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Structural control on drainage network orientation – an example from the Loučka drainage basin, SE margin of the Bohemian Massif (S Moravia, Czech Rep.)

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Abstract: This paper discusses the relationship between geological structure and drainage network orientation at both a meso-scale and local scale. The Loučka Basin, located at the SE margin of the Bohemian Massif (S Moravia, Czech Rep.), has been selected as the model region for these studies. In the Loučka Basin, the bedrock comprises the metamorphic rocks of the Moldanubicum Group, which are arranged in elongated bands and lenses and are fractured with the dense network of faults. There is no extensive cover of unconsolidated younger sediments in the basin, nor any deep weathering regolith. In these respects, the geological setting is extremely favourable for the quantification of structural features and their correlation with drainage orientation. The degree of correspondence between the direction of drainage network segments and the orientation of such structural features as faults, mylonite zones, thrust-fronts and rock lineations was investigated in five study areas. The third-order streams are those most influenced by structure. The higher the order of stream segment, the weaker the correlation, and the more important the overall inclination of the terrain as a controlling factor in stream flow orientation. However, there is a strong structural control of first order streams in the periphery of the Basin. The structural control of streamflow direction in the Loučka Basin, which is built up with Precambrian metamorphic rocks, varies between 30–50% of the rectified channel length; the upper limit is considered to be the maximum conditioned by a local very high density of various linear structural elements.

Key words: drainage network, direction of streamflow, geological structure, the Bohemian Massif, S Moravia

Introduction

One of the many ways of analysing drainage evolution is by determination of streamflow orientation. However, while the direction of streamflow is the key to understanding the way in which a drainage network comes to fill the space available to it, very little attention seems to have been paid to this topic. Typical dendritic patterns show a tendency to equal (random) distribution of flow directions (Morisawa, 1985). However, variations from this may result from an initial surface slope or geological structure. Thus, when analysing the evolution of a drainage network, it is usually presumed that the network, during its expansion into the space available, gradually adjusts its course to the underlying structure. A variety of structural features is presented in the literature as the controls of flow direction: joints, faults, inclined sedimentary strata and fold axes.

The relative influence of any particular structural feature is also dependent on the scale at which the study of flow orientation is conducted. Further, the scale chosen also determines the methodology which is to be applied. At the mega- and macro-scales, a good correlation between the composition of drainage networks and joint systems and fault lines generated by neotectonic stress fields (both of regional and global extent) is usually to be found. In contrast, at lower scales, joint systems are controlled by more local influences (Summerfield, 1991). The influence of both neotectonic and older stress fields on streamflow development at the macro-scale is discussed in the papers of Scheidegger (1979, 1980, 1981). Joint control of streamflow development at meso-scale was studied by Aghassy (1970) and Kosmowska-Suffczyńska (1998), and at the local level by Bannister (1980) and Bíl (2000).

Clearly, the possible influence of geological structure on streamflow direction is best studied in basins where there is an absence of weathering mantles and sedimentary fills, and, in these respects, the Loučka Basin, an important right-bank tributary of the middle course of the Svratka, is ideal. The Svratka drains a large area of the SE corner of the Bohemian Massif. The Loučka is one of many rivers which drain the south-east margin of the Bohemian Massif in south-eastern direction towards the Carpathian Foredeep Basin; it may be regarded as a consequent stream, i.e. one which follows the general SE tilt of the margin of the Massif (Fig. 1). The aim of this paper is to determine to what extent is this consequent course of the Loučka has been affected by the underlying rock structure. The analysis was conducted at a local or meso-scale, as defined by the degree to which stramflow direction has adjusted to fault traces, mylonite zones, thrust fronts and lineations of the crystalline rock basement of the Bohemian Massif. The paper also evaluates the influence of the initial surface slope.

