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L A N D F O R M E V O L U T I O N I N M O U N T A I N A R E A S

JÁN LACIKA (BRATISLAVA)

NEOTECTONIC EVOLUTION OF THE WEST CARPATHIAN DRAINAGE BASINS IN SLOVAKIA

Abstract. Geomorphological development of drainage systems in the Slovak part of the Carpathian Mountains in their neotectonic stage can be characterised as transformation of geomorphological networks under the effect of changing morphostructural and morphoclimatic factors. Geomorphological networks are those, which form rivers and valleys (depressive networks) or watersheds and inter-valley ridges (elevation networks). Old networks disappear and are replaced by younger ones, with parameters of arrangement which correspond to new conditions. Transformations are gradual and always with certain delay following the climatic and morphostructural changes. The main impetus of transformation of geomorphologica networs in the territory of the Slovak Carpathians is the morphotectonics. Replacement of older valley and ridge systems by the new ones takes place under the direction of morphostructural influences of different hierarchy. Research in this area should be focused on detailed morphostructural analysis of geomorphic networks of the individual basins of the Slovak Carpathians and the adjacent boundary areas in Hungary, Poland, Czech Republic and Ukraine.

Key words: morphotectonics, geomorphological network, West Carpathians

INTRODUCTION

Geomorphological evolution of the West Carpathians during the neotectonic phase has been characterized by a change in composition of the geomorphological networks. Geomorphological networks are composed of a pattern of rivers or valleys (depressive networks) and inter-valley ridges (elevation networks). Older networks tend to disappear and are replaced by the younger ones. Gradual transformation follows with a certain delay in response to climatic and tectonic changes. That is the reason of preservation of some older network segments in the recent relief. Therefore, the relief is partially fossil and does not correspond to actual morphoclimatic and morphostructural conditions. As a reducing element in the relief, the older network can be interpreted as a regressive type of geomorphological network. It was created under different conditions during the Palaeogene and Early Neogene. New networks have arisen following the development of the contemporary morphoclimatic and morphostructural conditions. This development commenced during the Badenian, which is considered as the lower limit to the neotectonic phase in the West Carpathian area. The developing and expanding new geomorphological networks can be named as progressive network types. Complicated transformation process of the West Carpathians has manifested itself by the existence of several generations of valley segments in the same river basin.

Geomorphological networks forming the individual basins of the Slovak Carpathians have not been formed accidentally. Their spatial composition is distinctly determined by the local structural-lithological morphostructure and also — in part — morphoclimatic situation. The basic attributes of valley and inter-valley patterns depend on the orientation of faults and other structures and on their nature. Geomorphological networks respond to different properties of the bedrock, such as the geomorphologic values of the rocks exposed in the basins, or changes of altitudinal position of the system of local erosional bases. The basin valleys and ridges can be compared to the "mirror", as they reflect both the existing and past morphostructural basin settings. By means of analysis of basic attributes, such as: the valley and ridge textures, their density, manifestations of asymmetry, parameters of longitudinal and transversal profiles or the selected characteristics, the relevant morphostructural properties of the territory in question can be identified and the basic stages of its development interpreted.

Geomorphological networks are open morphodynamic systems. They develop in certain morphoclimatic and morphostructural conditions subject to changes in time and space. The climatic and morphostructural changes take part in the network transformations not only in the territory of the basin, but also in adjacent and comparatively distant areas. Geomorphic effect of subsidence of the lowland morphostructures of the Pannonian Basin in the south and south-east, or in the foreland of the Carpathians in the north and the west is also observable in more distant mountain morphostructures of the Western Carpathians. Lowering of the base of erosion in the lower parts of basins, induced by tectonic subsidence, founds its response as far as the headwater basin parts in the form of accelerated deep a backward erosion or valley piracy.

RESEARCH METHODS IN A STUDY OF GEOMORPHOLOGICAL NETWORKS

Geomorphological networks possess certain properties (density, asymmetry, linearity, etc.) that can be studied by a set of selected geomorphological techniques. Their choice must take into consideration the specific characteristics of the valley (depression) or ridge (elevation) networks and, simultaneously, must respect the requirements of research application. Valleys connected with contin-

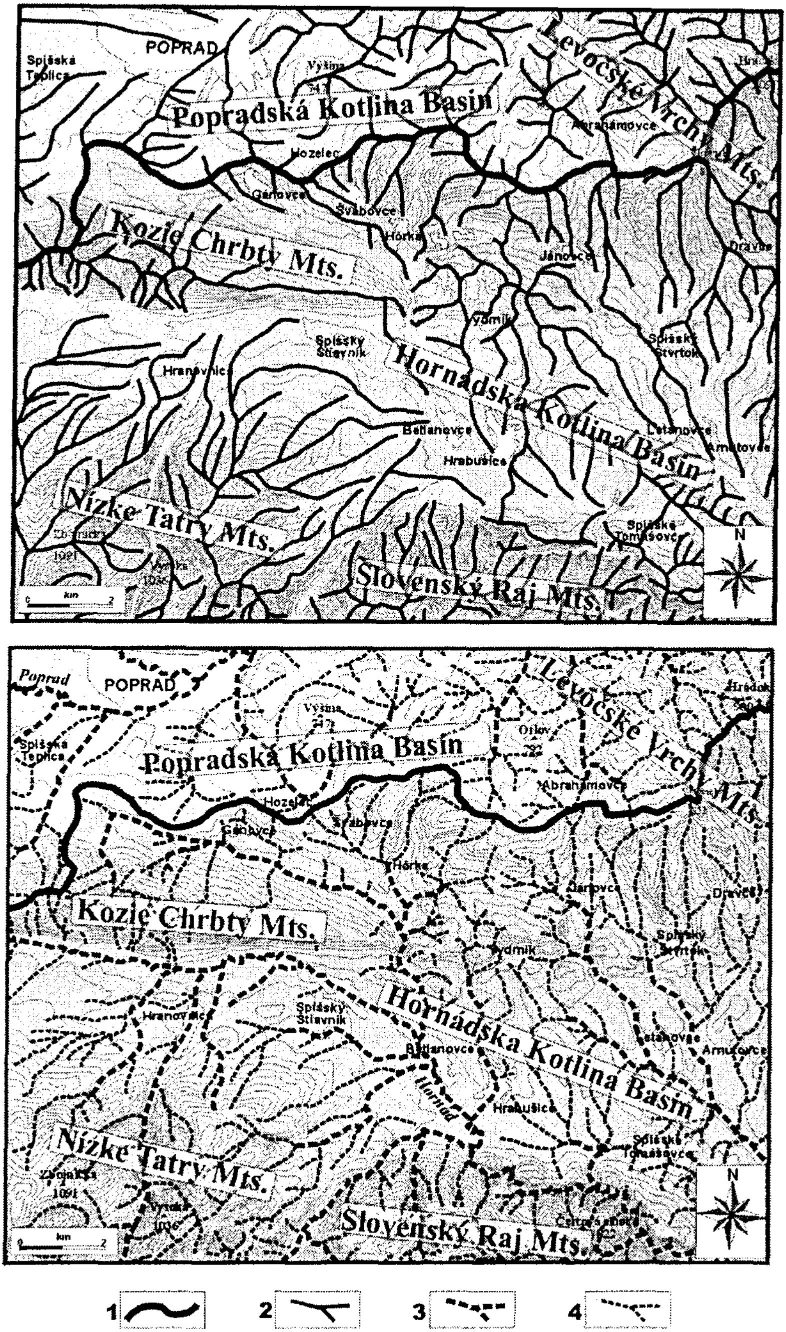


Fig. 1. Geomorphological network of the Gánovce area. 1 — main European watershed, 2 — elevation (interfluve or inter-valley) network, 3 — depression (valley) network of the 1st and 2nd order (according to *Strahler's* classification), 4 — depression (valley) network of the 3rd and higher order (according to Strahler's classification)

uous networks represent the integrating element of a geomorphological system. Knowledge of their spatial composition suggests the morphostructural nature of the basin in question and the dynamics of erosion-denudation processes proceeding in their individual parts. Inter-valley ridges (watersheds) joining into rather discontinuous networks usually block integration of the valley networks. This barrier effect, though, is reduced in some places (namely, in the sections of higher discontinuity) what leads to more radical transformations of the basin systems by means of migration of watersheds and valley piracy. Analysis of valley networks is more adequate for the study of change indicators within the studied basin. Analysis of elevation geomorphological networks, in turn, are aimed at reconstructing the relationships among individual drainage basins (catchments).

Analyses of geomorphological networks are conducted in two fundamental ways: palaeo-constructions and predictions. They are applicable to reconstruction of the history of the morphostructural development of a territory, as encoded in spatial arrangement, density and elevation of these networks. The prognostic application, i.e., forecasting of the developmental trend of geomorphological networks, is also important; it consists in fact in identification of those areas where the developmental changes are expected to change the future erosion-denudation characteristics of a territory.

