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STRUCTURAL GEOMORPHOLOGICAL STUDIES IN THE POLISH CARPATHIANS
A REVIEW

INTRODUCTION

Classic geomorphological 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 planation surfaces, history of fluvial changes, aided by more and more detailed palaeogeographic reconstructions performed with the help of palaeoclimatic, palaeohydrological, palaeontological, palaeoecological, archaeological, mineralogical-petrographical and geophysical techniques, should be listed as the most frequently discussed subjects.

The aim of this paper is to review some aspects of structural-geomorphological and morphotectonic studies that have been conducted in the Polish segment of the Carpathians during the last decade. Previous research in this domain has been summarized by Zuchiewicz (1995a, 1995c).

CHANGE OF FOCUS

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.

GEOLOGICAL SETTING

The Polish segment of the Outer West Carpathians is a typical fold-and-thrust belt (Fig. 1), composed of a series of thrust sheets piled one upon another during middle-late Miocene times (Książkiewicz 1977; Oszczypko 1996). The nappes are composed predominantly of Cretaceous through Lower Miocene flysch strata. The thrusting proceeded with time towards the north and the east as a result of oblique convergence between the North European and Pannonian plates (Oszczypko and Ślączka 1985). This convergence was nearly finished by latest Miocene time. Recent studies of balanced cross sections indicate that the only possibility of Plio-Quaternary deformations in the Outer Carpathians is due to reactivation of the inner parts of the orogenic belt via out-of-sequence thrusting, back-thrusting in the Silesian nappe or fault reactivation in the Dukla nappe (Roure et al. 1993).

In the Pliocene and Quaternary, the area witnessed differential vertical and some remnant horizontal movements, resulting in the formation of elevated and subsided areas (cf. extensive discussion in Zuchiewicz 1995c). Recent seismicity is confined to the Pieniny Klippen Belt and some oblique-slip faults cutting both the Slovak and Polish Carpathians (see Zuchiewicz 1989, 1995c). Infrequent focal solutions and breakout analyses point to a radial arrangement of the recent horizontal maximum stress axes, being perpendicular to the structural grain of the region (cf. Jarosiński 1997). Geodetically measured vertical crustal movements range from 0 to +1 mm/yr (e.g. Czarnecka 1986; Makowska and Jaroszewski 1987; Nikonov et al. 1987), the horizontal motions detected in the Pieniny Klippen Belt attaining 0.5 mm/yr (Ząbek et al. 1993).

PLANATION SURFACES: UNSOLVED PROBLEM

The 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. Four surfaces in the Outer Carpathians, and 4 to 6 in the Inner Carpathians have been distinguished (cf. Starkel 1972; Baumgart-Kotarba 1983; Zuchiewicz 1984; 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 Inner Carpathian area are the only exception (i.a. Kukulak 1991a, 1993; Bac-Moszaszwili 1993, 1995).