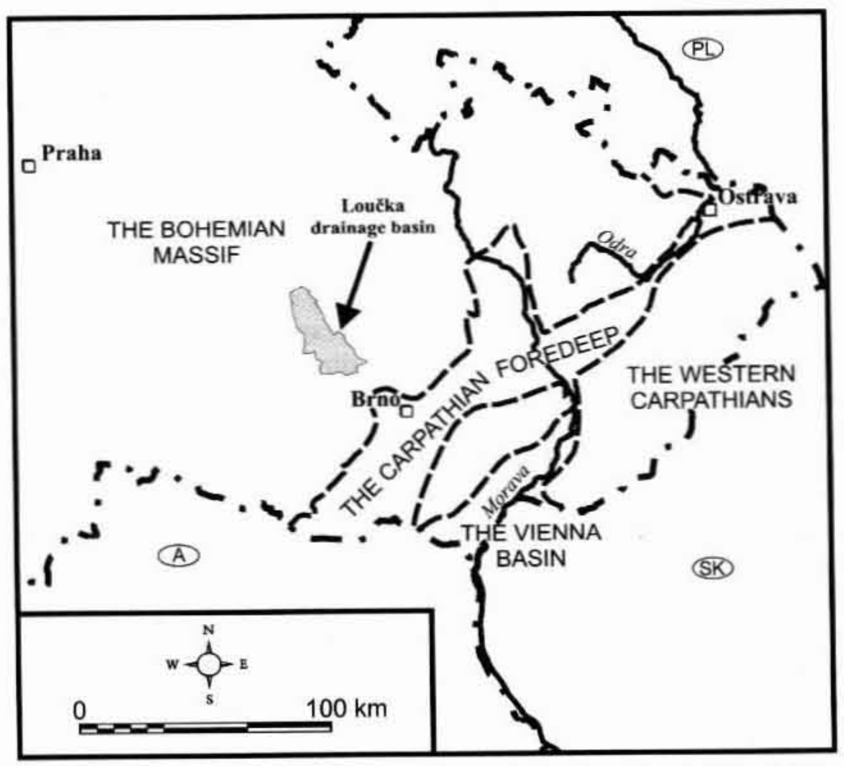

Fig. 1. Location of the Loučka drainage basin within the territory of Czech Rep. and its position within the Bohemian Massif

The study area

The structural features of the Loučka Basin are clearly expressed. The bedrock comprises crystalline rocks which are transected by a dense network of fractures. The component rocks are disposed in sub-parallel bands and lenses which vary in width from 100 to 750 m; these extend in some cases, for as much as 7 km. Such a spatial configuration of structural detail is unique to the eastern margin of the Bohemian Massif. The major part of the basin is floored by the metamorphic rocks of the Strážek Moldanubicum Group. In the southern part of the Basin, isolated plutons crop out, while in the east, small outcrops of metamorphic and igneous rocks of Moravicum Group are present (Fig. 2). The dominant rock types in the Basin are orthogneisses and paragneisses though there are minor developments of amphibolite, granulite, phyllite and granite. Two regionally important faults cross the Loučka Basin: the Křídlovice fault, which divides Strážek Moldanubicum Group into separate blocks and the Biteš fault which separates the Moldanubicum Group from the Svratka Dome of Moravicum Group (Fig. 2) (Mísař *et al.*, 1983).

The overall tilt of the SE margin of the Bohemiam Massif was initiated at least as early as the Miocene. The uplift of the Massif was partly due to block faulting and partly to a regional doming along a pronounced marginal flexure. The whole structure is clearly related to the geodynamic evolution of the Carpathian Nappes (Brzák, 1997). Prevailing wisdom holds that the flow SE-wards may date as far back as the Cretaceous (Dlabač, 1976) or the Palaeogene (Dvořák, 1995) and that, during the various transgressions and regressions of the sea in the Carpathian Foredeep Basin, only the length of the streams changed, not the direction. Marine transgressions had traditionally been ascribed to the sinking of the margin of the Bohemian Massif and regressions, with uplift. After each transgression, the original relief was exhumed and river valley development continued within the framework of the previous physiography. However, Hrádek (1997) suggested that river development is based on differential development of the eastern margin of the Massif during the

