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Effect of the geological structure on surface development and landforms in the Bükkalja

Theses of Ph.D. dissertation

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I. INTRODUCTION AND THE AIM OF THE DISSERTATION

Bükkalja is the southern double pediment levels of the Bükk Mountains, which is dissected with main and tributary valleys (MARTONNÉ ERDŐS K. 2002). It is the most extensive foothill area in Hungary (HEVESI A. – PAPP S. 1979; MARTONNÉ ERDŐS K. 2002).

The micro-region is one of Hungary's most thoroughly studied areas from a geological and geomorphological point of view. However, despite centuries of geological and geomorphological studies, more and more problems arise in connection with the surface development of the area.

Since the middle of the last century, geological and geomorphological mapping of Bükkalja has shown that the surface of the pediment has been dissected into"chessboard-like" fractures. These fractures developed as a result of the Bükkalja basins, and the tilted surfaces are also known as cuestas (local name: "nyomó") (BALOGH K. 1963, 1964; PINCZÉS Z. 1968). However, others in these forms are in many cases interpreted as a form of denudation, erosion based solely on rock quality (HEVESI A. 1978). Based on the morphometric examination of the pediment by VÁGÓ J. – HEGEDŰS A. (2011), they assumed that the height difference between the lower and upper pediment and the local differences in the elevation within the levels could not be traced back only to the processes of denudation. According to literature (SCHRÉTER Z. 1912, 1926, 1933; BALOGH K.1963, 1964; DOBOS A. 2000, 2002; HEVESI A. 2002a, 2002b; LESS GY. et al. 2005; NÉMETH N. 2005; PETRIK A. 2016), certain sections of the valleys of Tárkány, Eger, Ostoros, Kánya, Hór, Kács and Kulcsárvölgy creeks are probably structurally predicted. However, the relationship between the drainage network and the geological structure has not been proven yet.

My work aimed to outline the surface development of Bükkalja based on the current literature and data. This was conducted to supplement most up to date results of Bükkalja with my geomorphological and structural morphological observations, and largely with morphological/morphometric studies on DEM and DSM. The objective of my work is to detect and morphometrically analyse the Bükkalja basins and explore the effect of geological structural elements on the surface development and landforms, especially the formation of linear morphological elements (valleys and lineaments).

II. MATERIALS AND METHODS

I conducted thorough field trips to understand the topography of the area. I recorded the geomorphological observations (landforms) and the location of geological outcrops with the help of a GPS device and documented the observations using photographs. Where I had the opportunity, I performed structural geological measurements. I recorded the dips and their direction and where I had the possibility the dips of beds were also measured. I supplemented my field observations with morphometric and statistical studies performed using a digital elevation and surface model, during which I calculated to primary (e.g. *slope, aspect, curvature, relative relief, dissection index*) and complex (e.g. *Multiresolution Index of Valley Bottom Flatness, Multiresolution Index of Ridge Top Flatness* [GALLANT, J.C. – DOWLING, T.I. 2003], *Topography Position Index* [WEISS, A. 2001; JENNESS, J. 2006], *Morphometric Features* [WOOD, J. 1996, 2009]) morphometric parameters. The landforms were analysed using a swath profile (KORUP, O. et al. 2005; STOLAR, D.B. et al. 2007; ROBL, J. et al. 2008; TELBISZ T. et al. 2011, 2013). In addition, I examined the river sinuosity (TIMÁR 2003a, 2003b; PETROVSZKI J. 2013) and stream gradient (SL) (HACK, J.T. 1973; GÁBRIS GY. 1986a; VÁGÓ J. 2010, 2012).

My morphometric studies were based on digital surface model (DSM) and digital elevation model (DEM). Among the surface models, I used the 30 m spatial resolution EUDEM and the 25 m resolution HydroDEM. I made an own digital elevation model (DEM) from 1: 10 000 EOTR topographic maps based on digitised contour lines, elevation points, and valleys using ArcGIS 10.1 software *Topo to Raster* interpolation. The spatial resolution of this self-made model was 25 m. Due to methodological features, I used the self-made DEM, where I delineated the remnant surfaces. In contrast, I used the EUDEM for basins detection and the HydroDEM for my other morphometric analysis and to make the swath profiles. To calculate the river sinuosity, I used the 1: 28 800 scale maps of the Second Military Survey from 1806 to 1869, while the EOTR topographic maps were used to calculate the stream gradient index (SL).

In addition, during my research, I used the available geological maps of the area (FODOR L. et al. 2005; LESS GY. et al. 2005; NÉMETH N. 2005; MCINTOSH R. W. 2014; PETRIK A. 2016; GÁL P. et al. 2019a, 2019b, 2020; GULÁCSI Z. é.n), the database of earthquakes (TÓTH L. et al. 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011; GRÁCZER Z. et al. 2012, 2013, 2014, 2015, 2016, 2017, 2018) and the drilling data series published in the yearbooks of MÁFI (*Hungarian Institute of Geology and Geophysics*).

