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# Morphometric analysis as a tool for interpretation of tectonic activity: Spišská Magura and Tatry Mts., Western Carpathians

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## Abstract

Morphometric analysis is frequently used for the assessment of neotectonic/young tectonic movements. The analysis consists of several methods that, in some cases, may yield different results. We used six morphometric methods to evaluate 42 river/creek catchment areas comprising the Spišská Magura region and adjacent parts of the Belianske Tatry Mts. Each method evaluated the possible influence of tectonics on topography numerically (by parameters). The integration of the mean parameter values was used to obtain the relative tectonic activity index (Iat), based on which we determined the role of the tectonic activity in the evolution of each analyzed catchment area. A comparison of the integrated map of relative tectonic activity with the known tectonic lines shows the little match in the Spišská Magura region. This is especially valid for the areas along with a striking Subtatric-Ružbachy fault system (SRFS) that is assumed to be active in the late Pleistocene and where morphometric criteria only show little tectonic activity. In contrast, the parameters provided by some individual methods used for the integrated map of the relative tectonic activity indicate a good match with known tectonic lines. For example, the basin shape ratio and mountain front sinuosity suggest high tectonic activity along the border of the Spišská Magura region and the Pieniny Klippen Belt, which is also indicated in geological maps. The evaluation of U- versus V-shaped valleys (Vf index) shows more intensive uplift of the areas of the Belianske Tatry Mts. compared to the areas within the Spišská Magura region, which is also expected from the geological maps and other studies. The evaluation of individual morphometric parameters and the parameter obtained by their integration implies the necessity to use several morphometric methods for a more reliable assessment of the role of tectonics in the evolution of studied areas.

## Keywords

Relative tectonic activity, morphometric analysis, integration of data, Western Carpathians

## Introduction

Interpretation of tectonic structures is one of the most important steps in the prospection of geology aimed at any type of raw materials, including water and geothermal sources. Depending on the scale, several methodologies are used for identifying tectonics. Tectonic interpretation based on morphometric analysis is typical for large-scale mapping in the first stages of prospection (Napieralski et al., 2013). The morphology of terrain with typical morphological forms like linear features, facets, ridgelines, linear valleys, and slope breaks serve as basic tools for estimating tectonics in the region. The methodology of morphometric analysis performed in the 19th century was used for the analysis of relief (Gilbert, 1877), later for quantitative analysis of river basin morphology (Horton,1945; Strahler, 1952; Shreve, 1969), and for the analysis of active tectonics (Bull, 1984; Keller and Pinter, 2002). This methodology is based on the analysis of morphometric indices using the Digital Elevation Model (DEM), which provides vertical image reflection of the presence of faults and folds below the surface (Jordan and Schott, 2004; Seleem, 2013; Das and Pardeshi, 2018; Khan, 2019). These studies indicate that DEM data is sufficiently accurate and beneficial for assisting the interpretation of geological structures and can be applied in various areas with complex structural zones.

Morphometric analysis is currently a modern methodology used in geological research around the world, for example, in the north-western part of the USA (Rockwell et al., 1985), Spain (Silva et al., 2003), Pakistan and Afghanistan (Mahmood and Gloaguen, 2011), Iran (Bagha et al., 2014; Hosseinlou, 2017), India (Lone, 2017; Anand and Pradhaan, 2019; Kandregula et al., 2019), Turkey (Softa et al., 2018), Greece (Valkanou et al., 2020) but also in Slovakia (Buczek and Górnik, 2020). The results of various research, in which morphometric analysis was used, were obtained by analyzing digital elevation models using ArcGIS software and show that it is a suitable methodology for evaluating the current relative tectonic activity of the area.

In addition to morphometric analysis, we used the integration of existing geological and geophysical data and the interpretation of a digital relief model to evaluate the tectonic activity of the studied area. More detailed phases of prospection commonly apply geophysical and geological methodologies for identifying the tectonic structures. Geophysical investigations (e.g., seismic, gravity, electric and electromagnetic) belong to principal tools utilized for interpreting geological structures on the sub-surface, e.g., for mapping faults and fracture zones in natural exposures, tunnels, or structural characterization of discontinuities in rock slopes (Ganerod et al. 2006; Deparis et al., 2011). However, these techniques cannot be decoupled from geological and morphological observations, which are mandatory for understanding the mechanisms and interpreting geophysical data (Deparis et al., 2011).

The main aim of this paper is to show the applicability of a detailed morphometric analysis for the assessment of the role of tectonics in the evolution of the studied areas. We applied this methodology to the Spišská Magura region and the adjacent part of the Belianske Tatry Mts. in the Slovakian Western Carpathians. The obtained results were compared with the interpretation of tectonics known from geological and geophysical studies.

## Geological setting

The analyses were performed in two lithologically different units of the Western Carpathians – Spišská Magura region built by Paleogene sediments (mostly mudstone, sandstone, and conglomerate) and Tatry Mts. built by crystalline basement and Mesozoic sediments (Fig. 1).

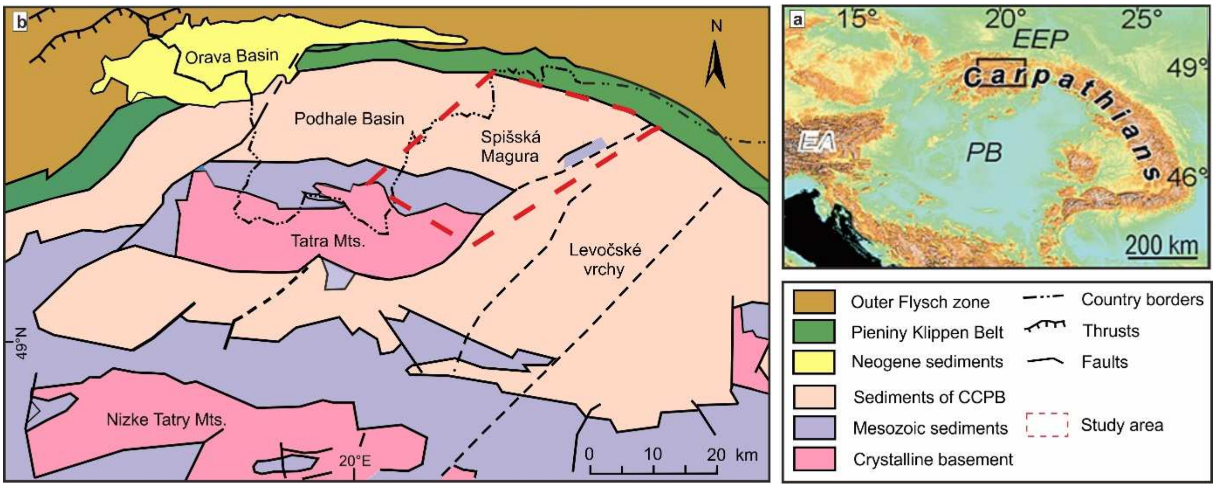

*Fig. 1. a) Sketch map of the Carpathian Mts. and b) the Spišská Magura region with the surrounding geological units. The studied area is marked by the red dashed line.*

The Spišská Magura region is part of the Central-Carpathian Paleogene Basin (CCPB), one of the largest Tertiary basins in the Inner Western Carpathians. The Paleogene sediments in the Spišská Magura region consist of three formations of the Subtatric Group (Gross et al., 1984). The basal Borove Formation (Middle and Late Eocene) transgressively overlies Mesozoic rocks of the Križna Nappe (Jacko & Janočko, 2000) and contains up to 100 meters thick succession of conglomerate, nummulitic limestone, and sandstone. These sediments are overlain by the Huty Formation consisting of more than 500 meters of mudstone and several thinner intervals of sandstone and conglomerate. In the Spišská Magura region, the formation is characterized by the occurrence of a more than 200 meters thick wedge of a conglomerate called Tokáreň Conglomerates occurred southeast of Ždiar village (Janočko, 2002, 2021) and approximately six meters massive and faintly parallel-laminated Bachleda sandstone interpreted as a part of basin floor fan deposited by high-density turbidity flows (Janočko, 2000). The sediments of Huty formation are covered by Zuberec formation with rhythmically alternating sandstones and mudstones up to 300 m thick. The investigated territory of the Spišská Magura region is tectonically bounded to the north by the Pieniny Klippen Belt (PKB), representing a large-scale shear zone composed of Jurrasic to Cretaceous rocks (Plašienka & Jurewicz 2006; Plašienka et al., 2007). In the southeast, it is bounded by the Subtatric-Ružbachy fault system formed by several subparallel faults (e.g., Jacko, 2001) to the Poprad Depression and Levoča Mts. In the west, the Spišská Magura neighbors the Belianske Tatry Mts.

The Tatry Mts. were formed during Cretaceous-Paleogene orogenic processes like an asymmetrical horst-like structure surrounded by the sediments of the Central-Carpathian Paleogene Basin (CCPB; Nemčok et al., 1993). They belong to the so-called core mountains of the Western Carpathians characterized by crystalline core covered by Mesozoic rocks. The crystalline core is composed of a composite granitoid intrusion and its metamorphic envelope (Gawęda et al., 2016). The Mesozoic sedimentary rocks belong to the three structural elements: 1. autochtonous sedimentary cover; 2. High Tatry nappes (Czerwone Wierchy Nappe and Giewont Nappe); 3. Subtatric nappes (the Choč and Križna Nappes) (Jurewicz, 2005). They are mostly composed of limestone, dolomite, and different types of shale. These rocks continue below the neighboring CCPB and are covered by Paleogene rocks (Janočko et al., 2000). Geomorphologically, the Tatry Mts. is divided into the Western and Eastern Tatry Mts. The Eastern Tatry Mts. is further divided into the High Tatry Mts. and Belianske Tatry Mts. (Mazúr and Lukniš, 1980). The mountains, with their main ridge arched to the south, have a north-south asymmetric form resulting in better preservation of Mesozoic rocks on their northern slopes and exposed crystalline core on their southern slopes. The southern boundary of the mountain is delimited by faults belonging to the sub-Tatry fault system (Nemčok, 1993) that are morphologically very distinctive. The Tatry Mts. morphology mainly resulted from tectonic and exogenic processes acting during the Neogene and Quaternary. During the Neogene, the relief-forming factors acted in the conditions of a subtropical climate, when weathering and fluvial processes were the most intense. The final geomorphological features were sculptured in the Pleistocene, when mountain glaciers contributed most significantly to their morphology.

