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SPATIAL (GIS) ANALYSIS OF RELIEF AND LITHOLOGY OF THE VSETÍNSKÉ VRCHY MOUNTAINS (OUTER WEST CARPATHIANS, CZECH REPUBLIC)

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Abstract: By combination of digital elevation models (DEM) with digital geological maps within GIS environment it is possible to detect manifestations of neotectonic movements. This technique has been demonstrated on the Vsetínské vrchy Mountains, a 367 km^2 large area in the Outer West Carpathians, the Czech Republic. The results have shown that steeper hillslopes, higher local relief (LR), and greater Strahler's hypsometric integrals (SHI) correlate well with regions of increased resistance to erosion, as opposed to less resistant bedrock geology which is correlated with predominantly gentle slopes, lower LR, and smaller SHIs. These facts do not support former opinions on significant neotectonic block faulting of the Vsetínské vrchy Mountains during the "neotectonic period". The relief topography is concordant with underlying strata of variable resistance. Thus, it seems probable that the youngest evolution of the study area has been proceeding steadily. The topographic relief has experienced the state of dynamic equilibrium, which has been caused by the rebounding of the Epivariscan European Platform. There is no reason to assume the alternation of periods of tectonic standstill and strong, mainly vertical, movements during several "neotectonic phases".

Key words: neotectonics, geomorphology, DEM analysis, hypsometric integral, rock resistance, Outer West Carpathians, Czech Republic.

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INTRODUCTION

Application of GIS to geomorphological research is topical today, due to increasing quality and quantity of digital topographic and geological data. Digital elevation models (DEM) can, thus, be used as a basic data source in analyses of complex relations among landscape features (Voženilek *et al.*, 2001) or they can solve the relation between lithospheric dynamics and the topography (Kuhni & Pfiffner, 2001; Tucker *et al.*, 2001).

The use of GIS and DEM in geomorphology is a new quality phase, which has developed from formerly plentifully used cartographic techniques (Hack, 1973; Kudrnovská, 1975; Bull & McFadden, 1980; McKeown *et al.*, 1988; Zuchiewicz, 1995b, 1998b, 2000; Goldrick & Bishop, 1995; Bíl & Máčka, 1999). The main merit of cartographic techniques was their efficiency. They served as a convenient tool for preliminary landform assessment. In fact, there is still not a more effective method in global geomorphology than an analysis of maps, whatever form they are in (Summerfield, 2000). Due to recent rapid computer development, these techniques can be easily integrated into GIS environment (Zevenbergen & Thorne, 1987; Longley *et al.*, 2001). The geological digital data, together with the topographic ones, can then bring a more complex view of landscape evolution (Tucker *et al.*, 2001; Kvapilová, 2002; Bíl, 2002a). The application of GIS in geomorphological studies can reveal the exact values of relief parameters (elevation, slope, local relief) and, thus, support or reject former conclusions on landscape evolution that were based solely on descriptive approach in the past.

The GIS analyses of DEM and digital geological maps, described here, were applied to the Vsetínské vrchy Mountains, a 367 km^2 large area in the eastern Czech Republic which belongs to the Outer West Carpathians (Fig 1). The study area is bounded by valley floors of the Rožnovská and Vsetínská Bečva rivers (Fig. 2), and by the main drainage divide between the Morava and Váh rivers. From the east to the west, the area measures 35 km, from the north to the south it is, in the broadest place, 20 km across, and then narrows to 4 km in the east. The highest point is Vysoká Mt. (1024 m a.s.l.) in the east, the lowest point is a place close to

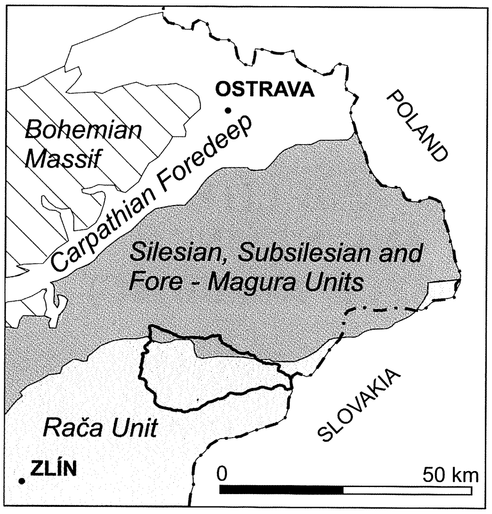

Fig. 1. Geological sketch of the surroundings of the study area

the junction of both the Bečva rivers (285 m a.s.l.). The most important river in the Vsetínské vrchy Mountains is the Bystřice river, whose basin area makes up 28% of the total study area.

GEOLOGICAL SETTING

The Flysch Belt of the West Carpathians in Moravia and Silesia is a complex allochthonous nappe system. During the Late Palaeogene and Lower Miocene Neo-Alpidic orogenic processes, the uppermost Jurassic to Lower Miocene strata were folded and thrust far northwestward over the southeastern margin of the North European Epivariscan Platform (Stráník *et al.*, 1993). The thrusting of the Carpathian flysch prism over the Platform exceeded in the West Carpathians 100 km during the Neogene (Kováč, 2000). The end of sedimentation in the Middle Badenian was caused here by break-off of the subducted plate (Kováč, 2000). The stress field inherited from these processes is, however, still preserved here, as documented, *e.g.* by "closing" of the Frenštát No. 1 mine, at a depth where the base of the Silesian nappe is situated (Dopita, 1997). The limnic sediments of Middle Badenian age near Opava are the last known Miocene sediments preserved in Moravia. That is why a reconstruction of the youngest (neotectonic) history of the study area and its surroundings is very difficult, due to the lack of geological data from sedimentary rocks. In the past, attempts to explore the youngest neotectonic evolution were made to detect the tectonic activity and its amplitude basing on analyses of planation surfaces (Czudek *et al.*, 1965; Demek, 1976; Kalvoda & Prášek, 1987). This approach, however, has recently been abandoned (*cf.* Zuchiewicz, 1998b; Urbánek, 1999; Bíl, 2002a).