I processed the DSM and DEM and the vector dataset in the QGIS 2.8.3, ArcGIS 10.1., SAGA GIS 2.1.2. I also used the GIS compatible Python 2.7.10 programming language to process the vector files. Representation of microtectonic measurements and directional statistics were performed in StereoNet 9.8.3 and RockWorks 16, while further statistical analyses were performed in MatLab R2017b. The figures and maps were completed in Adobe Photoshop CS6. The diagrams were created using Grapher 8 and MS Excel.

III. NEW SCIENTIFIC RESULTS

Based on my field observations, I identified a new valley basin in Bükkalja, which I call the Tard Valley Basin. As a result, the number of known basins in Bükkalja increased from five to six (Thesis I).

In Bükkalja, the literature has mentioned five basins so far: Tárkány, Bogács-Cserépfalu, Kisgyőr, Kács Basin and Hidegkút-laposa (KEREKES J. 1936; DOBOS A. 2000, 2002; MARTONNÉERDŐS K. 2002; HEVESI A. 2003; DÖVÉNYI Z. 2010). My field investigation concluded that in addition to the five above-mentioned basins, another one could be assumed in the middle section of the Tard creek, at the confluence with the Cserépváralja creek. The identification of the Bükkalja basins during field investigations is difficult due to the topography (e.g. Bogács-Cserépfalu Basin). Therefore, I attempted to detect the basins by applying morphometric analytic methods using a digital surface model (DSM).

Based on the examination of the histogram of the digital surface model (DSM), the Hidegkút-laposa and the Tard Valley Basin can be interpreted as a semi-basin; however, based on my field observations, they seem more like a basin/valley basin. The Tárkány, Bogács-Cserépfalu, Kács, Kisgyőr Basins and Hidegkút-laposa formed partly in the older pediments and partly in the older peneplain surface, while the Tardi Valley Basin formed on the border of the older pediments, into the younger pediments, which is supported by the performed morphometric studies.

In addition to the "basic" morphometry methods used for decades in geomorphological studies, the *Topography Position Index* (TPI) (*Figure 1*) and analysis of the digital surface model (DSM) elevation values (*histogram analysis, cluster analysis*) may also be suitable for detecting the basin as a landform. However, it is important to note that most of these analytic methods are highly dependent on the spatial resolution of the digital elevation/surface model and the size of the studied area. The mentioned methods can be used together for the detection of the Bükkalja basins, but they cannot replace the field observations!

I also carried out the morphometrical analysis of the basins; thus, I found that the basin I identified fits well into the group of previously identified Bükkalja basins. I also noticed that the Tárkány Basin differs significantly from the others in terms of shape.

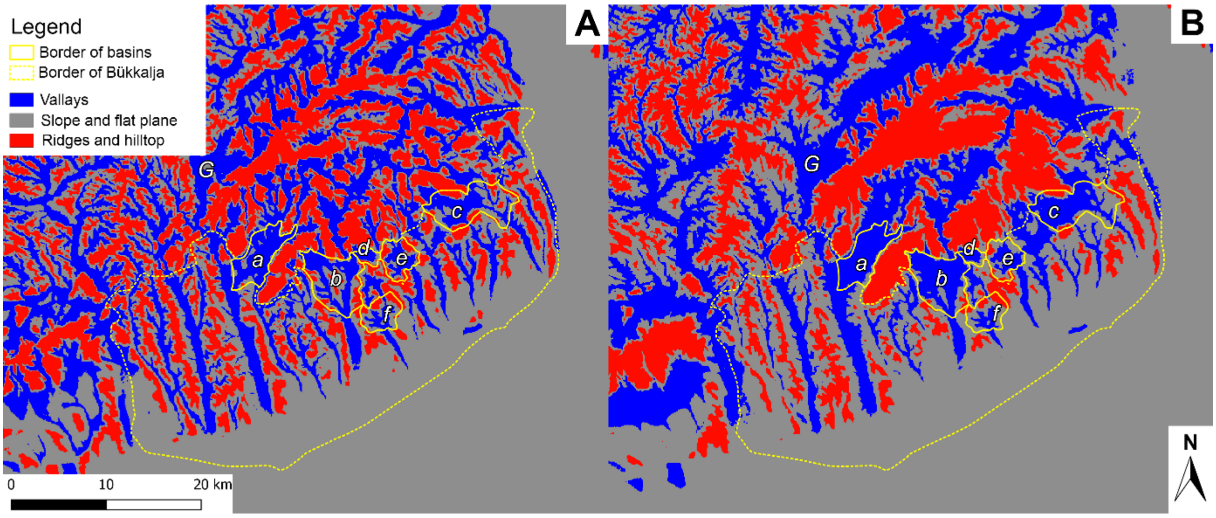

Figure 1. Simplified geomorphological map of Bükkalja and surrounding areas adapted from W*EISS*, *A (2001) method (**A**: 2000*2000 m-es, **B**: 5000*5000 m cell size). [a: Tárkány Basin, b: Bogács-Cserépfalu Basin, c: Kisgyőr Basin, d: Hidegkút-laposa, e: Kács Basin, f: Tard Valley Basin, G: Bélapátfalva Basin (not part of Bükkalja)].*

I interpreted the Bükkalja basins as structurally preformed landforms with a complex genesis (Thesis II).