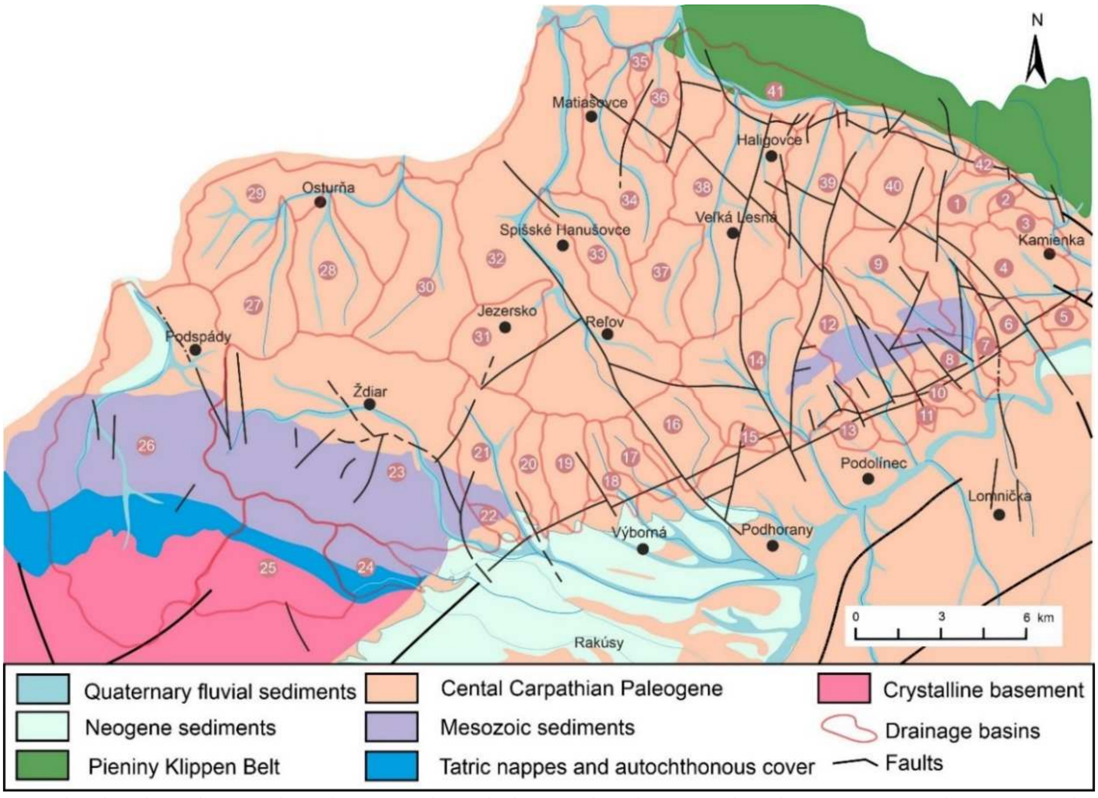

*Fig. 2. Simplified geological map of the wider area of the studied region (based on Nemčok et al., 1994; Gross et al., 1999; Janočko et al., 2000; Bezák et al., 2008)*

## Methodology

To evaluate a geological-tectonic structure of the area on the margins of the Belianske Tatry Mts. and in the Spišská Magura region, we applied a morphometric analysis complemented by interpretation of our own and archive structural, geological, and remote sensing data.

### *Morphometric analysis*

To analyze the morphometry of the studied region, we applied several types of morphometric parameters evaluated quantitatively. We analyzed the intensity of erosion and deposition related to lithological and geomorphological indices as well as tectonically derived features (Miccadei et al., 2021). For carrying out a detailed and systematic investigation, the study area was generally divided into subbasins. Analysis of the characteristics of subbasins is of great help in understanding the influence of drainage morphometry on landforms and its characteristics (Jasmin and Mallikarjuna, 2013). The indices selected to evaluate the degree of tectonic activity is the Stream-length gradient index (*SL* index), Asymmetry factor (*Af* factor), Basin shape ratio index (*Bs* index), Hypsometric integral (*Hi* integral), Valley floor width-valley height ratio (*Vf* index), Mountain-front sinuosity (*Smf* index) (Bull and McFadden, 1977; Bull, 1984; Keller and Pinter, 2002). The last step in the morphometric analysis was a calculation of a single index (*Iat* index) that expresses relative tectonic activity for every analyzed sub-basin (El Hamdouni et al., 2008).

### *Stream-length gradient index (SL index)*

The *SL* index is a morphometric parameter proposed by Hack (1973), which is often used to highlight the presence of anomalies in areas of intense fluvial erosion, as it is closely related to the stream power and is defined as

$$SL = (\Delta H / \Delta L) \times L, \qquad (1)$$

where $\Delta H$ is a variation of elevation, $\Delta L$ is the length of the segment, and $L$ is the horizontal length from the divide to the midpoint of the segment where the *SL* index is calculated. The *SL* index has been used in previous studies to identify morphometric anomalies along with river profiles and thus analyze the neotectonics and lithology of the study areas (Galve et al., 2014; Troiani et al., 2014; Khavari, 2017). The *SL* index is very sensitive to changes in the catchment area, which can be caused by rock resistance or tectonic activity. Several studies combine high *SL* index values with tectonic uplift. Conversely, low SL values may be related to stable to subsiding areas or may indicate streams flow through strike-slip faults (Keller and Pinters 2002; Troiani et al. 2008, El Hamdouni et al., 2008). The values of *SL* index are classified into three classes: class 1 ($SL > 500$), class 2 ($300 < SL < 500$) and class 3 ($SL < 300$) (El Hamdouni et al., 2008).

### *Asymmetry factor (Af factor)*

The asymmetry factor is a morphometric index used to express the degree of drainage basin geometries to elucidate the origin of the drainage basin and can indicate possible tectonic tilting during its development (Hare and Gardner, 1985; Keller and Pinter, 2002; Softa et al., 2018). The Af index is defined as:

$$Af = 100 \times (Ar / At), \qquad (2)$$

where $Ar$ is the drainage basin area to the right of the trunk channel facing downstream and $At$ is the total area of the drainage basin (Keller and Pinter, 2002). Values of *Af* indices are categorized into three classes: 1. Symmetric basin ($45 < Af < 55$), 2. Asymmetric east-oriented basin ($Af > 55$) and 3. Asymmetric western-oriented basin ($Af < 45$) (Ozskaymak and Sozbilir, 2012). In this study, we used a modified definition of Asymmetry factor as its absolute value minus 50. According to Pérez-Peña et al. (2010) classification, we classified absolute values into four classes: 1. Strongly asymmetric basin ($Af > 15$), 2. Moderately asymmetric ($Af = 10 – 15$), 3. Gently asymmetric ($Af = 5 – 10$), 4. Symmetric basin ($Af = 50$).

### *Basin shape ratio index (Bs index)*

In active tectonic areas, relatively young drainage basins tend to elongate parallel to the dip of the area. During further development or weakening of tectonic activity, elongated river basins can become circular (Bull and McFadden, 1977; El Hamdouni et al., 2008). Following the drainage basin relief based on his shape, we use the Basin shape ratio index calculated as:

$$Bs = Lb / Wb, \qquad (3)$$

where *Lb* is a maximum length of a basin measured from mouth to the most distant point on the drainage divide and *Wb* is the maximum basin width perpendicular to maximum length (Bahrami, 2013). According to Chang et al. (2015), the values of the *Bs* index are classified into the three classes: class 1($Bs > 2,9$), class 2 ($1,9 \leq Bs \leq 2,9$), class 3 ($Bs < 1,9$). The *Bs* index with a value greater than 1,9 indicates drainage basins with an elongated shape (class 1), while values less than 1,9 indicate a more circular shape of the drainage basin (class 3).

### *Hypsometric integral (Hi integral)*

Hypsometric integral is an index that describes the distribution of heights in the drainage basins. The *Hi* index is dimensionless and is independent of the catchment area. Hypsometric integral values can be calculated using a formula derived from the hypsometric curve (Strahler, 1952). The Hypsometric curve expresses the percentage of the surface area beyond a certain altitude (Strahler, 1952; Chen et al., 2003). It is plotted as a function of relative altitude to the relative area. A point on the curve indicates a proportion of the area that is higher than a given proportion of elevation. From the shape of the hypsometric curve, it is then possible to determine unstable young areas or older landscapes which have been more eroded and less affected by tectonic activity (El Hamdouni, 2008). The character of the curve can be expressed with a simple equation:

$$Hi = (E_{mean} - E_{min}) / (E_{max} - E_{min}), \qquad (4)$$

where $E_{mean}$, $E_{min,}$ and $E_{max}$ are the mean, minimum and maximum elevations within the drainage basin, respectively (Keller and Pinter, 2002). Values of hypsometric integral are classified into three classes: class 1 ($Hi > 0,5$), class 2 ($0,5 > Hi > 0,4$) and class 3 ($Hi < 0,4$) (El Hamdouni, 2008). The interval of hypsometric integral values ranges from 0 to 1. It is used for the indirect determination of the tectonic activity of the studied area. The *Hi* index is like the *SL* index because the values of both indices are affected by rock resistance and other factors. Higher values of the hypsometric index usually indicate unstable, active young areas with possible tectonic activity. Conversely, low values are related to older areas that have been more eroded and possibly less affected by tectonic activity (El Hamdouni, 2008).

### *Valley floor width-valley height ratio (Vf index)*

*Vf* index is used to differentiate valleys with a wide floor relative to the height of valley walls with a "U" shape compared to narrow, steep valleys with a "V" shape. Vf is defined as the ratio of the width of the valley floor to its average height (Bull and McFadden, 1977; Bull, 1978) and is computed by the equation:

$$Vf = 2Vfw / [(Eld - Esc) + (Erd - Esc)], \qquad (5)$$

where *Vfw* is the width of the valley, Eld and Erd are the elevations of the left and right divide facing downstream, and Esc is the elevation of the valley floor (Bull and McFadden, 1977). Valleys with a U shape generally have high values of *Vf*, whereas V-shaped valleys with relatively low values. According to El Hamdouni et al. (2008), the values of the *Vf* index are divided into three categories: 1 ($Vf \leq 0,5$), 2 ($0,5 < Vf < 1$), and 3 ($Vf \geq 1$).

