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NEOTECTONIC MOBILITY OF THE ROZTOCZE REGION, UKRAINIAN PART, CENTRAL EUROPE: INSIGHTS FROM MORPHOMETRIC STUDIES

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Abstract: The results of geological, geomorphic and hydrogeological research indicate spatially variable neotectonic activity of the Ukrainian part of the Roztocze region. This activity is confirmed by analysis of some geometric and morphometric coefficients (especially drainage basin elongation ratio, drainage basin circulatory ratio, drainage basin shape and lemniscate coefficient), which were calculated for 1646 drainage areas of the 3rd to 6th order, and morphometric linear coefficients (mountain-front sinuosity index and valley floor width-valley height ratio coefficient), which characterise the fault scarps. The south-western margin of the Rava Roztocze and Yaniv Roztocze regions, following NW–SE-trending faults, belongs to structures of the 1st or 2nd class of relative tectonic activity. On the other hand, in the north-eastern marginal zone in the Ukrainian part of the Roztocze region, a relatively active segment comprised between Maheriv and Zhashkiv shows a characteristic NW–SE orientation of valleys, controlled by a network of secondary sub-parallel faults. In the southern part of the analysed area, the Stavchanka River drainage basin related to the NW-striking fault zone, and the sub-parallel edge of the zone of the Vereshytsia-upper Mlynivka transverse depression are relatively active. Some relatively inactive areas are those of smaller drainage basins of the 3rd to 6th order, located within the zone of the main watershed between the Rata and Lubaczówka rivers in the Rava Roztocze region and the Zubra and Poltva rivers in the Lviv Roztocze region.

Key words: neotectonic mobility, morphometric coefficients, Ukrainian part of the Roztocze region, Central Europe.

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INTRODUCTION

The Ukrainian part of the Roztocze region is a tectonic horst, stretching NW–SE, elevated by 110–120 m (Palienko, 1993) with respect to the adjacent areas: Sandomierz Basin in the west, Upper Bug and Styr Basin in the east, and Lviv Opillia in the south (Roslyi, 1990; Hnatiuk, 2002) (Fig. 1). The area represents the watershed between the Vistula and Dnister river basins.

The boundaries of the region, particularly the south-western and the north-eastern ones, clearly show tectonic control related to the south-western marginal area of the East-European Platform, especially the marginal block of the Lviv mega-block in the slope area of the platform (Fig. 2). The south-western boundary of the region is connected with a set of the Stavchanka-Vereshytsia (Nemyriv-Shklo-Mal'chytsi) normal faults (Bogutsky *et al.*, 1998), separating the Carpathian Foredeep basin from Roztocze region (Ney, 1969). The north-eastern boundary is visible as a distinct morphological margin, related to the Rava-Rus'ka–Krehiv fault zone (Khiznyakov & Żelichowski, 1974), and to the Zhovkva–Lviv tectonic area (Bogutsky *et al.*, 1993), known as the Lysynets'kyi fault (Andreyeva, 1986). It separates the Roztocze region from the Upper Bug and Styr Basin (Fig. 1). In its northern section, the margin has a NW–SE orientation, typical of Roztocze region, and in the southern section, a NNW–SSE orientation prevails. The northern boundary of the Ukrainian part of the Roztocze region follows the sub-parallel Early Variscan faults separating the Mazowsze–Lublin mega-block from the Lviv block (Rava-Rus'ka–Horyniec). The southern boundary of the region is controlled by the Lviv–Mal'chytsi fault (Holohory), separating the Lviv and Peri-Dniestrian mega-blocks (Hofshteyn, 1979; Znamienskaya & Chebanenko, 1985; Hnatiuk, 2001).

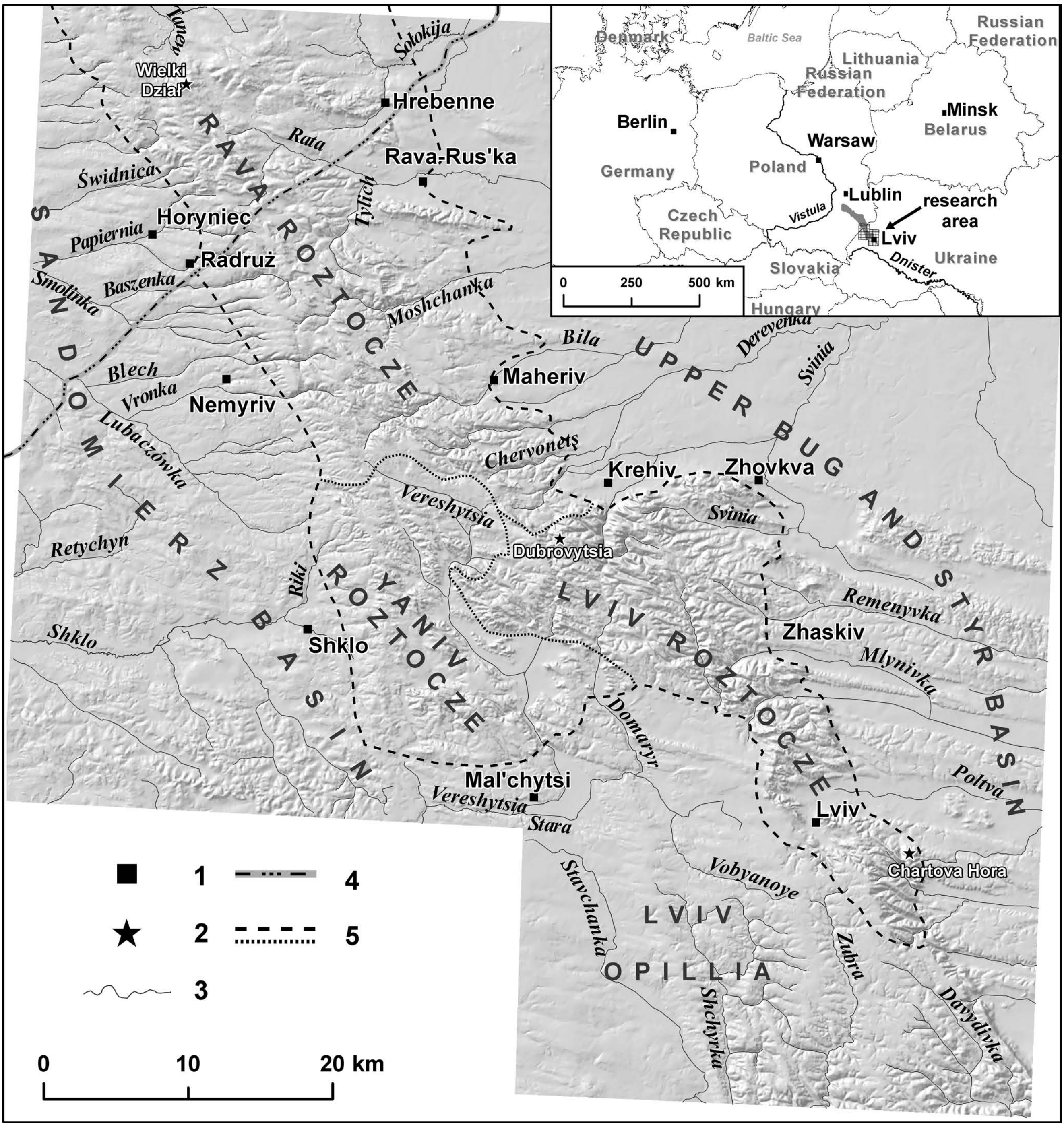

Fig. 1. Surface features in the Ukrainian part of the Roztocze region. Geomorphic regions and subregions in Roztocze according to Roslyi (1990) and Hnatiuk (2002). *1* – towns and places; *2* – the highest hills; *3* – rivers; *4* – boundary between Poland and Ukraine; *5* – boundaries of regions and subregions

In a surficial image of the geological structure of the Ukrainian part of the Roztocze region, lithologically varied Palaeogene and early Neogene (Miocene) rocks (Wysocka, 2002) and Upper Cretaceous (Maastrichtian) strata (Andreyeva, 1986) are prevalent (Fig. 2), locally covered by Pleistocene loess (Maruszczak, 1967) and Holocene sediments (Hnatiuk, 1997).

The problem of Neogene tectonic activity within the boundaries of the Ukrainian part of the Roztocze region has been a subject of geological (Hofshteyn, 1979; Sobakar' *et al.*, 1975; Palienko, 1990), geomorphological (Bogutsky *et al.*, 1993; Hnatiuk, 2001; Buraczyński, 2002) and hydrogeological (Michalczyk & Kovalchuk, 2002) research.

