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DEM-based directional statistical examination of linear features: the case study in Bükk Mountains (NE Hungary)

Péter PECSMÁNY[1]*, András HEGEDŰS[2] and János VÁGÓ[3]

Authors' affiliations and addresses:
[1] University of Miskolc Institute of Geography and Geoinformatics, Hungary, 3515 Miskolc Egyetemváros
e-mail: ecopeter@uni-miskolc.hu

[2] University of Miskolc Institute of Geography and Geoinformatics, Hungary, 3515 Miskolc Egyetemváros
e-mail: ecoeged@uni-miskolc.hu

[3] University of Miskolc Institute of Geography and Geoinformatics, Hungary, 3515 Miskolc Egyetemváros
e-mail: ecovago@uni-miskolc.hu

***Correspondence:**
Péter Pecsmány, University of Miskolc Institute of Geography and Geoinformatics, Hungary, 3515 Miskolc Egyetemváros
tel.: +36 49/565-111 1393
e-mail: ecopeter@uni-miskolc.hu

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Abstract

Analysis of linear features such as faults, valleys, interfluves, and escarpments is a commonly used method in structural morphologic and structural geologic research.
The aim of our study was to investigate the relationship between the linear features by directional statistical analysis, and we also examined the applicability of this method in a research area with a complex geological structure. The study area was the Bükk Mountains (NE Hungary) and its two catchment areas. The analysed features (drainage network, lineaments and dominant aspect) were derived from a DEM.
As a result of the research, we found that in the Sajó catchment, the direction of lineaments does not coincide with the direction of the valleys and structural elements, nor the dominant aspect, while in the Tisza watershed, the orientation of the main structural features notably differs from the direction of the other 3 feature sets.
In our opinion, this finding can be explained in three possible ways. The first possibility is that the applied method does not provide reliable results in a geologically complex area. The second explanation is that regional structural processes may affect drainage network evolution and the dominant aspect. The other explanation is that there may have been unknown structural elements in the research area, which affect the recent geomorphological settings and processes.
The results draw attention to the fact that besides the unmapped faults, there might be other factors affecting geomorphological processes (e.g., resistance to denudation of different rock types, microclimate), which have not been taken into account so far. The research was based only on directional statistical examinations; further geological and geophysical analyses are required to prove the existence of these hypothetical morphotectonic features.

Keywords

DEM, drainage, lineament, directional statistical analysis, morphotectonics, Bükk Mountains

Introduction

The GIS-based analysis of geomorphologic linear features (valleys, interfluves, escarpments) is a commonly used method in the structural morphologic and structural geologic studies for identifying the effects of structural elements (faults) on the evolution of recent surface landforms (Martz & Garbrecht, 1992; Ruszkiczay-Rüdiger et al., 2007; Jami et al., 2014; Pecsmány & Hegedűs, 2021).

The study area is the Bükk Mountains (NE Hungary, Fig. 1) and the small Uppony Hills in connection with it. This is the most complicated area of Hungary with respect to its geological structure (Csontos, 1988, 1999; Less et al., 2005; Petrik et al., 2014; Fodor et al., 2020). The area can be divided into two hydrological units, the Sajó- and the Tisza catchment areas. We carried out the directional statistical analysis of linear elements on both the two catchments and on the research area as a whole.

In our previous studies, we examined the southern part of the Bükk Mts. (Pecsmány, 2021; Pecsmány & Hegedűs, 2021; Pecsmány et al., 2021a). In this study, we extended the geomorphologic research to the entire region to examine the applicability of the directional statistical analysis method on an area with complex geological characteristics.

The aim of the study is to investigate the relationship between the valley network, lineaments, dominant aspect and structural features. According to Less et al. (2005), the linear tectonic elements (fault, overthrust, the boundary between different formations, etc.) do not have any connections with the significant valleys, although recent geomorphological-geological studies do not exclude the possibility that the structure affected the evolution of the drainage network (Szalai et al., 2002; Demeter & Szabó, 2009; Pecsmány & Vágó, 2020; Pecsmány et al., 2021b). This research may provide additional information to resolve this discrepancy.