The formation of the Tárkány Basin and the asymmetric terrace system of the basin can be traced back to structural characteristics based on the analysis of the swath profile. This is in line with the results of geological studies to date (LESS GY. et al. 2005; PETRIK A. 2016). Contrary to previous assumptions, I also traced the formation of the Kisgyőr Basin back to structural reasons (*Figure 2*), although the role of rock quality in its further development cannot be ruled out. The north and south boundaries of the basin can be designated along faults. The structural elements running in the basin also fragmented the remnant surfaces. In addition to rock quality, structural properties also played a role in the formation of the Bogács-Cserépfalu Basin, which is supported not only by previous structural geological and topological research (DOBOS A. 2000; LESS GY. et al. 2005; PETRIK A. 2016) but also by the results of the analysis of swath profile. The situation is similar in the case of the Kács Basin, where the southern boundary is structural based on the swath profile. The boundary of the northern edge of the Hidegkút-laposa can also be drawn along a structural element. However, the slope break at the southern edge, which can also be observed on the swath profile, could not be unequivocally connected to a specific structural element by my field investigations so that the basin can be interpreted as a structural-denudation basin (i.e. its formation was initiated by structural processes, but it is further development was controlled by denudation processes). I trace the formation of the Tard Valley Basin back to structural and rock quality reasons. The northern boundary of the basin shows a structural lithological boundary, and its southern boundary can also be interpreted as structural due to its morphological features.

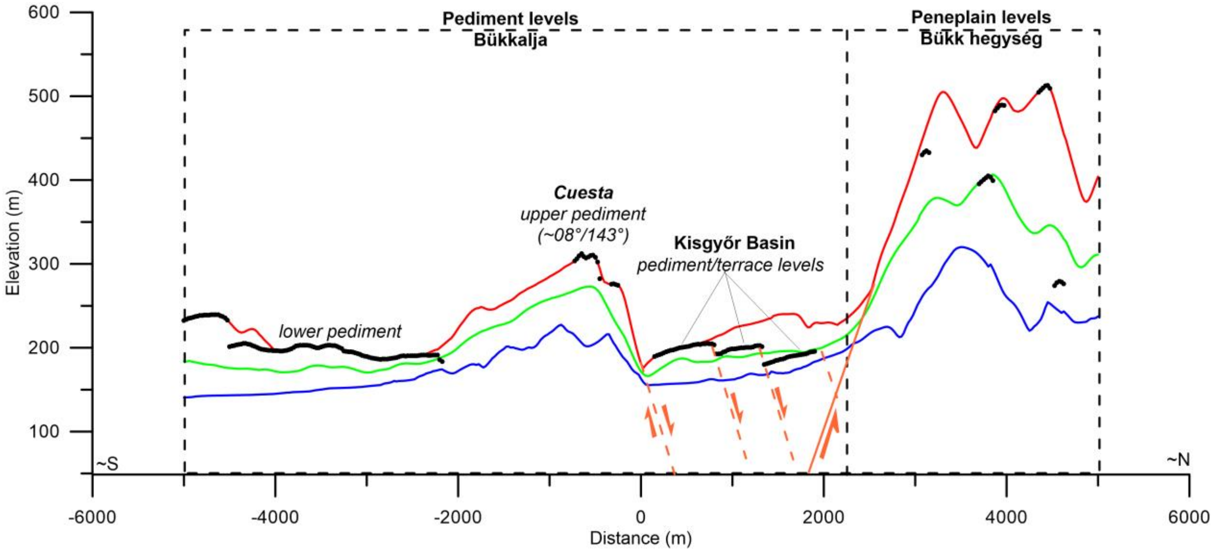

Figure 2. Swath profile of Kisgyőr Basin
(red: maximum value, green: mean value, blue: minimum value, dots: remnant surface)

A significant proportion of Bükkalja streams run in structurally preformed valleys on some sections (Thesis III).

The asymmetrical nature of the swath profile sections along the main valleys, the structural elements observed on the seismic sections, and the combined interpretation of the borehole and literature data suggest that a significant proportion of valleys were structurally preformed on some sections (*Figure 3*). The structural preformation of the Csincse Creek south of the rhyolite tuff strip, the Geszt Creek and the Száraztó-ér valley are questionable. The formation of the Kígyós Creek can be explained by denudation and erosion processes.

In many cases, the characteristic direction of the valleys and lineament follows the strike of the structural elements in the area, so their statistical analysis is of paramount importance in structural, morphological research (Gábris Gy. 1986b; Centamore, E. et al. 1996; Eyles, N. et al.1997; Ruszkiczay-Rüdiger Zs. et al. 2007, 2009; Radaideh, O. M. A. et al. 2016; Gioia, D. et al. 2018). Therefore, I also performed a directional statistical study of the traditionally digitised valley network, the drainage and valley network determined with a critical source area of 1 km^2 and 0.2 km^2 derived from the digital surface model (DSM) and on the digitally derived lineament network.

Based on the directional statistics of the Bükkalja stream network, it can be stated that the valleys are controlled, mostly running in the NNW–SSE direction. According to my stream order-based study, the valleys larger than second-order also show orientation. These directions coincide with the general slope direction of Bükkalja and the direction of transverse and diagonal faults.