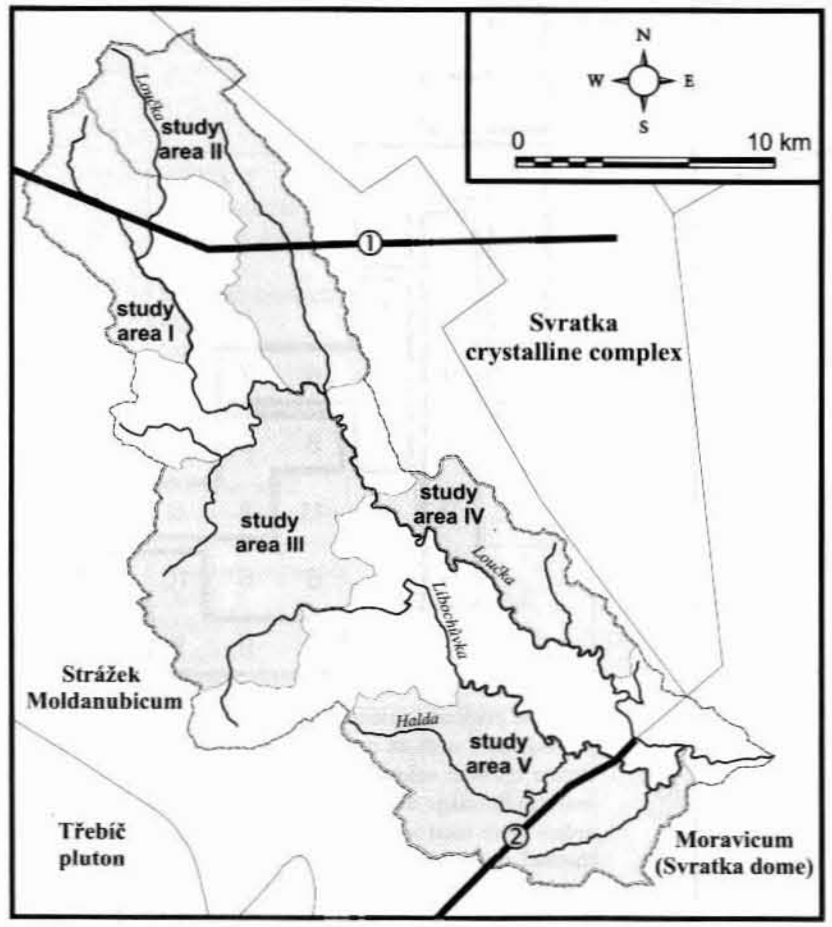

Fig. 2. Major streams of the Loučka drainage basin. Study areas of detail investigations of relationship between drainage direction and geological structure are marked in grey. The geological regions of metamorphic rocks are delineated. Numbers in circles indicate major faults of the area
1 – Křídlovice fault, 2 – Biteš fault

collision of the Carpathian-Pannonian blocks with the North European Platform. He considered that the southerly drainage across the Bohemian Massif was a reaction to the thrusting of the Eastern Alps towards its southern margin and the creation of the E–W trending Alpine Foredeep Basin. Certainly, the disruption of the drainage and its diversion eastwards did not occur before the Karpatian period of the Miocene when thrusting of the Carpathian Nappes began and the NE–SW trending Carpathian Foredeep Basin came into existence. The original southerly streamflow of the area is presumably indicated by the direction of the upper reaches of some of the rivers of western Moravia (eg. Moravská Dyje, Želetavka, Jevišovka) and the distribution of fluvial sediments containing tectites derived from the plume of the Ries impact structure.

The Loučka Basin lies in the NE part of the Bohemian-Moravian highland – a large geomorphologically distinct area which occupies a large part of western Moravia and eastern and southern Bohemia. The Loučka rises at the summit part of the Bohemian-Moravian highland close to the European Continental divide. In its middle reaches, it runs across gently undulating surface, part of which is clearly planated. Close to its confluence with the Svratka, it enters an area of high relief coincident with the dissected marginal flexure of the Bohemian Massif. For the purposes of this study, five study areas were selected in the Loučka Basin. In these, the relationship of streamflow direction to fault traces, mylonite zones, thrust fronts and rock lineations was investigated (Fig. 2). The particular areas represent the following geomorphological regions:

– the summit part of the Bohemian-Moravian highland (area 1 and 2),
– flat relief of planation surface (area 3),
– strongly dissected marginal flexure of the Bohemian Massif (area 4),
– tectonically deformed planation surface which is partly dissected by deep V-shaped valleys (area 5).

The principal criterion for adopting any of the areas was the generally unimodal nature of structural details (which thus made them amenable to quantification).

Methods

The drainage network was derived from topographic maps at a scale of 1:25,000. Both perennial and ephemeral streams were included. The network was then divided into segments, i.e. reaches between the source and a confluence or reaches between confluences. For each segment, the orientation and rectified length were determined, according to the recommendations of Scheidegger (1979) (Fig. 3). Measurements of structural elements were made from geological maps at a scale of 1:50,000 (Czech Geological Survey, 1991–1996). Lineations were grouped into twelve 15° intervals. The preferred streamflows were determined from the knowledge of the orientation and relative length of drainage elements and then compared with the structural detail. In order to express the spatial variability of orientation of streamflow direction, the drainage basin was compartmentalised into a rectilinear grid where each cell was 10 km^2 in area. In