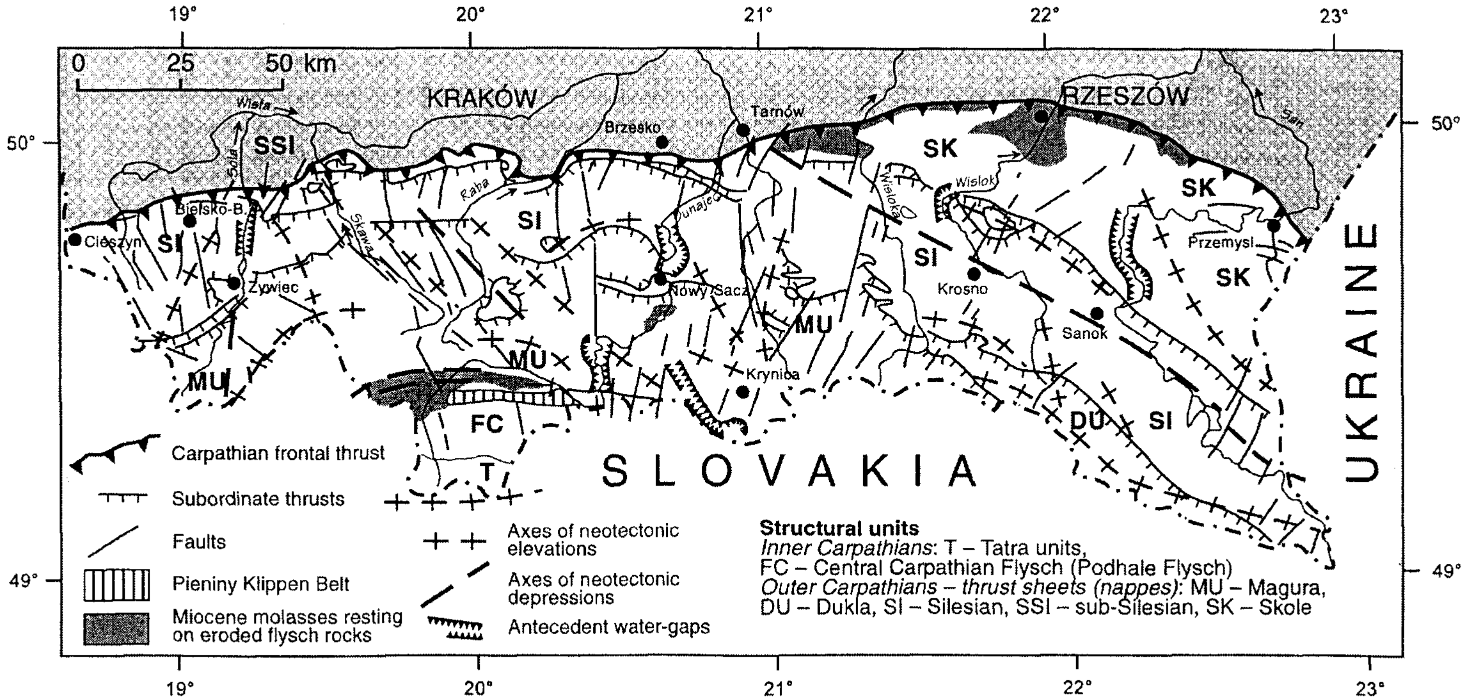

Fig. 1. Structural sketch of the Polish Carpathians (based on Książkiewicz 1977 and Zuchiewicz 1995c)

Ryc. 1. Szkic strukturalny Karpat polskich (wg Książkiewicza 1977 i Zuchiewicza 1995c)

Numerous pieces of evidence for the nearly permanent Neogene mobility of the Outer Carpathian thrust sheets (cf. Oszczypko and Ślączka 1985; Oszczypko 1996, 1997) 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/yr (Oszczypko 1997). 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 1995c).

STRUCTURAL CONTROL ON LANDFORMS

Structurally-controlled landforms have been either mapped or inferred from the analysis of morphometric maps and statistical modelling of the topography.

Evidence for Quaternary faulting in the Polish Carpathians is far from sufficient. Few examples have been documented, more or less convincingly, from the Orawa–Nowy Targ Basin (cf. Baumgart-Kotarba 1983, 1997; Pomianowski 1995), Podhale region (Kukulak 1985; Szczęsny 1987), Pieniny Klippen Belt (Czarnecka 1986), Jeleśnia Basin (Wójcik 1989), NW margin of the Nowy Sącz Basin (Tokarski 1978), southern part of the Jasło–Sanok Depression (Zuchiewicz 1987), and the south-western (Niedziałkowska and Szczepanek 1993–94) and south-eastern segments of the Carpathian Foredeep (Laskowska-Wysoczańska 1995).

Morphological manifestations of Quaternary tectonic activity include, i.a., disturbed longitudinal profiles of strath terraces (Starkel 1972; Zuchiewicz 1991, 1995c), 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; Ziętara 1988, 1991; Bajgier 1988, 1989, 1993; Poprawa and Rączkowski 1996; Wójcik and Zimnal 1996; Margielewski 1997). The largest landslides are usually confined either to fault zones or frontal thrusts of nappes and slices (Ziętara 1991; Bajgier 1993; Wójcik 1997) throughout the Outer Carpathians. 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, 1991b; Bajgier 1989, 1993) and/or seismic control have frequently been suggested (Bober 1984; Michalik 1987; Bajgier 1993; Poprawa and Rączkowski 1996; Wójcik 1997), without giving convincing evidence.