An assessment of the total amplitudes of vertical crustal movements in the Roztocze region showed that the average rate of post-Badenian uplift was 0.2 mm/year (Palienko, 1990). Moreover, the average gradient of the movement ratio was 0.2–0.3 mm/year in the hilltop zone of the region

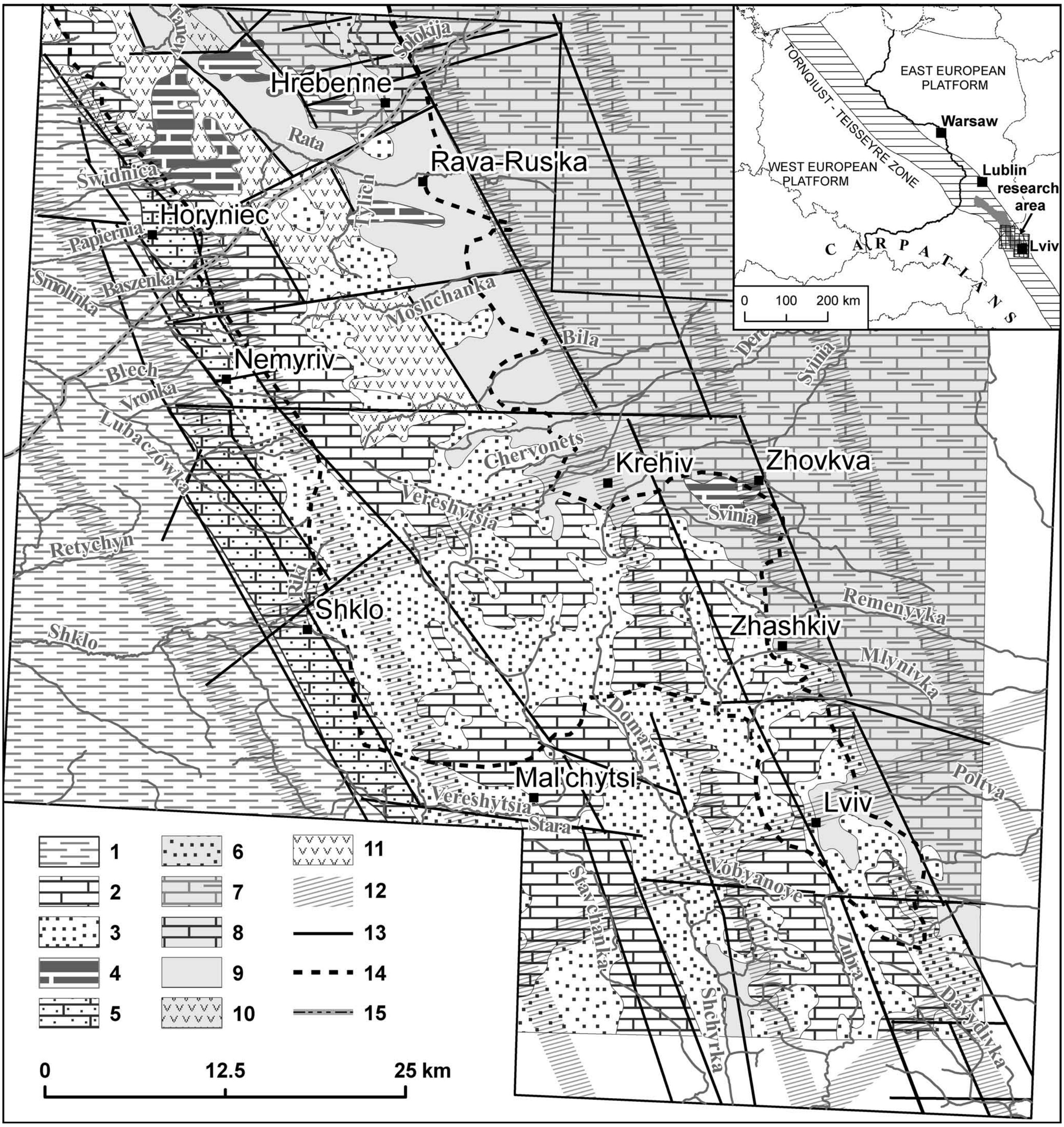

Fig. 2. Geological setting of the Ukrainian part of the Roztocze region, without Quaternary sediments (compiled by T. Brzezińska-Wójcik after: Łomnicki, 1887, 1898; Teisseyre, 1938; Naidyn, 1953; Cieśliński & Wyrwicka, 1970; Khiznyakov & Żelichowski, 1974; Glushko, 1988; Vyshniakov, 1990; Buraczyński & Krzowski, 1994; Popielski, 2000; Hnatiuk, 2001; 2002; Wysocka, 2002; Wysocka *et al.*, 2007; Świdrowska, 2007). Cainozoic: *1* – clays, silts (Sarmatian), *2* – reef and detrital limestones, sandstones (Upper Badenian), *3* – quartz and glauconitic sands (Upper Badenian), *4* – detrital limestones, sandstones and sands (Upper Badenian), *5* – detrital limestones, sandstones and sands (Lower Badenian), *6* – sands and glauconitic sandstones (Eocene); Mesozoic: *7* – marls, marly opokas and chalk (Upper Maastrichtian), *8* – marly opokas and marls (Lower Maastrichtian), *9* – gaizes and marly gaizes (Lower Maastrichtian), *10* – opokas and gaizes (Upper Campanian), *11* – gaizes and opokas (Lower Campanian); *12* – Palaeozoic faults; *13* – Meso- and Cainozoic faults; *14* – borders of Roztocze according to Roslyi (1990) and Hnatiuk (2002); *15* – Polish-Ukrainian border

and 0.4 mm/year – in the eastern marginal zone (Palienko, 1993). According to Hofshteyn (1979), the amplitude of the post-Sarmatian tectonic movements in the Roztocze region reached 300–350 m. An analysis of Pleistocene glaciofluvial deposits within the region suggests that after the Middle Pleistocene the area was uplifted by 30–40 m (Hofshteyn, 1979). The results of repeated precise levellings carried out along a transverse profile through the Roztocze–Lviv

Opillia zone indicate periodic variations of the rates of contemporary tectonic movements. The largest gradients of the gravity field have also been noted in this zone (in the Lviv area more than 0.2 mGal between 1966 and 1970), along with increased values of the heat flow (Sobakar' *et al.*, 1975).

As follows from geomorphic research (Bogutsky *et al.*, 1993), the most important tectonic zones are accompanied by parallel-trending river valleys, most of them showing an asymmetric cross section; one of them is the sub-parallel valley of the Stavchanka River. Boreholes drilled in this valley revealed a 150 m deep, NW–SE striking tectonic depression over a 30-km-long stretch. Towards the north, in the direction of the Vereshytsia River valley, the depression's amplitude changes to 20–30 m. Simultaneously, an analysis of the valley pattern in the Vereshytsia drainage basin (Bogutsky *et al.*, 1993) and longitudinal sections of the valley bottom (Buraczyński, 2002) lead to a conclusion that the sub-parallel Lviv–Mal'chytsi (Holohory) tectonic zone is currently active. This is also confirmed by observations of discharges of springs in this area. According to Michalczyk and Kovalchuk (2002), the largest discharges (20–110 l/s) are noted in the springs in the upper Shklo drainage basin in the Yaniv Roztocze region, whereas within the boundaries of the remaining part of the Ukrainian Roztocze region, the discharge of more than 70% of active springs does not exceed 0.5–2.0 l/s.

The aim of this study is to assess the neotectonic mobility of the Ukrainian part of Roztocze region using morphometric coefficients. The assessment was made using a digital terrain model (DTM; Nita *et al.*, 2007) and calculated on its basis geometric and morphometric parameters for drainage basins of the 3^{rd}–6^{th} order, as well as morphometric linear coefficients, which characterise fault scarps in the marginal zones of the study area and in some valleys cutting the south-western margin of the Ukrainian part of the Roztocze region.

GEOLOGICAL AND GEOMORPHIC SETTINGS

Structural features of the area have been shaped by its location within the marginal zone of the East-European Platform, the marginal part of which was affected by overlapping vertical crustal movements of large amplitude (Palienko, 1993). The overlapping of the structural plans: the primary NW–SE plan and the secondary W–E plan, explains the existence of a characteristic block arrangement of the structures (Fig. 2). Fault-controlled lines divide the Roztocze region into three subregions (Fig. 1): Rava Roztocze (its northern part being located in Poland), and Yaniv and Lviv Roztocze in the Ukraine (Roslyi, 1990; Hnatiuk, 2002).

In terms of lithology, the Ukrainian part of the Roztocze region is characterised by the prevalence of Miocene over Eocene and Upper Cretaceous strata (Fig. 2). The Upper Cretaceous carbonate and carbonate-siliceous rocks of different resistance (gaizes, silicate chalk, marl) are typical of the northern and eastern parts of the Ukrainian Roztocze region (Andreyeva, 1986; Bogutsky *et al.*, 1998; Świdrowska, 2007). Smaller areas built from Campanian gaize and silicate chalk are documented between Rava-Rus'ka, Nemyriv and Maheriv in the Rava Roztocze region. Less resistant marl, as well as Maastrichtian chalk occur in the northeastern part of the region. Small, eroded patches of Eocene strata (sands and quartz and glauconitic mudstone) have been identified locally in the southern segment of the Sołokija River valley (Buraczyński & Krzowski, 1994) and in the north of Maheriv (Rogala, 1912; Kudrin, 1966; Bogutsky *et al.*, 1998) in the Rava Roztocze region. Thin (20–60 m) Badenian formations do not form a continuous cover. Generally, shallow-water, marginal-type facies show variable development and thickness. Sedimentation gaps, erosional surfaces and great changeability of deposits are characteristic of Miocene formations. Over a large area, especially in the marginal south-western part of the Roztocze region, the Lower Badenian organodetrital limestone with sandstone and sand, crop out (Wysocka, 2002). Near Lviv and Radruż towns, Ratine limestone occurs, which is a counterpart of evaporitic-chemical beds in the Carpathian Foredeep basin (Peryt & Peryt, 1994). The most common in the Roztocze region are various Upper Badenian carbonate and terrigenous deposits classified as supra-evaporitic-chemical beds. Terrigenous formations have emerged as sands and quartz and glauconite sandstone, covered by highly eroded reef and organodetrital limestone, as well as coquina beds and lime sands with sandstone and clay intercalations (Palienko, 1993; Wysocka, 2002; Wysocka *et al.*, 2007).