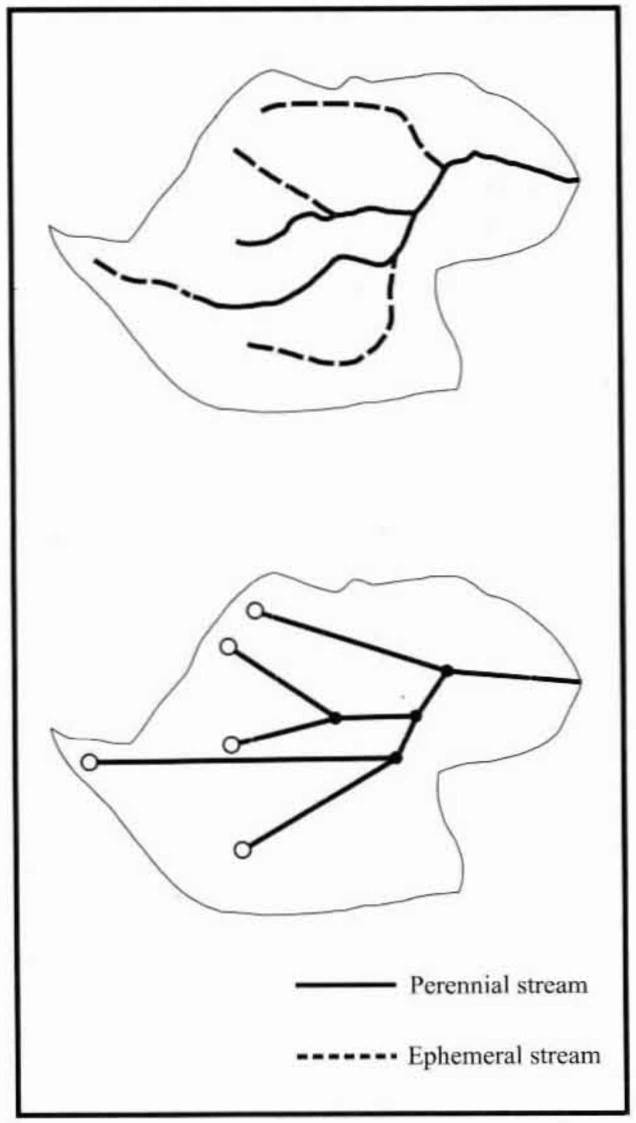

Fig. 3. An example of channel network rectification procedure. All segments of channel network in the Loučka drainage basin were converted into straight lines in this manner. Rectified orientation and length of segments were then measured

each of these a display of all stream order determinations was used to calculate preferred streamflow direction in each part of the network. Where adjacent cells showed the same patterns, these were grouped into regions; it is assumed that each region was probably conditioned by the same, unique set of controlling factors (Fig. 4).

The percentage rates of drainage elements oriented parallel with geological lineations was independently calculated for all five study areas (Table 1). Orientation data for both streamflow and structural elements were plotted as rose diagrams (Fig. 5). The data was then re-plotted in respect of external segments (first order streams), internal segments (streams of second and higher orders) and jointly for streams of all orders. This was so as to examine whether or not stream order

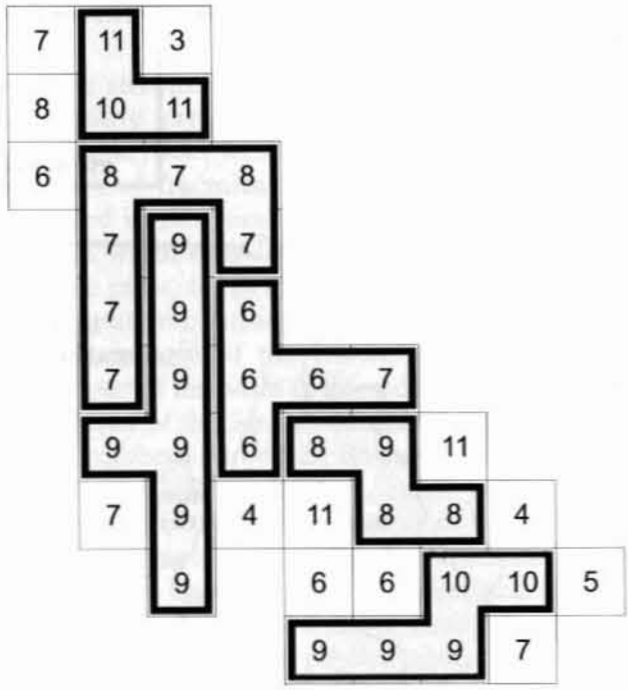

Fig. 4. The preferred orientation of channel network segments in grid cells with an area 10 km². Grid cells with similar stream channel orientation were grouped and regions with uniform drainage direction were delimited. Segments of all orders were used for the calculation of the preferred stream channel orientation in the grid cell. Numbers in cells indicate the relevant classes of stream channel orientation: 1 ... 0 – 15°/180 – 195°, 2 ... 15.1 – 30°/195.1 – 210°, etc.