The bedrock of the Vsetínské vrchy Mountains is composed of siliciclastic strata of the Rača unit (Magura nappe) and Silesian nappe. A small part of the Fore-Magura Unit occurs in the east, but its area is negligible as compared to the other units and, thus, it will be treated together with the Silesian nappe. Both nappes are composed of groups of slices which were thrust one upon another during the Savian and Styrian phases (Stráník *et al.*, 1993). The Rača unit comprises nearly 90 % of exposures in the study area (Fig. 2). It consists of the Zlín Formation (47% of the Rača Unit

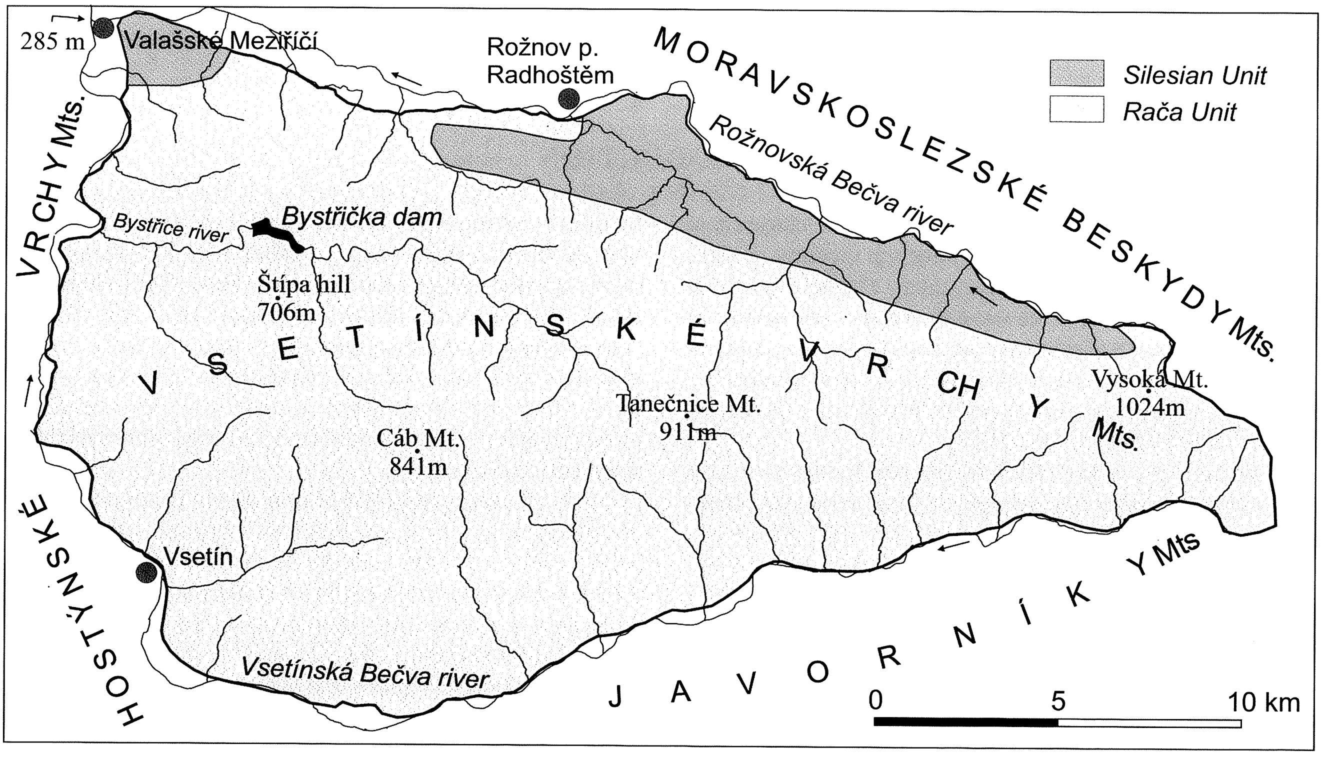

Fig. 2. The study area is bounded by valleys of the Rožnovská and Vsetínská Bečva rivers. Exposures of the Rača Unit cover almost 90% of the area

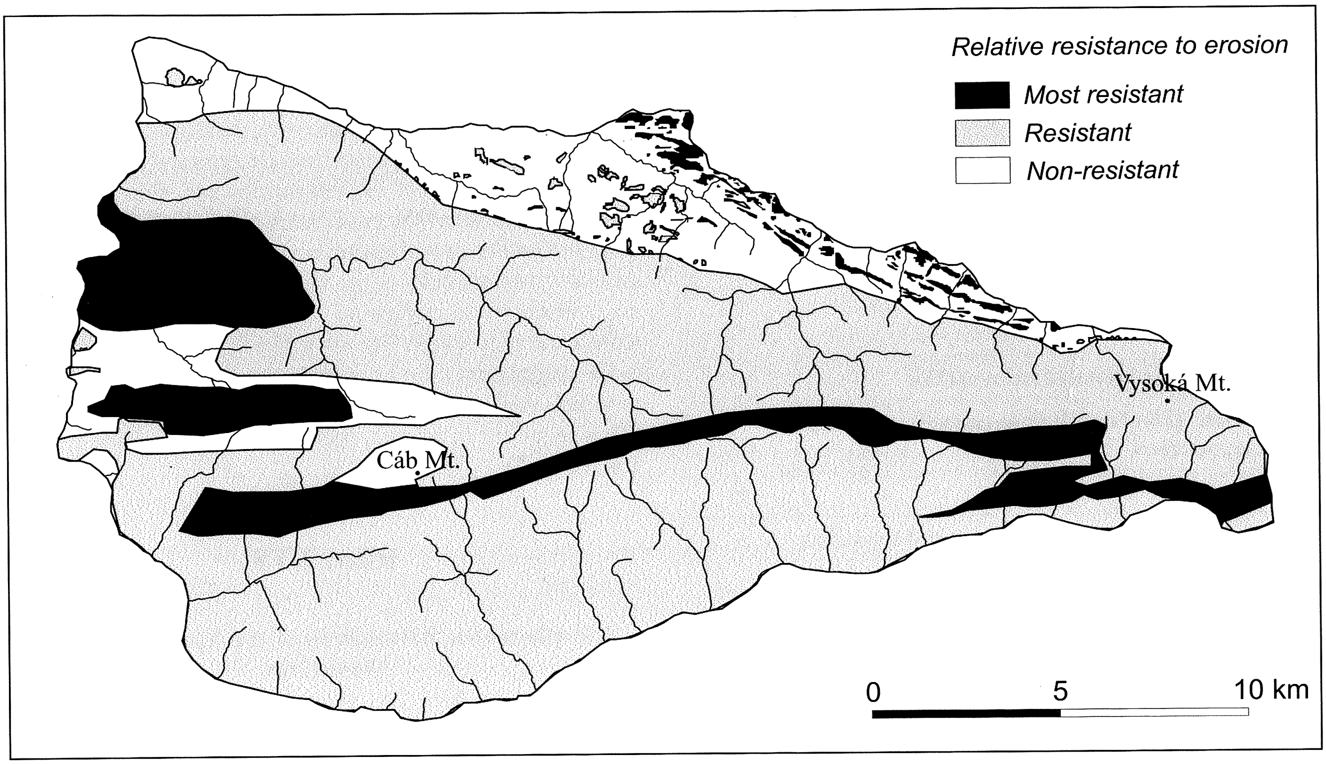

Fig. 3. Classes of relative rock resistance to erosion. Moderately resistant rocks cover the largest part of the area

exposures), Soláň Fm. (41%), Beloveža Fm. (11%), Kaumberg Fm. (0.9%), and Gault Flysch Fm. (0.1%). The Silesian Nappe contains the Submenilitic Fm. (40% of the Silesian Nappe exposures), Istebná Fm. (30%), Krosno Fm. (18%), Menilitic Fm. (8%), and Godula Fm. (4%).