Gravitational processes in suitable structural settings appear to be of primary importance for the formation of ridge-top trenches, rifts and other dilational, pseudo-karst features, both in the Outer (cf. Alexandrowicz and Alexandrowicz 1988; Margielewski 1997) and Inner Carpathians (Michalik 1987). Diversified lithology, structure and increased density of jointing control the development of waterfalls and rapids within Outer Carpathian river beds (Ziętara and Lis 1986).

Dense-contour maps constructed for the Podhale region show at least two linear zones oriented NW–SE to NNW–SSE and NNE–SSW to NE–SW that coincide with fault zones (Ozimkowski 1991). This coincidence does not necessarily mean recent reactivation of the faults; it rather indicates those valley stretches which use structural zones of weakness. Digital processing of dense-contour maps for the medial and eastern segments of the Outer Carpathians (Kuśmierek 1990; Magiera and Kuśmierek 1994) clearly shows the decisive control exerted by bedrock lithology.

RATES OF RIVER DOWNCUTTING

Rates of river downcutting 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).

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, characterised by the presence of young straths. A tentative climatostratigraphic subdivision of these terraces is shown in Fig. 2, based on the example of the Dunajec river valley, dissecting different physiographic units (Starkel 1972; Zuchiewicz 1989).

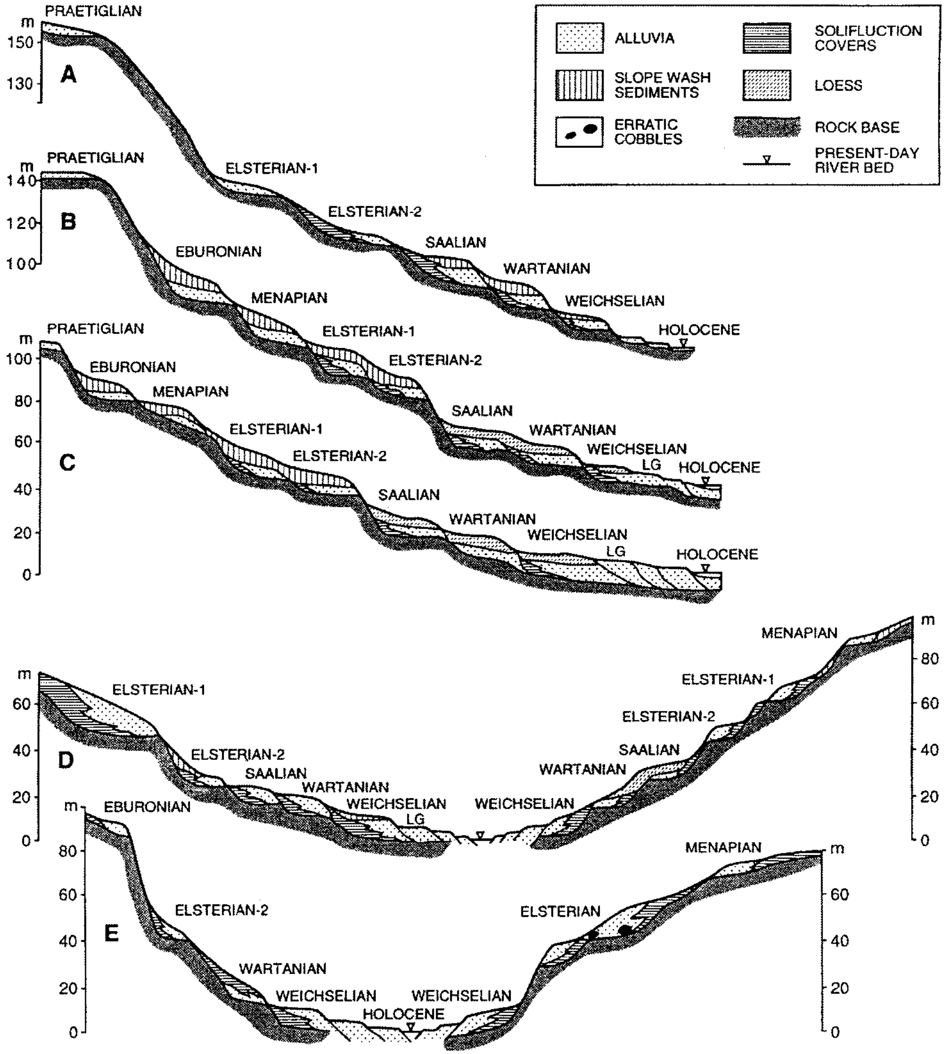

Fig. 2. Climatostratigraphic subdivisions of Quaternary fluvial and slope sediments in the Dunajec river valley, medial segment of the Polish Outer Carpathians, within different morphotectonic units, from the south to the north: A — Beskid Sądecki Mts, B — Łącko–Podegrodzie Foothills, C — Nowy Sącz Basin, D — Beskid Wyspowy Mts, E — Ciężkowice Foothills

Ryc. 2. Schemat klimatostratygraficzny osadów rzecznych i stokowych w dolinie Dunajca w obrębie wybranych jednostek morfotektonicznych: A — Beskidu Sądeckiego, B — Pogórza Łącko–Podegrodzkiego, C — Kotliny Sądeckiej, D — Beskidu Wyspowego, E — Pogórza Ciężkowickiego