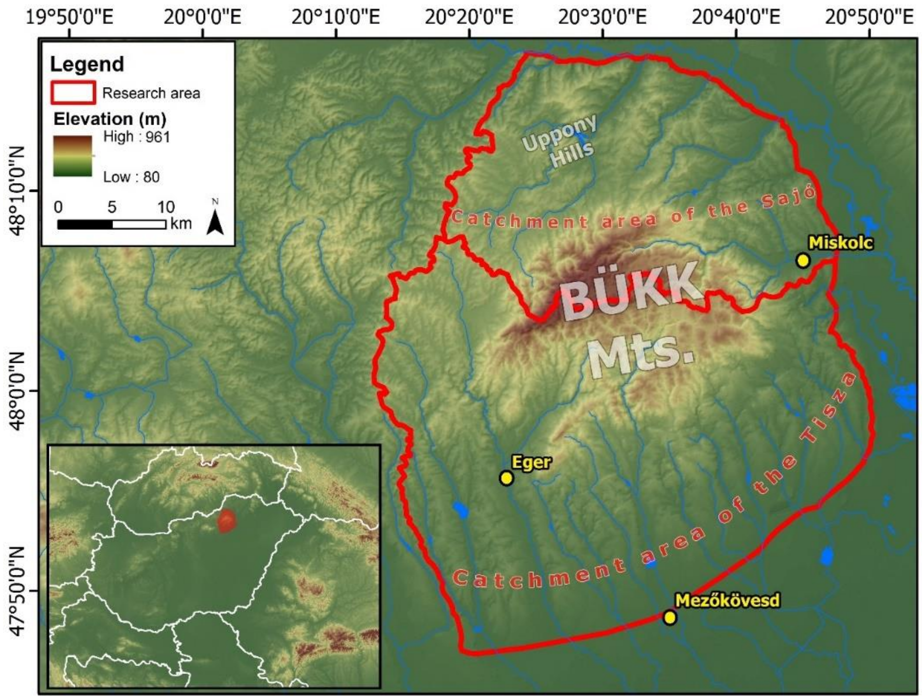

Fig. 1. Location and topography of the research area (source: EUdem).

Materials and Methods

Geographical and geological settings

The Bükk Mountains represent the second-highest mountain range in Hungary, with a maximum height of 961 m (Fig. 1). The central part of the mountain is the homogeneous-looking Bükk Plateau, which is divided by the Garadna Valley. Well-developed karst features, dolines, ranges of dolines, sinkholes, karstic gorges and large-sized caves can be found on the limestone area of the plateau. The foothills of the plateau are dissected by deep erosional valleys, the heads of which incise into the margin of the Bükk Plateau and trend radially outwards from the centre. The directions of the valleys also determine the spatial arrangement of the crests and ridges (Hevesi, 1978, 2002a, 2002b; Less et al., 2005).

The research area can be divided into two main geological-structural units: the Bükk and the Uppony Unit (Fig. 1). The most important structural element of the area is the fault system of the Darnó Deformation Zone (Fig.

2), which indicates the boundary between the two units, which moved to their recent geographic position by a lateral displacement in the Oligocene – Early Miocene (Less et al., 2005; Pospíšil et al., 2014; Gyalog, 2013).

The Palaeo-Mesozoic and partly the Palaeogene rocks that build up the units are different (Less et al., 2005; Hass et al., 2013). In the Uppony Unit, the Palaeozoic formations are dominant, while the Bükk Unit is mostly built up by Mesozoic carbonates. According to the reconstruction of the geological history, the oldest Palaeozoic formations in the Northern-Bükk Mountains and mainly in the Uppony Hills are coarse siliciclastic sediments (Csernelyvölgy and Rágyincsvölgy Sandstone Formation) represent the Late Ordovician Period. From the Ordovician–Silurian boundary, siliceous shale and lydite started to be formed (Tapolcsány Formation). The appearance of basic volcanites in succession indicates volcanic activity in the Middle Devonian; resulting metabasaltic lava rocks with crinoideal limestones and ankeritic-sideritic carbonate rocks, which have been affected by metasomatism (Strázsahegy Formation). The Devonian – Early Carboniferous sedimentation is characterised by the evolution of carbonate platforms; the oldest platform is the thickly bedded, slightly crystalline Uppony Limestone Formation. The metatuffitic limestone (cippolino) (Abod Limestone) with chlorite network and with characteristic cross-foliated, thin-bedded structure is the product of pelagic sedimentation. Following the basic volcanic activity that produced the Zsinnye Metabasalt Formation, platy or bedded, compact, flasered limestone with metasomatised ankerite-siderite and dolomite (Dedevár Limestone Formation) deposited. The Carboniferous limestones of Éleskő Formation are embedded in calcareous clay shale, silty clay shale and fine-grained sandstone matrix. The sedimentation of bedded, in some cases laminar limestone of Lázbérc Formation was occasionally interrupted by the deposition of calcareous sandstone and sandy limestone rocks of the Derennek Formation. The clayey and fine-grained sandy siltstones and sandstones of Zobóhegyese, Szilvásvárad, and Málуinka Formations are covered by Permian sandstone and siltstone (Farkasnyak Sandstone Formation) and black limestones (Nagyvisnyó Limestone Formation) (Less et al., 2005; Gyalog, 2013).