was related to geological structure. In study area 1, the relationship of streamflow direction to fault traces and zones of mylonite was investigated. In areas 2, 3 and 4, to fault traces and rock lineations; and in area 5, to fault traces and the old thrust front of the Moldanubicum Group. Where the structural features are not unimodal and in areas which lack a statistically-reliable number of lineations, quantitative analysis of any relationship between streamflow direction and structure is difficult at the meso-scale. This is especially the case for area 5, which is why the reliability of the conclusions is suspected here.

The analysis of orientation of streamflow direction in the Loučka drainage basin

The surface of the eastern margin of the Bohemian Massif slopes gently E and SE, as does its drainage which is therefore presumed to be consequent. The Loučka follows such a course downstream from its middle reaches but, in its upper course, there are significant deviations from this general trend. For a distance of 15 km from

Table 1. Percentage of segments oriented parallel to geological structures in the Loučka drainage basin, SE margin of the Bohemian Massif

	Segments parallel to		Total number of segments	Total structurally influenced (%)
	faults (%)	lineations (%)		
AREA 1				
All segments	36.0	27.7	218	54.1
External segments	45.0	15.2	103	52.6
Internal segments				
Order 2	28.5	12.7	48	36.3
Order 3	39.6	76.7	29	84.3
Order >3	8.1	50.7	38	56.3
Internal total	25.9	41.5	115	55.6
AREA 2				
All segments	34.6	32.3	269	43.4
External segments	22.6	23.4	136	31.3
Internal segments				
Order 2	22.6	44.8	68	57.8
Order 3	75.6	62.6	23	75.6
Order >3	57.4	35.9	42	59.8
Internal total	52.3	45.5	133	61.2
AREA 3				
All segments	11.9	24.7	250	36.6
External segments	9.1	28.5	123	37.6
Internal segments				
Order 2	7.6	13.1	54	20.8
Order 3	24.7	42.0	35	35.9
Order >3	20.4	42.0	38	62.5
Internal total	15.4	19.9	127	35.3
AREA 4				
All segments	27.9	23.3	231	32.5
External segments	17.1	17.9	108	21.9
Internal segments				
Order 2	32.3	15.5	58	33.4
Order 3	52.1	30.3	22	63.9
Order >3	42.9	43.9	43	48.3
Internal total	39.4	29.1	123	43.8
AREA 5				
All segments	16.7	10.4	282	23.6
External segments	10.8	6.7	136	15.2
Internal segments				
Order 2	30.8	14.4	60	37.6
Order 3	20.9	6.9	25	24.9
Order >3	20.9	19.8	61	37.3
Internal total	25.1	15.5	146	35.5

its source, it flows south. Two short sections then flow E and SSE, respectively. The east flowing section is particularly striking; this has several N–S reaches which diverge from the east flows at right-angled bends. Of course, this is highly suggestive of a structural control. In this area, the Loučka parallels the Křidlovice Fault Zone although the latter lies at least 5 km to the north. The courses of short N–S valley sectors are conditioned by proven faults. In the middle course, where the river flows SE, the valley deepens and well-developed incised meanders are striking feature. Indeed, incised menders are a characteristic landform of the lower reaches of many larger rivers which drain the SE margin of the Bohemian Massif.

The water divide between the Loučka and the Libochůvka, the second most important river in