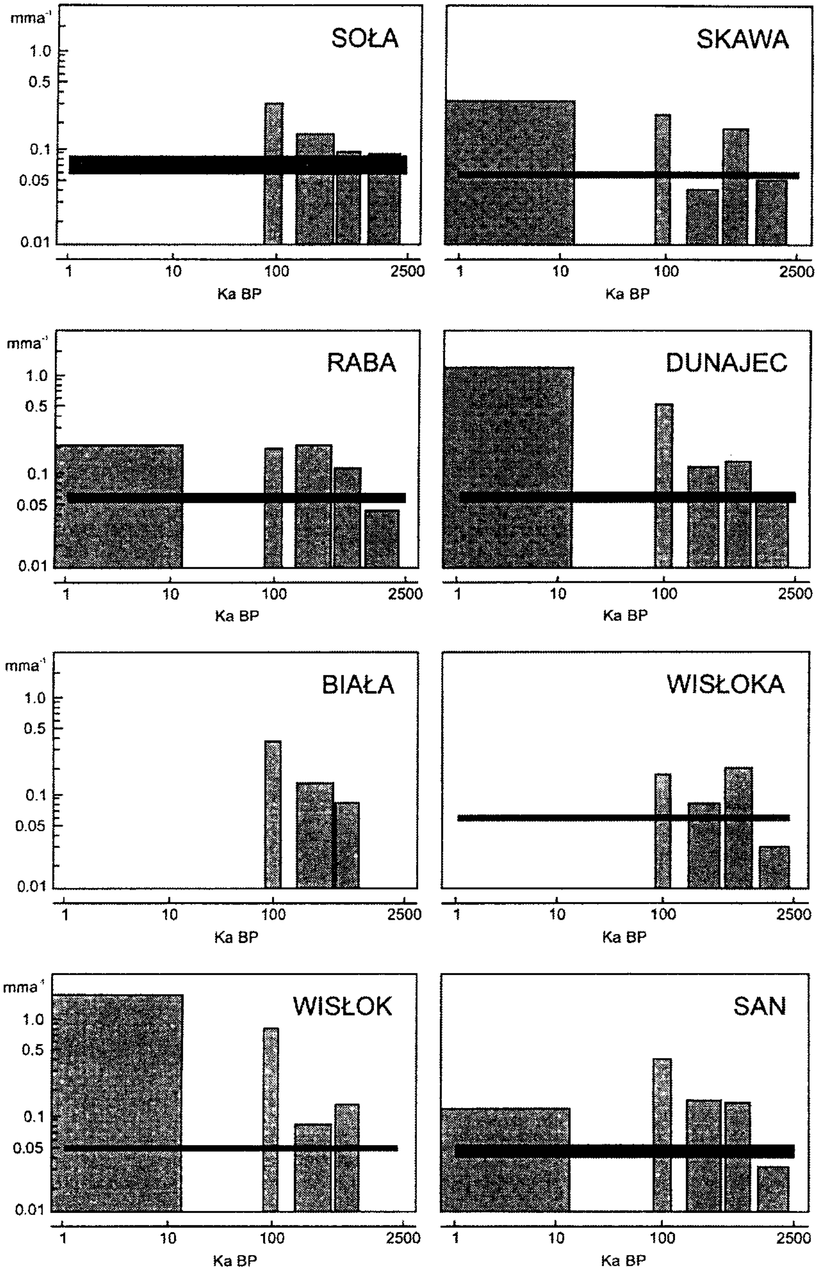

Fig. 3. Rates of Quaternary fluvial downcutting into strath terraces of the main Outer Carpathian rivers that truncate the highest-elevated morphostructures (based in part on Zuchiewicz 1991). Thick bold lines represent average rates for the whole of the Quaternary

Ryc. 3. Tempo czwartorzędowego rozcinania cokołów skalnych teras rzecznych w dolinach rzek rozcinających podnoszone neotektonicznie morfostruktury Karpat zewnętrznych (wg Zuchiewicza 1991). Linie pogrubione oznaczają średnie tempo rozcinania w czwartorzędzie

Longitudinal profiles of individual strath terraces frequently show divergence, convergence or tilting that can be indicative of young tectonic control (Zuchiewicz 1987, 1991, 1995c; 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 1995c), but their spatial differentiation appears to be influenced by tectonic factors as well. Figure 3 shows variable rates of fluvial downcutting of strath terraces within those valley reaches which truncate geomorphic units uplifted in Plio-Quaternary times. These figures differ from unit to unit, although three episodes of increased downcutting rates can be distinguished in the Polish Outer Carpathians as a whole (Zuchiewicz 1991), including the Cromerian–Elsterian 1/2 (0.15–0.21 mm/yr), Eemian–Early Weichselian (0.18–0.40 mm/yr) and Late Glacial–Holocene (0.2–2.0 mm/yr) time-spans. The actual rates must have been much more higher, when we accept Starkel's (1985) opinion on 10–20 thousand-year-long periods of deep downcutting of early interglacial channels.

MORPHOMETRIC INDICES: THE LURING BEAUTY OF STATISTICS

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 1995c, 1997).

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 (Zuchiewicz 1995d) or the valley floor width/valley height ratios (Zuchiewicz 1995b, 1995c). The zones of abnormally high and low values of the first (Fig. 4) and second (Fig. 5) parameter, respectively, are aligned subparallel to the structural grain of the Outer Carpathians, their number in-