Quaternary sediments are represented by an alluvial fill which consists of gravel, sand, and/or clays. The valley gravel fills of the both bounding rivers (Vsetínská and Rožnovská Bečva rivers) are up to 12 m thick (Bíl, 2002b). It was probably caused by selective erosion during incision at the end of the Pleistocene. Only some fragments of river terraces of unknown age are preserved. Deluvial cover is seldom thicker than 2 m, except for some places at the base of slopes, where colluvial sediments occur. The whole area has been subject to denudation since the Late Badenian.

METHODS

The morphology of the Vsetínské vrchy Mountains has been studied using an ArcView GIS technique. The whole study area is covered by six topographic map sheets at the scale of 1:25,000. These vector contour maps were merged to form a polygon theme. The boundary of the study area (river valley floors and drainage divides) acted as another polygon theme which was used for clipping the previous one. The river network and important breaks in slopes were added into the clipped theme. Finally, the DEM was generated. The resulting DEM in the form of a triangulated irregular network (TIN) is not suitable for further analyses. That is why it was converted into GRID (raster mesh) with 20 x 20 m pixel size. Grid size influences the representation of topography. The bigger resolution would not be expedient here, because small exogenous landforms could be then detected, and detection of young erosional landforms is not the scope of this work. The river basin areas and drainage divides were directly obtained by manual digitising of the contours. Except for DEM, digital geological maps in the form of polygon themes were used.

During conversion from TIN to GRID, each pixel obtains its elevation value. From the resulting elevation GRID, other raster files (slope and local relief) were derived. The technique of calculation of the slope is based on the elevation of the central point and its eight neighbours in a 3 × 3 pixel mesh. The local relief was derived from a 5 × 5 m pixel mesh. Thus, it represents a 100 × 100 m frame. After computing a range value from all 25 pixels, the result was ascribed to the central one. Then the frame was moved with one pixel step to the right. The basic statistical characteristics for each polygon (represented here by river basin or lithological type) were then derived from both the above mentioned raster files. Hence, the distribution of pixels within a polygon was obtained.

An attempt to detect neotectonic movements is based on the following assumptions. The hillslope angles and local relief (LR) values depend on rock resistance. Rocks with low detachability (showing high resistance to erosion) will always build steeper slopes, if no neotectonic movements occur, and high LR will prevail in them and vice versa. This dependence will be only disturbed if neotectonic impact appears. Then, the high values of LR and steeper slopes will be situated upon neotectonic elevations which need not to be built of resistant rocks. The discrepancy between morphometric values and bedrock lithology can point to the places where neotectonic movements are likely to occur.

Exact determination of the rock resistance is very difficult, because strength parameters determined by laboratory analyses often neglect discontinuities and, thus, are much higher than those of the entire rock mass (Kuhni & Pfiffner, 2001). Another complication arises from the fact that very similar types of rocks occur in the study area. They are all siliciclastic strata consisting of alternating layers of sandstones and claystones. The rock resistance varies according to the component ratio of both types of rocks and the degree to which they are consolidated. Therefore, I tried to establish a sequence of relative rock resistance classes (*cf.* Table 1 and Fig. 3).

Table 1

Relative resistance of rocks to erosion

Description of lithological types	Resistace to erosion
Lukov Mbr. (Soláň Fm.) – thick-bedded sandstones and conglomerates	1
Sandstones of Godula Fm.	1
Ciężkowice sandstones (Submenilitic Fm.)	1
Thick-bedded sandstones of Beloveža Fm.	1
Rusava Mbr. (Zlín Fm.) – coarse grained sandstones and conglomerates	1
Sandstones of Istebná Fm.	2
Ráztoka Mbr. (Zlín Fm.) – sandstones and claystones	2
Vsetín Mbr. (Zlín Fm.) – claystones and sandstones (ratio 2:1 – 10:1)	2
Claystones of Istebná Fm.	3
Claystones of Menilitic and Submenilitic Formations	3
Thin-bedded flysch and claystones of Beloveža Fm.	3
Krosno Fm. – Claystones and non-resistant sandstones	3

After Z. Stráník and Krejči (pers. comm.); 1 – most resistant rocks, 3 – least resistant rocks

RESULTS

Morphometric parameters of the Vsetínské vrchy Mountains

The study area is covered by 916,531 pixels, 400 m^2 each, which yield an overall area of 367 km^2. The whole area has been sliced into eight 100-m-high elevation intervals (*see* Table 2 and Fig. 4). The largest area (99.4 km^2) belongs to 501–600 m band which makes up 27.0% of the total area. The areas larger than 20% have two more intervals: 401–500 m (22.9 %) and 601–700 m (22.9 %). The heights over 800 m a.s.l. compose only 5.5 % of the study area.

The main slope value for the study area is 14.4°. The steepest slope (51.2°) appears on the eastern side of the