Source data for the analysis of geomorphological networks are obtained from the basic topographic maps with contour line grid. In case of the Slovak Carpathians, maps at the scale of 1 : 25,000 which depict practically all elements of these networks — valleys and inter-valley ridges — are perfectly sufficient. The grid consisting of linear signs tracing the network axes is preserved in analysable form even after 6- or 8-fold reduction. Figure 1 shows an example of the geomorphological network map.

ANALYSIS OF VALLEY NETWORKS

We can analyse the following attributes of the geomorphological network elements: hierarchy, textures, density, linearity, and asymmetry. Hierarchisation of the network elements is carried out following the method of A. N. Strahler (1952). Analysis of the network element texture takes into account the different patterns, for example, valleys arranged into tree- or fan-like forms, grid, parallel, rectangular, radial or other textures. The identified textures are indicators of certain morphostructural properties of a given territory. The density of network elements is measured as the sum of the valley or ridge axes within squares of an area of 1 square kilometre (in $km \cdot km^{-2}$). Such measurements need not have to be applied to the whole research territory. They are carried out in selected areas showing relatively homogeneous density. Delimitation of such areas is done visually, according to the obvious change of the number of delineated valley or ridge axes. The linearity of network elements is the specific property of valley or ridge segments which indicates the presence of linear morphostructural divides. This linearity consists in visual joining of valley or ridge segments arranged in lines. Not only valleys or ridges within one partial basin, but also the segments of adjacent basins are joined into lines.

Analysis of network element linearity consists of two steps, conducted at gross and more detailed scales. Such an approach provides indications of morphostructural divides of different hierarchies, both local and regional ones. The results of the presented analysis of valley linearity were confronted with the map of linear and non-linear divides of the West Carpathian Mts made by J. Kvitkovič and J. Feranec (1986), following the interpretation of spatial images. As far as the network element asymmetry is concerned, three types of this attribute of valley or ridge networks were identified: ground plan, profile longitudinal and profile altitudinal types. The ground plan asymmetry is manifested by different levels of development of the basin parts situated on the right and left sides of the axial valley. Profile-longitudinal or altitudinal asymmetries are observable on the transversal profile of the valley or ridge. The longitudinal asymmetry applies to situation when the inclinations of the right and left sides of the profile are different, one being steeper than the other. The gentler side is often terraced whereas the river terraces are absent on the steeper side or they occur in fragmented and incomplete form. The profile altitudinal asymmetry manifests itself by different altitude of the interfluves on the given valley profile.

ANALYSIS OF INTERFLUVES

The interfluve is the place of "fight" between two adjacent basins for the territory. Backward erosion and, in certain circumstances, also the lateral erosion take part in the shift of the watershed to the side of the less "aggressive" basin. The watershed is pushed back which means reduction or regressive development of this basin. The development of the opposite river basin side is progressive; it expands its area. Apart from progressive shift of the watershed, the radical transformation of the valley network over the watersheds by means of piracy also occurs. Piracy is the result of different altitudinal position of erosional bases of the opposite valleys. The valley showing a lower situated base of erosion is predestined to capture a part of the basin of an higher situated base of erosion. The extent of shift of the basin or even piracy depends on the rate of the barrier effect of the corresponding segment of the interfluve. The barrier effect was identified by means of the following morphometric parameters: sea level altitude, relative altitude, and arrangement of isobasites. The sea level altitude of the watershed is only an auxiliary criterion for the assessment of the rate of its barrier effect. It helps to locate the important culminations at the watershed, the bottom culminations (saddles), and upper culminations (tops). The value indicating the relative altitude of the basins in respect to the nearest local erosional basis is more valuable. The point of the valley network where valleys of the third order meet and wherefrom farther downstream the valley attains the higher hierarchical position was chosen as a local erosional basis. The maps of isobasites compiled after G. H. Dury (1952) and V. P.

Filosofov (1960, 1970), as well as those of W. Zuchiewicz (1980,1981), successfully applied to morphostructural research, and finally in accord with J. Lacika (1993, 1997b, 1999, 2000, 2001a), J. Lacika and A. Gajdoš (1997) and J. Lacika and J. Urbánek (2000), provide a suitable auxiliary database which makes it possible to assess the rate of the barrier effect in a basin. The largest barriers, as well as the weakened spots of the barrier effect are clearly represented on these special morphometric maps. The pattern of isobasites (including their elevation and density) indicates the course of the axes of principal morphostructural units, i.e., ridges and valleys. Highly elevated isobasites delimit the main barriers. Important saddles often cause disintegration of isobasite networks.

Longitudinal valley profiles represent the auxiliary source material for the study of barrier effect of the interfluves. Profile curves of opposite valleys are compared on both sides of the watershed or, according to M. Lukniš (1954), the neighbouring valleys are taken into account if lateral piracy, classified by J. Lacika (2002) as K and Y types of piracy, is presumed. The analysed curves offer information on curvature anomalies of the compared valleys and on elevation of the local erosional bases and situation of anomalous sections.

MORPHOSTRUCTURAL CHARACTERISTICS OF THE WEST CARPATHIANS

Morphostructural and morphoclimatic conditions of the territory of the Slovak Carpathians in the course of the Neogene and Quaternary were changeable, as manifested by the cyclic transformation of the present geomorphological networks. Morphostructural situation has been changing in time and space, the morphoclimatic changes taking place more in time than in space. In other words, the territory in question was more heterogeneous in terms of morphostructure in the neotectonic stage while the morphoclimatic conditions were not as spatially heterogeneous. No important climatic differences did exist among individual basins, but on the other side they differed from the point of view of morphostructure. That was the reason why this study concentrates more on morphostructural aspects of basin transformation or transformation of their geomorphological networks.

Leaving aside the details, the shape of the West Carpathians is that of a huge dome. Its ellipsoid ground plan and asymmetry was first noted by E. Mazúr (1979). They were described in more detail by J. Lacika and J. Urbánek (1998a, b; see Fig. 2). The modelling of the dome started in the Early Badenian and it was accompanied practically from the beginning by breaking into a complicated system of tectonic blocks of different size and ground plan. This was how the one of the basic features of the West Carpathians originated. It is the system of intra-mountain basins. The mosaic of mountain ranges and tectonic basins was individualised already in the Miocene. Their composition did not substantially