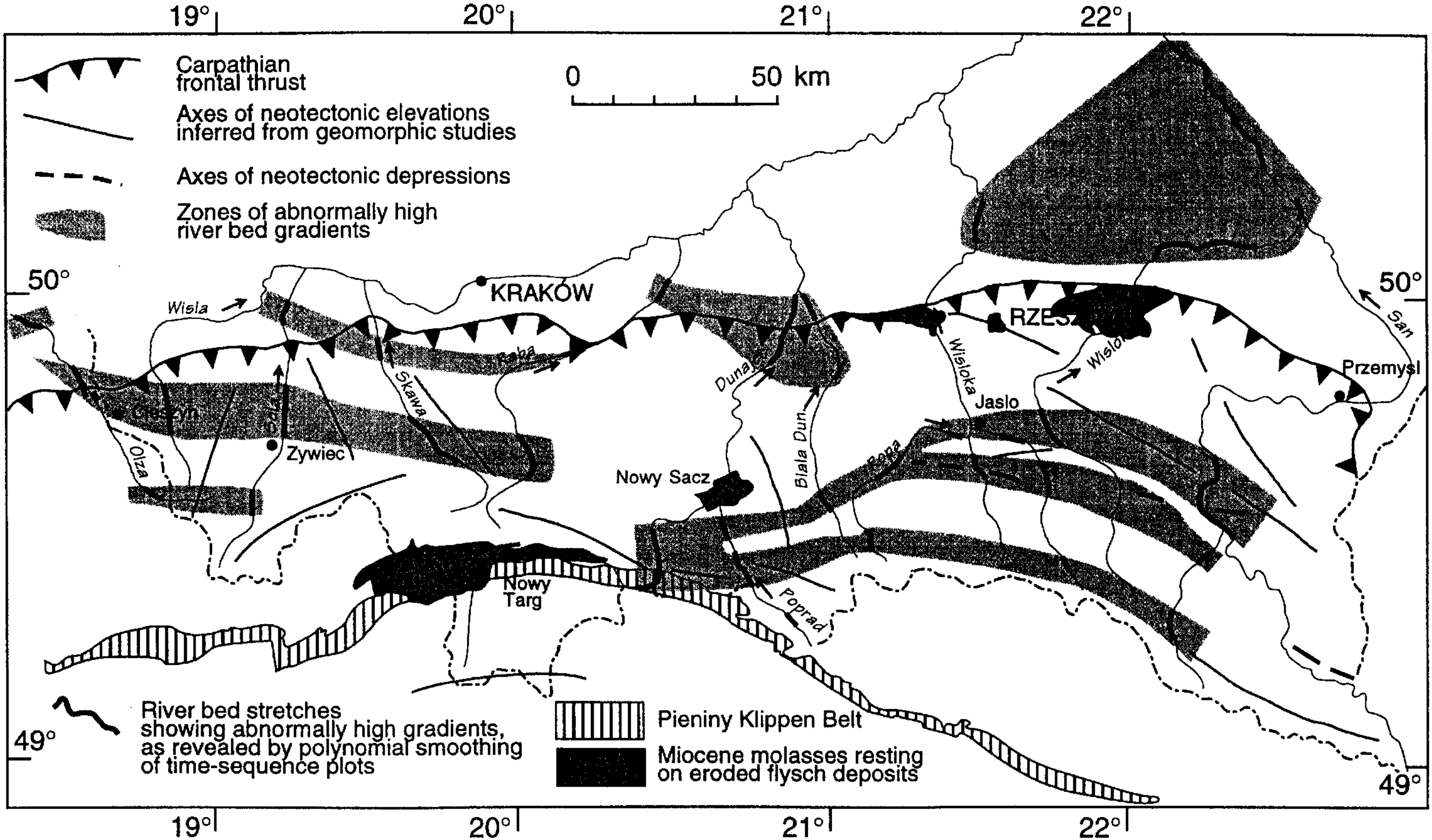

Fig. 4. Neotectonic sketch of the Polish Carpathians, showing river-bed stretches of abnormally high gradients (based on Zuchiewicz 1995d)

Ryc. 4. Szkic neotektoniczny Karpat polskich z uwzględnieniem odcinków koryt rzecznych o anomalnie dużych spadkach (wg Zuchiewicza 1995d)