### *Mountain front sinuosity (Smf index)*

*Smf* index is an indicator that is often used to evaluate relative tectonics along the mountain fronts (Silva et al., 2003). This index shows a balance between tectonic uplift, which tends to maintain a straight line of mountain foothills, and river erosion, which contributes to the formation of irregular mountain fronts (El Hamdouni et al., 2008). Index of mountain front sinuosity is defined by

$$Smf = Lmf / Ls, \qquad (6)$$

where *Lmf* is the length of the mountain front along the foot of the mountain and *Ls* is a length of a straight line of the mountain front (Bull and McFadden, 1977; Bull, 1978). According to El Hamdouni et al. (2008), the resulting values of the *Smf* index are divided into three classes: class 1 ($Smf < 1$), class 2 ($1,1 \leq Smf \leq 1,5$), and class 3 ($Smf > 1,5$). Tectonic active areas usually have low Smf index values, while high values indicate inactive areas that are largely affected by erosion processes (Bull and McFadden, 1977).

### *Relative tectonic activity index (Iat index)*

The relative tectonic activity index is used to evaluate relative tectonic activity in the study area. This index was created by a combination of the morphometric parameters described above (*SL* index, *Af* factor, *Bs* index, *Hi* integral, *Vf* index, and *Smf* index) as an average value for each drainage basin (El Hamdouni et al., 2008). The relative tectonic activity index can be described using a simple equation:

$$Iat = (SL + Af + Bs + Hi + Vf + Smf) / 6. \tag{7}$$

$Iat$ values can be divided into four classes: class 1 ($1 \leq Iat < 1,5$), class 2 ($1,5 < Iat < 2$), class 3 ($2 < Iat < 2,5$), and class 4 ($2,5 < Iat$) (Hamdouni et al., 2008). Relative tectonic activity index values that are less than 1,5 indicate very high relative tectonic activity, values between 1,5 and 2 indicate high relative tectonic activity and resulting values above 2,5 indicate low relative tectonic activity (El Hamdouni et al., 2008).

### Field data

Geological-structural data were obtained from rock exposures in the field. We described the lithology of rocks in the exposures and photographed and measured their structural elements by geological compass. We evaluated 43 rock exposures, mostly in the Spišská Magura region, and obtained 350 measurements of structures and 150 stratification measurements.

### Integration of data

In addition to morphometric analysis of the study area and performance of field research, we also integrated previously published geological and geophysical data to widen the database for interpretation of the tectonic structure in the studied area. We used existing geological maps at different scales (1:10 000 to 1:500 000; e.g., Nemčok et al., 1994; Gross et al., 1999; Janočko et al., 2000; Bezák et al., 2008), tectonic maps at scale 1:500 000 (Bezák et al., 2004), gravimetric and magnetic maps (Grand et al., 2001; Szalaiová et al., 2004; Kubeš and Gluch, 2009), which provided additional information on tectonics, lithology, stratigraphy, and geodynamic phenomena. Important data came from vertical electrical sounding performed in the studied area in the past (Szalaiova et al., 2004).

We have also used analysis based on the digital relief model (DRM), providing elevation and morphometric parameters, which contain data on relief slope, orientation, and horizontal and normal curvature (Šúri et al., 1996). In geological interpretation using a digital model of relief, it is possible to interpret tectonic structures shown as 1. Areal elements that include tectonic units, tectonically distinguishable rock complexes of different rock types, etc., and 2. Linear elements (morpholineaments) with the predominantly linear or nonlinear (circular and arcuate) trend, which may coincide with the direction of different genetic types of faults and tectonic boundaries (Feranec et al., 2010). The interpretation of these structures is based on monitoring geomorphological changes in mountain ridges, valleys, or river networks, which are easily identifiable in the DRM. These changes most likely indicate the presence of structural elements.

## Results

### Morphometric analysis

In this study, first, the delineation of watersheds and hydrological parameters for the study area were derived from the digital elevation model (DEM) as well as Hydrology processing tools in ArcGIS 10.3 software. To automatically generate the derived watersheds and streams from DEM, several ArcGIS tools were used: Fill, Flow direction, Flow accumulation, Stream order (Raster), Stream order (Vector), and Basin (Strahler, 1952). All the parameters, such as drainage basin area, basin perimeter, stream length, basin width, minimum and maximum elevation, etc., were calculated using ArcGIS software to evaluate the basin characteristics (Das and Pardeshi, 2018). Morphometric analysis of 42 basin watersheds was performed on the study area of Tatry Mts. and Spišská Magura region, which are spread over an area of approximately 480 km$^2$ (Fig. 3).

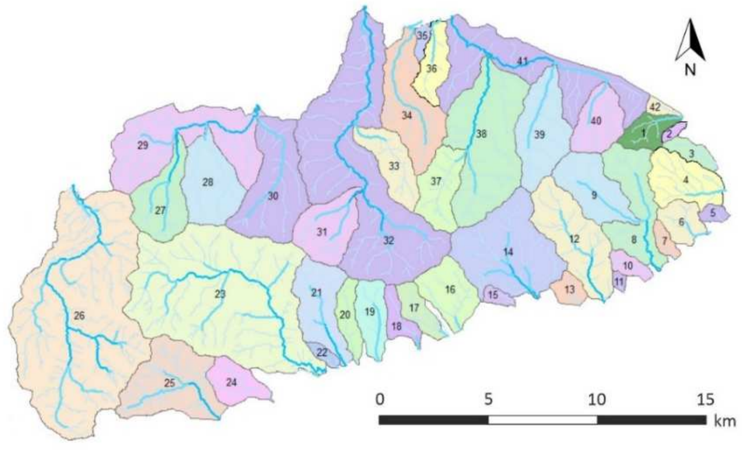

*Fig. 3. Drainage map of the study area showing drainage basins and stream ordering*

The lowest average value of the *SL* index reached the value of 13,13 in drainage basin no. 6, which is in the south-eastern part of the study area. On the contrary, the highest value of the *SL* index was equal to the value of 320. This value was captured in drainage basin no. 24. In addition to this drainage basin, high values of the SL index were also detected in drainage basins no. 25 and no. 26. All these three drainage basins with higher values of the *SL* index are located on the western side of the study area in Tatry Mts. Of the 42 drainage basins analyzed, three river basins were classified into the second class ($300 < SL < 500$), and 39 river basins were classified into the third class ($SL < 300$). From the obtained values of the *SL* index, it is observed that the result of this parameter was influenced by the lithology of the studied area. In areas formed by more resistant rocks to erosion and weathering, the values of the *SL* index were higher than in the Central Carpathian Paleogene Basin, mainly formed by sedimentary rocks less resistant to erosion and weathering. In addition to the dominant influence of lithology, the resulting values also indicate higher tectonic activity and uplift in the western part of the studied area (Tatry Mts.) in comparison with the area of Spišská Magura.

The asymmetry factor values ranged from 26,429 to 77,073. The highest values were calculated for drainage basins no. 15, 30, 31, 35, 40, and 42, which were classified into the first class and represented 14.29% of drainage basins of the study area. The drainage basins belonging to the second class present 57.14% of all studied drainage basins, and 28.57% are the drainage basins classified into the third class.

Absolute values of the asymmetry factor were classified into four classes. In the first class are drainage basins with an absolute asymmetry index value greater than 15. This class indicates strongly asymmetric drainage basins that have been affected by tectonic activity. In the Spišská Magura region were observed 14 of them, which represents 33.33% of strongly asymmetric drainage basins. Most symmetrical drainage basins are in the southern and northern part of the Spišská Magura region. These seven drainage basins (16.67%), whose absolute value of the asymmetry factor is less than 5, indicate stable drainage basins without the influence of tectonic activity. Other river basins were classified in the second and third class (50%), which are gently to moderately asymmetric, and their development was not largely influenced by tectonic activity.

The studied drainage basins were divided into three classes based on calculating values of the *Bs* index. The first class includes 8 basins (19%), the second class includes 20 river basins (47.61%), and the third class includes 14 drainage basins (33.33%). The drainage basins which belong to the first class are characterized as elongated drainage basins in shape. This elongated shape signals stronger tectonic activity, which affects the development of the drainage basins. On the contrary, the drainage basins classified into the third class with nearly circular shapes indicate the basin's development without a significant effect of tectonic activity.

From the analysis of the hypsometric integral, it was recognized that most basins belonged to the third class, indicating older areas that were more affected by erosive than tectonic activity. Up to 21 river basins belong to this category, which represents 50% of the study area. Thirteen drainage basins (30.95%) were included in the second class. Eight river basins with their value oh Hi integral greater than 0,5 were evaluated as unstable active areas affected by tectonic activity.

The width-to-height ratio of the valley is a useful indicator of tectonic activity based on the shape of the valleys.

Measured values of the *Vf* index were grouped into three classes based on the shape of the valleys. The V-shaped drainage basins belong to the first class. These V-shaped basins indicate the importance of tectonics in their evolution. In our studied area, especially in the southwestern part, there are the most V-shaped basins - 17 drainage basins (40.47%). Basins with *Vf* index values greater than 1 were classified into the third class. These basins are U-shaped, which indicates the formation of valleys that were not affected by tectonic activity. Most U-shaped valleys (33.33%) are in the central and eastern part of the Spišská Magura region.

*Smf* index was used to evaluate the relative tectonic activity along the mountain fronts of the studied area. The *Smf* index was calculated for eight mountain fronts, which values were divided into three classes. Mountain fronts no. 7 and no. 8 located in the northeastern part of the study area, achieved an *Smf* index value of less than 1,1, so the drainage basins located near these mountain fronts were classified into the first class. This means that low Smf index values in this area indicate active tectonic areas. *Smf* values of basins near mountain fronts no. 1, 3, 4, 5, and 6 indicate a moderate tectonic activity, and mountain front no. 2, located in the southern part of the study area, indicates an inactive tectonic area that was more affected by erosion processes.