The Upper Cretaceous, Eocene and Badenian strata are covered with Pleistocene and Holocene sediments of varying lithology, thickness and origin (Bachynskiy & Zubritskiy, 1979; Buraczyński *et al.*, 2003; Maruszczak, 1994). Pleistocene sediments in the Roztocze region are only preserved as fragments of loess covers between Maheriv and Krehiv towns, and along the eastern edge of the Roztocze region near Lviv (Maruszczak, 1967). In river valleys and basin-shaped depressions (Rata River valley, Vereshytsia River basin), there occur Holocene organogenic deposits of up to a-few-metre thickness. Holocene mineral-organic muds are also documented in the valleys (Bogutsky *et al.*, 1993; Buraczyński, 2002).

Three major NW–SE oriented tectonic zones (south-western – Stavchanka-Vereshytsia, middle – Zubra and south-eastern – Zhovkva-Lviv, called Lysynets'ka) are clearly visible in the Ukrainian part of the Roztocze region, as they follow the deeply entrenched, discontinuous Palaeozoic structures (Fig. 2). The zones stretching sub-parallel are of subordinate character. The south-western boundary of the Roztocze region and the relatively narrow and rectilinear valleys of the Vereshytsia and Stavchanka rivers are related to the Stavchanka-Vereshytsia zone (Ney, 1969; Khiznyakov & Żelichowski, 1974). The Zhovkva–Lviv, also called Lysynets'ka, zone is followed by the eastern boundary of the Roztocze region. In the south-east of Lviv, it is expressed as an elevated step rising at about 60 m. Within the boundaries of Lviv city, the structure is exposed as an overthrust of Maastrichtian marls over Badenian sands, dipping at an angle of 30–40°. In the north-west of

Lviv, the zone is repeatedly dislocated, and it shifts towards the central part of the Roztocze region (Fig. 2). Between these two structures the Zubra zone occurs, being paralleled by the narrow and rectilinear valleys of the Zubra and Mlynivka rivers. Sub-parallel faults are considered to be younger and overlapped with the NW–SE system. This overlapping of the structural plans was a precondition for a characteristic block-type character of the Roztocze structure (Bogutsky *et al.*, 1993).

Characteristic morphologic parameters: relatively high absolute and relative heights, structural levels, outliers and the dominant orientations of the valley network – W–E and/or NW–SE, all result from lithological and tectonic features of the area (Fig. 1). Maximum elevations change from 389.5 m a.s.l. in the Rava Roztocze region (Wielki Dział within the borders of Poland) through 396.9 m a.s.l. (near Dubrovytsia) to 401.4 m a.s.l. in the Lviv Roztocze region (Chortova Hora), while the minimum heights range from, respectively: 227.5 m a.s.l. in the Sołokija River valley through 260.0 m a.s.l. in the Fuyna River valley to 248.5 m a.s.l. at the mouth of the Mlynivka River valley. Thus, the relief energy of these three units is 162.0 m, 136.9 m, and 152.9 m, respectively.

Within the borders of the subregions, three basic structural levels can be distinguished at the following altitudes: 310–330 m a.s.l. (in the Rava Roztocze region), 350–360 m a.s.l. (in the Rava Roztocze and in the Yaniv Roztocze regions), and 380–390 m a.s.l. (in the Yaniv Roztocze and in the Lviv Roztocze regions) (Buraczyński, 2002). Isolated hills – denudation remnants – are rising above hilltop level up to a height of 20 to 30 m, mainly in the watershed zone.

The Roztocze region shows a peculiar orientation of the drainage network. Valleys, which play an important role in the regional subdivision, are mostly related to tectonic zones, including grabens filled with deposits of different age – from Eocene sands in the Sołokija River valley to Quaternary sediments in the valleys of Stavchanka, upper Vereshytsia, Fuyna and Poltva rivers (Teisseyre, 1938; Buraczyński & Krzowski, 1994; Buraczyński *et al.*, 2003).

METHODS AND MATERIALS

Geometric and **morphometric** coefficients, which describe drainage areas, and **morphometric linear** coefficients describing fault scarps within the margins of the area and in some valleys cutting through the margins, are parameters which illustrate well the relationships between the river system and amplitudes of vertical crustal movements. Most of the parameters and coefficients applied in this study were used more than thirty years ago to analyse semi-desert mountain areas in Nevada and California (cf. Bull, 1977; 1978; Bull & McFadden, 1977) and some mountain areas in the monsoon climate zone (Cuong & Zuchiewicz, 2001), as well for mountains situated in the temperate climate zone: the Carpathian Mountains (Zuchiewicz, 1980, 1981, 1995a, 1995b, 2000; Krawczyk & Zuchiewicz, 1989; Forma & Zuchiewicz, 2002), and the Sudety Mountains (Badura & Przybylski, 1995; Sroka, 1997; Badura *et al.*, 2003, 2007). Some of the parameters and coefficients were also calculated for an upland area, *i.e.* the Polish part of the Roztocze region (Brzezińska-Wójcik, 1994, 1995, 1998, 1999; Brzezińska-Wójcik & Miłkowska, 2002; Brzezińska-Wójcik & Superson, 2004; Brzezińska-Wójcik & Hołub, 2007; Brzezińska-Wójcik *et al.*, 2003).

Despite some ambiguity comprised in this methodology, it is possible to estimate the dynamic diversification within a geologically heterogeneous system. Such conditions are met in the Ukrainian part of the Roztocze region, built up of Mesozoic, Palaeogene (Eocene) and Lower Neogene (Miocene) strata (Bogutsky *et al.*, 1998; Wysocka *et al.*, 2007). The area is also characterised by a high degree of climate continentality (Kaszewski *et al.*, 2002).

A Digital Terrain Model (DTM) was developed for the Ukrainian part of the Roztocze region using 1:50,000 topographic maps at the "1942" setting. The maps were registered in a set of coordinates and then the river network, contour lines and altitude points were digitized giving them the attribute of altitude. Using the Topo_to_Raster tool, part of ArcGIS software, a numerical model of the surface features at a resolution of 20 m was obtained. On the basis of the model, assisted by a contour line drawing, the drainage areas of the 3rd to 6th order were marked, digitized and classified in accordance with a classic hydrographic model.

The data prepared in such a way served then to calculate **geometric** parameters and coefficients: maximum basin length *L*, drainage basin area *A*, drainage basin perimeter *P*, drainage basin mean width *W*, drainage basin elongation ratio *Re*, drainage basin circulatory ratio *Rk*, form ratio *Rf*, lemniscate coefficient *k*, as well as **morphometric** parameters and coefficients: maximum height H_{max}, minimum height H_{min}, mean height $H_{śr}$, maximum relief *H*, relief ratio *Rh* (C_F), and relative relief ratio *Rhp*, characterising the distinguished 3rd – 6th order basins (Table 1).

In addition, **morphometric linear** coefficients were calculated, *i.e.* the mountain-front sinuosity index *Smf* and the valley shape index *Vf*, which describe fault scarps in the marginal area zone and in some valleys dissecting these margins, respectively (Figs 7, 8). The mountain front sinuosity index *Smf* (Bull, 1977, 1978) is calculated as a ratio of the length of the mountain front measured along the foot of the mountain at the pronounced break of slope *Lmf* to the straight line length of the mountain front *Ls* (Table 1). The valley floor width and valley height ratio *Vf* parameter (Bull, 1977, 1978; Bull & McFadden, 1977) is calculated as:

$$Vf = 2Vfw/[(Eld - Esc) + (Erd - Esc)];$$

where *Vf* is the width of the valley floor, *Eld* and *Erd* are the elevations of the left and right valley divides, respectively, and *Esc* is the elevation of the valley floor.

RESULTS

Geometric parameters obtained for 1,646 drainage basins of the 3rd–6th order vary significantly (Table 2). The drainage basin surface *A* ranges between 0.01 km^2 (5th order drainage basins) and 315.34 km^2 (4th order drainage basins), attaining averages of 1.26 km^2 (6th order drainage

Table 1

Parameters describing 3^{rd}–6^{th} order drainage basins in the Ukrainian part of the Roztocze region

Parameter	Symbol	Formula	References
Geometric parameters of drainage basins			
Total area	A [km^2]		Horton (1945)
Maximum basin length	L [km]		Horton (1945), Schumm (1954)
Basin perimeter	P [km]		Smith (1950)
Mean width of the basin	W [km]	A/L	
Basin elongation ratio	Re	$2(A/\pi)^{0.5}/L$	Schumm (1954)
Circulatory ratio	Rk	$4\pi A/P^2$	Miller (1953), Gregory & Walling (1973)
Form ratio	Rf	A/L2	Horton (1945)
Lemniscate coefficient	k	$\pi L^2/4A$	Chorley (1971), Gregory & Walling (1973)
Morphometric parameters of drainage basins			
	H_{max} [m a.s.l.]		
	H_{min} [m a.s.l.]		
	H_{med} [m a.s.l.]	$(H_{max} – H_{min})/2$	
Maximum relief	H [m]	$H_{max} – H_{min}$	Strahler (1954), Schumm (1954)
Relief ratio	Rh	H/L	Strahler (1954), Schumm (1954)
Relative relief	Rhp	H/P	Melton (1957, 1958)
Morphometric linear coefficients			
Mountain-front sinuosity index	Smf	Lmf/Ls	Bull (1977, 1978)
Valley floor width and valley height ratios	Vf	2Vfw/[(Eld – Esc) + (Erd – Esc)]	Bull (1977, 1978), Bull & McFadden (1977)

basins) to 4.58 km^2 (3^{th} order drainage basins). The maximum basin length *L* (Horton, 1945; Schumm, 1954) is the distance between the most distant points of the drainage basin measured along a straight line (Dobija, 1979). The calculated values vary from 0.35 to 31.94 km (4^{th} order drainage basins), attaining averages of 1.64 km (6^{th} order drainage basins) to 2.47 km (3^{th} order drainage basins). Extreme values of the perimeter of the analysed basins *P* change from 0.85 to 136.34 km for the 4^{th} order drainage basins, and average 4.36 km (6^{th} order drainage basins) to 6.92 (3^{th} order drainage basins). The mean width of the basin *W* varies between 0.01 km (5^{th} order basins) to 11.11 km (3^{rd} order basins), averaging 0.55 km (6^{th} order drainage basins) to 0.86 (3^{th} order drainage basins).