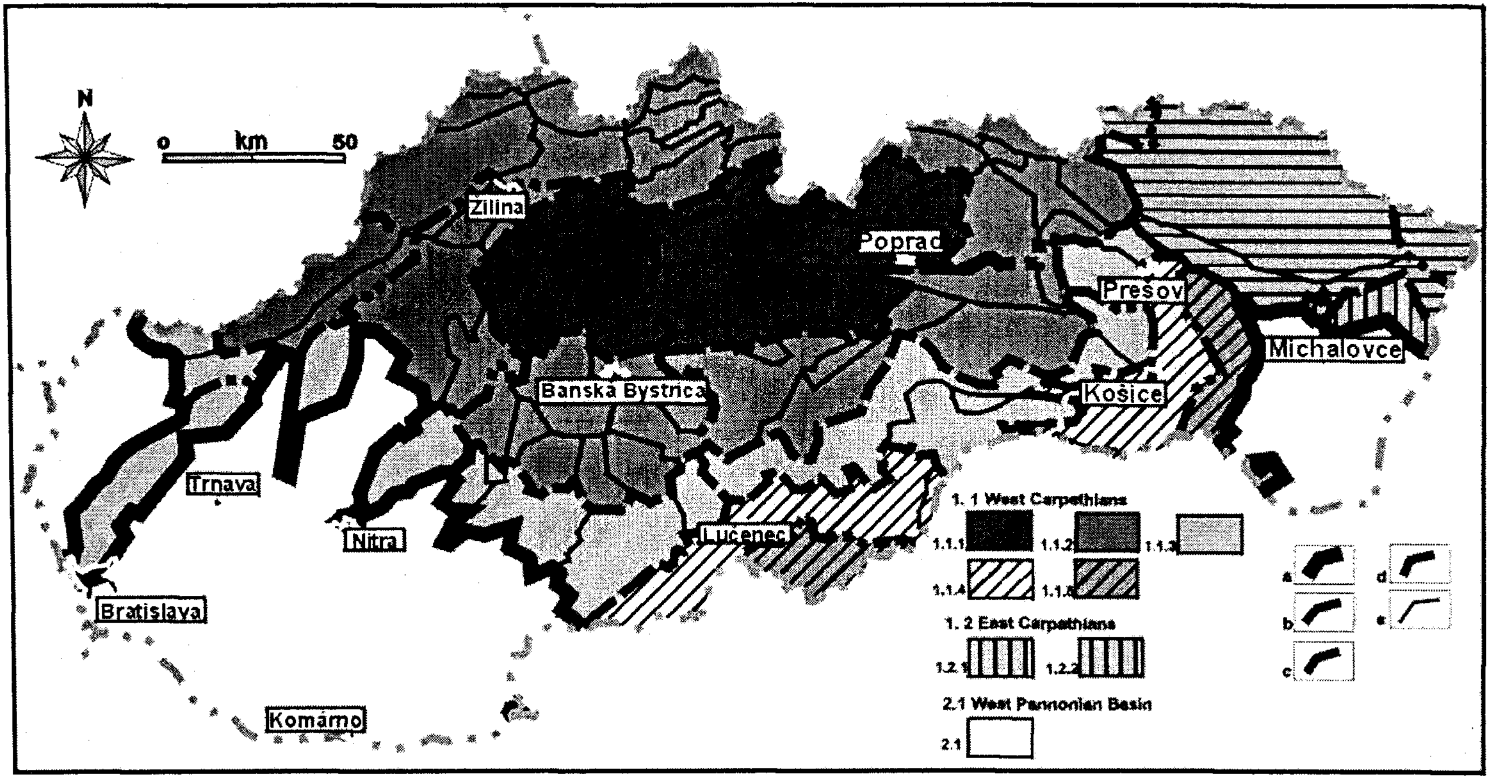


Fig. 2. Morphostructural subdivision of Slovakia. 1.1. — West Carpathians, 1.1.1. — Central morphostructures of the West Carpathian dome, 1.1.2. — Transitive morphostructures of the West Carpathian dome, 1.1.3. — Marginal morphostructures of the West Carpathian dome, 1.1.4. — Southern subsided morphostructures, 1.1.5. — Southern elevated morphostructures, 1.2. — East Carpathians, 1.2.1. — Outer zone morphostructures of the East Carpathians, 1.2.2. — Inner zone morphostructures of the East Carpathians, 2.1. — West Pannonian Basin. Morphostructural boundaries of the: a — 1st level, b — 2nd level, c — 3rd level, d — 4th level, e — 5th level

change in the Pliocene and Quaternary; only their geomorphological contrasts deepened under the effect of tectonic movements. Positive tectonic movements were dominant in the whole dome. The basins were uplifted less strongly than the mountain ranges, resulting in relative subsidence and deepening of the former. Special development took place at the southern end of the West Carpathian dome where the faults became suitable for volcanic eruptions. According to V. Konečný et al. (1984) and J. Lacika (1997a), two principal stages of volcanic activity are discernible in the Early Badenian and Sarmatian, producing an extensive complex of the volcanic mountain rages of the Slovenské Stredohorie and the Matransko-slánska regions, built up of andesites, rhyolites, and their volcanoclastics. The intensity of volcanism was progressively decreasing. It culminated in the Pliocene by sporadic volcanism of basaltic type. Seismic activity of seismogenic faults testifies to the still unfinished mobility of the West Carpathians.

The top of the dome of the West Carpathians is not situated precisely at its centre (Fig. 2), being shifted towards its north-eastern edge (Lacika and Urbánek 1998a, b). The top of the dome is occupied by the Tatra massif. This dome slopes from its asymmetrically situated centre over its circumpherential and peripheral parts to the lowland area of the Pannonian Basin on the south-west and south-east, and to the Juhoslovenská depression in the south. On the opposite side this depression is limited by the belt of elevations of the Matra-Slaná morphostructure. The individual morphostructural units are arranged in the form of rings around this dome of the West Carpathians in contrast to those of the East Carpathians which are arranged in belts.

The central morphostructures are the most uplifted portions of the West Carpathians and the whole Carpathian arch. Their mountain ranges (Tatra Mts, Nízke Tatry Mts, Malá Fatra Mts, Veľká Fatra Mts, and Turčianska kotlina basin) reach the greatest sea level altitude, and the Podtatranská and Turčianska basins are the highest situated ones in Slovakia. The central part is also the most dissected and contrasting one. The difference between the mountain ranges and basins reaches the highest values (up to 2,000 m) in the central part of the dome. Within the central part, two units of the 4th level are distinguished: the Tatra and Fatra central morphostructures.

The transitional part of the dome is less uplifted than the central one, and more than the peripheral parts. The amplitude of uplift of the partial morphostructures is less distinct, i.e., the relief is less contrasting than in the centre of the dome. The unit consists of five lower morphostructural units which differ from each other by composition of elevations and depressions and the properties of passive structures in the relief. In other words, the mosaic of mountain ranges and basins changes from place to place. Geological setting of this territory is very heterogeneous, showing all the basic structural units. The morphostructural character of the transitional part of the dome is also very heterogeneous. There occur relatively stable units of the Slovenské Rudohorie and substantially more dynamic klippen belt, as well as the mosaic of intra-mountain basins.

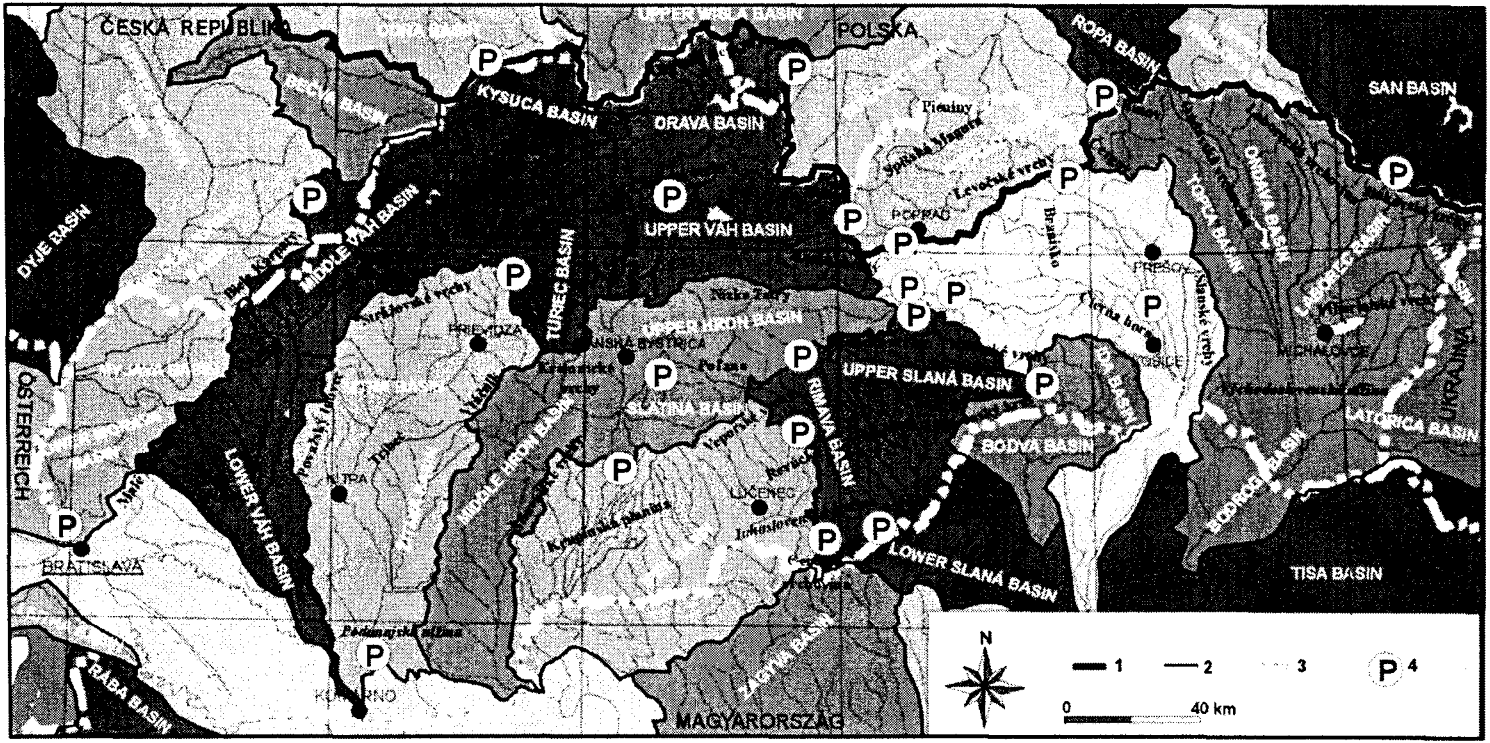


Fig. 3. Main geomorphological network of Slovakia. 1 — main European watershed, 2 — watersheds of the main drainage systems, 3 — watersheds of the partial drainage systems, 4 — watershed segment with weak barrier effect (real or potential piracy)

The peripheral part next to the South-Slovakian morphostructure is the least uplifted part of the dome of the West Carpathians. Simultaneously, the nature and rate of differentiation into the uplifted and subsided blocks varies. The mountain ranges drop into wide lowland bays between the mountain ranges or to the elongated South-Slovakian morphostructure. The belt-like arrangement is most conspicuous on the southern side of the dome of the West Carpathians. The relief in southern Slovakia and northern Hungary is arranged into two distinct tectonically individualised belts. The belt of the southern, depressed morphostructures (South Slovakia and Košice basins) is the one situated farther in north, whereas the belt of the southern elevated morphostructures (Burda Mts, Cerová vrchovina Mts, and Slanské vrchy Mts) is situated farther to the south of the two regions.