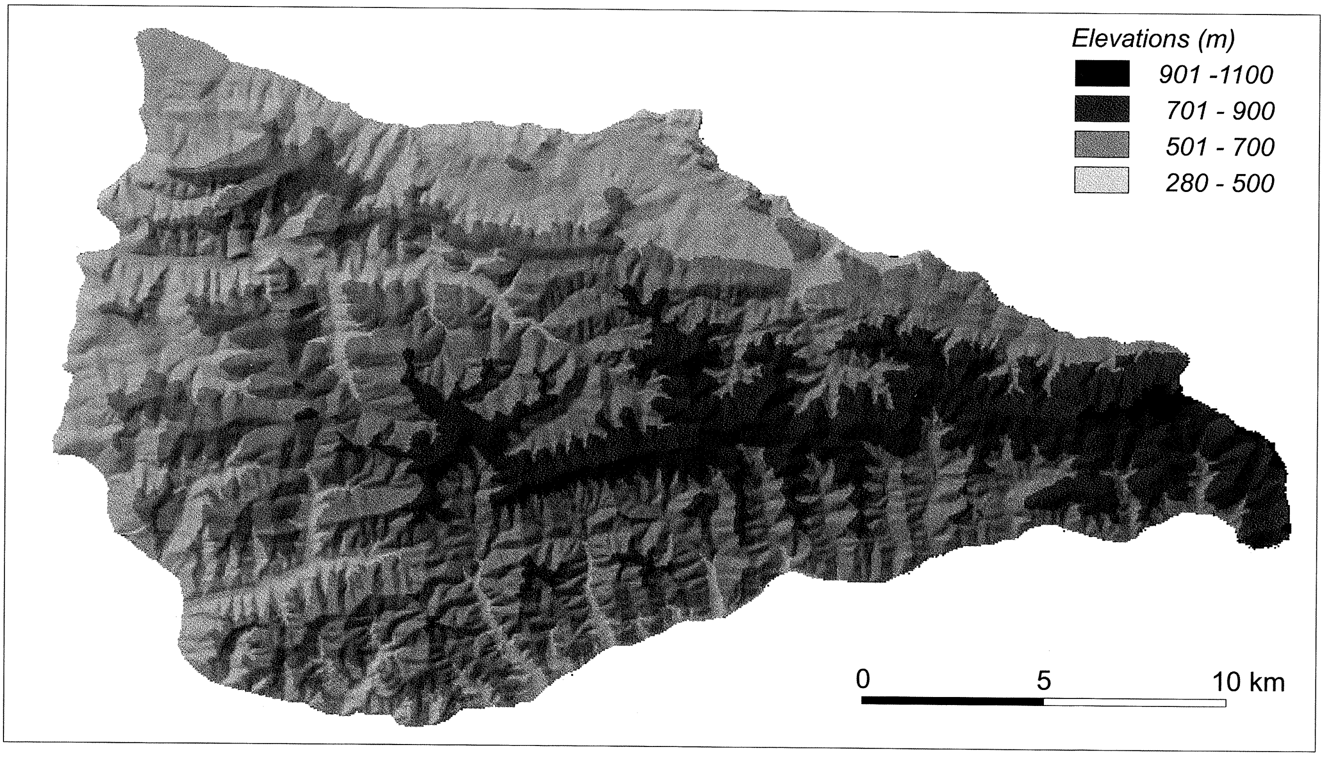

Fig. 4. Digital elevation model of the study area. The darker the hue, the higher the elevation. The number of elevation intervals was reduced to 4 for better readability

Table 2

Basic elevation parameters of the study area

Elevations m a.s.l.	No. of pixels	Area km^2	Frequency %	Cumulative Frequency %
280–400	76605	30.6	8.4	8.4
401–500	210438	84.2	22.9	31.3
501–600	**248425**	**99.4**	**27.0**	**58.3**
601–700	210178	84.1	22.9	81.2
701–800	121483	48.6	13.3	94.5
801–900	45085	18.0	4.9	99.4
901–1000	4199	1.7	0.5	99.9
1001–1100	118	0.1	0.1	100.0
Sum	916531	366.7	100.0	–

Table 3

Slope angle distribution

Slope angle (°)	Frequency %
0.0–2.0	1.9
2.1–5.0	5.1
5.1–10.0	16.9
10.1–18.0	**47.2**
18.1–30.0	28.3
30.1–45.0	0.5
45.1–90.0	0.1

Štípa Hill (706 m a.s.l.), south of the Bystřička dam. Slope distribution into intervals (Table 3 and Fig. 5) was made according to the techniques used by the Czech Geological Survey during engineering geological mapping. The largest area belongs to the slope interval 10.1–18.0° (47.2%). Very steep slopes occur at few places which are located upon very resistant rocks. As discussed earlier, some smaller terrain phenomena like frost river cliffs or gorges could not be detected by a 20 x 20 grid. That is why there occur very steep slopes up to 90°, but they always correspond with exogenous landforms. The lowest slope angle value (0.0°) can be mainly found either at flat valley floors or on tops of some ridges. Gentle slopes (below 5°) cover an area of 25.7 km^2 (7.0 %).

Table 4 and Fig. 6 demonstrate the distribution of LR in the 100 x 100 m frame. Maximal frequency (35.2 %) belongs to 20.1–30.0 m interval, whereas the minimal frequency (0.1%) falls into 70.1–85.0 m interval. The mean LR value in the 100 x 100 m frame for the study area is 26.0 m.

Dependence of morphometric parameters on lithology

If the areas of polygon themes (lithology or basin) are summarized over any grid theme (slopes, LR), it will result