The drainage basin elongation coefficient *Re* (Bull & Mc Fadden, 1977) is one of indirect indicators of young tectonic activity. It is calculated as a ratio of the circle diameter, the area of which is equal to the area of a drainage basin, to the maximum basin length (Schumm, 1954; Eagleson, 1970). According to Strahler (1964) and Eagleson (1970), values close to 1.0 are typical of poorly dissected basins, while values around 0.6–0.8 characterise basins with steep slopes and varied topography. Drainage basins in arid and semiarid climates tend to show *Re* values ranging from <0.50, through 0.50–0.75 to >0.75 for tectonically active, slightly active and inactive settings, respectively (Bull & McFadden, 1977). Extreme values of the basin elongation ratio *Re* in the Ukrainian part of the Roztocze region vary between 0.26 (5^{th} order basins) and 1.00 (4^{th} and 6^{th} order basins), and average 0.66–0.67 (Table 2, Fig. 3).

The circulatory ratio *Rk* (Miller, 1953; Gregory & Walling, 1973) compares the drainage basin area to a circle, whose perimeter is the same as that of the basin. The values of *Rk* lower than 1.0 are typical of elongated basins. In the Ukrainian part of the Roztocze region, the extreme values of the coefficient vary from 0.20 (4^{th} order drainage basins) to 0.89 (5^{th} and 6^{th} order basins) and average 0.61–0.62 (Table 2, Fig. 4).

The form ratio *Rf* (Horton, 1945) compares the outline of the drainage basin to a rectangle. Lower values are typical of elongated basins, while *Rf* > 1.0 typify wide basins, whose outline is close to a square. The value of the *Rf* coefficient decreases with the increase of the basin area (Eagleson, 1970; Gregory & Walling, 1973). In the Ukrainian part of the Roztocze region, extreme values of *Rf* change from 0.05 to 1.00 (extreme coefficients for basins of the same order, characterised by minimum and maximum R_e values) and average 0.35–0.37 (Table 2, Fig. 5).

The lemniscate coefficient *k* varies between 0.74 (6^{th} order basins) and 14.49 (5^{th} order basins) to 2.56 (3^{th} order drainage basins), averaging 2.42 (4^{th} order drainage basins) to 2.56 (3^{th} order drainage basins) (Table 2, Fig. 6).

It appears from the analysis of the differentiation of the surface values of *Re*, *Rk* ¸ *Rf* and *k* geometric indicators (*cf.* Figs 3–6) that the drainage basin elongation ratio *Re* and the drainage basin shape coefficient *Rf* correlate very well (Pearson correlation coefficient 0.99), in contrast to the values of the circulatory ratio *Rk* (0.05–0.11). In order to better illustrate the spatial differentiation of the intensity of tectonic activity throughout drainage basins, a compilation of

Table 2

Average, maximum and minimum values of selected geometric and morphometric parameters of the 3rd–6th order drainage basins in the Ukrainian part of the Roztocze region

Parameter	Drainage basins of selected orders											
	3rd order (172)			4th order (412)			5th order			6th order		
	average	max	min	average	max	min	average	max	min	average	max	min
Geometric parameters of drainage basins												
A [km^2]	4.58	188.83	0.12	3.88	315.34	0.05	2.15	137.36	0.01	1.26	34.56	0.08
L [km]	2.47	23.14	0.70	2.37	31.94	0.35	1.94	31.92	0.44	1.64	10.96	0.38
P [km]	6.92	82.92	1.60	6.60	136.34	0.85	5.17	86.21	1.25	4.36	37.31	1.20
W [km]	0.86	11.11	0.16	0.80	9.87	0.12	0.63	4.91	0.01	0.55	3.15	0.14
Re	0.66	0.96	0.43	0.67	1.00	0.33	0.67	1.00	0.26	0.67	1.00	0.33
Rk	0.61	0.84	0.30	0.62	0.92	0.20	0.62	0.89	0.23	0.62	0.89	0.23
Rf	0.35	0.89	0.15	0.37	1.00	0.09	0.36	0.97	0.05	0.36	1.00	0.09
k	2.56	5.37	0.88	2.42	8.99	0.77	2.48	14.49	0.81	2.47	8.98	0.74
Morphometric parameters of drainage basins												
H_{max} [m a.s.l.]	349.814	401.590	280.720	337.702	404.250	226.290	328.080	404.250	231.170	330.007	404.250	235.310
H_{min} [m a.s.l.]	298.721	344.080	237.960	285.866	359.410	209.930	274.478	349.180	208.690	273.120	345.520	215.310
Hmed [m a.s.l.]	326.033	367.100	257.530	311.718	378.580	219.300	301.493	374.670	222.510	302.651	369.370	222.190
H [m]	51.093	121.830	16.510	51.835	190.950	8.590	53.601	191.950	13.480	56.887	169.040	9.570
Rh	0.039	0.086	0.003	0.032	0.106	0.005	0.038	0.196	0.006	0.044	0.146	0.009
Rhp	0.011	0.036	0.001	0.012	0.044	0.001	0,015	0.063	0.002	0.017	0.057	0.003

the values of *Re*, *Rk*, *Rf* and *k* coefficients has been made (Fig. 7). The following principles were adopted in such a comparison: values of the coefficients ranging between 0.00–0.50 (*Re*, *Rk*), 0.00–0.25 (*Rf*) and 4.1–15.0 (*k*) were allocated 3 points and then, respectively, 0.50–0.75, 0.25–0.50 and 2.1–4.0 – 2 points each, and 0.75–1.00, 0.50–1.00 and 1.0–2.0 – 1 point each. This is how a spatial image was created of the distribution of basins of a relatively high tectonic activity (10–12 points), slight tectonic activity (7–9 points) and weak activity/no activity (4–6 points) (Fig. 7).

In the light of the adopted value brackets for the *Re*, *Rk*, *Rf* and *k* coefficients (Fig. 7), the values of R_e < 0.50 (after Bull & McFadden, 1977) and the values of *Rk* < 0.50, *Rf < 0.25 and k* – 4.1–15.0, defined by us in this paper (Table 2, 3), the following drainage basins are tectonically relatively active: (1) Stavchanka River (3rd order) basin; (2)

Table 3

Tectonic activity classes in the light of selected values of geometric and morphometric parameters

Selected geometric and morphometric parameters						*Vf* parameter			
R_e (Bull & McFadden, 1977)	***Rk*** (this paper)	***Rf*** (this paper)	***k*** (this paper)	***Smf*** (Bull, 1977, 1978; Rockwell *et al.*, 1984; Wells *et al.*, 1988)	Tectonic activity classes	(Keller & Pinter, 1996)	Tectonic activity classes	(Bull, 2007)	Tectonic activity classes
0.00-0.50	0.00-0.50	0.00-0.25	4.1-15.0	< 1.4	1 (tectonically active)	0.43-0.80	1 (tectonically active)	0.06-0.51	1 and 2 (tectonically active)
0.50-0.75	0.50-0.75	0.25-0.50	2.1-4.0	1.4-3.0	2 (moderately active)	1.8-1.9	2 (moderately active)	1.2-1.7	3 (moderately active)
0.75-1.00	0.75-1.00	0.50-1.00	1.0-2.0	> 3.0	3 (slightly active or inactive)	>1.9	3 (slightly active or inactive)	1.0-7.0	4 (slightly active)
								2.0-7.8	5 (inactive)