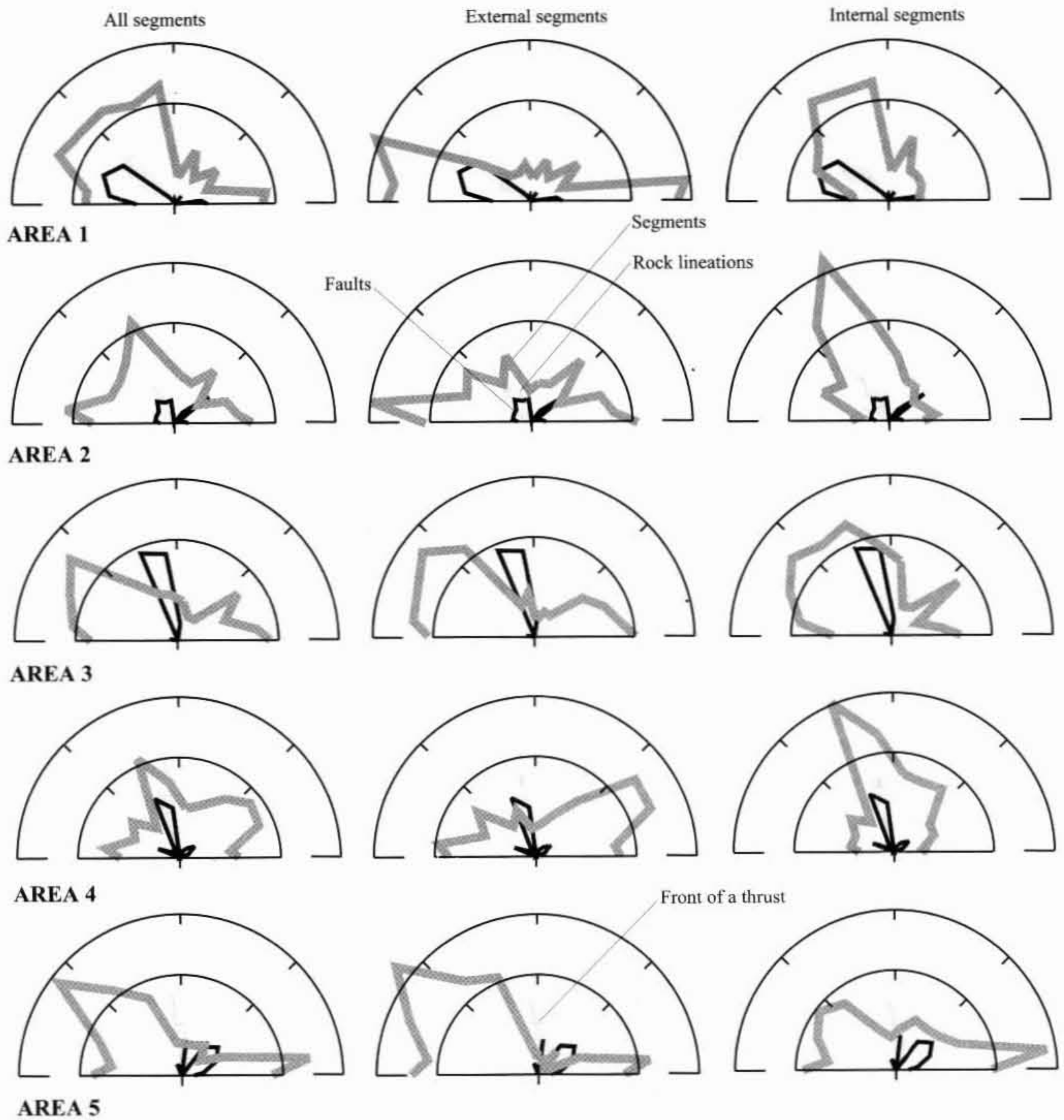

Fig. 5. Rose diagrams showing segment orientation and orientation of geological structures in five study areas in the Loučka drainage basin. Orientation of internal, external and all segments and orientation of faults and rock lineations are depicted

the basin, is unusual. Both channels run sub-parallel until close to their confluence. Up to the latter, each course is 11.5 km long and the inerfluve is about 1.5 km wide. However, the drainage divide lies much closer to the Libochůvka, which has very few left bank tributaries. In the western part of the basin, the drainage is in a converse, i.e. northerly direction. Such a direction is followed by both the Libochůvka and some of its tributaries, including the Luční creek, an important right bank tributary of the Upper Loučka. These seemingly anomalous features of the upper course of the Libochůvka are presumably explained by the post-tilting tectonic highs and lows which have warped the original surface (Fig. 6). The form of original surface was reconstructed by contouring the summit level surface, using the technique of Clark (1966). It is concluded that the skeleton of the modern drainage system evolved on this initial slope and was then remodelled during incision into the underlying basement, its course there being determined by linear belts of weakness, such as fault zones. Thus it seems reasonable to postulate two hierarchical

levels in the evolution of the drainage, both of which have been a considerable influence on flow orientation: firstly, a general tilting of the SE margin of the Bohemian Massif mainly towards the SE, though locally to the SSE, followed by regional tectonic elevations and depressions (Svatá hora elevation, Deblín highland, Libochůvka depression). Evidently, the higher order stream directions are independent of geological structure; in many cases, stream orientation is highly oblique or even perpendicular to the dominant structures in the basement.