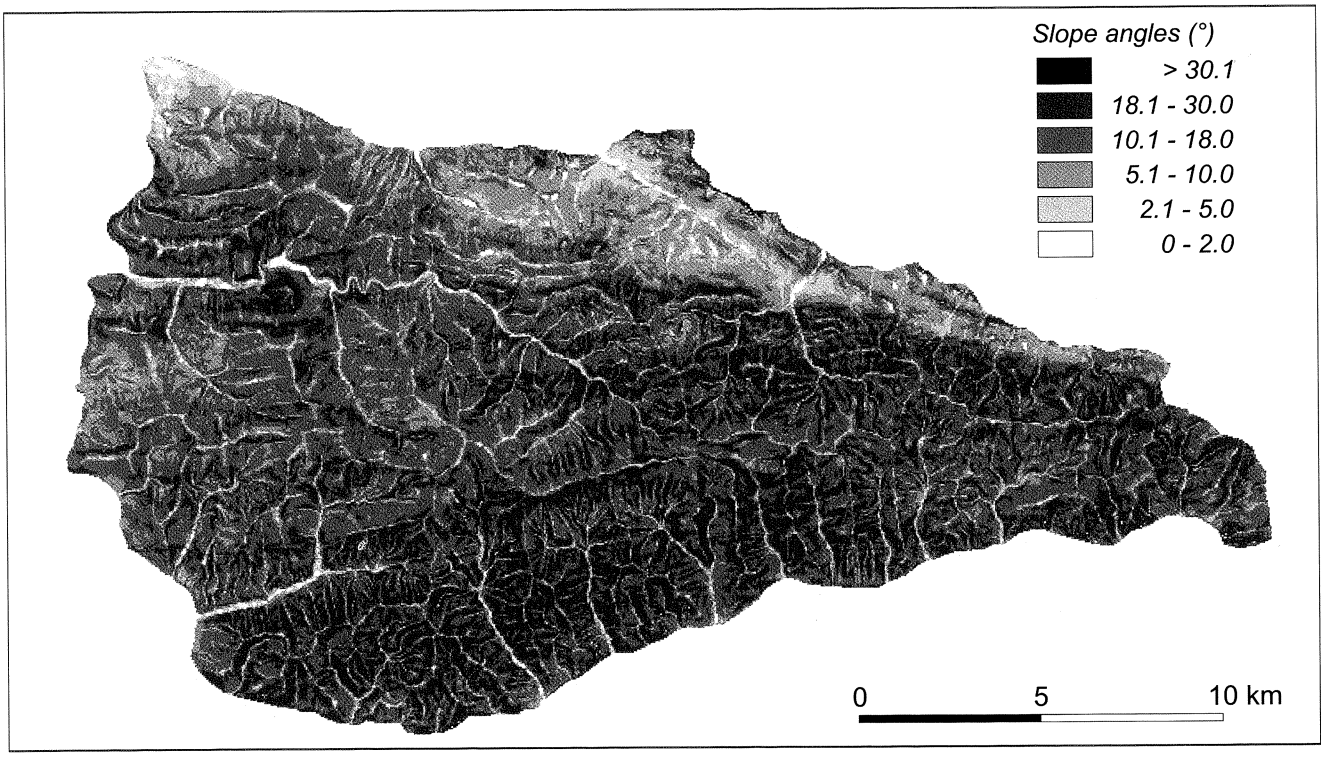

Fig. 5. Slope angle distribution. The darker the hue, the steeper the slope

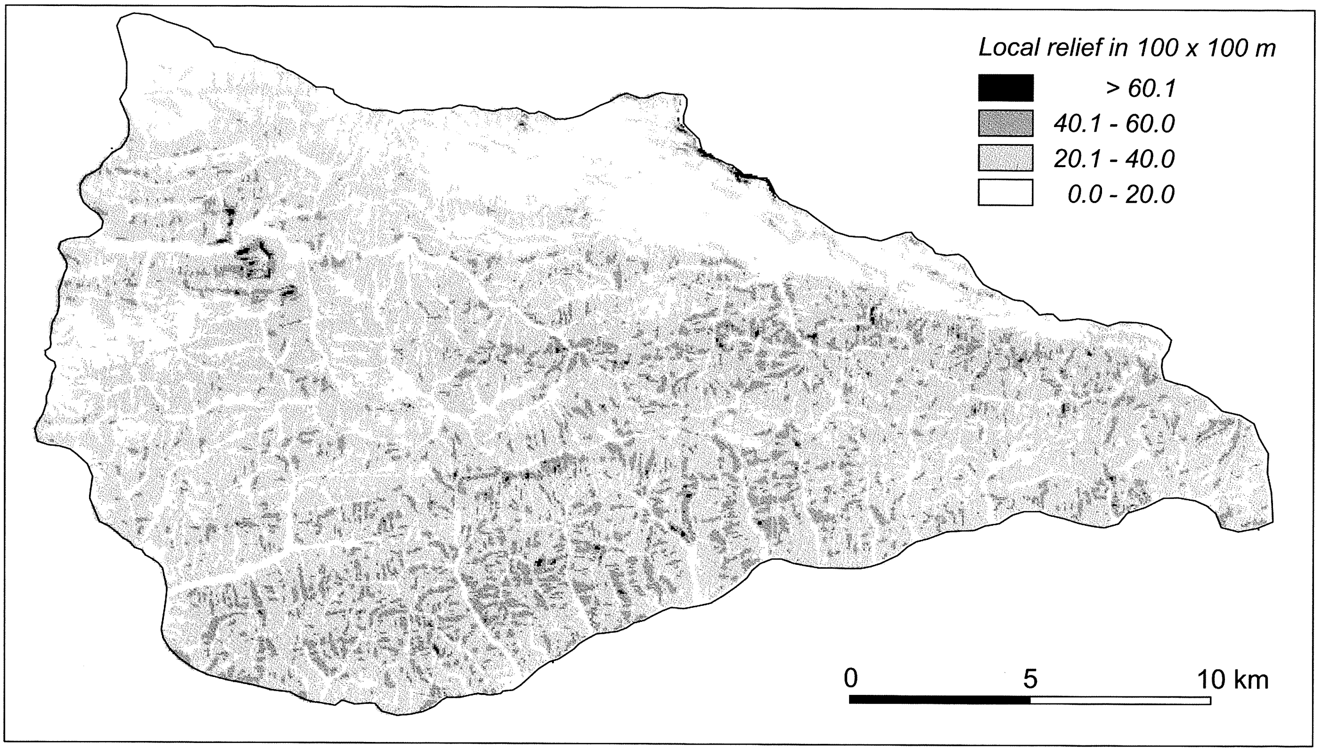

Fig. 6. Distribution of local relief (LR) in a 100 x 100 m frame. The darker the hue, the greater LR

Table 4

Local relief for a 100 x 100 m frame

Local relief m	Frequency %
0–10.0	6.4
10.1–20.0	21.9
20.1–30.0	**35.2**
30.1–40.0	26.2
40.1–50.0	8.6
50.1–60.0	1.4
60.1–70.0	0.2
70.1–85.0	0.1

Table 5

Slope angles and bedrock lithology

Formation	Slope angle (°)			Standard deviation (°)
	Minimal	Maximal	Mean	
Beloveža	0	38.8	13.5	4.9
Zlín	0	**51.2**	16.8	5.6
Soláň	0	45.7	15.6	5.3
Kaumberg	0	31.7	12.3	4.7
Menilitic	0	24.1	8.6	3.4
Krosno	0	20.7	6.9	3.2
Submenilitic	0	26.9	8.8	4.6
Istebná	0	43.1	12.8	7.4
Godula	2.5	38.6	**18.6**	7.3

in an histogram for each polygon. The distribution of slopes versus bedrock lithology is shown in Table 5. The table does not comprise valley floors, because their flatness is the result of either deposition or river dynamics and, hence, they are not affected by underlying lithology as are slopes at other places. Flat surfaces are, for the purpose of the following analyses, situated always upon ridges.