Contrary to the Uppony Hills, The Bükk Mountains structural unit is dominated by Mesozoic carbonates such as Triassic limestone dissected by marl films (Gerennavár Limestone Formation); laminated limestone dissected by sandstones, siltstones and shales (Ablakoskővölgy Formation); thick-bedded–massive limestone of Steinhalm Limestone Formation; dolomite (Hámor Dolomite Formation), and limestone (Fehérkő Limestone Formation, Berva Limestone Formation, Bükkfennsík Limestone Formation, Kisfennsík Limestone Formation, Felsőtárkány Limestone Formation) (Velledits & Péró, 1987; Császár et al., 1997; Haas et al., 2004, 2013; Velledits, 1998, 2000). Due to the Triassic volcanic activity, lava, agglomerate, tuff and ignimbrite dissect the carbonate layers: metaandesite (Szentistvánhegy Metaandesite Formation), metarhyolite (Bagolyhegy Metarhyolite Formation) and metabasalt (Szinva Metabasalt Formation, Létrás Metabasalt Formation), (Szoldán, 1990; Less et al., 2005).

In the Jurassic limestone (Jómarci Limestone Formation), radiolarite (Bányahegy Radiolarite Formation), turbidite (Lökvölgy Formation), shaley siltstone and limestone (Oldalvölgy Formation), Thickly-bedded silicified sandstones (Vaskapu Sandstone Formation), limestone olistostromes in shaley siltstones (Mónosbél Formation), and basalt (Szarvaskő Basalt Formation) deposited (Less et al., 2005; Haas et al. 2011).

Mesozoic rocks that are younger than Late Jurassic are not known from the Bükk Mountains, except the Upper Cretaceous Nekézseny Conglomerate Formation, which is made up of the thickly-bedded conglomerate with sandstone and clay marl intercalations (Brezsnyánszky & Haas, 1984; Less et al., 2005).

The mountain range is surrounded by a large foothill area which is built up by terrestrial Eocene sandy gravel (Kosd Formation), marine and limnic sediments (Szépvölgy Limestone Formation), Oligocene marl (Buda Marl Formation), clay (Tard Clay Formation, Kiscell Clay Formation) and silty clay marl with poorly preserved mollusc fauna (Eger Formation), (Báldi & Sztanó, 2000a, 2000b; Less et al., 2005).

Most of the Neogene sediments are Miocene pyroclastites (Harsány Rhyolite Lapilli Tuff Formation, Tar Dacite Lapilli Tuff Formation, Dubicsány Adesite Formation, Bogács Dacite Lapilli Tuff Formation, Tihamér Rhyolite Lapilli Tuff Formation) (Less et al., 2005, Lukács et al., 2010, 2018, 2022), terrestrial, fluvial and shallow marine clay, sand, gravel and fine-grained silt, clay and clay marl (Salgótárján Lignite Formation, Egyházasgerge Formation, Garáb Schlier Formation, Kozárd Formation, Sajóvölgy Formation, Zagyva Formation) (Less et al., 2005).

The bulk of the overlying Quaternary deposits are fluvial-alluvial deposits, terrace sediments, proluvial debris transported by short torrential flows, slope debris moved by solifluction, travertine and loess (Less et al., 2005; Gyalog, 2013) (Fig. 2).

The structure of the Bükk Mountains can be characterised by folding, which has been modified by fault patterns (Csontos, 1988, 1999; Less et al., 2005). The entire research area and its hydrological subunits (Sajó- and Tisza catchments) are dissected by a fracture system (Fig. 2). However, due to the younger cover sediments, these structural elements cannot be followed over longer distances. During a rifting phase (17.5–14.5 Ma) of the Carpathian Basin, several NW–SE trending troughs and a few strike-slip related basins were developed in a NE–SW extensional stress field. In the late Mid-Miocene, several roughly NE–SW trending depressions were formed, such as the Vatta–Maklár Trough and the Felsőtárkány Basin. The research area is dominated by N–S to NE–SW trending normal and/or strike-slip faults (Fig. 2), the latter are sub-parallel to the Mid-Hungarian Shear Zone (Tari, 1988; Petrik et al., 2014). The geological structural elements were digitised from geological maps (Less et al., 2004, 2005; Fodor et al., 2005; Németh, 2005; Petrik, 2016).