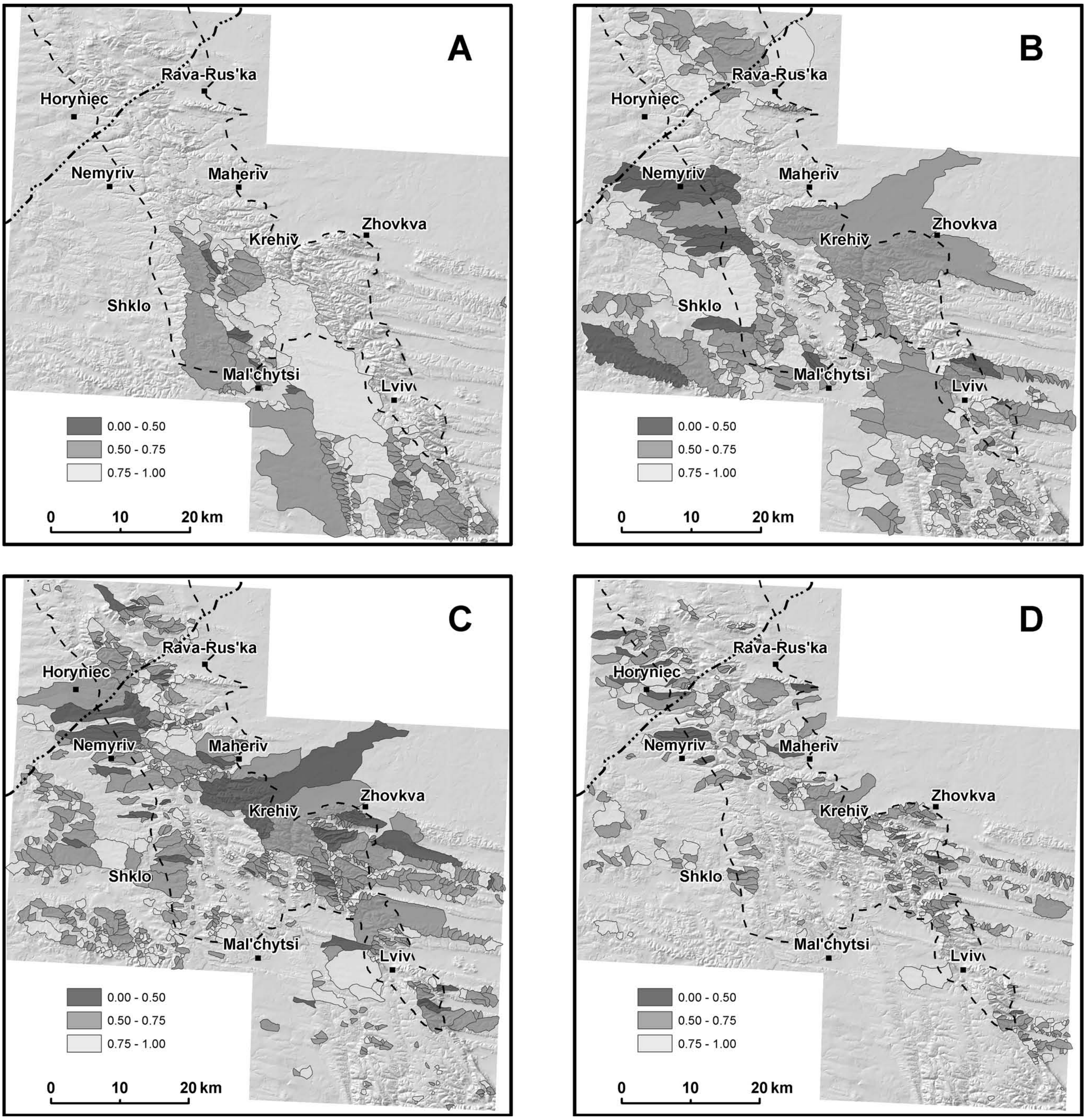

Fig. 3. Spatial distribution of values of the basin elongation coefficient R_e in the 3rd–6th order drainage basins. **A** – 3rd order basins; **B** – 4th order basins; **C** – 5th order basins; **D** – 6th order basins

drainage basins transverse to the south-western margin of the Rava Roztocze region between Nemyriv and Shklo (4th order); (3) drainage basins of the Bila, Derevenka and Svinia, and Mlynivka rivers (4th–5th order), transverse to the north-eastern margin of the Roztocze region; and (4) basins transverse to the south-western margin of the Roztocze region between Horyniec and Nemyriv (5th–6th order).

Slight activity (Fig. 7) has been identified in the basins of the upper Vereshytsia and Zubra rivers (3rd–4th order). Relatively inactive are the areas of small drainage basins of the 3rd–6th order, located in the zone of main watershed, namely: the Rata and Lubaczówka rivers in the Rava Roztocze region, and the Zubra and Poltva rivers in the Lviv Roztocze region.

Morphometric characteristics obtained for the 3rd–6th order drainage basins are also considerably diversified (Table 2). The maximum altitude H_{max} ranges from 226.29 (4th order basins) to 404.25 m a.s.l. (5th and 6th order basins), averaging 328.08 (5th order drainage basins) to 349.81 (3th order drainage basins), while the minimum altitude H_{min} change from 208.69 (5th order basins) to 359.41 m a.s.l. (4th order basins) and average 273.12 (5th order bas-

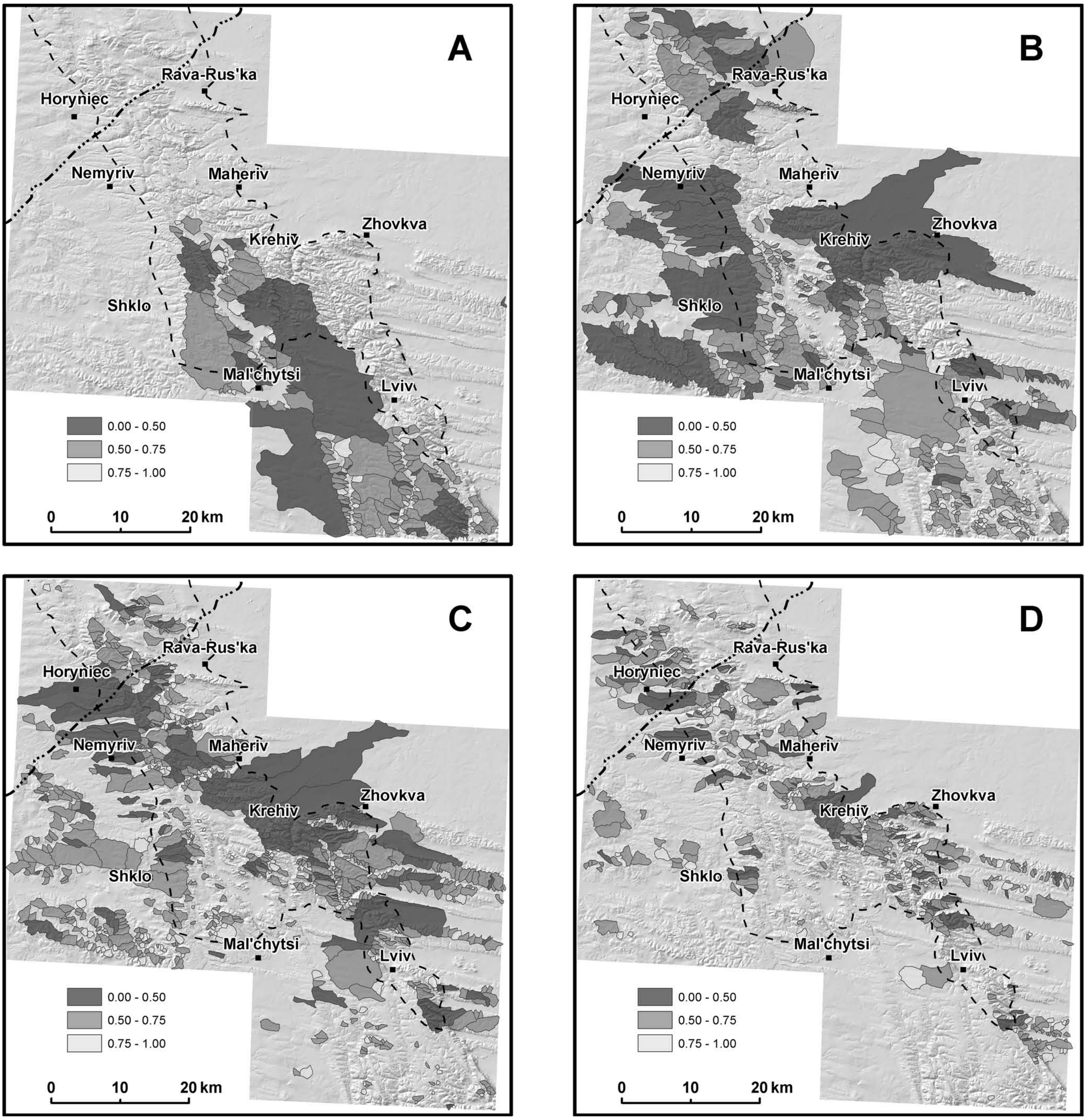

Fig. 4. Spatial distribution of values of the basin circulatory ratio R_k in the 3rd–6th order drainage basins. **A** – 3rd order basins; **B** – 4th order basins; **C** – 5th order basins; **D** – 6th order basins

ins) to 298.72 m a.s.l. (3th order drainage basins). Mean altitudes in the analysed drainage basins are situated within the range of 219.30 to 378.58 m a.s.l. and reflect extreme values typical of the 4th order drainage basins.

The maximum relief *H* (Strahler, 1954; Schumm, 1954) is calculated as a difference between the minimum and maximum altitude and informs about the degree of rejuvenation of the landscape (Krawczyk & Zuchiewicz, 1989). In the analysed Roztocze basins, the maximum relief *H* index varies between 8.59 m (4th order drainage basins) and 191.95 m (5th order drainage basins), averaging between 51.09 m (3th order drainage basins) and 58.89 m (6th order drainage basins) (Table 2).