The directional analysis of the stream network also showed that in the case of the valley network generated by applying a critical source area of 1 km^2, the NNW–SSE direction dominates all orders. Based on this, I conclude that valleys of this size, most of them have watercourses, i.e. the stream network has a parallel pattern. While the sections generated by a critical source area of 0.2 km^2 – i.e. the valley network – have a dendritic pattern.

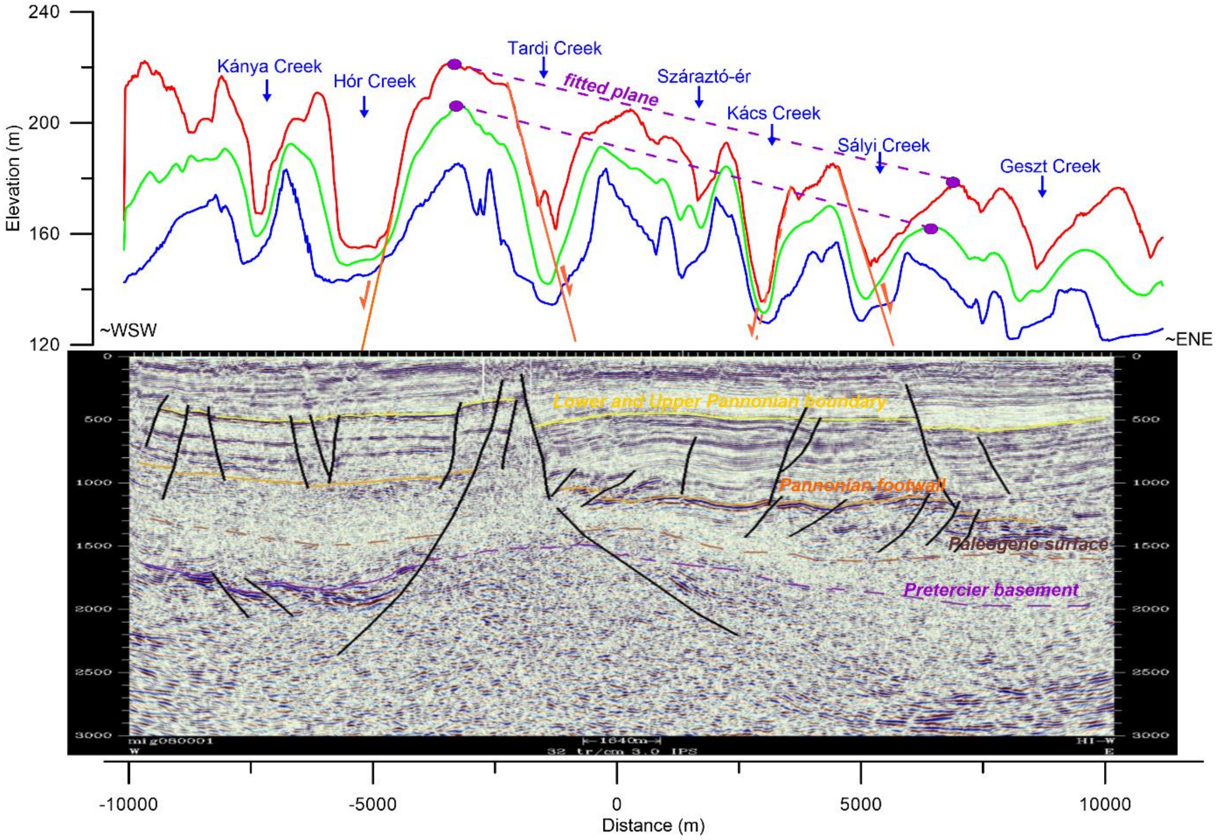

Figure 3. The evaluated seismic section marked HI-W and the swath profile made along it (red: maximum value, green: mean value, blue: minimum value)

I also examined the relationship between the structural elements and the linear elements appearing in the topography (valleys, lineament) locally. In the case of 25 geological outcrops/mining walls/road cuts, I performed microtectonical measurement. Within a radius of 2 km of the observations, I analysed the longitudinal and directional frequencies of the valleys and lineaments. I compared the results with the directional frequency and directional frequency by length of already mapped geological structural elements within this radius and the impact directions measured in the outcrops. This study also confirmed the relationship of valleys and lineaments to geological structural elements.

The NE–SW strike faults may have been active during the Quaternary. Thus, the Quaternary surface development of Bükkalja is determined and modified by young structural movements to this day (Thesis IV).

Change of the river sinuosity and stream gradient may indicate young epeirogenic movements (OUCHI, S. 1985; KELLER, E.A. – PINTER, N. 1996; TIMÁR G. 2003a, 2003b; PETROVSZKI J. – TIMÁR G. 2010; MAHMOOD, S.A. – GLOAGUEN, R. 2012; PETROVSZKI J. et al. 2012; PETROVSZKI J. 2013). Therefore, I calculated the sinuosity and stream gradient of 21 Bükkalja streams. Then, I compared the results with the geological structural elements mapped in the area. Based on these results I concluded that there are neotectonic processes in the area. In the vicinity of 39 faults/fault sections, I found a significant change in meander development (*ratio of change in river sinuosity to the number of streams cut through the geological structural elements*). I calculated an activity ratio for the faults causing the change in river sinuosity. I measured a maximum (1) activity ratio for 23 faults/faults sections, and only 3 faults had the lowest activity ratio (0.33), and 13 faults had a medium (0.5 to 0.75) activity ratio (*Figure 4*).