MAIN RIVER BASINS OF THE SLOVAK WEST CARPATHIANS

The position of Slovakia in Europe is that of a "roof". The Carpathians, compared to their environs, represent an elevation which contains the headwater parts of the river-valley systems. The main European drainage divide which separates the Baltic and Black Sea drainage basins runs along its ridges (Fig. 3). The greater part of the territory, except for the small area including the drainage basins of Poprad and Dunajec, is inclined to the Black Sea. The older network, dated by M. Lukniš (1972) to the Palaeogene, was significantly transformed during the neotectonic stage. The formation of the dome of the West Carpathians and its further disintegration due to faulting was accompanied by the formation of a new network, showing different outline and geomorphological features. This network reflected new morphostructural conditions. In spite of the progressing transformation which took place about 20 Ma, segments of the older Palaeogene networks did survive in the Slovak Carpathians.

The West and South-West of the West Carpathians

The drainage basin of the Váh River is the largest one (Fig. 3). It integrates the valleys of an area of 15,755 square kilometres on the territory of the West Carpathians and the Západopanónska panva (Podunajská nížina lowland). The Váh River marks the longest side of the West Carpathian dome. It leaves behind its centre after the longest route. Neotectonic fault deformations of the intramontane basins were conserved in the probably pre-Miocene establishment of this direction. In the Neogene, the Váh River followed the regressing lakes. It responded to the tectonic uplift of the transversal horsts (the Veľká Fatra and Malá Fatra Mts) by generation of antecedent gorge-like valleys.

The general direction of the Váh River valley changes beyond Žilina. Deviation toward the south-west can be interpreted as a certain response to the distinct subsidence of the Podunajská nížina lowland. Moreover, its course in this reach is linked to the erosion-denudational furrow along the Klippen Belt which relatively sank in the Neogene. The Váh River flowed into the Late Miocene sea which transgressed from the Vienna Basin as far as the present territory of Považská Bystrica. In the Pliocene, the Váh River continued as far as the Ilavská and Trečianska basins where it flowed through the fresh-water lakes. The lower reach of the Váh River flows through the Podunajská nížina lowland. It is its youngest reach, since it has been following the diminishing Pontian lake. The aggrading river prevents joining of the lateral streams and the basins taper into the narrow belt of alluvial plains. Aggradation of the stream is caused by the young (Quaternary) subsidence of the lowland bay between Nové Mesto nad Váhom and Sereď. It is near Sereď town where Váh diverses again, in this case in the south-eastern direction and maintains its course as far as its mouth into the Danube near Komárno. M. Lukniš (1972) explains this bent as a response to the formation of the huge alluvial fan of the Danube.

Weakening of the barrier effect was identified on the main European watershed which bordered the Váh river basin on the northern side. It is best observable in Kysuce, Orava, and Spiš regions, as well as in the Nízke Beskydy Mts. T. Pánek (2002) identified valley piracy of the Predmieranka brook (tributary of the Kysuce river) at the cost of the Černá brook in the Ostravica drainage basin. M. Baumgart-Kotarba (1992, 1996) analysed the watershed separating the Orava and Dunajec rivers in the Oravská kotlina basin. Tectonic development of the basin caused the loss of a part of the Orava basin in favour of that of the Dunajec River.

The fight for the watershed also takes place between the Váh and Nitra or the Hron rivers. There are favourable conditions in the Žiar, Kremnické vrchy and Starohorské vrchy Mts which represent depressed dividing lines among the Nízke Tatry Mts and the Veľká and Malá Fatra Mts. Tributaries of the Váh River showing higher situated local erosional bases are regressive in this case. In case of the Žiar Mts, this difference amounts to 150 m. The central part of the Považie regions, where local tectonic disturbances of the mobile Klippen Belt have been the cause of pushing back of the main ridge of the Biele Karpaty Mts by backward erosion of the right-side tributaries of the Váh River, remains in progressive development. M. Lukniš (1972) describes this phenomenon. Expansion of the basins of the Vlára, Drietomica, Bošáčka and Klanečnica Rivers acts in the detriment of the valleys on the left side of the Morava River. Similar development takes place within the Váh drainage basin between the upper reach of the Váh River in the Liptovská kotlina basin and the Orava River. The weak barrier in this case is the narrow mountain range of the Chočské vrchy Mts.

The Hron River can be referred to as the "small Váh". The ground plan of its drainage basin is similar: nib-like texture of tributaries and deviation of the bottom part of the basin in the southern direction. Downstream from its headwaters up to Banská Bystrica the Hron River follows, as M. Lukniš (1972) asserts, the post-Palaeogene megasynclinal riverbed between the Nízke Tatry Mts and the Slovenské Rudohorie Mts. The whole upper reach of the Hron River valley is morphologically delimited by the very distinct watershed formed by massive mountain ranges. The comparatively narrow valley widens only in the tectonic Breznianska kotlina basin, showing a rectangular valley texture. The middle reach of the Hron River valley developed under strong influence of intensive volcanic activity in the area of the Slovenské stredohorie Mts. In the Badenian, the Hron River probably mouthed into a bay of the Neogene sea, which later retreated to the south, while its course was limited by volcano-tectonic events. It is difficult to reconstruct the course of the Hron River in the area of erupting stratovolcanoes and subsiding large volcano-tectonic depressions. The dynamic and complicated development of the middle Hron River took place until the Pliocene when three contemporary intra-mountain basins of the Slovenské stredohorie became individualised. The Zvolenská and Žiarska kotlina basins were filled by the Pliocene lakes which were then probably connected by the Hron River. Its existence is testified to by the occurrence of the Hron gravel formation (H a l o u z k a 1998) which occurs in the present Hron River valley from the lower Horehronie up to the Žiarska kotlina basin. The present Hron River valley between Žarnovica and Kozárovce follows a distinct fault system which separates farther in the north the mountain range of Vtáčnik from the Žiarska kotlina basin. Before the Hron River mouths into the Podunajská nížina lowland, it passes through the Slovenská brána gate and overcomes the south-eastern protuberance of the Štiavnické vrchy Mts (Kozmálovské vŕšky hills). In the Pliocene, the river flowed into a lake and deposited its delta there. The occurrence of Early Pleistocene fluvial sediments on the ridges of the northern part of the Hronská pahorkatina hilly land testifies to the fact that after the regression of the Pliocene lake, the Hron River probably flowed in the south-western direction to the area of what is today the valley of the Žitava River. It created its typical bent to the south during the Early Pleistocene. Since that time, the lower reach of the Hron River heads to the existing valley between the Hronská and Ipeľská pahorkatina uplands. Asymmetry of its terraced steps points to the gradual migration of the riverbed to the east, probably as a result of tectonically-induced inclination of this area.

The watershed of the Hron drainage basin has its weak points above all on the left side, where it neighbours on the progressively developing basins of the southern wing of the West Carpathian dome. The most massive mountain range of the Slovenské Rudohorie Mts with central high plains prevents closer contacts. The isolated place in this area, where the valley piracy manifests itself, is the saddle of Zbojská between Brezno and Tisovec. The Hron drainage basin has been reduced here in favour of the Rimava drainage basin (part of the Slaná basin). The lower barrier effect is also observable in the Podkriváň saddle, between Detva and Lučenec. In this case, the Krivánsky potok brook in the Ipeľ River basin with lower situated local erosional basis is more aggressive. The valley piracy is also a typical phenomenon in the southern part of the Pliešovská kotlina basin (south of Zvolen). The watershed proceeding on the low ridges of the basin is the place of "fight" between the Neresnica (tributary of the Hron River) and Krupinica (tributary of the Ipeľ River). In this case too, the Ipeľ River basin enlarges at the cost of the Hron River basin. Several local manifestations were described by J. Lacika (2002) in the area of the Cerová vrchovina Mts, at the watershed between the Ipeľ and Slaná drainage basins. These are mostly controlled by fault tectonics and volcanic activity.

The drainage basin of the Nitra River is younger than those of the Váh and Hron Rivers, between which it is situated. According to M. Lukniš (1972), its formation started in the Late Miocene together with the rise of the volcanic mountain range of Vtáčnik. Volcanic products blocked the Hornonitrianska kotlina basins and caused concentration of local streams. Only the Nitrica River did create its valley out of the reach of volcanites. In the Pliocene, a temporary flow-through lake, fed by deltas of the brooks, originated in the upper reach of the Nitra River. As the Pliocene lake retreated, the Nitra River prolonged in the direction of the Podunajská nížina lowland where, together with the Váh River, it fell under the influence of the extensive alluvial fan of the Danube which compensated subsidence of a part of the Žitný ostrov inland island.