Apart from the Godula Fm., flat surfaces (slope 0.0°) occur on each bedrock lithology. The steepest slope (51.2°) belongs to the Rusava Member of the Zlín Formation. These rocks are very hard and resistant sandstones (*see* Table 1). The highest mean slope (more than 15°) can be found upon the Godula (18.6°), Zlín (16.8°) and Soláň (15.6°) Formation exposures. These values are higher than those for all the study area which is 14.4°. The gentlest mean slopes are situated on the Menilitic (8.6°), Krosno (6.9°) and Submenilitic (8.8°) Formations. These formations are very detachable. They consist mostly of either claystones or sandstones of low resistance (*see* Table 1). The last column in Table 5 shows the standard deviations (*s*) for slope value distributions for each rock type. These values of *s* do show greater dispersions for rocks of higher resistance, because different slope angles occur there. Conversely, in rocks of low resis-

Table 6

Frequency distribution (in %) of slope angles

Slope angle (°)	Beloveža	Zlín	Soláň	Kaumberg	Menilitic	Krosno	Submenilitic	Istebná	Godula
0.0–2.0	0.6	0.7	0.8	1.2	5.3	7.7	4.7	3.4	0.0
2.1–5.0	2.7	1.9	1.9	4.1	6.2	19.1	13.8	7.8	2.0
5.1–10.0	20.4	8.9	10.8	26.2	**58.0**	**59.4**	**48.6**	29.1	13.3
10.1–18.0	**58.8**	**45.2**	**54.1**	**56.7**	29.5	13.4	28.8	**38.7**	30.9
18.1–30.0	17.4	42.5	31.8	11.7	1.0	0.5	4.0	18.1	**48.8**
30.1–45.0	0.2	0.7	0.5	0.0	0.0	0.0	0.0	2.9	5.0
45.1–90.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7

Frequency distribution of slope angle values for members of the Zlín ans Soláň Fms.

Slope angle (°)	Zlín Formation Frequency (%)				Soláň Formation Fr. (%)	
	Vsetín	Újezd	Rusava	Křivské	Ráztoka	Lukov
0.0–2.0	0.5	1.2	0.6	2.2	0.7	0.7
2.1–5.0	1.4	2.4	1.6	9.5	1.7	2.0
5.1–10.0	6.6	12.8	6.3	40.0	9.1	9.9
10.1–18.0	42.8	**62.1**	32.6	**42.9**	**48.9**	**49.8**
18.1–30.0	**48.1**	21.3	**52.4**	5.3	38.9	37.1
30.1–45.0	0.6	0.3	6.5	0.0	0.7	0.5
45.1–90.0	0.0	0.0	0.0	0.0	0.0	0.0

tance the *s-values* have smaller dispersion due to the predominance of gentle slopes.

Different rock resistance becomes obvious when the slopes are divided into intervals (Table 6). Table 6 shows a close relationship between rock resistance (according to Table 1) and the distribution of slopes. More resistant rocks attain their maximum frequency in steeper slope intervals and vice versa. Almost 87% of the Krosno Fm. exposures are situated on slopes gentler than 10°. In case of the Menilitic and Submenilitic Formations these gentle slopes cover approximately 70% of their extent. Very resistant Godula Fm. shows maximal frequency in the 18.1–30.0° (48.8%) interval, whereas the peaks for other formations lie within 10.1–18.0° intervals.

Since the exposures studied are built predominantly of the Zlín and Soláň Formations, it is necessary to show slope frequency for their particular members (Table 7). The Křivské Mb. is the least resistant and that is why approximately 95% of its exposures lie on slopes gentler than 18°. The Rusava Mb., where more than 50% of its exposures lie in 18.1–30.0° interval, is the most resistant one.

Table 8 shows the values of LR in the 100 × 100 m frame. Frequencies for the Zlín and Godula Formations are the greatest in 30.1–40.0 m interval (35.6% and 34.7%). The relief on these formations is thus more rugged than that on other formations, especially on the Krosno, Menilitic and Submenilitic Formations. In these less resistant formations, a large proportion of LR smaller than 20 m is typical (93.3% – Krosno Fm., 83.6% – Menilitic Fm., and 75.7% – Submenilitic Fm.).

Morphometric characteristics of river basins

The study area has been divided into 28 river basins, according to their river network parameters (Fig. 7). Every basin is both an inlet of the Rožnovská or Vsetínská Bečva rivers and its river network must be at least of the 3rd order (after Strahler's system – Strahler, 1964) with at least six tributaries (magnitude; Shreve, 1966). For each basin, the hypsometric integral (SHI – Strahler's Hypsometric Integral; Strahler, 1952) was calculated. The SHI relates horizontal cross-sectional area of a drainage basin to the relative elevation above the basin mouth. It has no dimension and that is why the values can be compared irrespective of the true

Table 8

Frequency distribution (in %) of LR in a 100 × 100 m frame

Local elevation (m)	Beloveža	Zlín	Soláň	Kaumberg	Menilitic	Krosno	Submenilitic	Istebná	Godula
0–10.0	2.5	1.6	1.7	4.4	13.4	32.3	20.9	9.3	1.8
10.1–20.0	29.6	12.1	15.8	37.6	**70.2**	**61.1**	**54.8**	**36.9**	12.7
20.1–30.0	**43.0**	34.0	**40.7**	**42.7**	15.7	6.2	19.0	30.3	23.3
30.1–40.0	20.6	**35.6**	31.0	13.9	0.7	0.4	4.8	14.1	**34.7**
40.1–50.0	3.7	13.8	9.3	1.3	–	–	0.5	5.3	20.1
50.1–60.0	0.4	2.5	1.3	0.1	–	–	–	2.7	7.3
60.1–70.0	0.1	0.3	0.1	–	–	–	–	1.1	0.1
70.1–85.0	0.1	0.1	0.1	–	–	–	–	0.3	–