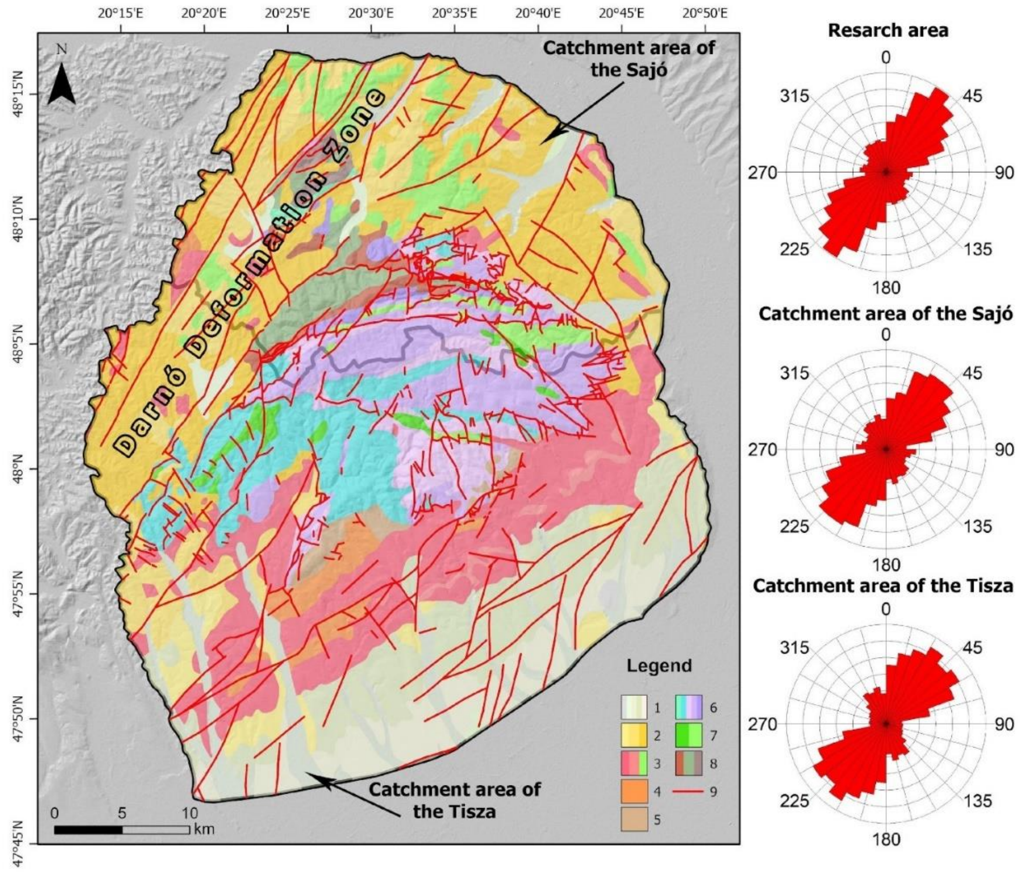

Fig. 2. Geological map of structural elements of the research area and the rose diagram of the direction of faults 1: Quaternary sediments, 2: Miocene sediments, 3: Miocene volcanoclastics, 4: Oligocene sediments, 5: Eocene sediments, 6: Mesozoic sediments, 7: Mesozoic metavolcanics, 8: Palaeozoic sediments and metavolcanics (Gyalog, 2013), 9: major faults (Less et al., 2004, 2005; Fodor et al. 2005; Németh, 2005; Petrik, 2016).

Derivation of drainage network

In our research, we used a derived drainage network which was created from a 25 m spatial resolution digital elevation model (DEM). This network is a theoretical drainage network, which - according to our previous research - highly correlates to the valleys of real streams (Pecsmány, 2021; Pecsmány et al., 2021a).

The steps of the process were done by ArcGIS Pro software, applying the “Fill”, “Flow Direction”, and “Flow Accumulation” tools. Only those DEM pixels were considered as parts of drainage, which have a critical source area of a minimum of 1 km^2. Then we vectorised these pixels; the resulting polyline network draws the drainage network. The stream sections’ Strahler-orders (Strahler, 1957) were also defined by the ArcGIS “Stream Order” tool (Fig. 3).