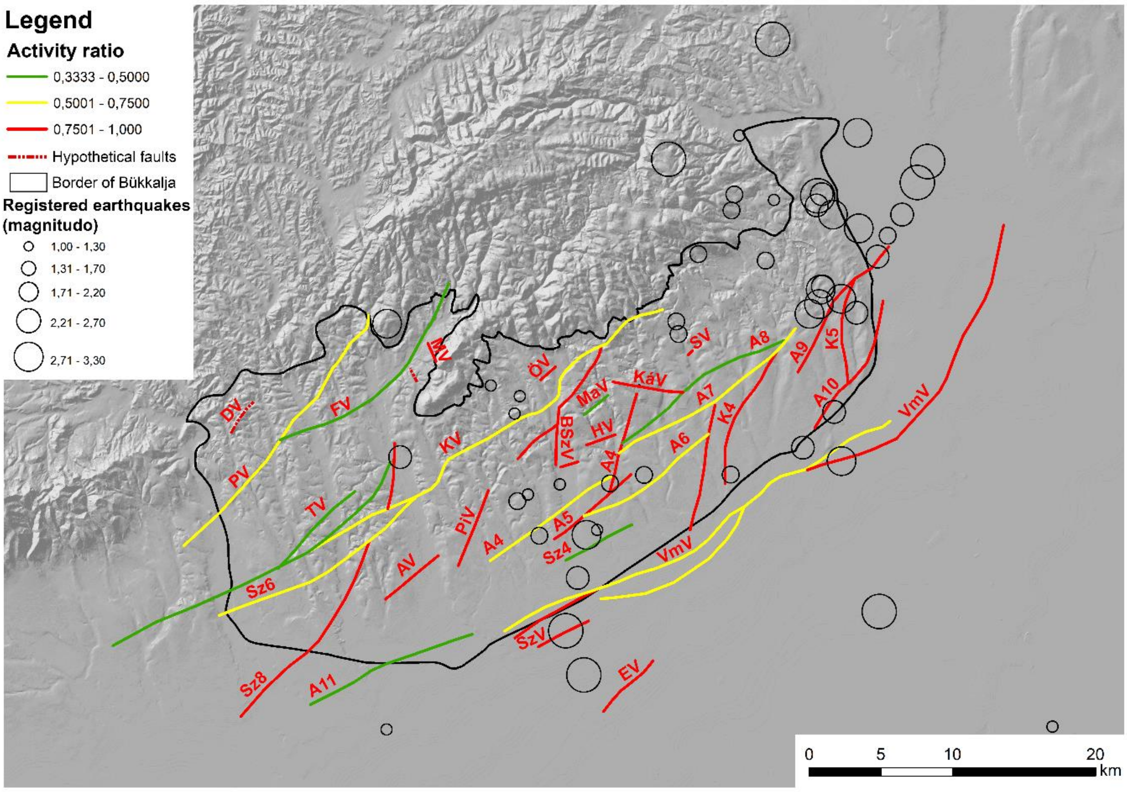

Figure 4. Active faults based on river sinuosity and their activity rate, as well as magnitude of earthquakes in the research area (TÓTH L. et al. 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011; GRÁCZER Z. et al. 2012, 2013, 2014, 2015, 2016, 2017, 2018)
(DV: Dongó-f., PV: Pirittyó-f., FV: Felnémet-f, MV: Mészvölgy-f., TV: Tárkány-f., KV: Kökötő-f., AV: Andornaktálya-f., PiV: Pipis-f., BSzV: Bogács-Szomolya-f., MaV: Mangó-f., HV: Hosszújáró-f., KáV: Kács-f., SV: Sály-f., SzV: Szihalm-f., EV: Egerfarmos-f., VmV: Vatta-Maklár-f.).

Analysing the stream gradient conditions of the main valleys, I identified 123 local maximum values. Thirty-three (33) out of them were related to geological structural elements that can be assessed as active based on the results of river sinuosity analysis, and the location of 4 local maximum values coincide with faults where earthquakes occurred. The existence of stream captures, earthquake data, asymmetric terrace systems identified by swath profile analysis,"local anomalies", and the run-off of faults on the seismic section towards young sediments reflect neotectonic processes. Based on these results, the NE–SW strike faults may have been active during the Quaternary, although with changed kinematics.

I managed to delineate the remnant surfaces of Bükkalja by morphometric and statistical methods performed on a digital elevation model (Thesis V/a - methodological thesis). I successfully further developed the river sinuosity method to detect active geological structural elements (Thesis V/b - methodological thesis).

In my PhD thesis work, I applied numerous "novel" but already known morphometric analytic methods. Due to the characteristics of my research area I further developed some of these methods. I would like to highlight two of them.