The relief ratio *Rh* (Strahler, 1954; Schumm, 1954, 1956) represents the mean inclination of a drainage basin. According to Morisawa (1962), it is particularly useful to characterise elongated basins. Lower values of this coefficient are typical for drainage basins built from resistant bedrock and suggest a tectonic uplift of the area. The relative relief ratio *Rhp* (Melton, 1957, 1958) reflects the ratio of maximum relief in a drainage basin to its perimeter. The values of *Rh* and *Rhp* coefficients, calculated for the 3rd–6th

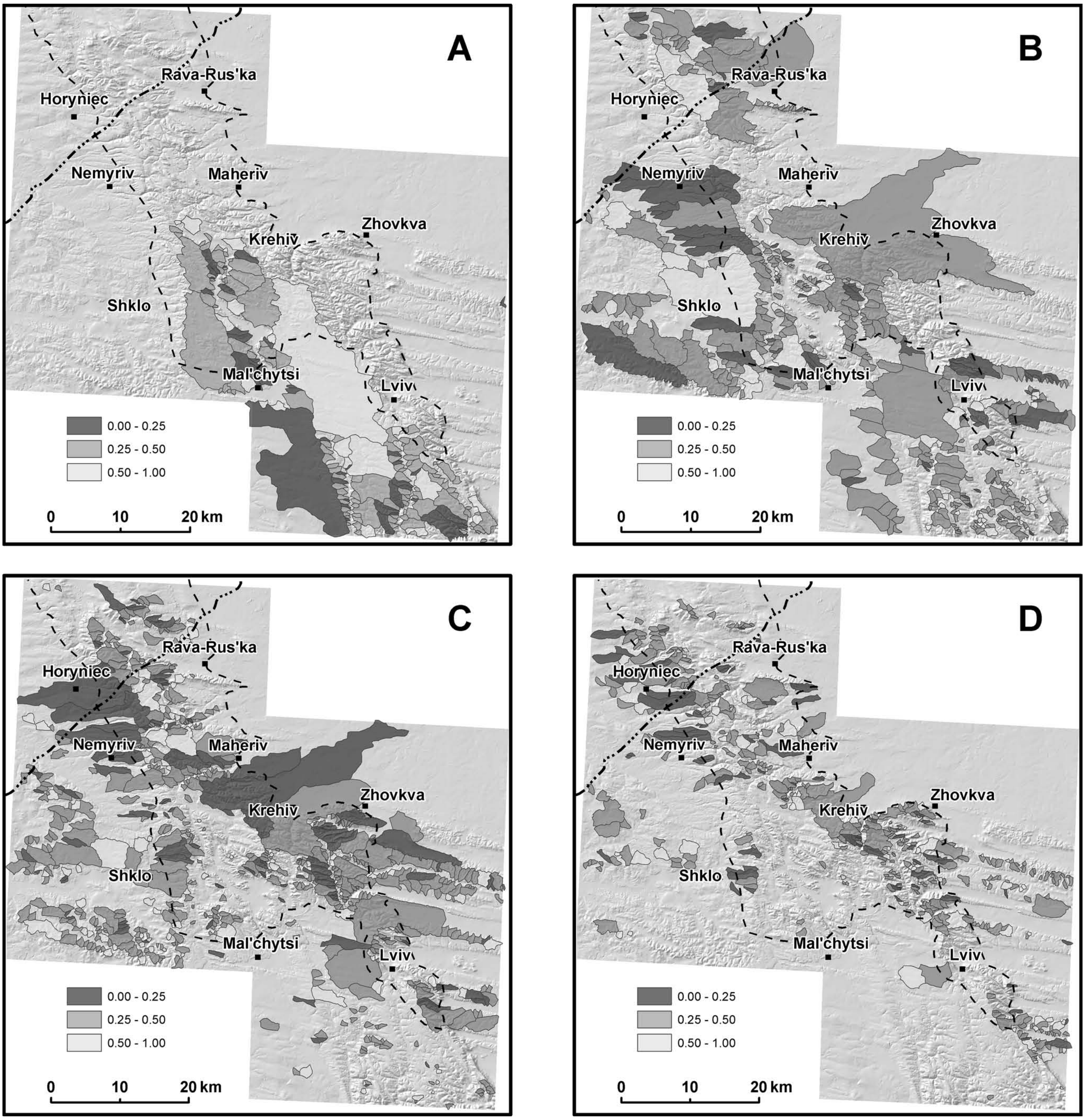

Fig. 5. Spatial distribution of values of the drainage basin shape coefficient R_f in the 3rd–6th order drainage basins. **A** – 3rd order basins; **B** – 4th order basins; **C** – 5th order basins; **D** – 6th order basins

order drainage basins in the Roztocze region vary, respectively, from 0.0009 and 0.003 (3rd order basins) to 0.063 and 0.196 (5th order basins) (Table 2).

The **linear parameter**, mountain front sinuosity index *Smf*, attains values of 1.0–16 for rectilinear, tectonically active scarps developed in dry climate conditions in the Basin and Range Province. Areas of weak or insignificant tectonic activity show values within the range of 1.4–3.0 and from 1.8 to > 5.0, respectively (Bull, 1977, 1978). Generally, the *Smf* values less than 1.4 indicate tectonically active fronts (Rockwell *et al.*, 1984; Wells *et al.*, 1988), whereas those greater than 3.0 are related to inactive fronts, in which the initial range-front fault may be more than 1 km away from the present erosional scarp (Bull & McFadden, 1977).

In the Ukrainian part of the Roztocze region, the lowest values of the *Smf* index (1.11–1.43) were obtained for the sub-parallel escarpment framing the zone of transverse depression of the Vereshytsia-Stara-upper Mlynivka rivers valley (Fig. 8) in the north. Similar values (1.16–1.80) were obtained for the sub-parallel escarpment framing the valley of the Svinia River west of Zhovkva town. Slightly higher values (1.23 to 1.60) were defined for the south-western

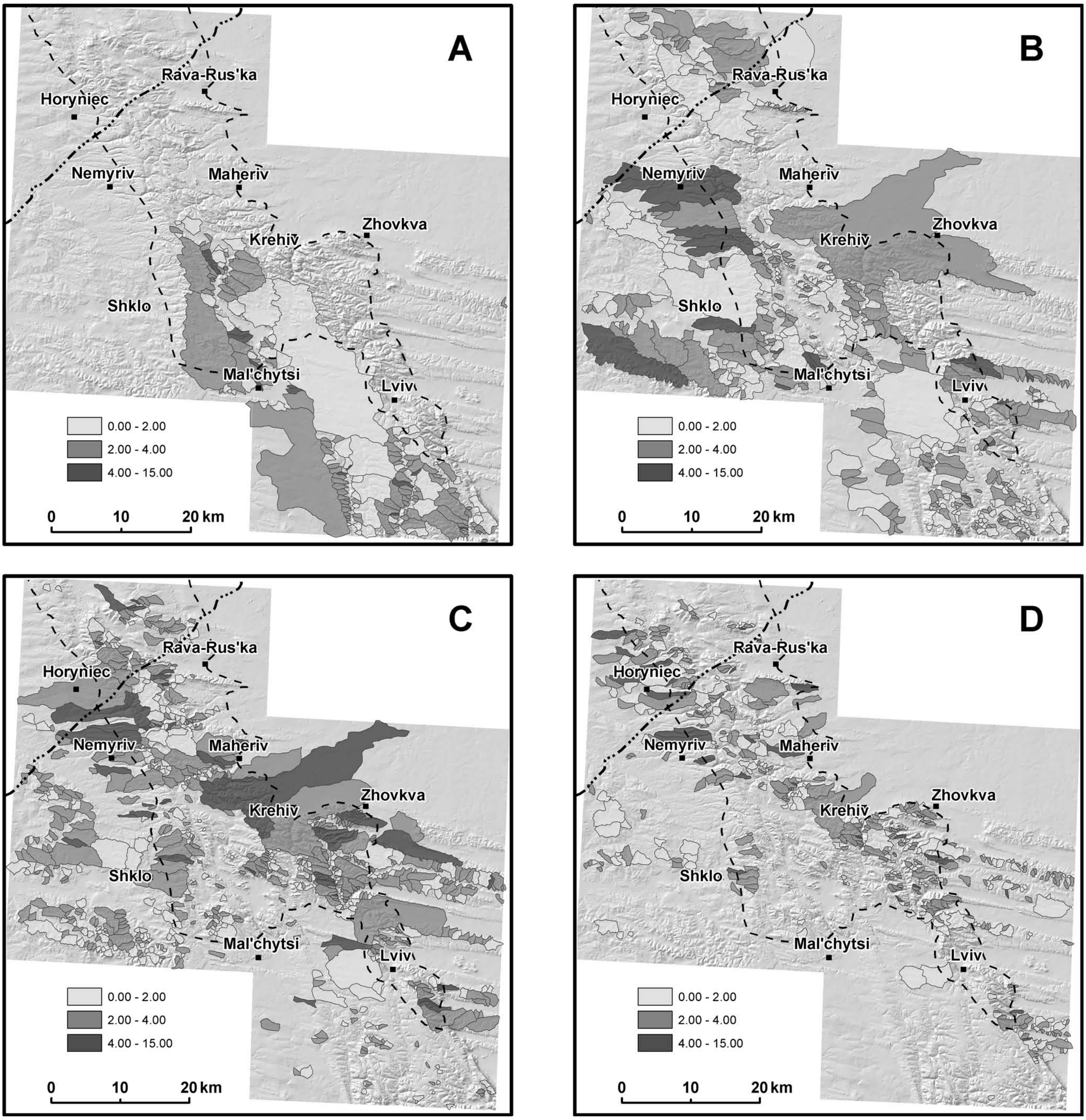

Fig. 6. Spatial distribution of the lemniscate coefficient *k* in the 3rd–6th order drainage basins. **A** – 3rd order basins; **B** – 4th order basins; **C** – 5th order basins; **D** – 6th order basins

margin of the Rava Roztocze and the Yaniv Roztocze regions between the sub-parallel valleys of the Baszenka and the upper Vereshytsia rivers. The highest values (1.43–1.88) were obtained for the north-eastern margin of the Lviv Roztocze region, SE of Lviv. A compilation of these values shows that a relatively high tectonic activity occurs in: the marginal edge separating the inversion horst of the Roztocze region from the Carpathian Foredeep basin, and a perpendicular to it sub-parallel margin following the Vereshytsia-Stara-upper Mlynivka rivers zone, as well as a sub-parallel margin – slope of the valley of Svinia River to the west of Zhovkva town.