The "fight" between the local and more global tectonic effects can be demonstrated on the drainage basin of the Ipeľ River. The higher hierarchy of the basin determines the position of its axis, which is shifted to the south. Its asymmetry corresponds to the position on the periphery of the West Carpathian dome. The reach of the tectonic influences of lower hierarchy — young fault systems determining the shape of the Juhoslovenská kotlina basin — conditioned the general direction of the east-west orientated stretch of the stream. This direction, in contrast to the Váh and Hron rivers, is a younger one. Basing on the occurrence of Pontian gravels on the ridge of the Cerová vrchovina upland, M. Lukniš (1972) supposed that the Ipeľ River flowed first to the south, where it became integrated into the system of the Slaná River. Generation of the local elevation of the dome-horst type interrupted this direction and formed the contemporary texture of the basin's valleys. The Ipel' River detours in southern direction and mouths through the gorge over the Hungarian volcanic mountain range Börzöny into the Danube, in the centre of the gorge-like Visegrad gate. In the Krupinská planina plateau, the network of right-side valleys of the Ipeľ basin displays a radial eccentric texture which indicates the presence of denuded Neogene stratovolcano of Javorie.

The South and East of the West Carpathians

The south-eastern side of the West Carpathian dome is drained by the valley networks of three basins, namely those of the Slaná, Bodva, and Hornád Rivers, which merge close to the mouth of the Tisa River in the Hungarian part of the East Pannonian basin. The Slaná River drainage basin is a product of the neotectonic development of the West Carpathians. It has been shaped since the Early Badenian on the southern side of the West Carpathian dome (Lacika 2001a). The dome-like uplift of this main morphostructure has directed the valley network from the centre to the periphery, towards the south and south-east of the dome. The faults, which followed, created the basic arrangement of the geomorphological network in the progressively developing Slaná River drainage basin. This basin is a progressively developing basin with a tendency to expand at the cost of the neighbouring drainage basins (Fig. 4). The picture of the older geomorphological networks on the territory in question from the pre-Badenian times is more or less an hypothetical one, because it was transformed in the

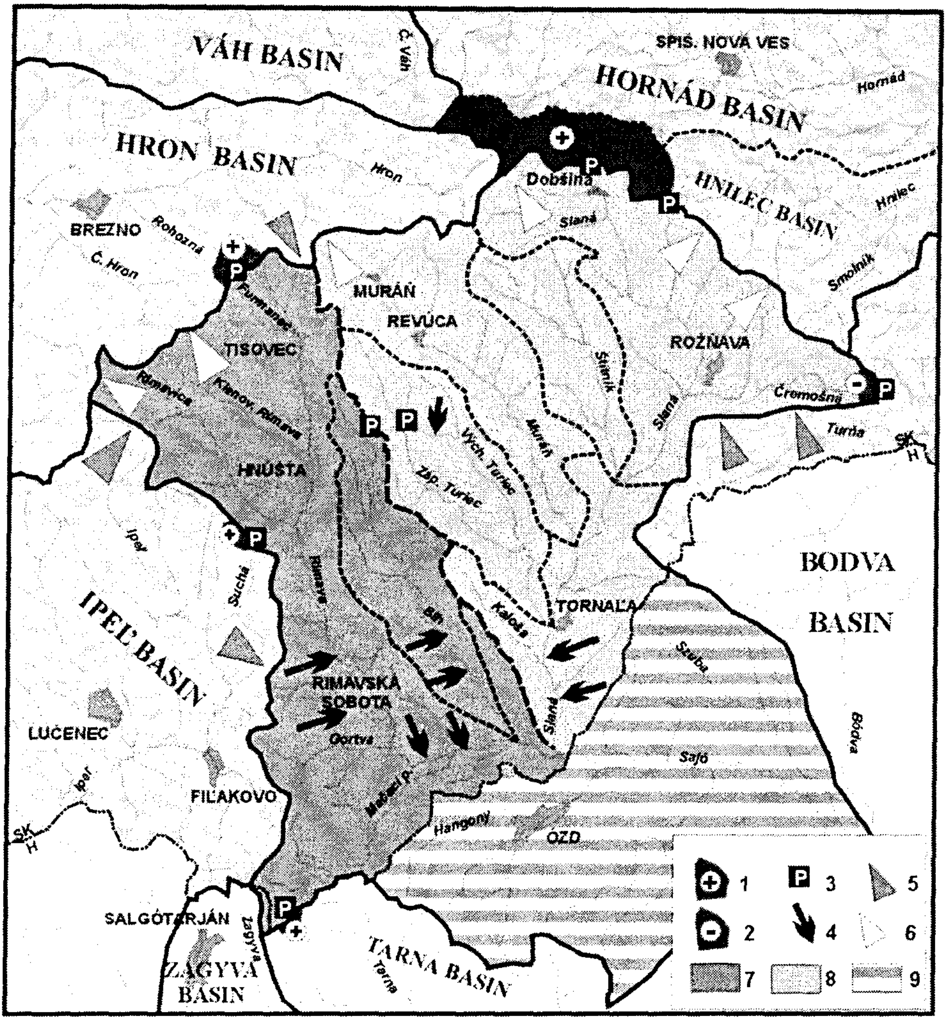


Fig. 4. Prediction of the evolution of the geomorphological networks in the Slaná drainage basin. 1 — acquired area of the neighboring drainage basin by potential river piracy, 2 — lost area of the Slaná drainage basin by potential river piracy, 3 — place of potential piracy, 4 — migration tendency of the asymmetrical valley axis, 5 — migration tendency of the progressive developed part of the Slaná drainage basin watershed, 6 — migration tendency of the regressive developed part of the Slaná drainage basin watershed, 7 — Rimava partial drainage basin, 8 — Upper Slaná partial drainage basin, 9 — Hungarian part of the Slaná drainage basin

younger stages. It is obvious that this old composition of the valleys and ridges was different from the present one. The palaeovalleys have probably followed the palaeo-Alpine tectonic structures, such as the Muráň fault system characterized by L. Pospíšil et al. (1989). That is the reason why contemporary valleys, which follow this system are considered the remnants of the pre-Badenian geomorphological network, which escaped transformation due to their position. The present-day valley network, as M. Lukniš (1972) asserts, was formed at the end of the Miocene when the originally parallel flowing Štítnik, Muráň, Turiec, Blh, and Rimava streams became integrated into the newly-formed and asymmetrically developing Rimavská kotlina basin. The greatest tributary of the Slaná River on the territory of Slovakia is the Rimava River, and that is why the basin has a distinctly asymmetrical ground plan with the more developed right side.

Results of the analysis of geomorphological networks existing in the Slovak part of the Slaná River make it possible to suggest that the territory in question will progressively develop. It means that if the basic morphostructural situation does not change, it will widen at the cost of the neighbouring catchments. The widening will proceed by gradual retreat of the watershed by means of headward erosion or valley piracy. The overall increment gained by piracy is estimated at 90 to 130 square kilometres. Progressive development is expected at the major part of the main watershed limiting the Slaná River basin. It means that its stretches should be shifted outwards, i.e., towards the neighbouring basins. This is especially true for the watershed stretches of the Slaná River basin in relation to the catchments of the Hnilec and Hron. A contradictory tendency appears to be obvious in the watershed area in relation to the Bodva basin, as in the case of the Ipeľ River.

The shift of the watershed is normally very slow, as it consists of high, massive, and often convex watershed. However, the barrier effect of the watersheds running on the karst plateaus of Muráň and the Slovak Karst is questionable. Inside these massifs, a high risk of weakening of otherwise morphologically very distinct dividing walls in cave systems is probable. Progressive development in the Slaná drainage basin should apply to the catchments of the Hnilec and upper Hron Rivers, where the most important cases of valley piracy are presumed. Potential piracy identified near the Zbojská saddle (725 m) in the Veporské Vrchy Mts would widen the basin of the Slaná River by the upper stretch of the Rohozná catchments. The Dobšinský brook (near Dobšiná town) has a tendency to catch an extensive territory in the headwater part of the Hnilec basin. The relative altitude of the watershed allows the presumption that this piracy will take place in about hundred thousands or million years. Another, smaller widening of the Slaná drainage basin caused by piracy is probable south of Kokava nad Rimavicou (at the cost of the Ipeľ basin and near Tachty in the Cerová Vrchovina Mts; at the cost of the Tarna River). Regressive development can be inferred only in case of the easternmost part of the Slaná drainage basin (in the Slovak Karst area), where territory can be lost in the partial river basin of the Čremošná brook in favour of the Zádielsky brook in the Bodva river basin. The loss would be about 8 square kilometres.