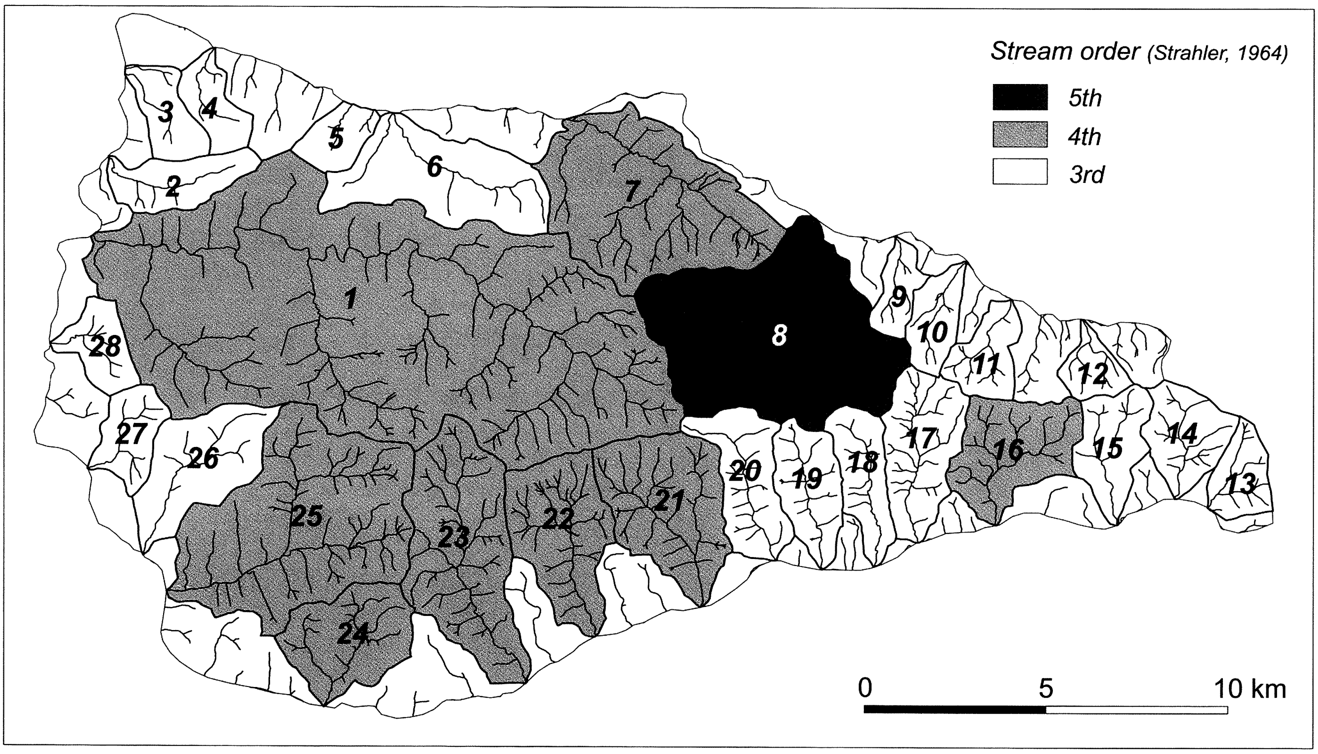

Fig. 7. The study area was divided into 28 river basins of the 3rd, 4th and 5th order with a minimal number of tributaries (magnitude – Shreve, 1966). For code names of the basins – see Table 9

scale. This method served as a tool for the determination of stages of landscape evolution during the cycle of erosion (Strahler, 1952).

In spite of general rejection of the concept of the cycle of erosion (*e.g.*, Summerfield, 2000), the SHI can be used for detection of neotectonic movements within river basins (McKeown *et al.*, 1988; Bíl, 2001; Bíl, 2002a). This approach has been applied here and, hence, it will be shortly explained. To detect any neotectonic movement with cartometric tools, it is first necessary to rank the bedrock according to its resistance to erosion. After that we can assume that during landscape evolution the SHI values of basins will only depend on the different detachability of bedrock lithologies. The SHI values will thus be greater on more resistant rocks, and vice versa. Under such conditions, the presence of a higher SHI value in a basin on less resistant rocks could detect a significant disruption, and neotectonic movements should be taken into account.

The Raďkov and Uzgruň basins have the highest SHI value of 52 (*see* Table 9), and the Křivský stream shows the lowest value (29). The mean SHI value for the whole study area is 43. Comparing these figures with lithological contrasts, the link between SHI and detachability becomes obvious. Basins showing low SHI values are situated predomi-

Table 9

Strahler's Hypsometric Integrals (SHI) for 28 basins in the study area

Basin	SHI	No.	Basin	SHI	No.	Basin	SHI	No.	Basin	SHI	No.
Raďkov	52	19	Bzové	47	18	Lýkový p.	44	28	Kyvňačka	40	9
Uzgruň	52	13	Hluboký p.	47	10	Rybjanka	44	15	Jasenice	40	25
Bučkový p.	51	11	Mšadla	47	12	Brodská	44	21	Maretka	36	6
Solánecký p.	49	8	Hovězí	47	24	Bystřice	44	1	Střítež	36	5
Jezerné	48	17	Medůvka	47	2	Babská	43	14	Hrachovec	31	4
Kobylská	48	20	Jasenka	46	26	Dinotice	42	23	Hažovický p.	30	7
Vesník	48	27	Miloňovský p.	45	16	Lušová	42	22	Křivský p.	29	3