The last step in the analysis of tectonic activity using morphometric parameters was the calculation of relative tectonic activity expressed by *Iat* index. The highest value of the index of relative tectonic activity was reached in drainage basin no. 14 classified into the fourth class. The value of the Iat index in this basin was 2,83. Approximately equally high values of the Iat index were also reached in basins located in the southern part of Spišská Magura. Based on the *Iat* values, tectonic activity did not affect the development of these basins. Most basins (61,9%) belong to the third *Iat* class, indicating a low tectonic activity. Five river basins were classified into the second class, which expresses high relative tectonic activity. This group includes basins in the southern part of Spišská Magura, in the northern part near the Pieniny Klippen belt, in the central and the northeastern part of the Spišská Magura region. The lowest value of the *Iat* index was observed in basin no. 36. That was the boundary value between the first and second classes of the *Iat* index. There is any basin in the studied area which would belong to the first class expressed by very strong tectonic activity.

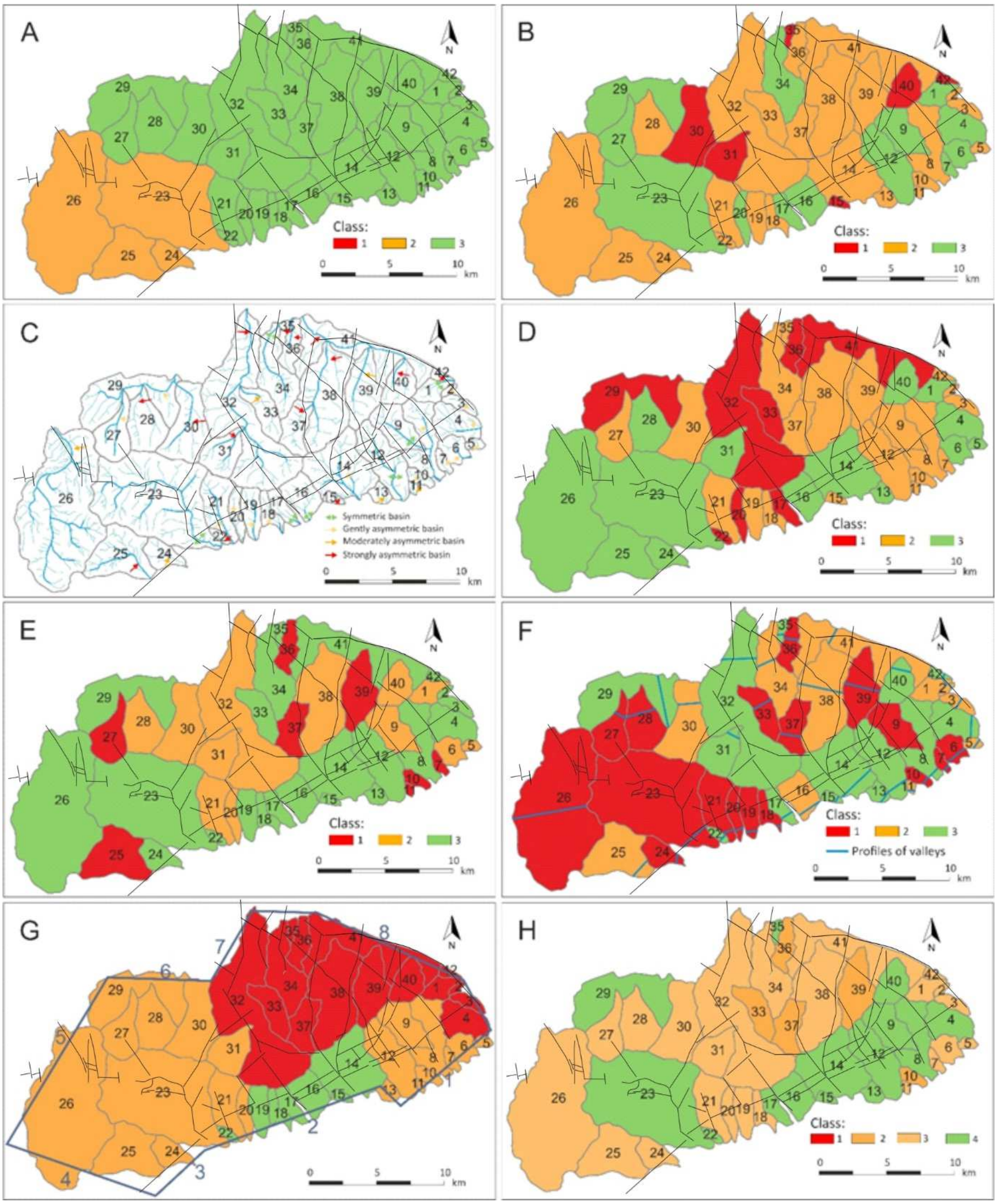

*Fig. 4. (A) Distribution of SL index classes in selected basins (B) Asymmetry factor classes (C) absolute values of asymmetry (D) Distribution of the basin shape ratio classes (E) Distribution of HI classes in the study area (F) Classes of the Vf and their distribution (G) Location of mountain fronts and distribution of Smf classes (H) Distribution of relative tectonic index in the selected basin. The tectonic lines (according to Janočko et al., 2000) are also displayed.*

## Interpretation of geological, geophysical, and digital relief model data

### *Geological-structural analysis*

The structural analysis was performed on the Oligocene sediments of Huty and Zuberec Formations. Our field data collection contains approximately 150 bedding measurements and 350 measured tectonic structures gathered in three areas: 1. Ždiar village and its surroundings, 2. surroundings of the village Podspády, 3. surroundings of the Polish village Jurgów (Fig. 5).

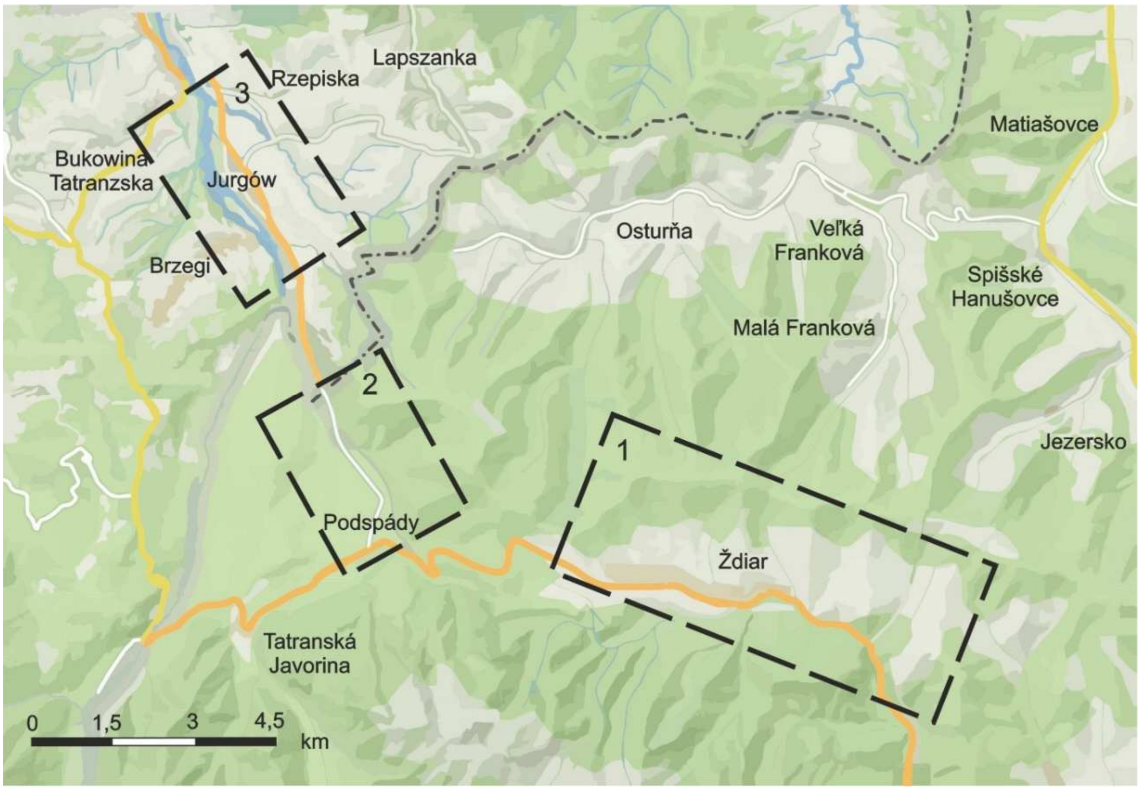

*Fig. 5. Maps of the study areas and villages where fieldwork was conducted*

The structural analysis of the first area was carried out on the outcrops of the Bachleda sandstones, which belong to the sediments of the Paleogene Huty Formation of the Subtatric Group (Gross et al., 1984). A total of 23 sites with exposed Bachleda sandstone were analyzed in the village Zdiar and its surroundings. The sandstones are up to 7 meters thick, have tabular geometry, and are sandwiched by the mudstones of the Huty Formation. They are mostly massive and parallelly laminated with occasional ripple cross-stratification. The individual thick beds are frequently amalgamated. The strike and dip direction of the bedding is in the range 345° - 035° / 15° - 40°, and the average value of the strike and dip direction of the sandstones is 0° / 30° (Fig. 6). Generally, the sandstone is deformed steep faults grouped into two populations: 1. Conjugate faults with SW-NE orientation and 2. faults with orientation NE-SW (Fig. 6, Bp-1). The dip of the fault planes is between 50 ° and 80 °. Based on the presence of striations showing movement toward SE, we interpreted the faults as oblique faults with the NW - SE direction. The conjugate faults represent normal faults with the NW - SE direction. Generally, we distinguished four groups of tectonic structures according to their dominant orientations: 1. NW - SE, 2. SW - NE, 3. ENE - WSW, 4. E - W. Evidence of calcite veins in Biela River sandstone is related to extension with SE-SW direction. Parallel calcite veins were also founded in the NE-SE direction.