Since our goal was to examine and compare the orientation of the stream network to the structural elements’ direction, the smaller oscillations of short valley sections were smoothed by the Demeter & Szabó (2009) method, applying the ArcGIS “Generalization” tool. Using the breakpoints (vertices) of the streams, we split each polyline into straight-line segments. Based on the coordinates of vertices, we calculated the length and direction of the straight stream segments by applying the RockWorks 16 software. The direction frequencies by length were plotted on rose diagrams with 10-degree scale intervals using RockWorks 16 “Creating Rose Diagrams from Endpoint Data” tool. The rose diagrams were analysed by traditional visual interpreting methods (Ricchetti & Palombella, 2007; Romshoo et al., 2012; Radaideh et al., 2016; Petrik & Jordán, 2017; Gioia et al., 2018; Suha et al., 2021).

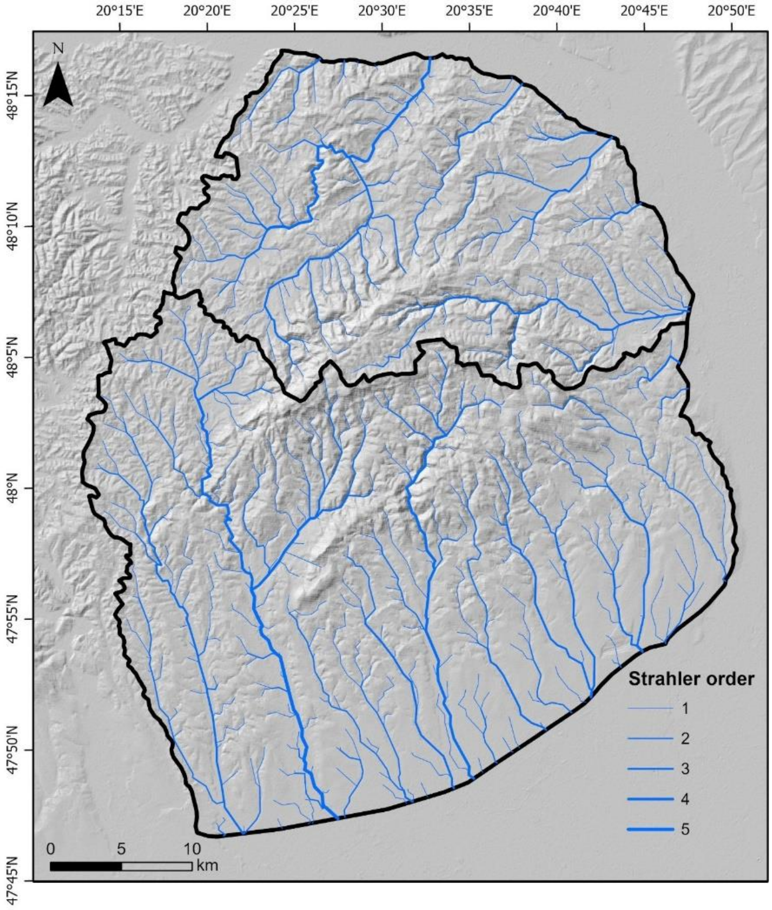

Fig. 3. Derived drainage network of the research area.

Mapping of lineament network

Lineaments are linear morphologic features on the surface, such as faults, valleys, escarpments, and cuestas (Twiss & Moores, 2002). Visual interpretation of satellite images (Leech et al., 2003; Unger & Timár, 2005; Al-Rawashdeh et al., 2006), digital elevation models and their derivatives (Radaideh et al., 2016; Petrik & Jordán, 2017; Suha et al., 2021), or their combined use (Chaabouni et al., 2012; Akinluyi et al., 2018; Mukhopadhyay et al., 2019) is a usually applied method for identifying lineament networks, although it is a subjective technique. Striving for objectivity, in our research, we used the method published by Al-Obeidat et al. (2016) for mapping lineaments: a Canny edge detection algorithm was applied on a DEM derivative hillshade image. A multidirectional hillshade was created in ArcGIS Pro 2.8 software, and then the edge detection algorithm was run on it in MatLab R2017b software. The result raster was vectorised in ArcGIS Pro. Then the polylines were smoothed using ArcGIS “Generalization” tool. We examined only the lineaments longer than 500 m (Fig. 4) because these are more likely associated with fault lines than shorter ones (Pecsmany et al., 2021a). Direction frequencies by the length of lineaments were plotted on rose diagrams with 10-degree scale intervals using RockWorks 16.