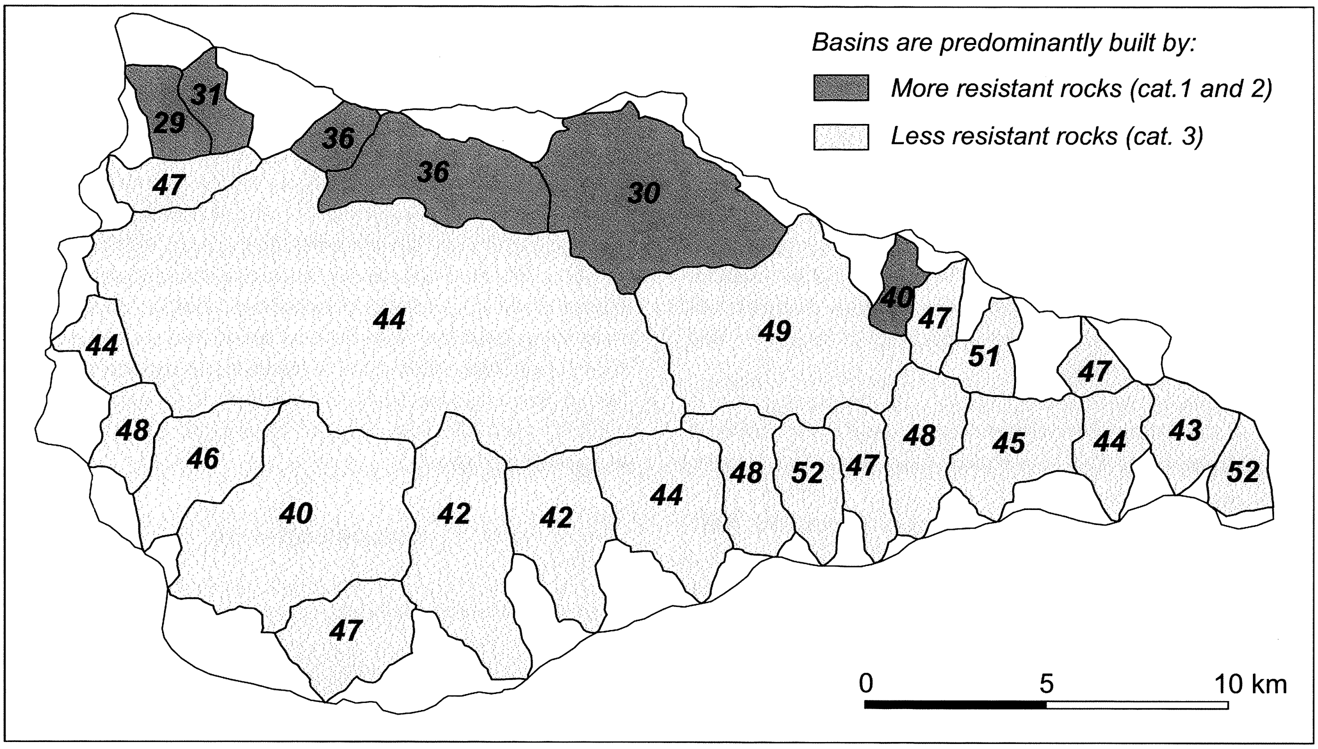

Fig. 8. The Strahler's hypsometric integral (SHI) values for basins on less resistant rocks (category 3, Table 1) are mainly lower than those on more resistant rocks (categories 1 and 2). According to the t-test, the difference between SHI mean values (see Table 10) is statistically significant at = 0.05

nantly on less resistant rocks of both the Silesian nappe, and Křivské Mb. (Zlín Fm.). The higher SHI values belong to more resistant rocks of the Rača nappe. Since there is no basin built predominantly on the most resistant rocks (category 1, Table 1), categories 1 a 2 were, for statistical purposes, merged to form a category named "more resistant rocks". Thus, there are two types of basins: located on more and less resistant rocks (Fig. 8). According to the Student t-test, the difference between SHI mean values is statistically significant at α = 0.05 (Table 10).

The SHI values increase from the junction of the Rožnovská and Vsetínská Bečva rivers in the west towards the east, where the main drainage divide on the axis of the Carpathian mountain arc occurs (Fig. 8). This moderate

Table 10

The difference between SHI means is, according to t-test, statistically significant at α = 0.05

	Predominance of rocks according to their resistance to erosion in basin outcrops	
	Less resistant rocks	More resistant rocks
Number of basins	6	22
SHI mean	33.0	46.5

growth (increase of rock mass to be eroded) corresponds well to the models concerning evolution of mountaineous topography evolution (Kooi & Beaumont, 1996; Hovius, 2000; Champion *et al.*, 2001).

DISCUSSION AND CONCLUSIONS

A GIS analysis of the Vsetínské vrchy Mountain's DEM has shown the following results:

1. The dependence of hillslope angle distribution on bedrock lithology is such that steep slopes correspond to regions of hard bedrock lithology, and vice versa.
2. The same is true for local relief. On harder rocks the more rugged topography occurs.
3. The SHI values correspond to prevailing bedrock lithology of river basins.
4. An increase in rock mass to be eroded (SHI values) towards the east is in agreement with the models concerning mountain building without any significant neotectonic disruption.

These facts imply that the massif of the Vsetínské vrchy Mountains could not have been split into blocks by neotectonic movements. This conclusion can be supported in part by two geological sections running across the westernmost part of the study area (Menčík, 1983a; Menčík & Tyráček, 1985), which do not show any neotectonic disturbances. These sections are based on interpolations of boreholes and, thus, are not fully reliable.

The predominant theory concerning the youngest evolution of the Vsetínské vrchy mountains and their surroundings assumes that the mountains were split into several blocks during several "neotectonic phases" (Stehlík, 1964; Kopecký, 1972; Demek, 1976; Zeman & Bezvodová, 1983; Ondřej, 2000). This theory is only based on differences in the vertical positions of the so-called planation surfaces. However, the so-called planation surfaces are not dated. There were some attempts to correlate their age with analogous surfaces in Poland and Slovakia. This approach was based on either similarities of their vertical elevations above river bottoms (*e.g.*, Stehlík, 1964, Czudek *et al.*, 1965), or on assumptions of analogous evolution of the whole Carpathian arc (Král, 1985). The latter is not correct (*e.g.*, Oszczypko & Ślączka, 1985; Kováč, 2000). Planation surfaces are very often situated on nearly horizontal strata. Thus, the bedrock structure is very often the reason for their existence (Menčík, 1983b). There occur many young deep-seated landslides in the highest parts of the Vsetínské vrchy Mountains, which are probably of Holocene age (Krejčí *et al.*, 2002). The dating of landslides in the Polish Carpathians supports this assumption (Margielewski, 1998; Alexandrowicz & Alexandrowicz, 1999). The flysch rocks are very unstable and that is why the preservation of planation surfaces on tops of ridges (since Sarmatian times) is very unlikely (Ivan & Kirchner, 1998; Ivan *et al.*, 2000; Bíl, 2002a). The concept of several planation surfaces has been largely abandoned due to their unclear origin and the assumption of "interrupted evolution" which is necessary for their genesis (Zuchiewicz, 1998b).

According to the facts mentioned above, it seems likely that the youngest evolution of the Vsetínské vrchy Mountains proceeded without any significant fault-neotectonic disruptions (possibly from the Late Badenian onwards) to the Recent. However, older (Late Badenian–Sarmatian?) fault movements cannot be (on the basis of relief analysis) totally excluded due to the overall low resistance of flysch rocks to erosion. Recent topography is the result of the distribution of rock formations showing differentiated resistance to erosion. There is no reason to assume the presence of periods of tectonic standstill there. The topographic relief probably underwent the state of dynamic equilibrium. The overall and slow uplift of the study area and its surroundings (Zoetemeijer *et al.*, 1999) was caused by an isostatic rebound of the Epivariscan European Platform which started after the slab break-off (Kováč, 2000) and still persists until recent times (Vyskočil & Zeman, 1980). Nevertheless, some neotectonic vertical movements of small magnitude (up to tens of meters) probably occur at the border of the study area (Krejčí, 1955; Bíl, 2002b). The assumed low neotectonic fault activity in the westernmost part of Outer West Carpathians is in accordance with the results of other studies (*e.g.*, Zuchiewicz, 1995a, 1998a). The neotectonically uplifted areas become more numerous from the west to the east which suggests an eastward-increasing tectonic activity of the Outer Carpathians (Zuchiewicz, 1998a).

The GIS analysis can be helpful in solving problems of detection of neotectonic movements. Raster DEM yields many morphometric data for any landscape unit (*e.g.*, river basin) and, thus, allows for a comparison among them, although any interpretation of morphometric characteristics of DEM must take into account geological and geophysical settings of a region.

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