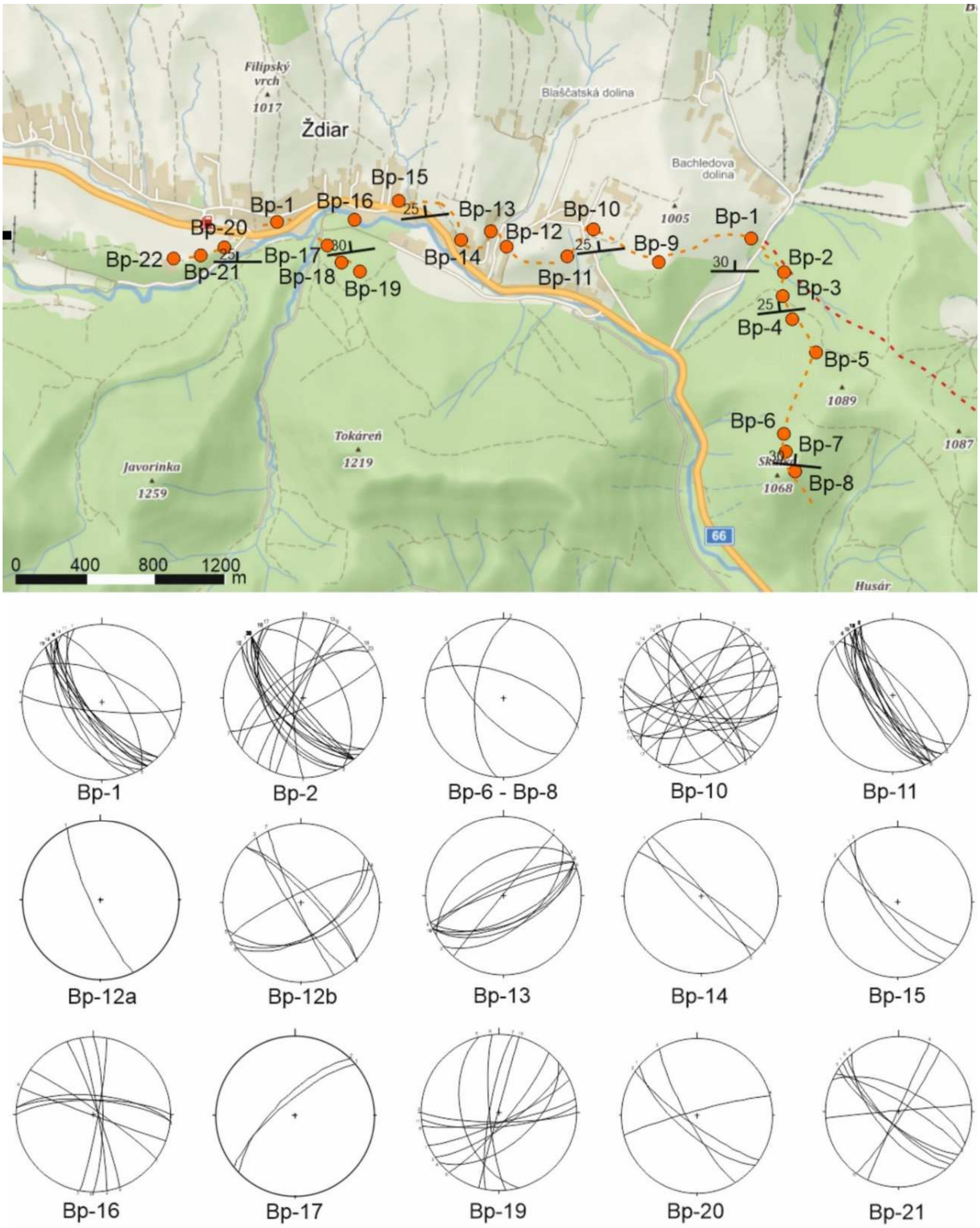

*Fig. 6. Map of the first locality with marked outcrops (BP-1 to Bp-22) and tectonograms of measured tectonic structures*

The second area stretches west of the village of Podspády, along the river Javorinka and Goliašov creeks. This area is built-up of sediments belonging to Oligocene Huty and Zuberec Formations. In this area, we analyzed a total of 8 outcrops.

The studied localities along the Goliášov creek are characterized by alternating sandstones and mudstones. The thickness of the sandstone beds ranges from 20 to 35 centimeters, and the mudstone beds reach a thickness of 20 to 100 centimeters. Generally, the beds dip toward the north with an inclination of approximately 25°.

Three groups of tectonic structures were documented in the outcrops located along the Goliašov creek: 1. parallel extension joints with NW-SE orientation, 2. joints with NE - SW direction, 3. joints with the orientation E - W and ESE - WNW directions. The exposures located along the Javorinka River show thinly laminated mudstone beds occasionally alternating with medium-thick beds of sandstone dipping toward N and ENE (0° - 030°) with a dip of 5° - 30°. The sandstones are deformed by joints having an E-W direction (Fig. 7). The mudstone occasionally shows boudins with their axis orientation of 130° - 145°/ 70° - 88°, suggesting NE-SW extension.

Common tectonic structures described in other exposures (Fig. 7, Pd-6 to Pd-8) are joints in SW – NE direction and normal faults in SW – NE and S – N directions.

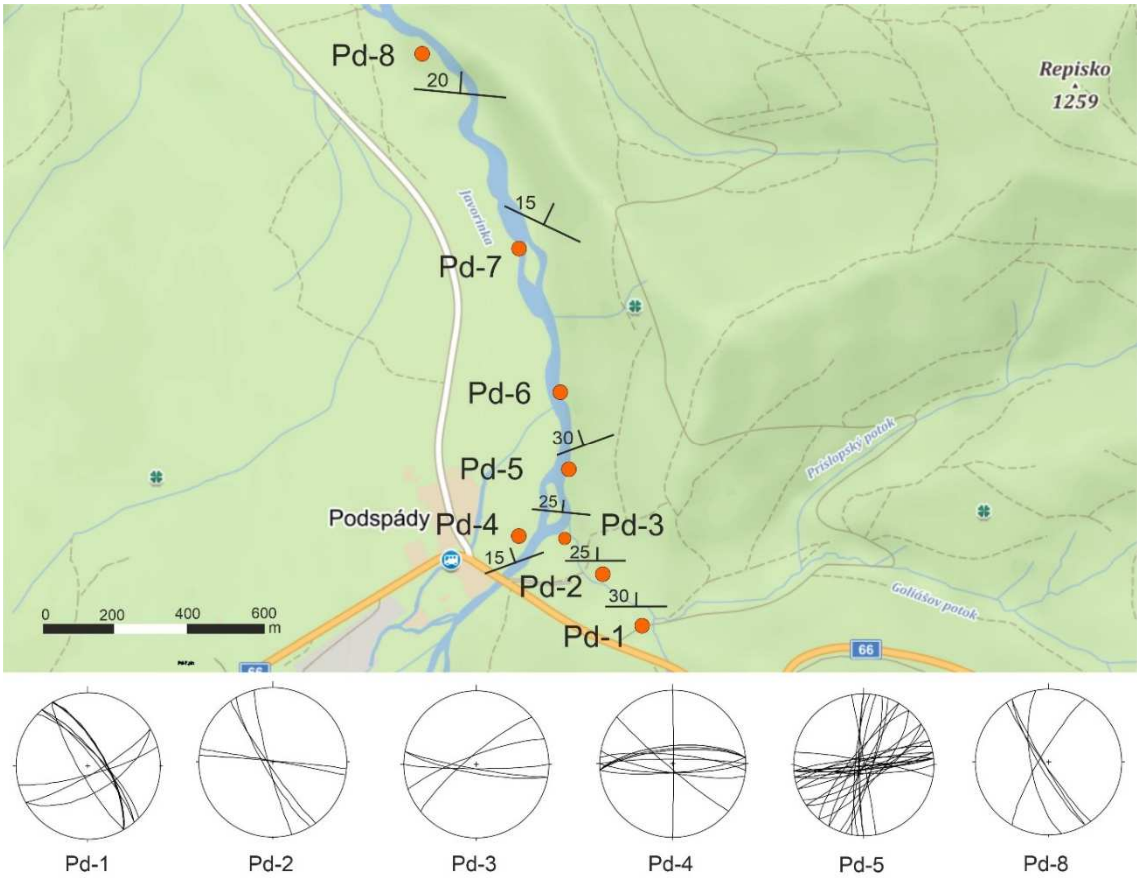

*Fig. 7. Map of the second locality with marked outcrops (Pd-1 to Pd-8) and tectonograms of measured tectonic structures*

In the Jurgów area, we analyzed fourteen outcrops along the Bialka River. The sediments at these localities show alternation of sandstones and mudstones with ratios of 1: 1, 2: 1, and 1: 2 typical for the Oligocene Zuberec Formation (Gross et al., 1984). The sandstones are approximately 15 to 40 centimeters thick, in some outcrops up to 1.8 m thick. Mudstone intervals have a thickness of 1 m to 1.6 meters and sometimes up to six meters.

According to the bedding, we can divide the Jurgów area into two parts. The first part includes the outcrops, on which the direction/inclination range from 245° - 355° / 5° - 30° (Fig. 8). The second part of the area is built-up of sediments with bedding with the direction from 115° to 220° and the dip from 5° to 30°. The sediments are deformed by normal faults and joints subdivided into four groups according to their orientation: 1. NE - SW, 2. S - N and NNW - SSE, respectively 3. ENE - WSW to WNW - ESE, and 4. NW - SE. The typical structure of this area is the orthogonal system of parallel joints in the sandstone layers with an NNW - SSE and ENE - WSW. In addition, there are parallel extensional veins filled with calcite with an NNW - SSE to the NNE – SSW directions.