The Hornád River drainage basin is the mirror image of the Váh or Hron drainage basins. It is shorter, as it was formed on the shorter south-eastern slope of the dome of the West Carpathians. The upper reach of the Hornád River is orienttaed east-west. It follows the old consequent valley which was influenced to a certain extent by younger neotectonic processes, which dissected its basins into horsts and grabens. The horst of the Čierna Hora antecedently truncated by the Hornád River is the most conspicuous of them. The phenomena of the marginal epigenesis (the gorge of the Hornád River cutting the northern edge of the Slovenský Raj) are also present. According to M. Lukniš (1972) and J. Jakál (1992), the Hornád River obtained the uppermost part of its basin at the turn of the Pliocene and Pleistocene by capturing the Bystrá and the Vernársky potok brooks of the Poprad drainage basin (Fig. 5 a, b, c). The fight for the relative low watershed between the Poprad and Hornád Rivers has continued throughout the Quaternary until present time. The Hornád River, situated 60–100 m lower, is more aggressive. Another typical feature of the Hornád River is its epigenetic gorge on the northern edge of the Slovenský raj Mts. M. Lukniš (1972) associated the bent of the Hornád River near Kysak with accumulation of volcanic material of the Slanské Vrchy Mts during the Early Miocene. The barrier of the volcanic mountain range has also steered the lower Torysa and Olšava Rivers towards the south. This trend was supported by activation of the north-south faults of the Hornád system which delimits and differentiates the Košická kotlina basin. These faults can foster the Hornád River to prolong its valley towards the east and, thus, reduce its way to the relatively sinking Košická kotlina basin near Lemešany. The greatest left-side tributary of the Hornád River is the Torysa River, flowing in the dynamic morphostructural environment of the shortest side of the West Carpathian dome. On the stretch between Lipany and Prešov, it follows a conspicuous depression whose part is occupied by the narrow Klippen Belt.

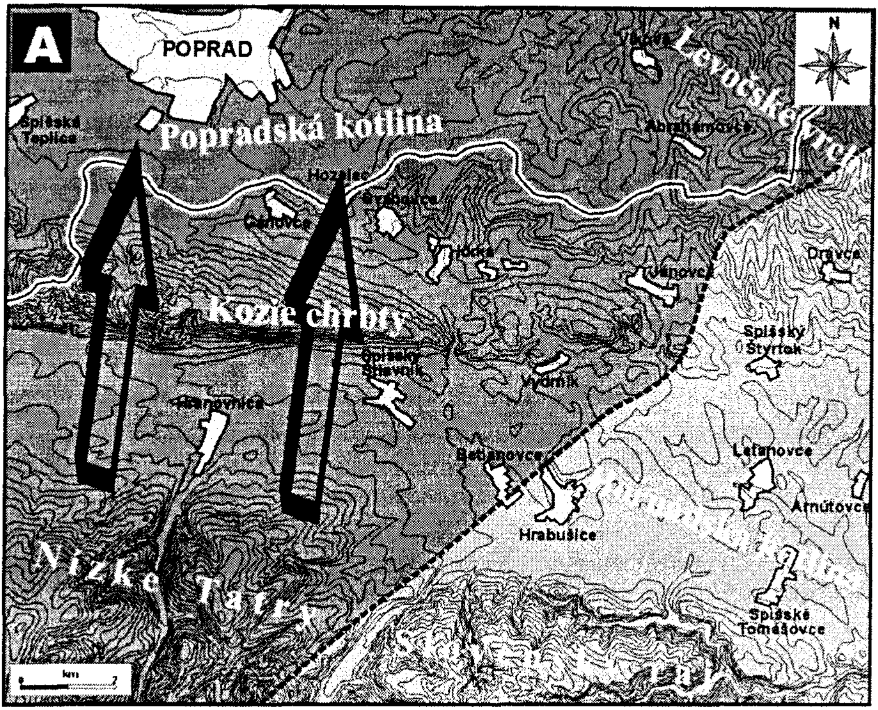
The Hnilec drainage basin (right tributary of the Hornád River), studied by J. Lacika (2001b), shows several special features (Fig. 6). It differs considerably from the other rivers basins of the West Carpathians. This basin has been developing very regressively with a strong tendency to reduction in favour of the neighbouring basins. The process consists of the retreating water divide as a result of backward erosion and piracy. The shift of the interfluve has differed depending on the rate of the barrier effect of the watersheds. Analyses of the geomorphological networks showed the most vulnerable stretches of the watershed of the Hnilec drainage basin (i.e., sections of the lowest barrier effect) where reduction in the basin area could have occurred. Sections of the watershed between the villages of Hnilčík and Bindt, and the saddles of Kopanec near Dobšinská Ľadová Jaskyňa cave and Vernár village can be captured by the Hornád River. Great potential piracy was identified in the southern section of the Hnilec basin watersheds between Hnilec and Slaná drainage basins (Figs 4, 6). There is no probability of incidence of piracy across relatively high watershed between Hnilec and Bodva basins (near Smolník village). Slow pushing of the watershed by more intense backward erosion of the Bodva tributaries to the side of the Smolnícka valley, showing 210 m higher situated local base of erosion, appears to be more probable.

The valley network in the south-east of the Slovenské Rudohorie Mts and south of the Košická kotlina basin has developed under the influence of young active fault tectonics. The Quaternary uplift of the low basin horst south-west of Košice separated the river Ida from the Hornád River and included it into the Bodva basins. South of Moldava nad Bodvou it arranged the network in the form of a large fan. A part of the basin is the eastern periphery of the Slovak Karst. Within it, there are favourable conditions for generation of what is referred to as hidden or subsurface valley piracy which takes place in cave systems (Lacika 2002).

The Poprad along with Dunajec Rivers represent one common river-valley network of two equivalent rivers. They are the only rivers in Slovakia which drain their waters northward by the Vistula to the Baltic Sea. The upper parts of catchments of the Poprad and Dunajec Rivers are situated in the centre of the West Carpathian dome-like megamorphostructure (Mazúr 1979). In the Poprad drainage basin it is possible to identify older and younger segments of geomorphological networks. According to M. Lukniš (1972), one can identify there distinctly transformed remnants of older, pre-Neogene valley networks, namely those which follow the strike of the pre-Neogene geological structures.

Transformation of the Poprad and Dunajec river valley network after the Miocene is mostly due to creation of a new morphostructural plan of the Western Carpathians (Lacika 1998, 2000). In many cases, the pre-Neogene parts of the valley networks became rejuvenated during the neotectonic stage. While preserving the general direction of the Klippen Belt and the Outer Carpathian flysch units, the rivers have been deeply cut into young, positively developing morphostructures and created there a gorge-type antecedent valleys with deeply-cut meanders (Zuchiewicz 1980, 1995), such as the Niedzica, Pieniny, and Beskid Sądecki goerges of the Dunajec River, and the Muszyna gorge of the Poprad River at the Slovak-Polish boundary. The Ružbašska brana gate between Podolínec and Hniezdne is an example of a different gorge which transversally cuts the pre-Neogene morphostructures. In this case it is not possible to talk about rejuvenation of an older network, but rather of creation of a completely new one, which connected the previously separated pre-Neogene valley networks draining the catchment of the contemporary upper Poprad into that of the Hornád and Torysa Rivers.