The valley floor width and valley height ratio *Vf* (Bull, 1977, 1978; Bull & McFadden, 1977) helps to differentiate between wide-bottom valleys with high *Vf* values and narrow canyons with uneven gradient and low *Vf* values. Abnormally low values of this ratio usually indicate actively uplifting areas (Keller & Pinter, 1996). The values quoted by Bull and Mc Fadden (1977) for the Garlock Fault zone in California are contained within the 0.05–47.0 range and are

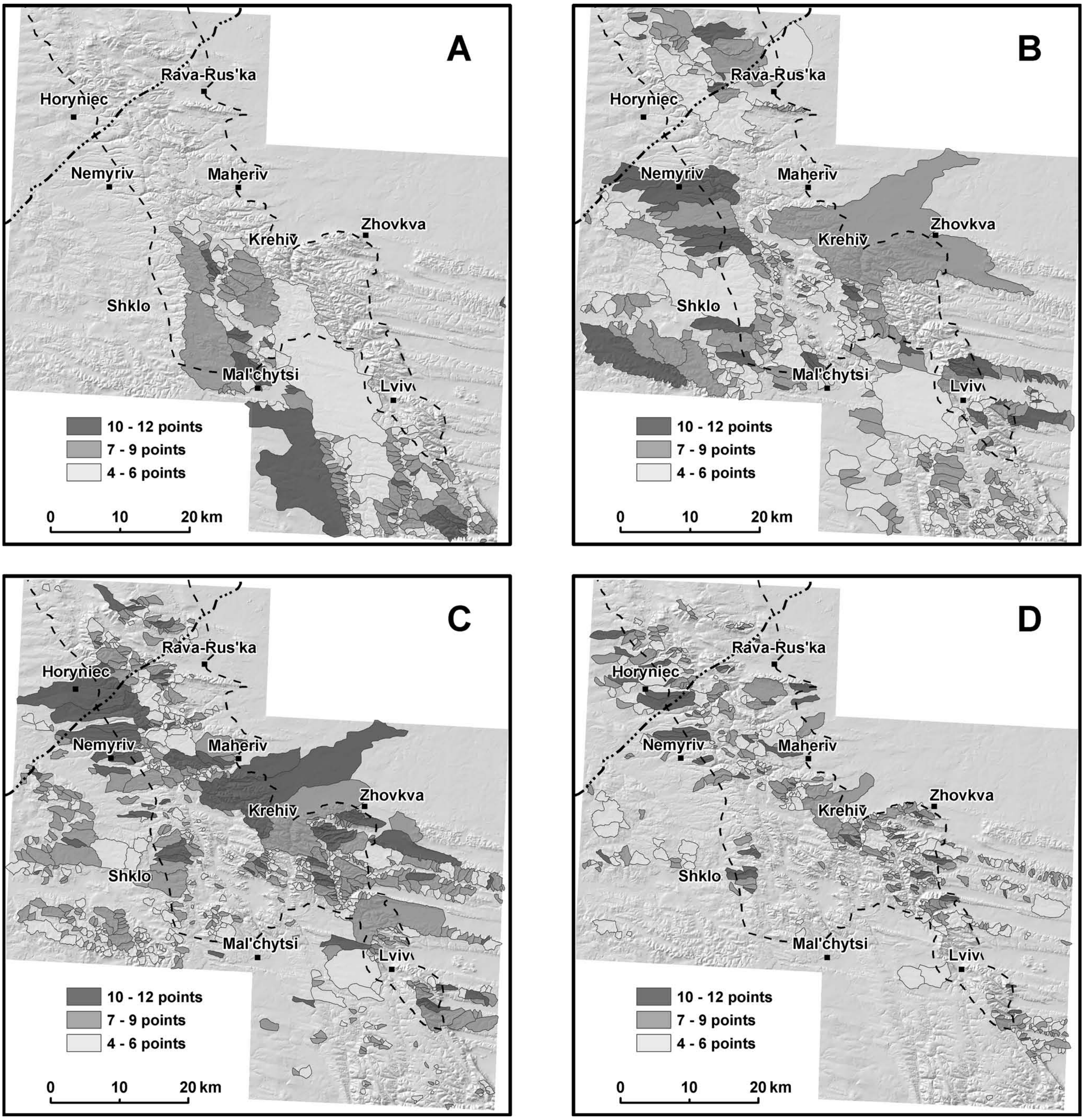

Fig. 7. Tectonic activity in the 3rd–6th order drainage basins, on the basis of accumulated values of the following coefficients: *Re* elongation coefficient, R_k circulatory ratio, R_f drainage basin shape coefficient and lemniscate coefficient *k*. **A** – 3rd order basins; **B** – 4th order basins; **C** – 5th order basins; **D** – 6th order basins

between 1.3–11.0 on average. Tectonic activity classes of mountain fronts in west-central Nevada (Bull, 2007) reveal the following mean values of *Vf*: classes 1 and 2 (tectonically active) 0.06–0.51, class 3 (moderately active) 1.2–1.7, class 4 (slightly active) 1.0–7.0, and class 5 (inactive) 2.0–7.8. For the Western Transverse Ranges (California), in turn, these values fall into intervals of 0.43–0.80 (class 1), 1.8–1.9 (class 2), and >1.9 (class 3) (Keller & Pinter, 1996).

The values of *Vf* coefficient, calculated for valleys transversely dissecting the south-western margin of the Rava Roztocze and the Yaniv Roztocze regions, fall into the interval between 12.89 and 28.42 (Fig. 9). The lowest value (12.89) was noted in the Radrużka River valley, transversely dissecting the edge south of Horyniec town, while the highest (28.42) was observed in the Vronka River valley, situated south-west of Nemyriv town.

In the context of *Vf* values obtained for various fault scarps from other regions (Bull & Mc Fadden, 1977; Keller & Pinter, 1996; Bull, 2007), it is possible to assume that equivalent values obtained only for a small part of the analysed area suggest a lack of tectonic activity. However, calculations were based on 1:50,000 topographic maps, avail-

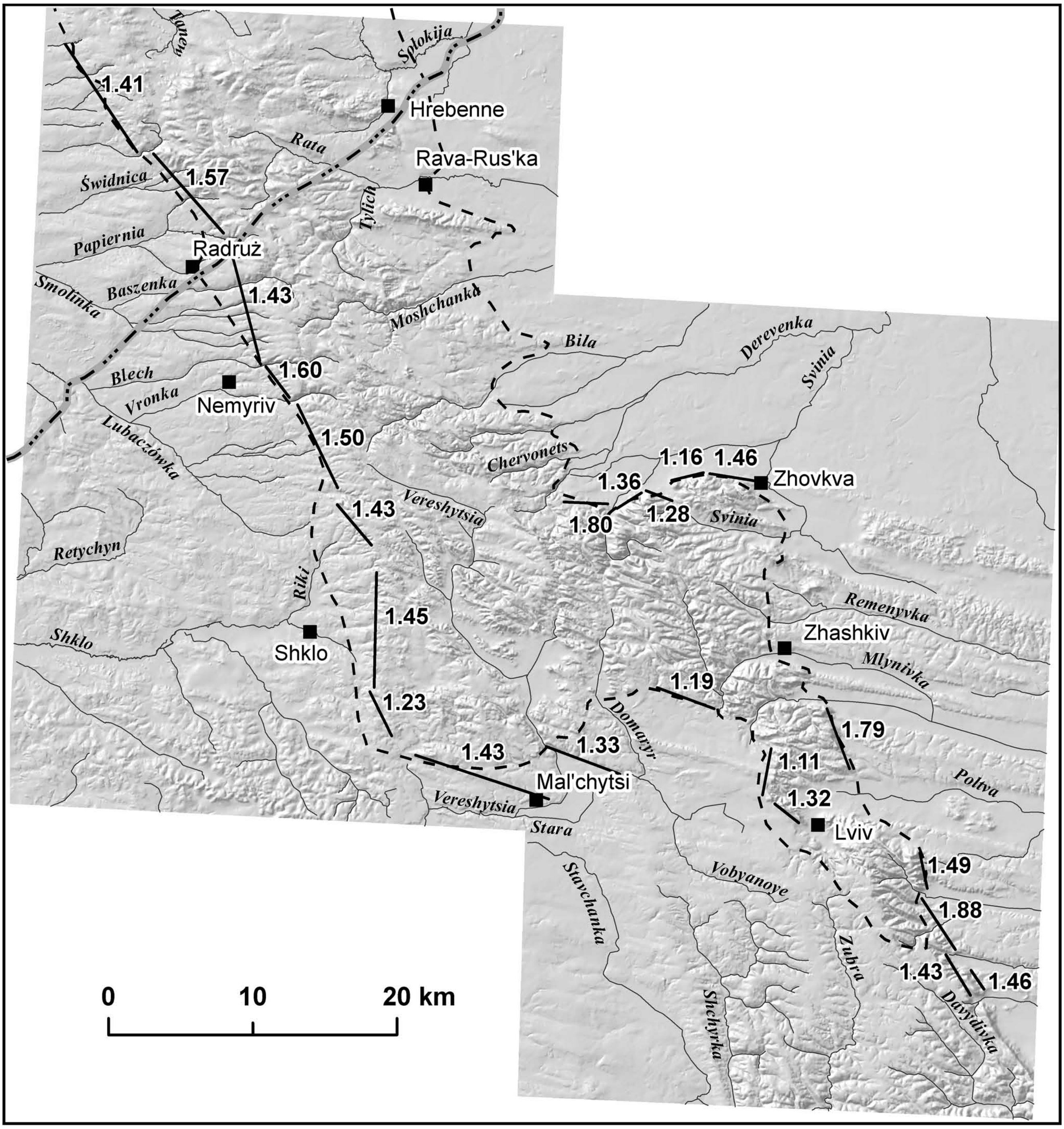

Fig. 8. Spatial distribution of the values of *Smf* mountain front sinuosity index in the Ukrainian part of the Roztocze region

able at the moment. In future, when 1:10,000 or more detailed maps become available, calculations will be repeated, and then it will be possible to compare *Vf* values with those obtained for other tectonically active areas in a more reliable way.