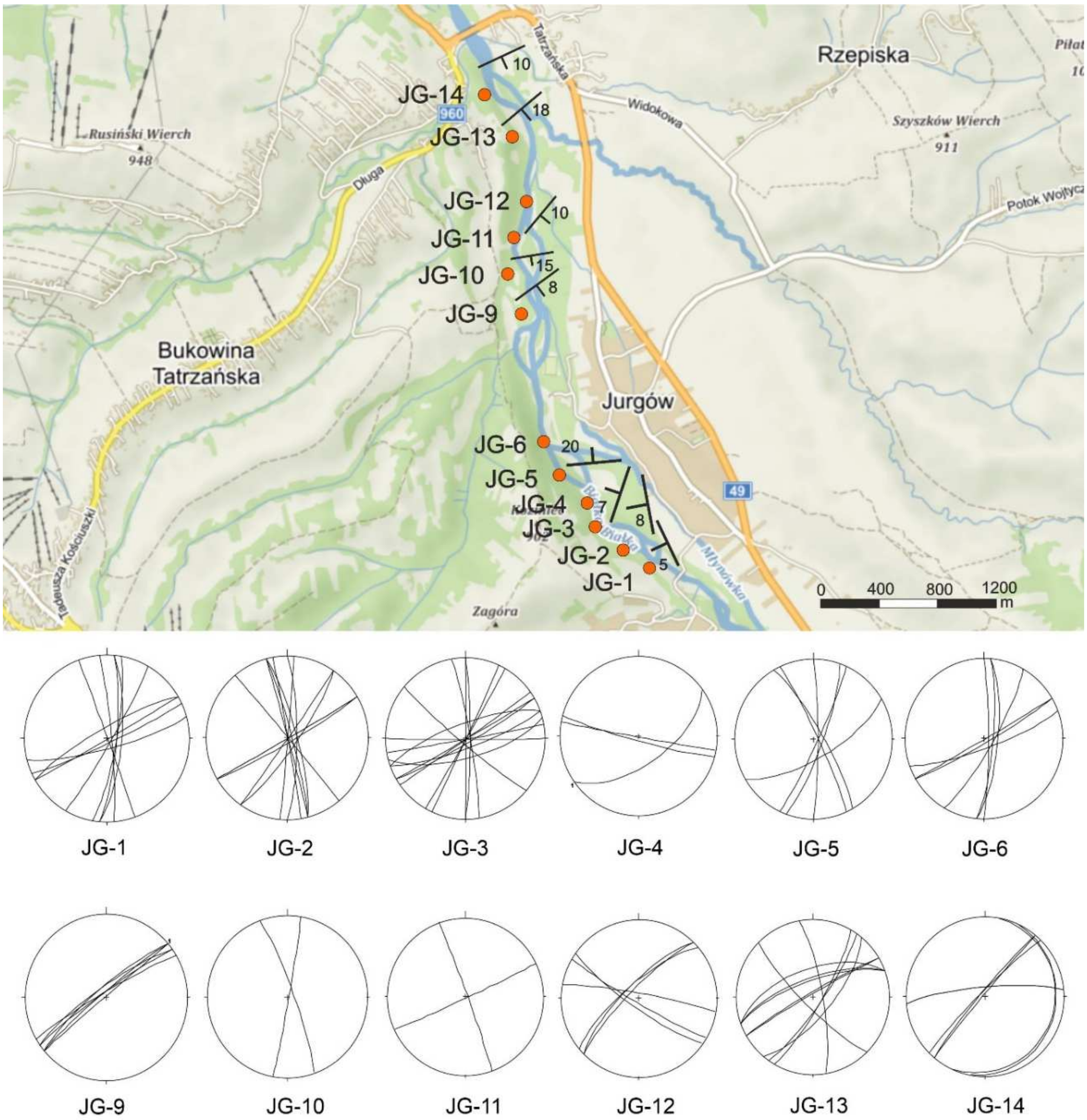

*Fig. 8. Map of the third locality with marked outcrops (Jg-1 to Jg-14) and tectonograms of measured tectonic structures*

### *Vertical electric sounding*

The vertical electric sounding exploration performed by Májovský (1981) focused on the characterization of the contact between the Paleogene and underlying Mesozoic sediments and on the characterization of the tectonics in the studied area. The electric profiles were generally oriented in the S-N direction to identify assumed W-E normal faults separating the Tatry Mts. from the neighboring Central-Carpathian Basin. The four profiles were realized in the eastern part of the Spišská Magura region, while the longest profile was measured between Biela and Dunajec river valleys (Fig. 9). The profiles confirmed the block-like structure of the marginal part of the Spišská Magura region neighboring the Tatry region. The blocks gradually subside toward the north. Unfortunately, the orientation and density of the profiles do not allow a precise determination of the trend of normal faults triggering the block-like subsidence. The gradual subsidence toward the north generally implies the W-E orientation of the normal faults. The thickness of sediments in individual blocks reveals that some of the faults might be syndepositional (growth faults, Fig. 10).

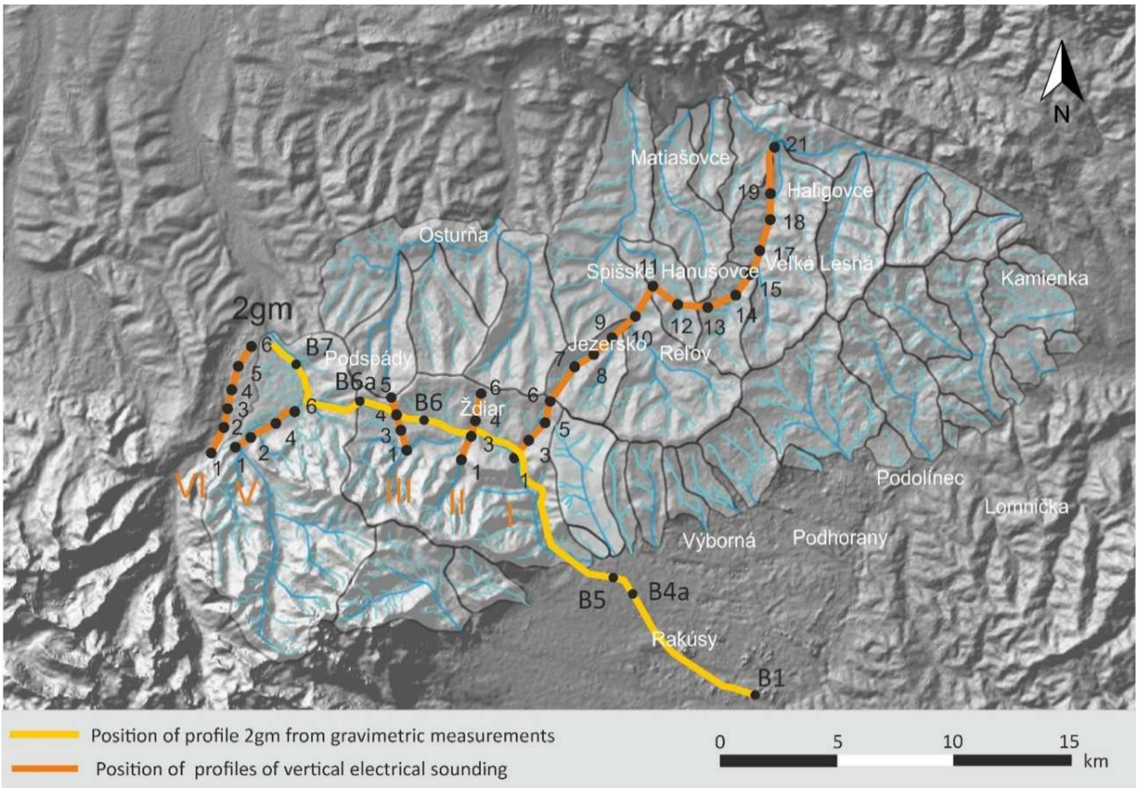

*Fig. 9. Map of Spišská Magura and his surrounding with the position of profile 2 gm and five profiles from measurements of vertical electrical sounding. The individual basins used for the morphometric analysis in this study are also shown.*

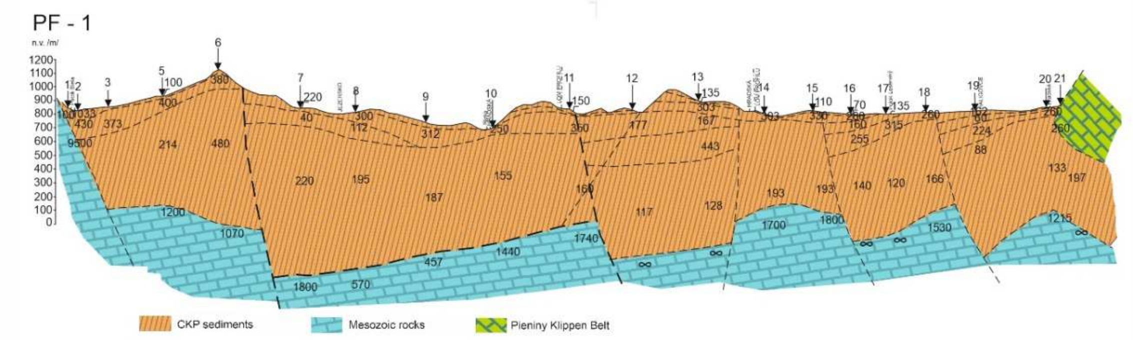

*Fig. 10. Interpretation of Profile I from vertical electrical sounding measurements (Májovský, 1981, modified).*

Gravimetric measurements along the profile 2gm trending from the town Kezmarok to the village Lysá Poľana (Szalaiová et al., 2004, Fig. 9) revealed an extensive gravity gradient interpreted as the Sub-Tatric fault near Tatranská kotlina. As the gravity gradient is very striking at this point, it could not be interpreted as a single tectonic line but as a system of parallel tectonic lines (Szalaiová et al., 2004). Based on the different thicknesses of sediments on both sides of the fault system, we assume that the system was active during the deposition of the Paleogene sediments. The gravimetry also revealed a negative Bouger anomaly close to village Rakúsy at the front of the Tatry Mts. The anomaly has been interpreted as local depression filled by Paleogene sediments (Szalaiová et al., 2004) and may be interpreted as a result of the Subtatric-Ružbachy fault system.