Delineation of remnant surfaces:

Among the landforms, the mapping of peaks, ridges, gentle slope segments is paramount, as these areas can be interpreted as former remnant surfaces (peneplain, pediment, terrace). By separating the remnant surfaces and analysing their height, we can conclude the surface development of the area (HEGEDŰS A. 2008, 2011; VÁGÓ J. – HEGEDŰS A. 2011; SZEBERÉNYI J. 2014; PECSMÁNY P. et al. 2020).

Many Hungarian (HEGEDŰS A. 2004; 2005; 2011; TELBISZ T. 2009; SZEBERÉNYI J. 2014) and foreign (WEISS, A. 2001; JENNESS, J. 2006; IWAHASHI, J. – PIKE, R.J. 2007) researchers have recently been involved in the preparation of geomorphological map sketches based on the digital elevation model (DEM), which also includes the selection of remnant surfaces. However, the methods they have developed can be used with good results in areas where the landforms (in their quantifiable properties) are more distinctly separated, and there is less variability within each form. However, in foothill areas, such as the Bükkalja, the landforms gradually pass into each other, and the shape of the landforms is diverse (e.g. very wide and narrow valley bottoms occur next to each other). Therefore, it is difficult to distinguish from each other based on a few morphometric parameters. For this reason, I considered several primary (*slope, curvature*) and complex (*Multiresolution Index of Valley Bottom Flatness, Multiresolution Index of Ridge Top Flatness* [GALLANT, J.C. – DOWLING, T.I. 2003], *Topography Position Index* [WEISS, A. 2001; JENNESS, J. 2006], *Morphometric Features* [WOOD, J. 1996, 2009]) morphometric parameters by combining them into a multi-channel image using the *Composite Bands* module built into ArcGIS. The procedure has been used successfully to analyse satellite images; a composite image (multi-channel image) carry additional information. Then I performed a cluster analysis on the composite file using the ArcGIS *Iso Cluster Unsupervised* module, assuming that on the basis of the common morphometric properties, the remnant surfaces can be grouped. Based on a dendrogram, the optimal number of clusters was 5. After the cluster analysis, the peaks, ridges, gentle slope segments were divided into the third cluster. Reclassifying the resulting raster of the cluster analysis, I delineated the possible remnant surfaces (*Figure 5*).