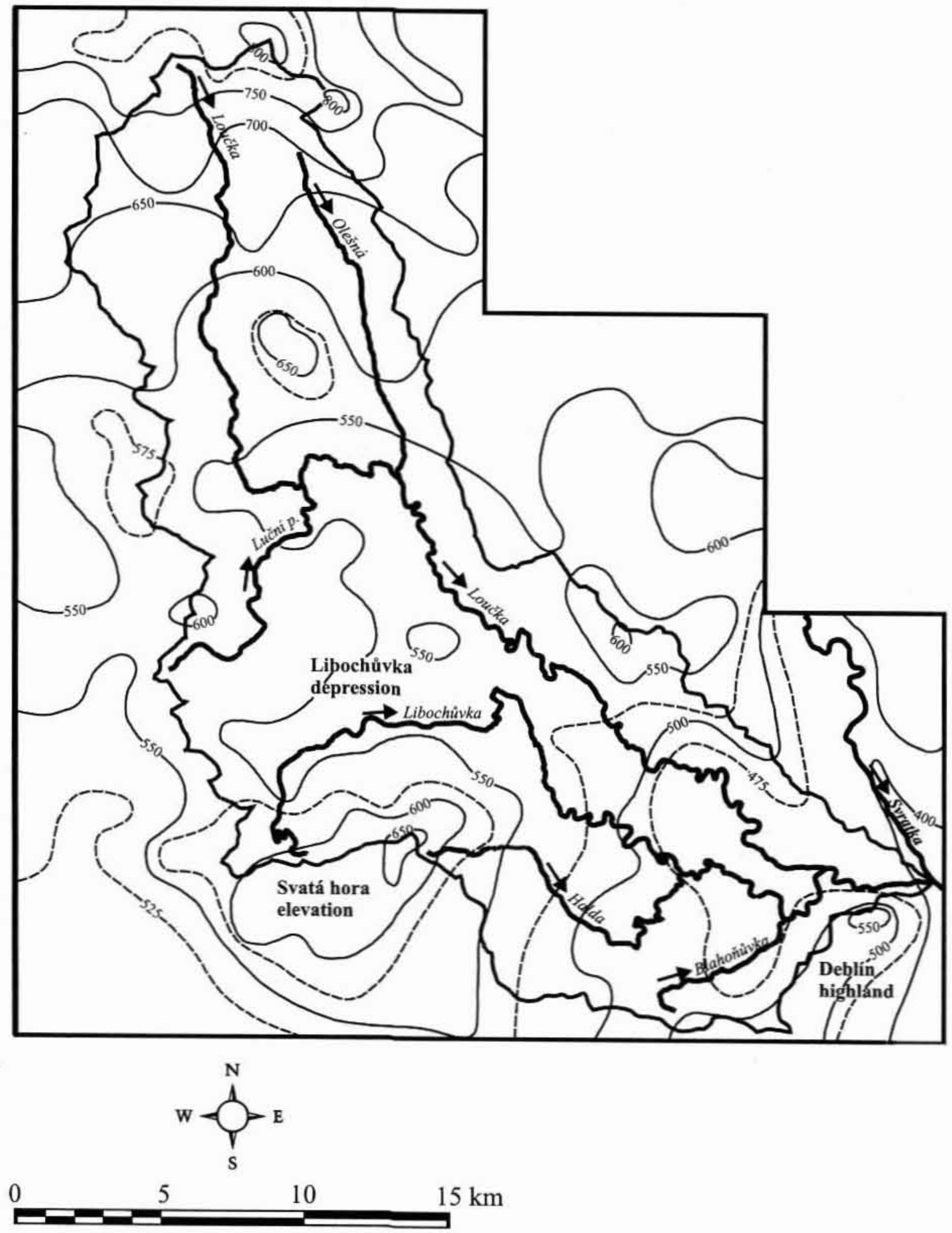

Fig. 6. The map of hypothetical initial surface on which the development of channel network in the Loučka drainage basin began. The surface was reconstructed on the basis of summit level altitude determination. Numbers at the lines indicate elevation in m a.s.l.

The orientation of streamflow in respect of geological structure

When the spatial distribution of areas with uniform drainage direction are compared with the orientation of structural features (Fig. 4) and bearing in mind the form of the original slope (Fig 6), it is seen that the relationship between the uniform areas and geological structures or initial surface is negative. It is presumed, therefore, that the spatial distribution of the uniform areas is probably the result of several controlling factors. The association of such areas with geological structure is also obscured by the inclusion of each and every datum concerning stream order; all segments were included in this comparison, regardless of rank.