### *Interpretation of Digital Terrain Model*

We used a Digital Terrain Model (from the GeoMapApp application) to visualize and analyze the tectonic situation of the studied area based on the orientation and density of morpholineaments on the earth's surface, which can reflect subsurface tectonic structures. Using the analysis of the digital Terrain Model, we divided the most significant morpholineaments into four groups according to the following directions: 1. NE - SW; 2. NW - SE; 3. ESE - WNW to ENE – WNW and 4. NNW - SSE to NNE – SSW (Fig. 11). The deformation of NW-SE morpholineaments by NE - SW morpholineaments (e.g., in the vicinity of Ždiar and Matiašovce villages) suggests that NE-SW lineaments are younger. The Digital Terrain Model clearly shows striking tectonic structures, such as the Subtatric-Ružbachy fault system bordering Spišská Magura from the southeast, the faults separating the Pieniny Klippen Belt and the CKP Basin as well as the sediments of CKP Basin and the Mesozoic rocks of the Tatry Mts.

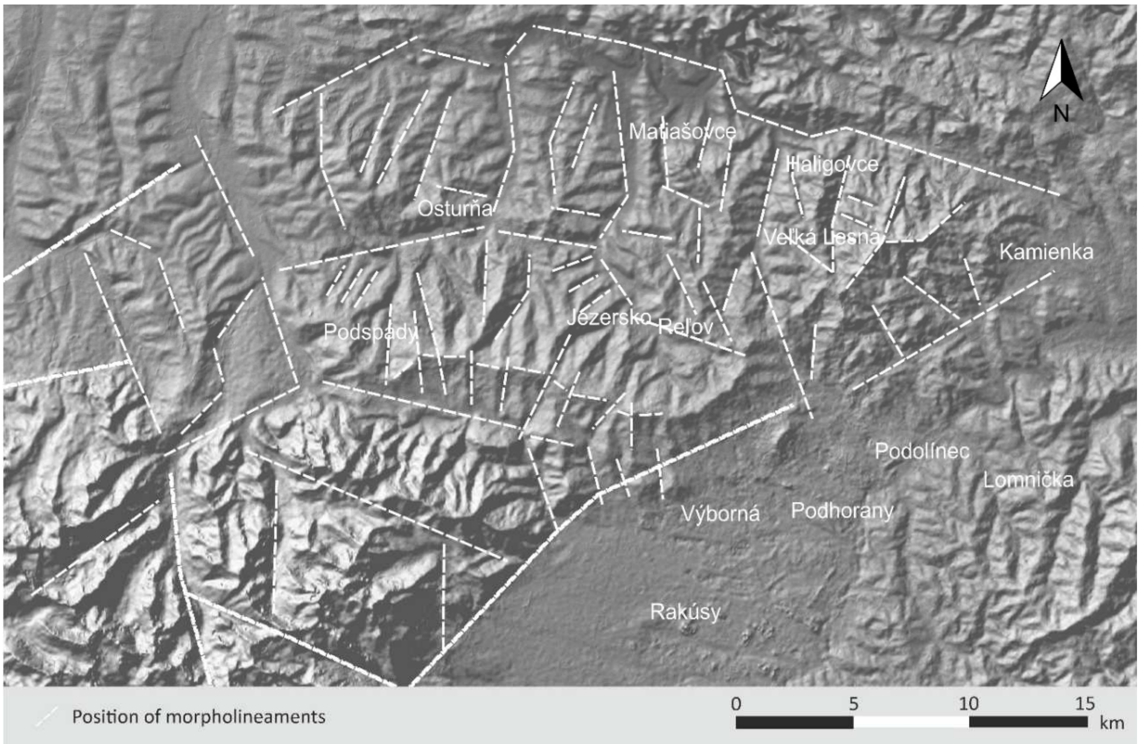

*Fig. 11. Map of morpholineaments against the background of slope-shaded relief*

## Integration of geological results

The integration of morphometric parameters used in our analysis was used for developing the map of relative tectonic activity of the studied area. To understand the tectonic evolution of the studied region suggested by this map, we also used integrated data characterizing the tectonics from different sources besides the data from geophysics and DRM (Fig. 12). They include geological and tectonic maps of various scales (Fusán et al., 1964; Nemčok, 1994; Bezák et al., 2008; Janočko et al., 2000; Lexa et al., 2000; Vojtko et al., 2010), and their text explanations (Nemčok et al., 1993; Gross et al., 1999; Janočko, 2000). From the studies of these sources, an overview of the tectonics, the deformation stages, and the resulting tectonic structures of the studied area was created.

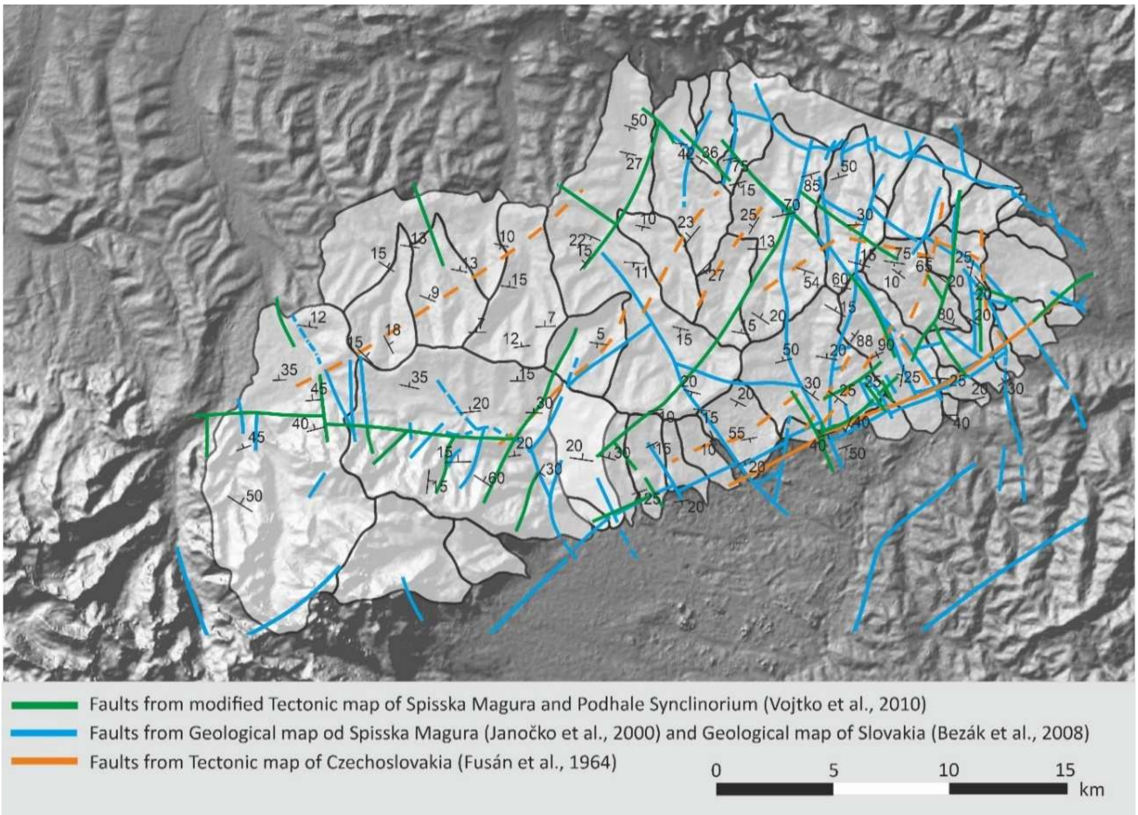

*Fig. 12. Simplified tectonic map modified from Tectonic map of Spišská Magura and Podhale Synclinorium (Vojtko et al., 2010), Geological map of Spišská Magura (Janocko et al., 2010), Geological map of Slovakia (Bezák et al., 2008) and Tectonic map of Czechoslovakia (Fusán et al., 1964). The individual basins used for the morphometric analysis in this study are also shown.*

One of the most significant tectonic structures bordering the Spišská Magura region from the south and southeast is the Subtatric-Ružbachy fault system (SRFS). The system represents a group of subparallel faults with NE - SW to ENE – WSW direction. Its activity and characteristics are related to several deformation stages that affect the tectonics of the surrounding area (Jacko and Janočko, 2000; Sperner et al., 2002; Anczkiewicz et al., 2015). The oldest stage of its activity is assigned to the Oligocene as evidenced structurally (e.g., Jacko and Janočko, 2000), sedimentologically (Janočko and Basilici, 2021), and by dating and thermal modeling (e.g., Kohút and Sherlock, 2003, Anczkiewicz et al., 2015). The last activities of the SRFS were proved from the middle-late Miocene (e.g., Králiková et al., 2014; Smigielski et al., 2016). The Quaternary activity of the SRFS was recently demonstrated by Pánek et al. (2020). Based on LiDAR detection, they suggested the activity of SRFS younger than the Last Glacial Maximum. The SRFS is assumed to be one of the most important features influencing the huge amount of exhumation of the Spišská Magura region, interpreted to be originally covered by some 4 – 9 km thick sediment column (e.g., Uhlík et al., 2002; Anczkiewicz et al., 2015).

Another significant tectonic structure bordering the Spišská Magura region in the north is the Pieniny Klippen Belt, with complicated and similarly polyphase tectonic evolution from which the last one is a phase resulting in dextral strike-slip faults indicating dextral transpression (e.g., Ratschbacher et al., 1993; Plašienka and Mikuš, 2010).

The inner part of the Spišská Magura region also shows a complicated tectonic structure that is a result of four deformation stages (Janočko and Jacko, 2011). The oldest stage is characteristic only for the basement of Mesozoic sediments, which was affected by the extensional stress generating normal faults of NW - SE, and E – W directions. The next deformation stage is related to the compressional stress with the NNE - SSE direction and the extensional stress towards NNW - SSE. This stage results in the conjugate system of faults characterized by the ENE - WSW dextral strike-slip faults and sinistral strike-slip faults with the WNW - ESE direction. In addition to these structures, various types of mesoscopic folds are also represented. The third stage is characterized by the presence of the WNW – ESE reverse faults with the course of WNW - ESE and perpendicular normal faults with the ENE - WSW direction. The earliest deformation stage is characteristic of the prevailing extensional stress component in Paleogene sediments, where the most significant extension component operated in the NW - SE direction, associated with normal faults with ENE – WSW, and WSW – ESE direction (Janočko and Jacko, 2011). Younger tectonic structures of the NE - SW fault system, which is often faulted by NW - SE faults, are typical for all areas of Spišská Magura. These structures are visible nearby the Pieniny Klippen Belt. Tectonic structures with the NW - SE direction are observable in the Subtatric-Ružbachy fault system, which is segmented by these structures. Many of these structures with the NW - SE direction has been identified as strike-slip faults but also as normal faults or small reverse faults. The youngest fault system characterized by N – S direction was evident only near the Ružbachy Mesozoic rocks (Janočko, 2000).