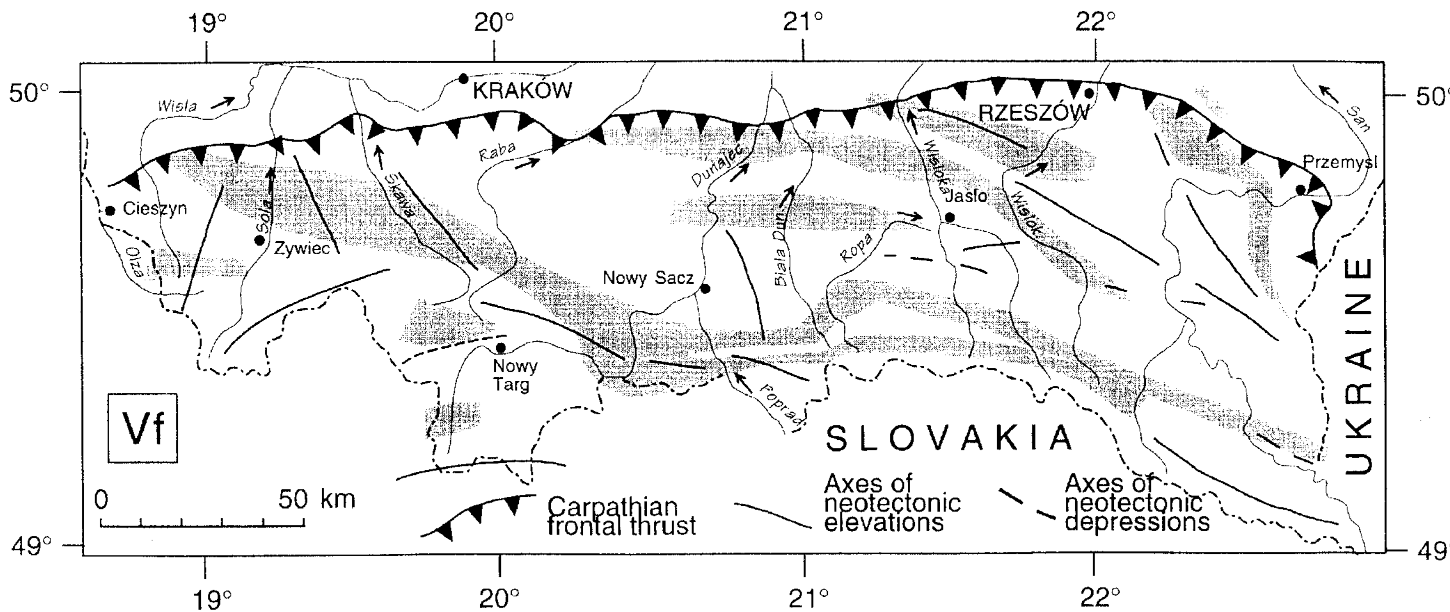

Fig. 5. Neotectonic sketch of the Polish Carpathians, showing the spatial distribution of zones of abnormally low valley floor width/valley height ratios (Vf), based on Zuchiewicz (1995b)

Ryc. 5. Szkic neotektoniczny Karpat polskich z zaznaczeniem stref o anomalnie niskich wartościach wskaźnika szerokości dna/wysokości zboczy doliny (Vf), wg Zuchiewicza (1995b) creasing 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, 1995c) 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.

PERSPECTIVES

The abridged and far from complete review of structural and morphotectonic studies conducted 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.

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STRESZCZENIE

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PRZEGLĄD BADAŃ STRUKTURALNO-GEOMORFOLOGICZNYCH W KARPATACH POLSKICH

W ostatniej dekadzie zaznaczyła się istotna zmiana zainteresowań geomorfologów strukturalnych pracujących w Karpatach. Badania nad genezą wielkoskalowych form rzeźby, powierzchniami zrównania, czy też układami sieci dolinnej, ustąpiły miejsca coraz bardziej zaawansowanym rekonstrukcjom paleogeograficznym, prowadzonym przez specjalistów z różnych dyscyplin, a także mniej lub bardziej wysublimowanym analizom morfometryczno-statystycznym parametrów fizjograficznych zlewni i dolin rzecznych, studiom nad osuwiskami strukturalnymi oraz długo- i krótkookresową ewolucją rzeźby w warunkach zróżnicowanych ruchów tektonicznych. W polu zainteresowań geomorfologów pozostała tradycyjnie kwestia relacji klimat/tektonika w kształtowaniu systemów terasowych. Wiele z prezentowanych hipotez i modeli ma charakter spekulatywny; dalsze badania powinny skupić się na wykazaniu rzeczywistych relacji między ewolucją form i osadów a młodą mobilnością tektoniczną.