Providing that the contemporary morphostructural development of the Poprad drainage basin does not change, it is possible to expect another transformation of the valley network, of reversible character. This transformation tends to a certain restoration of the pre-Neogene valley network which was disturbed by individualization of young fault morphostructures in the Miocene. The barrier effect of the dividing ridge in the area around Gánovce, Pusté Pole, and Frička is be-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Vydrník
Hranovnica
Betlanovce
Hrabušice
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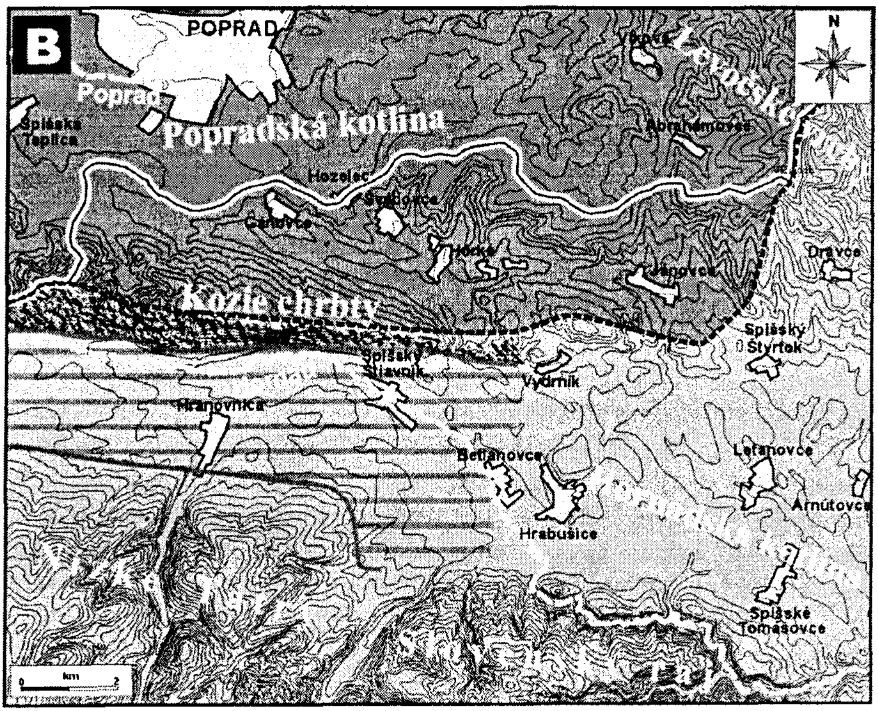
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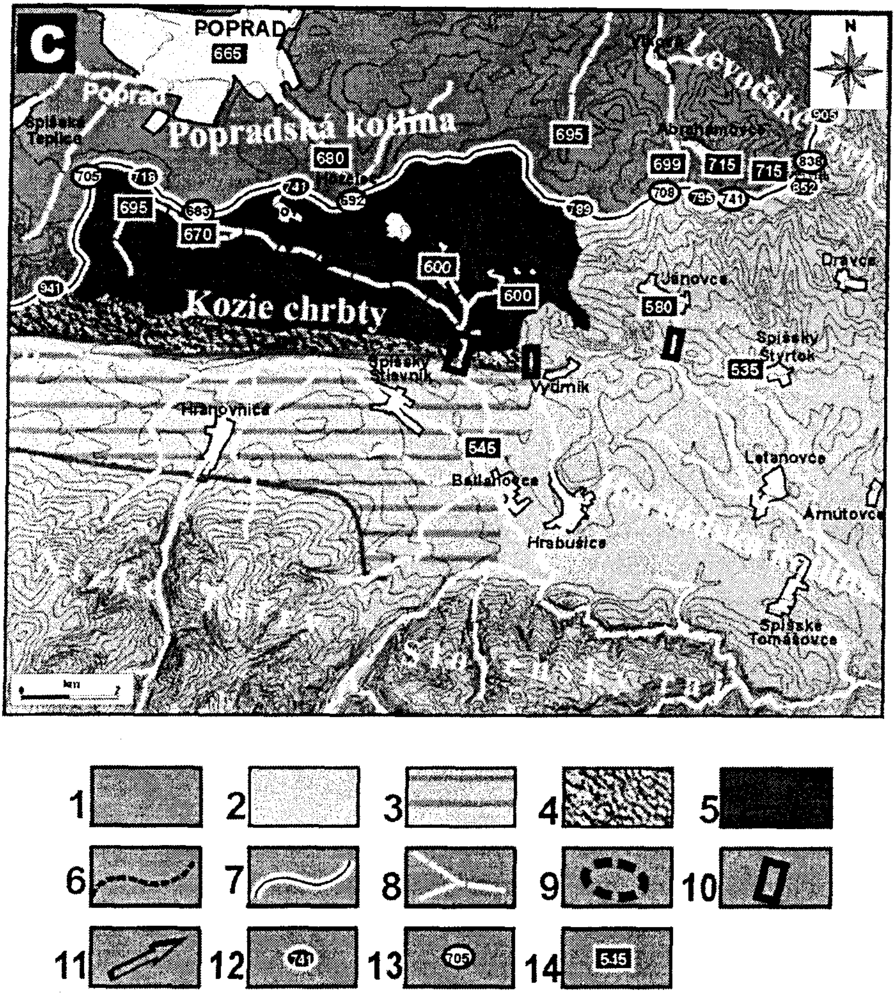

Fig. 5. Neotectonic evolution of the main European watershed (Gánovce area). A — 1st stage (late Pliocene/early Pleistocene), B — 2nd stage (late Pleistocene), C — 3rd stage (recent time). 1 — Poprad drainage basin, 2 — Hornád drainage basin, 3 — bottom of the Vikartovce Graben, 4 — fault scarp of the Vikartovce Graben, 5 — captured area of the Gánovský potok brook, 6 — hypothetical watershed before piracy, 7 — recent main European watershed, 8 — axis of the recent valleys of the 3rd and higher order (according to Strahler's classification), 9 — area of travertine occurrence, 10 — narrow through-valley dissected the Kozie chrbty horst, 11 — direction of the former valleys before early Pleistocene river capturing, 12 — elevation (summit) of the main European watershed (in m a.s.l.), 13 — depression (saddle) of the main European watershed (in m a.s.l.), 14 — local base of erosion (altitude in m a.s.l.)

ing deminished to such an extent that the Poprad River can be captured by the side streams — the Hornad, Torysa, or Topľa Rivers. The barrier effect of the Tatra, Spišská Magura, Malé Pieniny, and the western part of the Beskid Sądecki Mts does not offer any ground for expecting similar changes of the valley network

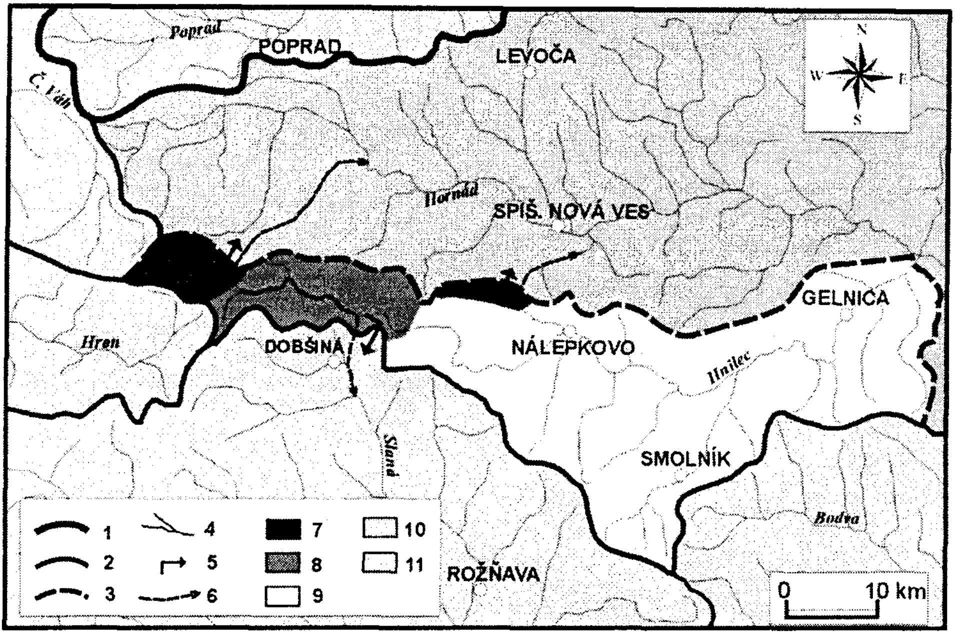

Fig. 6. Expected changes of the valley network in the Hnilec drainage basin. 1 — main European watershed, 2 — watersheds of main river basins, 3 — watersheds of the partial river basins, 4 — rivers, 5 — place of the expected river piracy, 6 — new river after capturing, 7 — part of the Hnilec drainage basin integrated into the Upper Hornád basin after piracy, 8 — part of the Hnilec drainage basin integrated into the Slaná drainage basin after piracy, 9 — residual Hnilec drainage basin after piracies, 10 — Hornád drainage basin, 11 — other neighbouring drainage basins

between Slovak parts of the Dunajec and Poprad drainage basins. Only a slow migration of the dividing ridge closer to regressively developing river of the Poprad does take place here.

The final prognostic map (Fig. 7) tries to interpret the future arrangement of valley network of the Poprad drainage basin after transformation in the nearest geological future (hundred thousands of years). This prognosis is based on the stability of morphostructural conditions or preservation of the contemporary trend of ever more distinct contrast of the mosaic of partial morphostructures of the Western Carpathians and the contiguous Neogene tectonic basins. It admits morphoclimalic changes. Climatic oscillations should not cause the developmental turnover; at most they can accelerate or slow down the overall trend of transformation. The most typical change of valley networks is expected in the upper part of the Poprad drainage basin. Judging by the least hydrological barrier of the water divide it should take place first. Piracy is expected over the low dividing ridge near Gánovce (Fig. 5). The headweard erosion of the Gánovsky potok brook will capture at first the Hozelecký potok brook, and then also the river Poprad, and the whole valley system into a new direction. The Hornad drainage basin will expand by this piracy, gaining two thirds of the southern slopes of the High Tatra Mts, and about the same share of