## Discussion

Morphometric analysis is a methodology used for the assessment of the relative tectonic activity in the studied areas. This technique is based on the evaluation of several criteria recognizing potential tectonic influence on morphometry, such as stream-length gradient, basin-shape etc. The advantage of the analysis is that it integrates several methods and provides the best model for evaluating the relative tectonic activity. The reliability of tectonic indication by a single method is lower as the parameters may be influenced by other factors (e.g., lithology). Even if the methodology integrates several techniques, it is necessary to realize that it is just one of the tools used for the evaluation of tectonic imprints on geological structures in studied areas.

The map of relative tectonic activity (Fig. 4H) calculated for each basin by mean values of six morphometric parameters shows that most of the southern part of the studied area has not been influenced by tectonics. Considering that these areas neighbors the SRFS, the result is relatively surprising. Pánek et al. (2020) observed morphological escarpments along the Subtatric fault, suggesting this fault's activity before 15 ka. The easternmost site of this observation was near the Studený Potok creek (near the village Smokovce). According to these authors (Pánek et al., 2020), the activity of the SRFS is also suggested by distinct knickpoints that have largely retreated from the SRFS. Such a knickpoint is visible on the Bela River at the site of the tributary of the creek coming from the Bachleda valley to the Bela River. The comparison of the base elevations of the youngest terraces along the reach of the Bela River shows these same values of some 2-3 m above the recent stream. This may suggest the migration of the knickpoints older than these terraces. The analysis of the *SL* parameter, which should reflect changes in the longitudinal profile of the river in the analyzed basin, indicates medium tectonic activity in the Bela River basin (Fig. 4A). According to the results of *SL* parameters from all the basins occurring in the Spišská Magura region, the tectonic activity is low. The asymmetry factor shows prevailing stable catchment areas without tectonic activity along the SRFS. The only one basin indicates high asymmetry (Fig. 4B). The distribution of basin shape ratio classes (Fig. 4 D) reveals relatively young drainage basins with elongated shapes typical for active tectonic settings in the central part of the Spišská Magura region and at the border zone between the Spišská Magura and Pieniny regions. Evaluation of *HI* classes shows their random distribution in the entire studied area. The evaluation of U- versus V-shaped valleys (*Vf* index, Fig. 4F) indicates prevailing uplift of the western part of the Spišská Magura region, including marginal parts of the Belianske Tatry Mts. The observation of mountain front sinuosity (*Smf* index, Fig. 4H) suggests active tectonics along the boundary between the Spišská Magura region and Pieniny Klippen Belt.

To evaluate possible young tectonic activity, we analyzed the map of the Quaternary thickness (Maglay et al., 2002). The map shows that in the Spišská Magura region, no larger accumulations of these sediments occur. They are better preserved to the south of the Spišská Magura region in the Popradská kotlina basin (Fig. 13), separated from the Spišská Magura region by SRFS. The distribution of their thickness shows that there is a significant change from a line Lendak – Spišská Belá. The change probably reflects the change in the type of catchment areas differing in the Tatry Mts. and Spišská Magura region (lesser areal extent, topography) and intensity of sediment input during the Pleistocene (the glaciated catchment areas in the Tatry Mts.). Generally, the distribution of the thickness of the Quaternary sediments does not show any significant changes that might be the result of the active tectonics along the SRFS. Interestingly, the similar work performed along the SRFS in the stretch between Western and Eastern (Belianske) Tatry Mts. revealed similar results when the area along the SRFS indicated low tectonic activity (Buczek and Górnik, 2020).

The comparison of the map of relative tectonic activity developed by integration of individual morphometric parameters shows a small match with the tectonic lines characterizing the geological structure of the Spišská Magura region (Fig. 4H). Analysis of the match between individual methods and tectonics from the geological maps reveals relative inconsistency between indices provided by individual methods (Fig. 4). The inconsistency may affect the resulting assessment of the relative tectonic activity. On the other hand, the analyses also suggest that using only one method for the definition of tectonics may not be sufficient. Another drawback of the methodology used in this study is that it suggests the possible influence of tectonics on the entire studied basin. This fact hampers assigning the indicated tectonics to simple tectonic lines used in geological (and geophysical) maps.

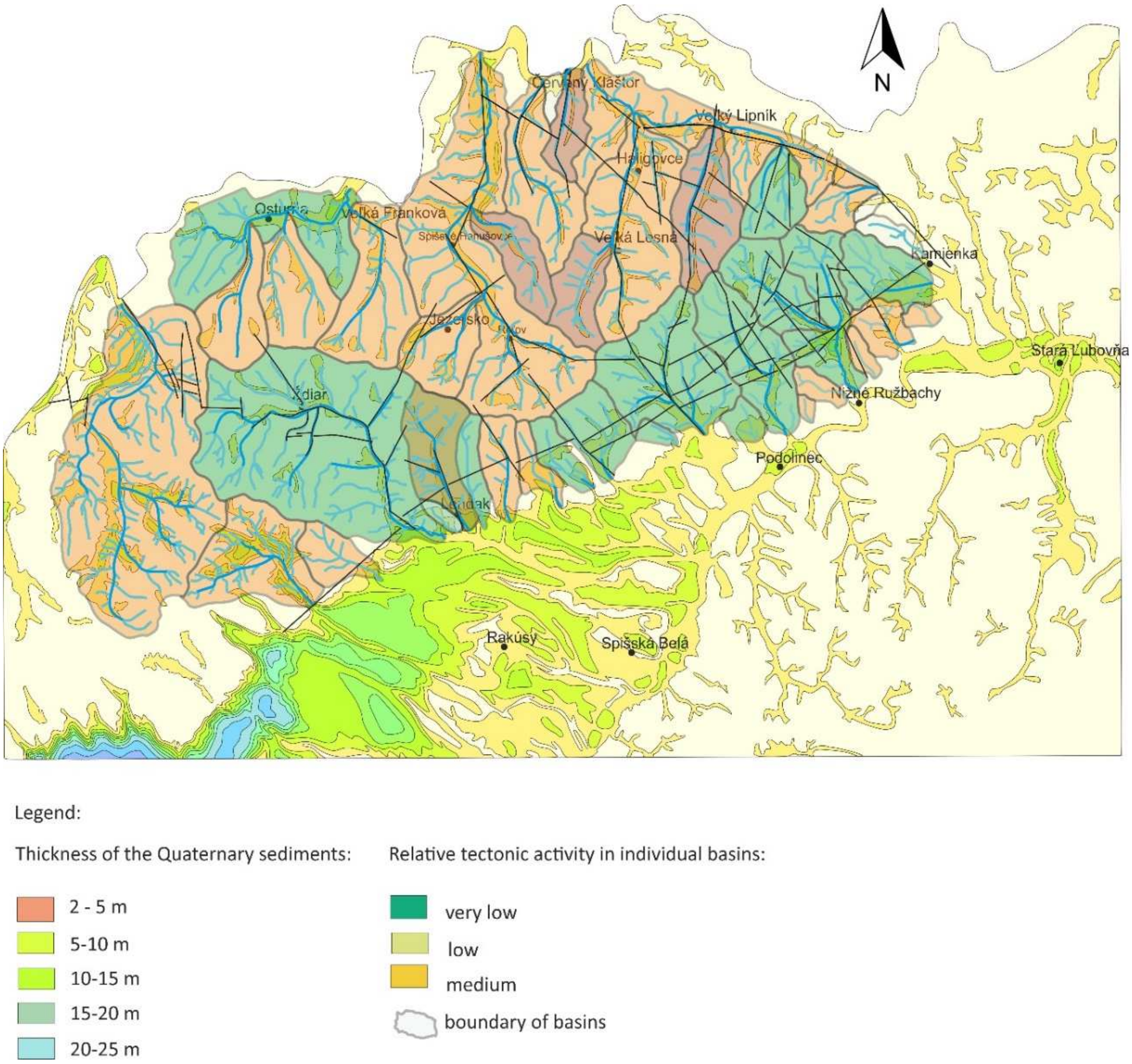

*Fig. 13. Map of the thickness of Quaternary sediments in the wider area of the studied region (Maglay et al., 2002, modified). The individual basins and tectonics based on Janočko et al. (2000) are also shown.*

## Conclusions

Morphometric analysis, which we performed in the area of Spišská Magura Mts. and adjacent part of the Belianske Tatry Mts., was based on the evaluation of six morphometric parameters and their final integration into the map of relative tectonic activity. The parameters characterize 42 catchment areas of rivers and creeks. These areas and evaluation of their morphometry were realized using a digital elevation model and ArcGIS 10.3 software. We analyzed the Stream-length gradient index, Asymmetry factor, Basin shape ratio index, Hypsometric integral, Valley floor width-valley height ratio, Mountain-front sinuosity, and Relative tectonic activity index. The results of individual methods differ in showing possible tectonic activity of partial catchment areas in the studied region. The relative tectonic index, calculated by integrating all the analyzed morphometric parameters, suggests only low and medium tectonic activity in the studied region. The comparison of this result shows a little match with tectonics interpreted on the base of geological and geophysical data even along with the Subtatric-Ruzbachy fault system that is assumed to be active in the Quaternary. Similarly, the tectonic influence in the areas adjacent to the boundary with the Pieniny Klippen Belt, which also is assumed to be active in the Quaternary, is indicated by basin shape ratio and mountain front sinuosity parameters; however, not by the integrated relative tectonic activity index. The more intensive uplift of the Belianske Tatry Mts. part of the studied region that is generally accepted was only confirmed by U-versus V-shaped valley factor (Rf).

The morphometric analysis is based on an evaluation of recent morphology. Our analysis results show that the formation of the recent relief of the Spišská Magura region and adjacent part of the Belianske Tatry Mts. has been more affected by the exogenous processes than by the tectonic activity. We think that the imprint of these processes overlaps the imprint on the morphology done by older tectonics.

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