Polish Carpathians and have enabled recognition of the morphostructures that display the most intensive Quaternary uplift or subsidence (fig. 10).

Statistical approach

Additional methods used in the analysis of the neotectonic history of the Polish Carpathians have been mathematical-statistical studies aimed at the construction of theoretical "equilibrium" river-bed profiles (Zuchiewicz, 1980; Bober and Oszczytko, 1984; Bober and others, 1985), the calculation of concavity ratios of normalized river-bed profiles (Zuchiewicz, 1980, 1987), and the statistical processing of physiographic parameters of small drainage basins (Zuchiewicz, 1980; Krawczyk and Zuchiewicz, 1989). Other approaches consist of reconstructing paleostress directions deduced from the drainage patterns (Zuchiewicz, 1986) and evaluating the compaction-induced subsidence of the Carpathian foothills (Oszczypko and others, 1986).

Mathematical models of the so-called "equilibrium profile" of a river bed are based on the channel equilibrium theory and the general diffusion equation. Numerous algorithms have been proposed to approximate the longitudinal river profile; none of them, however, proved satisfactory when applied to the Polish Carpathians (fig. 10). The question of usefulness of the equilibrium profile of a river bed

remains unanswered (Baumgart-Kotarba, 1986; Zuchiewicz, 1987), and any future solution must include hydrological and paleohydrological data.

Longitudinal profiles of river beds plotted on standardized diagrams, which show both vertical and horizontal distances between headwaters and mouths scaled to values ranging from 0 to 1.0, make it possible to compare streams of different lengths and gradients. The concavity ratio serves as a measure of the river-profile maturity, for this ratio increases as the intensity of uplift diminishes. The distance between inflection point and river mouth represents the sector that is dominated by bank erosion and fluvial aggradation, and the length of this sector becomes shorter as uplift accelerates.

Statistical processing of drainage-basin parameters also may be helpful in neotectonic studies (table 1). The most useful physiographic indices (fig. 11) include those that indicate the influence of young tectonic movements upon drainage-basin morphology (relative length of first-order valleys, basin relief, valley gradient, length ratio) in small drainage basins, as well as those that reflect drainage-basin maturity (drainage density of Krawczyk and Zuchiewicz, 1989). Lithological differentiation of solid rocks within a given catchment area is best reflected by the maximum basin length and the basin perimeter. An increased number of first-order valleys could indicate that strong rejuvenation of relief is related to recent tectonic activity. In the Polish Carpathians, these figures are generally higher in the western part of the orogenic belt (75–80 percent). Special attention should be given to low N_1/N (number of first-order valleys to the total number of valleys) values (66–67 percent) in the southern part of the Jasło-Sanok Depression, where recent subsidence is known (fig. 3).

In the case of large drainage basins, the bifurcation ratio and basin magnitude are very important parameters (Zuchiewicz, 1987; Krawczyk and Zuchiewicz, 1989). These values increase within the areas that display neotectonic uplift, as long as the lithology of the underlying rocks is not highly diversified.

Another opportunity for morphotectonic and neotectonic inference is provided by studies on the orientation of principal stress axes. These axes are inferred from the orientation of the rectified drainage network (see Scheidegger, 1980; Zuchiewicz, 1986) and then are

Figure 10.—Neotectonic elements in the Polish Carpathians. Explanation: 1, uplifted areas detected on morphometric (base-level, goniobase, isolong) maps; 2, axes of longitudinal elevations inferred from geomorphic studies; 3, neotectonic depressions; 4, Pliocene-Quaternary escarpment 100–150 m high; 5, river beds. Theoretical river-bed profiles indicative of neotectonic: 6, subsidence; 7, stability; 8, uplift. Additionally: 9, Carpathian frontal thrust; 10, State boundary.

Figure 11.—Typical patterns of interrelated drainage-basin parameters within areas of different neotectonic behavior, based on 1,500 drainage basins of the Polish Carpathians (taken from Krawczyk and Zuchiewicz, 1989). Correlation coefficient: 1, above (+) 0.6; 2, below (–) 0.6. See table 1 for explanation of symbols.

Table 1.—Drainage-basin parameters applied to neotectonic studies

Characteristic	Most suitable parameters
Lithology of underlying rocks	R_L
Landscape type	A, F_v , D_v
Degree of landscape rejuvenation	L_w , S, H, F_v , D_v
Direct influence of young tectonic movements (small drainage basins)	L_w , H, S, R_L
Indirect influence of young tectonic movements (large drainage basins)	R_b , M, L_w , D_v , S

DEFINITIONS

- A, basin area, in km^2
 L_b , maximum basin length, in km
 L_1 , total length of first-order valleys, in km
 L_w , relative length of first-order valleys, shown in percent of the total valley length
 L_u , total length of valleys of a given order, in km
 Total L, total length of all valleys in a given basin, in km
 S, valley gradient, in m/km
 H, basin relief ($H = H_{\max} - H_{\min}$), in m
 P, basin perimeter, in km
 R_b , bifurcation ratio (N_u/N_{u+1})
 R_L , length ratio (L_u/L_{u+1})
 D_v , drainage density (total L/A), in km/km^2
 F_v , valley frequency (N_u/A), in N/km^2
 T, basin texture (N/P), in N/km
 M, basin magnitude, expressed by the number of headwaters
 u, valley order, established according to Horton-Strahler's hierarchy
 N, number of valleys

compared with parameters of the stress field that is reconstructed on the basis of fault and joint measurements. Such a comparison indicates that the maximum axis of compression during recent Quaternary time is aligned N. 20° W. in the Polish Carpathians.

Final remarks

All the techniques used in neotectonic reconstructions (as discussed above) should be verified, one by one, through careful geological mapping, remote-sensing studies, and geophysical profiling. Also, a wide range of various methods should be applied to the reconstructions in an attempt to distinguish between facts, indirect evidence, and pure, although sometimes very elegant, hypotheses.

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