CONCLUSIONS

An analysis of the values of selected **geometric parameters** (*Re*, *Rk*, *Rf*, *k*) of drainage basins and of **linear morphometric** coefficients and indices (*Smf*, *Vf*) shows that the features specific to rectilinear scarps of young faults are to be found in the south-western margin of the Rava Roztocze and the Yaniv Roztocze regions between the sub-parallel valleys of the Baszenka and the Vereshytsia rivers (Fig. 10). Low values of such indices, such as: drainage basin elongation coefficient, drainage basin circulatory ratio, drainage basin shape, lemniscate coefficient, mountain-front sinuosity index and valley floor width-valley height ratio make it possible to classify this area, developed along NW–SE faults, as composed of structures showing the 1st and 2nd class of relative tectonic activity.

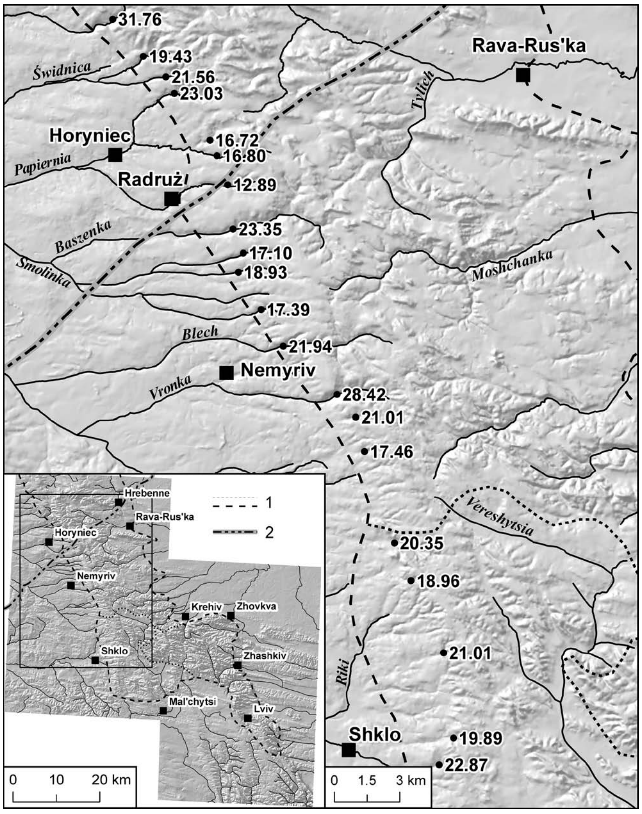

Fig. 9. Spatial distribution of the values of *Vf* valley floor width and valley height ratio in transverse profiles of selected drainage basins in the south-western margin of the Ukrainian part of the Roztocze region

The entire north-eastern marginal zone of the Ukrainian part of the Roztocze region appears to be more differentiated in terms of geomorphology and shows characteristics of an area of relatively weak contemporary tectonic activity. It is only the area situated between Maheriv and Zhashkiv towns, with a characteristic valley pattern of the upper Svinia and upper Mlynivka rivers controlled by a network of secondary sub-parallel faults, that in the light of differentiation of morphometric coefficients (especially the drainage basin elongation ratio, drainage basin circulatory ratio, drainage basin shape, lemniscate coefficient and mountain-front sinuosity index) belongs to structures assigned to the 1st or 2nd class of relative tectonic activity.

The southern part of the analysed area is also interesting, as far as tectonic activity is concerned. The 3rd order drainage basin of the Stavchanka River is relatively active (showing the lowest values of drainage basin elongation ratio, drainage basin circulatory ratio and drainage basin shape), related to the NW–SE orientated fault zone and the sub-parallel margin framing the zone of the transverse depression of the Vereshytsia-upper Mlynivka rivers in the north (with the lowest values of the mountain-front sinuosity index).

The multi-stage character and variable thickness of sedimentary infill largely reflect Quaternary tectonic mobility of the Stavchanka and upper Vereshytsia rivers.

The following areas of smaller 3rd–6th order drainage basins, located within the main watershed zone, are relatively inactive: the Rata and the Lubaczówka river basins in the Rava Roztocze region and the Zubra and the Poltva river basins in the Lviv Roztocze region.

The changeable values of the remaining basin parameters (perimeter, mean width, as well as relief ratio and relative altitude coefficient) reflect considerable diversity of the area with respect to hypsometry. It results from its lithological and tectonic features, which will be a subject of future research.

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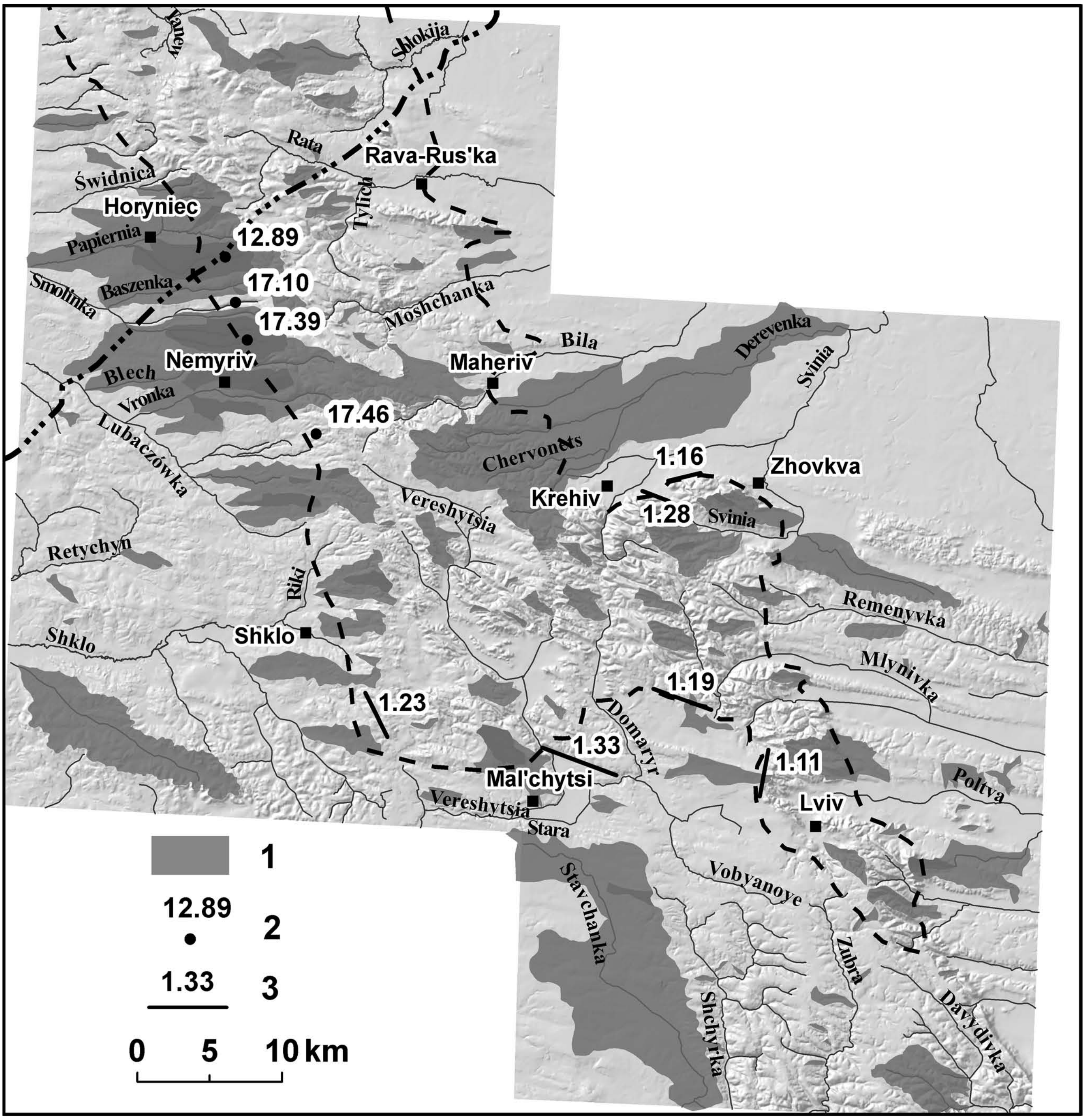

Fig. 10. Relative tectonic activity areas of the Ukrainian part of the Roztocze region. *1* – areas of relative tectonic activity distinguished on the basis of the lowest values of the following coefficients: *Re* basin elongation ratio, R_k circulatory ratio, R_f drainage basin shape coefficient and lemniscate coefficient *k*; *2* – areas relatively uplifted in the light of *Vf* valley floor width and valley height ratio; *3* – relatively tectonically active fronts/escarpments in the light of *Smf* mountain front sinuosity index

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