Study areas 1 and 2 are both situated in the summit area of the Bohemian-Moravian highland, where the structural features are generally oriented NW–SE. The Křidlovice Fault runs through both areas. In both areas, the peaks of the structural plots lie in the same interval; further, the fault traces have a minor peak in the direction perpendicular to the major, i.e. NE–SW. Study area 3 is situated in the sub-basins of the Libochůvka and the Luční creek. The network of faults here is not so dense as it is in areas 1 and 2; nevertheless, the rock lineations are also dominant in the NE–SW sector. The fault traces here significantly trend NNW–SSE. Study area 4 is situated in the left bank of the lower course of the Loučka. Here, a dense network of faults and rock lineations both peak at NNW–SSE on the plots. Study area 5 is situated in the sub-basins of the Halda and Blahoňůvka in the Jinošov and Deblín highlands. Two significant structural features run across this area – the Bíteš Fault and thrust-front of Moldanubicum Group over Moravicum Group. However, they do not produce major peaks on the structural plot.

The clearly-expressed parallelism of structural features and the coincidence of fault traces with rock lineations in study areas 1–4 should, theoretically, produce a high degree of structural control of streamflow there. This should particularly apply in areas 1 and 2, where exists the highest rates of structurally-influenced sectors. In fact, study area 1 is structurally controlled over more than 50% of the length of the channel network (Table 1). In study areas 3 and 4, this control is much weaker, which may be explained by the high rate of structurally controlled sectors of the first and second order in area 1 and, to a lesser degree, in area 2. Within the other study areas, the sensitivity of the first and second order streams to structure is much weaker and their directions are fashioned more so by the local slope, i.e. the valley side slopes. Area 1 is remarkable in respect that the preferred orientation of first order streams along fault traces (45% of the stream length) compares so well with that along rock lineations (15%). In study area 2, orientation parallels both types of structural features to a comparable degree (22% along faults; 23% along rock lineations). The significant local dependence of first order sectors on structure might be explained, firstly, by the exceptionally high density of structural features in this area; secondly, by the location of the area in the preferential zone of drainage network expansion close to the European Continental divide. The first order streams which are the agent of this expansion have utilised for their preferential growth the lines of weakness (represented here by faults and lineations). The degree of structural control on the internal sectors (streams of second and higher orders) is also fairly high in study area 1, while, in area 2, the value may even exceed 60%.

The general trend in all study areas is an increase of geological control with stream order, the maximum being reached at the third order level. However, the coincidence of 4th order streams with meso-scale structures is weaker and the importance of the initial slope factor increases proportionally.

Conclusion

Investigations concerning the relationship of streamflow orientation with geological structure in the Loučka Basin shows that, generally, the least influenced flows are those of first order; less influenced are the first order streams which are governed simply by the valley side slopes on which they developed. However, in certain geological and geomorphological situations, there are clear exceptions to this generalisation; certainly, locally, geological control of these small streams may be even higher than in many streams of higher order. In the peripheral parts of the Basin, expansion of drainage into the available space has obviously been easiest along lines of weakness and, as a consequence of this, streams of the first order come to exhibit a high degree of adjustment to the underlying structure.

The maximum structural control is usually reached by the streams of the third order, this is true of all five study areas. Towards the higher orders, the influence of structure becomes weaker and the nature of the initial slope seems to be the overriding influence. In respect of the Loučka Basin, two hierarchical levels may be distinguished. In the first, an older slope which is inclined to SE towards the Carpathian Foredeep Basin; secondly, the superimposed later tectonic features which have caused local elevation and depression. Evidently, these have affected the drainage system profoundly. Quantification of the relationship between streamflow direction and structure did not identify any particular structural feature as a preferred route for the drainage expansion. Further, the measurements made did not clearly indicate whether streams of any particular order are preferentially adjusted to any specific structural feature. The analysis suggests that, in those parts of the Loučka Basin where the expression of structural features is marked, the control on drainage is normally 30–50% of the entire drainage length. In regions which have a much denser than average network of structural features oriented unimodally, the relationship reaches 50% in the extreme case, though there are significant departures from this generalisation. It would be particularly instructive to supplement these measurements at the meso- and local level by direct structural measurements of joint patterns and foliation of metamorphic rocks, i.e. to repeat the investigation at the micro-scale.

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