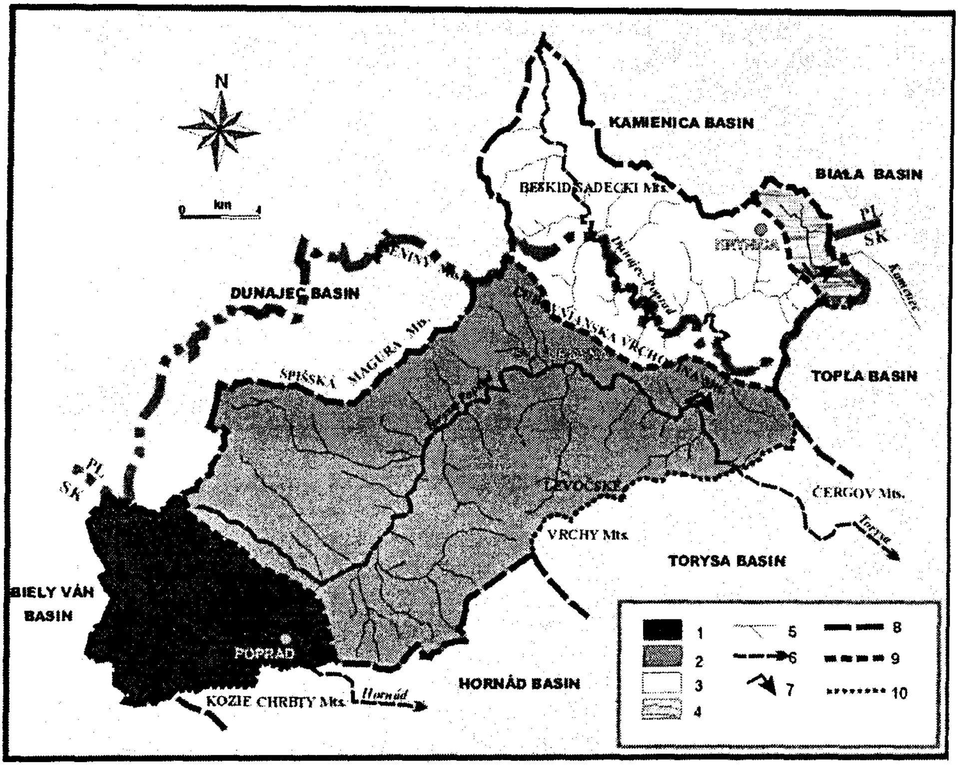

Fig. 7. Expected changes of the valley network in the Poprad drainage basin. 1 — part of the Poprad drainage basin integrated through piracy into the Hornad basin, 2 — part of the Poprad drainage basin integrated through piracy into the Torysa basin, 3 — residual drainage basin of the Poprad River after triple piracy, 4 — part of the Poprad drainage basin integrated through piracy into the Topľa drainage basin, 5 — axes of the contemporary valley network of at least 3rd order, 6 — main axes of the transformed parts of the Poprad drainage basin (arrow indicates the sloping), 7 — the point of assumed river piracy, 8 — watersheds with unchanged hierarchy after transformation of the valley network, 9 — watersheds with increased hierarchy after transformation of the valley network, 10 — watersheds with reduced hierarchy after transformation of the valley network

the Popradská kotlina basin (up to the interfluve between the Slavkovský and Studený potok brooks). We labelled the axial river of this new valley network Hornádsky Poprad or Hornád´s Poprad. Judging by the hydrological barrier effect, the second to occur is transformation of the valley network of the Poprad River, owing to piracy favoured in area of Pusté Pole saddle near Šarisské Jastrabie village. Regressive erosion of the left tributaries of the Torysa River tends to capture the Ľubotínka and Hradlová brooks and later the Poprad. We can call the axial river of this new network, after the second reduction, the Torysský Poprad or Torysa´s Poprad. After two piracies, the area of the original Poprad drainage basin will be reduced to a quarter. This reduction, however, does not mean an end to its regressive development. Further losses can occur in the upper part of a partial river basin of the Muszynka brook in Poland, which may also become a part of a more progressively developing catchment of the Topľa River by capturing the Kamenica brook. The altitude of the watershed between the Polish Tylicz and Slovak Frička villages leads to assumption that the third piracy will occur as the last one. The axial river of the original drainage basin was called Dunajecký Poprad or Dunajec´s Poprad.

M. Lukniš (1973) and R. Halouzka and W. Rączkowski (1993) described the case of real valley piracy and changes of river network in the area of the Štrbské sedlo saddle. These changes have been dated at the turn of the Pliocene and Pleistocene. Distribution of the Lower Pleistocene alluvial fans shows that a shift of tributaries to the east in the Poprad basin, and another shift of tributaries to the west in the Váh basin took place after the Pliocene. The present uplift tendency of the Štrbské sedlo saddle postpones the capture of streams.

CONCLUSIONS

The transformation of geomorphological networks on the territory of the Slovak Carpathians has been mainly controlled by morphotectonics. Replacement of the older valley and ridge systems by the new ones has been taking place under the influence of morphostructural factors of different hierarchy. Formation of the West Carpathian dome and its tectonic deformation due to faulting, both of local and regional importance, have played their role as well. Asymmetry of the top of the dome differentiates morphostructural dynamics of the territory. The basins situated on the larger, western side of the dome and the centre (the upper Váh, Hron, Poprad and Ipeľ Rivers) have developed mostly regressively. Progressively developing partial basins, for instance in the area of central Považie or in the Hornád basins, have been affected by local fault tectonics or influenced by extensive subsidence of the Podunajská and Východoslovenská nížina lowlands. Development of basins of the southern and south-eastern sides of the dome of the West Carpathians has been distinctly progressive. These are parts of morphostructurally very dynamic environment situated between the dome's centre and subsiding lowlands in the Hungarian Potisie area. Future research in this area should focus on detailed morphostructural analysis of geomorphological networks of individual basins in the Slovak Carpathians and the adjacent boundary areas in Hungary, Poland, Czech Republic, and the Ukraine.

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Geografický ústav SAV, Štefánikova 49
814 73 Bratislava, Slovak Republic
E-mail: geoglaci@savba.sk

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STRESZCZENIE

J. Lacika

EWOLUCJA NEOTEKTONICZNA ZLEWNI RZEK KARPAT ZACHODNICH NA SŁOWACJI

Ewolucja geomorfologiczna sieci drenażu w słowackiej części Karpat w trakcie etapu neotektonicznego (tj. od badenu) dokonywała się dzięki transformacji sieci geomorfologicznych pod wpływem zmiennych czynników strukturalnych i klimatycznych. Sieci geomorfologiczne obejmują układ rzek i dolin (sieci depresyjne), względnie działów wodnych (sieci elewowane). Zanik sieci starszych i tworzenie nowych postępowało stopniowo w miarę zmieniających się warunków klimatycznych i morfostrukturalnych. Dzięki temu w obrębie poszczególnych zlewni/dorzeczy współwystępują elementy rzeźby powstałe w warunkach odbiegających od współczesnych, aczkolwiek ich udział stopniowo maleje. W pojedynczej zlewni występuje zatem kilka generacji segmentów sieci, odzwierciedlając cykliczny charakter rozwoju geomorfologicznego.

Zróżnicowanie przestrzenne sieci geomorfologicznych w zlewniach rzek Karpat słowackich jest ściśle uwarunkowane przez lokalne własności strukturalno-litologiczne oraz sytuację morfoklimatyczną. Podstawowe parametry układu dolin i działów wodnych zależą od orientacji uskoków, cech skał podłoża, a także zmiennej bazy erozyjnej. Analiza parametrów teksturalnych, gęstości sieci, jej asymetrii, a także profili podłużnych i poprzecznych umożliwia odtworzenie cech morfostrukturalnych oraz etapów rozwoju.

Sieci geomorfologiczne tworzą otwarte systemy morfodynamiczne, dzięki czemu zmiany strukturalne i klimatyczne zaznaczają się nie tylko w obrębie danej zlewni, ale także w odległych niekiedy od niej obszarach. Skutki geomorfologiczne tektonicznej subsydencji w Kotlinie Panońskiej, a także na NW przedpolu Karpat są dobrze widoczne w obrębie morfostruktur Karpat Zachodnich. Obniżanie bazy erozyjnej rzek sprzyja wzmożonej erozji wgłębnej oraz wstecznej, jak również kaptażom sieci rzecznej w źródłowych odcinkach dolin. Analiza sieci geomorfologicznych zmierza zarówno do rekonstrukcji palaeogeograficznych, jak i predykcji rozwoju sieci w przyszłości. Materiałem źródłowym dla takich badań w Karpatach słowackich były mapy topograficzne w skali 1 : 25 000.

Głównym motorem transformacji omawianych sieci w słowackiej części Karpat były zmienne warunki morfotektoniczne o różnej randze. Ważną rolę odegrało powstanie kopuły Karpat Zachodnich i jej późniejsze deformacje uskokowe. Kopuła ta odznacza się wyraźną asymetrią. Zlewnie usytuowane na zachodnim, dłuższym skłonie kopuły oraz w jej centrum (górny Wag, Hron, Poprad, Ipola) wykazywały rozwój regresyjny. Zlewnie cząstkowe o rozwoju progresywnym, na przykład w środkowej części dorzecza Wagu oraz Hornadu, podlegały lokalnemu uskokowaniu, względnie znalazły się w zasięgu oddziaływania subsydencji Nizin Naddunajskiej i Wschodniosłowackiej. Ewolucja zlewni usytuowanych na południowym i południowo-wschodnim skrzydle kopuły Karpat Zachodnich, w strefie przejściowej między podnoszonym centrum kopuły a obniżaną częścią Niziny Panońskiej w dorzeczu Cisy, przebiegała w sposób progresywny.

Dalsze badania powinny skupić się na szczegółowej analizie morfostrukturalnej poszczególnych zlewni Karpat słowackich i przyległych obszarów Węgier, Polski, Czech oraz Ukrainy.