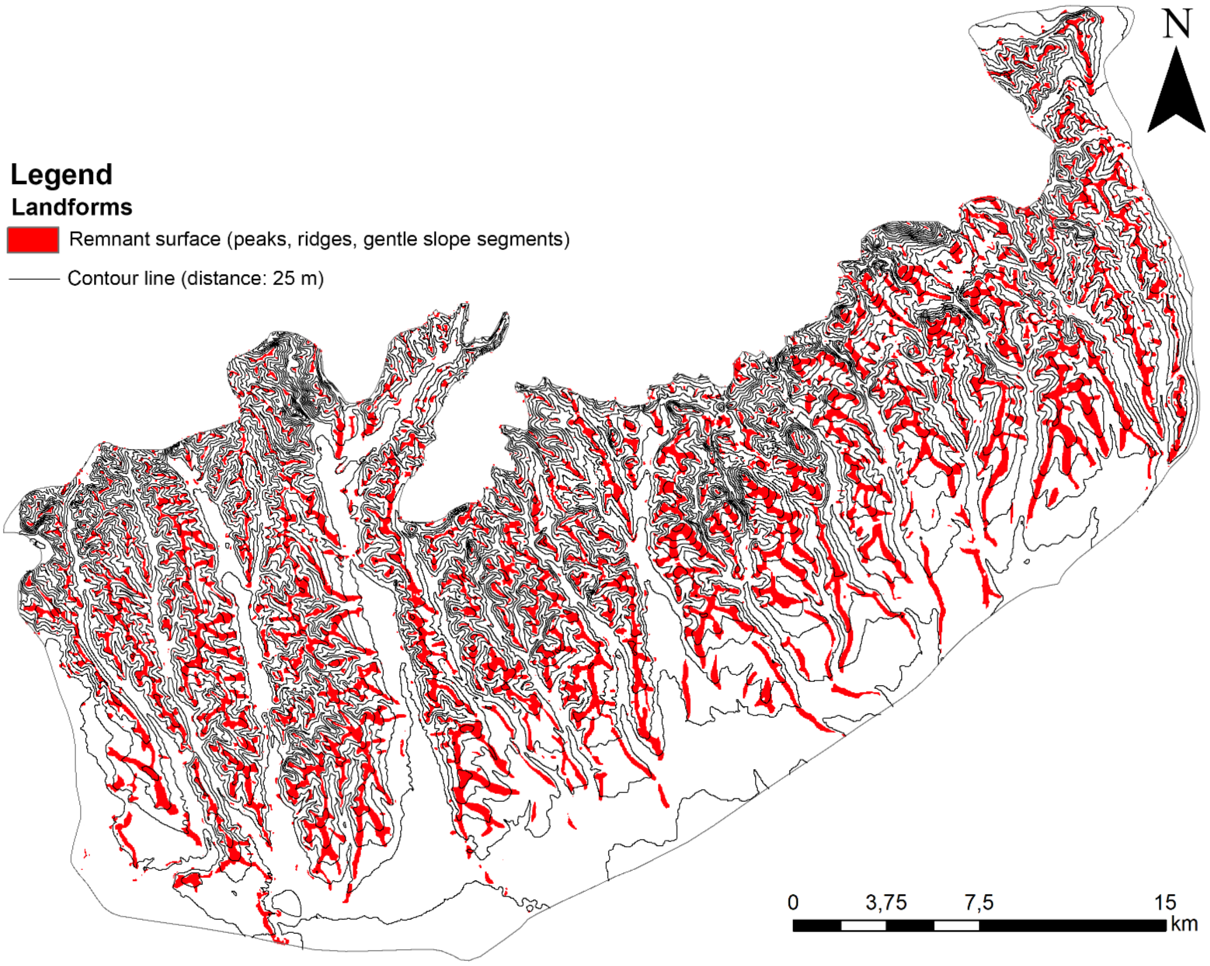

Figure 5. 1: 25 000 scaled remnant surface map of Bükkalja.

River sinuosity analysis, methodological development:

Rivers react relatively quickly to subsidence and/or elevations caused by structural movements, as evidenced by laboratory experiments (Ouchi, S. 1985; Marple, R.T. – Talwani, P. 1993; Twidale, P. 1996, 2004; Timár G. 2003a, 2003b; Petrovszki J. – Timár G. 2010; Petrovszki J. et al. 2012; Petrovszki J. 2013). Many river-related surface-forming processes and forms are used for studying fault activity. Tectonic study of meander development (*river sinuosity analysis*) is very common in the international literature. However, a relevant proportion of these researches dealt only with larger rivers and did not conclude the activity of a particular fault, but of a fault zone in general (Tímár G. 2003a; Petrovkszki J. 2013). In order to be successfully applicable in Bükkalja, I further developed and supplemented the methodology of the river sinuosity for the detection of active structural elements.

The river sinuosity (S) is the quotient of the bed distance along the river (A) and the Euclidean distance (D) (Schumm, S.A. 2005; Petrovszki J. 2013) (*Formula 1*).

$$S = \frac{A}{D} \qquad (1)$$

Formula 1 and *Figure 6* show well that the sinousity is calculated for a certain section, and the value is assigned to the centre+1 point of the section. Different values are obtained by changing the section size (A) (Petrovszki J. – Tímár G. 2010; Petrovszki J. et al. 2012; Petrovszki J. 2013). During the study, I calculated the river sinuosity for 11 section sizes (A = 100, 200, 300, 400, 500, 1000, 1500, 2000, 3000, 4000, 5000 m) and assigned the values to their "center".

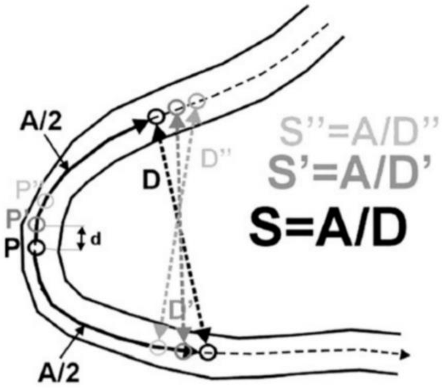

Figure 6. Calculate of river sinuosity (Petrovszki J. – Tímár G. 2010).

Subsequently, the river sinuosity values were plotted like a "heatmap" (*river sinuosity spectrum*), showing each section size (*Figure 7*). In contrast to Petrovszki J. (2013), I also performed the normalisation of the sinuosity values and similarly plotted this. This was necessary, on the one hand, to deal with outliers, so that both small and large changes appear uniformly in the representation, and, on the other hand, to be able to compare streams with each other, since we have to talk about streams of roughly similar magnitude.

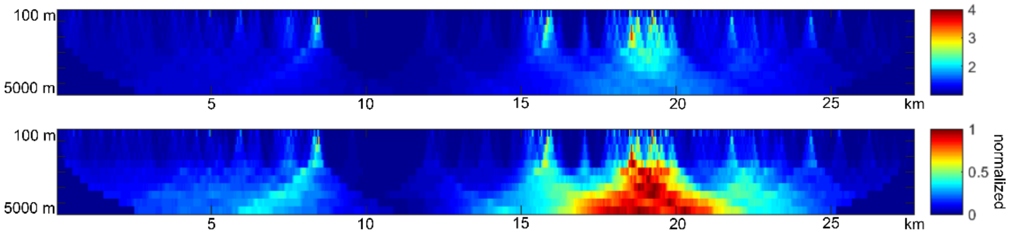

Figure 7. A "heatmap" -like visualization of the river sinuosity of the Tard Creek. The upper is the unscaled river sinuosity; the lower shows the values scaled between 0 and 1.

Representation is key in this case because if the change in river sinuosity appears with both smaller and larger section sizes (*Figure 7 - outline of pyramid-like shapes in the river sinuosity spectrum*), then it is possible that structural reasons also contribute to the change in river sinuosity (PETROVSZKI J. – TIMÁR G. 2010; PETROVSZKI J. et al. 2012). This pyramid-like shape was manifested in both scaled and unscaled dataset.

In addition to the "heatmap" -like representation, we also have the option of displaying river sinuosity on a map. In this representation, the section size that could be related to tectonics first had to be determined. TIMÁR G (2003a) and PETROVSZKI J. (2013), based on LANCASTER, S.T. and BRASS, R.L. (2002), chose the section size where the standard deviation was the highest. However, in my case, this method resulted in a very small section size (400 m), which would have fragmented the visualization too much. Plotting the mean river sinuosity values of a stream with different section sizes as a function of section size in the Descartes-coordinate system, it can be seen that the mean value of the sinuosity suddenly increases as the section sizes increase, then stagnates, then a slight increase in mean value is observed. TIMÁR G. (2003a) also depicted this relationship at the Tisza river, and at the section size where the mean value of the river sinuosity started to "stagnate", it was roughly the same as the optimal section size based on the standard deviation. Therefore, instead of applying the standard deviation, I tried to determine the section size related to active tectonics by examining the mean values. I established this for each stream, and then I considered the most common section size (~ 1000 m) as an indicator of the active structural elements, which I also plotted on a map. After that, I performed smoothing (noise filtering) on the data file of the selected section size in order to be able to eliminate minor errors of technical sources (digitisation errors, georeferencing errors). On the data system, the smoothing was performed in MatLab software using the LOESS function. Subsequently, I also determined the local minimum values (using the findpeaks function) in MatLab for each creek. Local minima were needed to determine the points before or after the change; these points are the sites of significant sinuosity changes. Two hundred eight (208) local minimum values were detected on the sinuosity graphs of the 21 creeks of Bükkalja. I compared these local minima locations with the structural elements marked on the geological maps (LESS GY. et al. [2005] scale: 1: 50 000; PETRIK A. [2016] scale: 1:100 000). One hundred forty-four (144) minima values fell on one side of a fault, this is almost 70% of the total values. I also represented the location of these significant sinuosity changes on a map and determined the distance between each point and the fault closest to it. After that, I performed non-hierarchical cluster analysis on distances in MatLab software. There were also outlier values in the data system, therefore I used the robust City-block (Manhattan) distance method to calculate the distances between objects during group formation. The optimal cluster number was 4 using the SSE (Sum of Squared Errors) method (Steiner F. 1990).

The first and second clusters included points related to significant meander changes closer than ~509 m (508,944 m) to the structural element. The established tolerance can still be considered acceptable in the case of the used data sets, since both the geological maps (Less Gy.et al. 2005; Petrik A. 2016) and the Second Military Survey, as well as its georeferencing (Timár G. et al. 2006), digitisation, can lead to errors. The map of the geological structural elements in the alluvial fan area was made based on seismic profiles and borehole data (Petrik A. 2016); therefore, the location of the faults on the surface might be a few 100 meters away (Fossen, H. 2010).

If both the minima values on either side of the fault fell into these two clusters, I chose the minima value where a major change in sinuosity occurred.

The points that fell into the corresponding cluster were also examined on the sinuosity spectrum. If the change was detectable in the spectrum (i.e., both methods can be detected), it can be assumed that the change in meander was caused by neotectonic processes.

Figure 8 gives a schematic overview of the procedure I have modified and supplemented.

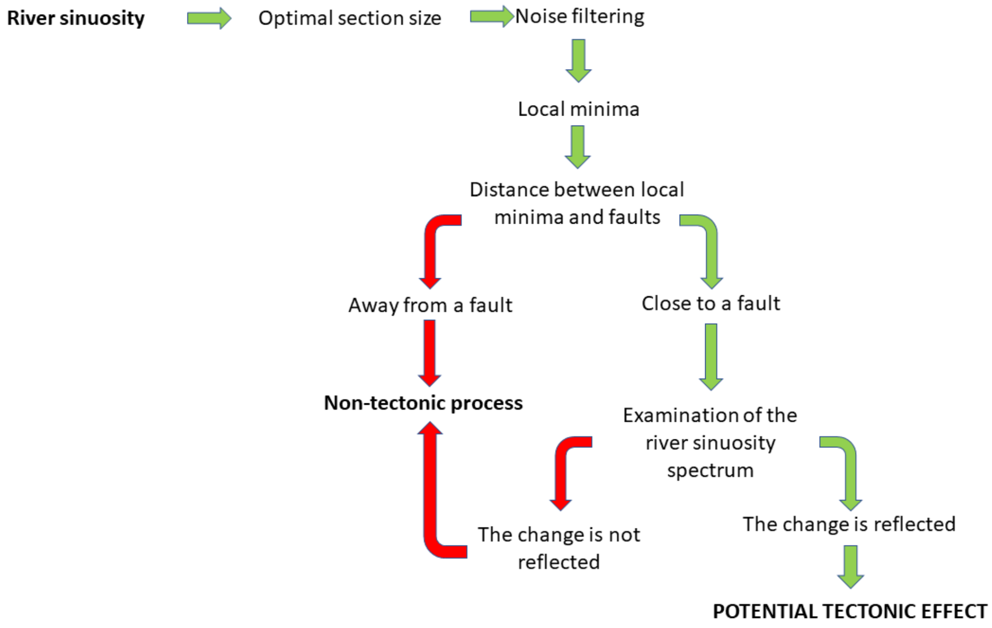

Figure 8. Simplified flowchart of methodological development for the detection of active structural elements.

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