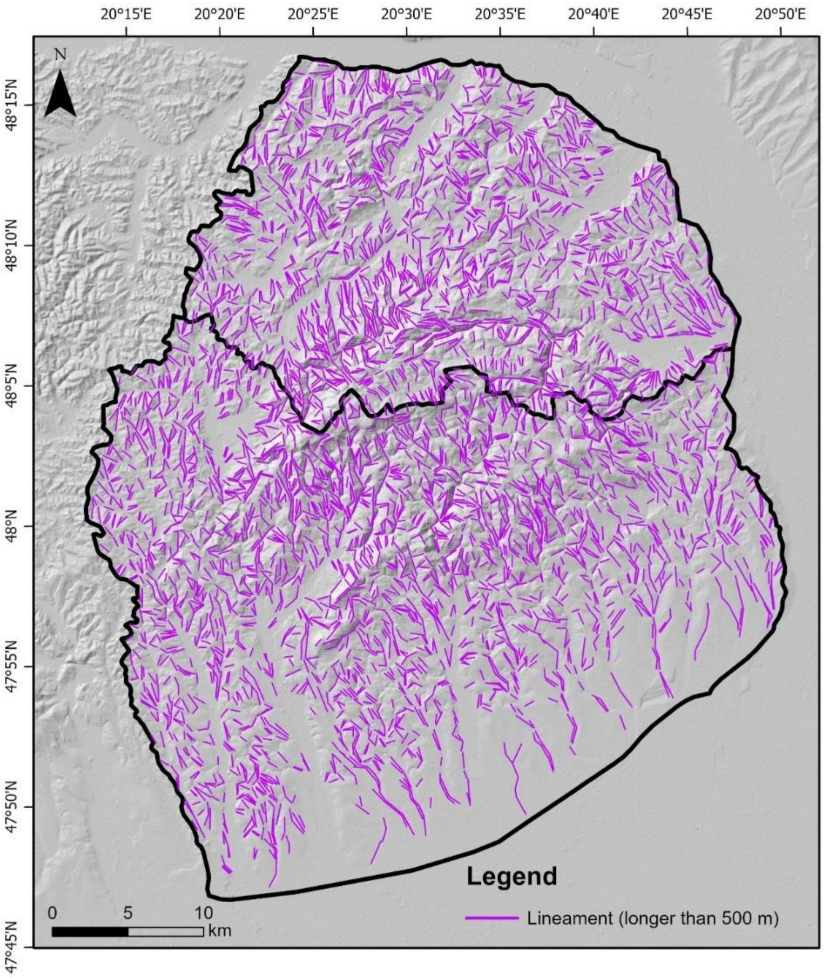

Fig. 4. Lineament network of the research area.

Determination of the dominant aspect

The direction of slopes (aspect) of a given area determines the general direction of waterflows. Both subdivisions of the research area, namely the Tisza and Sajó catchments, are highly dissected. Therefore, the single-aspect tool cannot provide reliable results for the dominant aspect. In order to derive that, we fitted a 1st order trend (ArcGIS Pro - trend interpolation tool) on the DEM's local maximum elevations. The local maximum points were identified by applying the Telbisz (2009) method. Then the slope direction of the trend was calculated as the dominant aspect.

Results

The directional statistical analysis of structural elements, drainage (valley) network, lineaments and dominant aspect of the entire research area and its two catchments gave the following results:

- The faults on the entire area and on both its catchments are striking in the NE-SW direction, although the variation is bigger in the case of the Tisza catchment area than in the Sajó's. There is a slight secondary direction to the NNW-SSE in the Tisza catchment (Fig. 2).
- In the Sajó catchment area, the valley network has no main direction, although there are 3 equally frequent directions to the NW-SE, NE-SW and E-W. The NW-SE direction originates from the 1st order valleys, the NE-SW direction is specific for the 2nd, 3rd and 4th order valleys, while the E-W direction belongs to the 3rd order valleys (Fig. 5).
- In the case of Tisza, the dominant direction is NNW-SSE in the entire catchment and in all valley orders.
- Analysing the entire research area, the main direction is similar to the Tisza catchment, NNE-SSW. However, in the case of 4th order valleys, there are two equally frequent secondary directions: N-S and NE-SW (Fig. 5).

- The main direction of lineaments is NNW-SSE on the entire area and on both subunits, although the divergence is bigger in the Sajó catchment, and there is an N-S secondary direction as well (Fig. 6).
- The dominant aspect of the research area is SE (143,12°). In the Sajó catchment, it is NE (37,72°), and in the Tisza catchment, it is SE (151,31°).

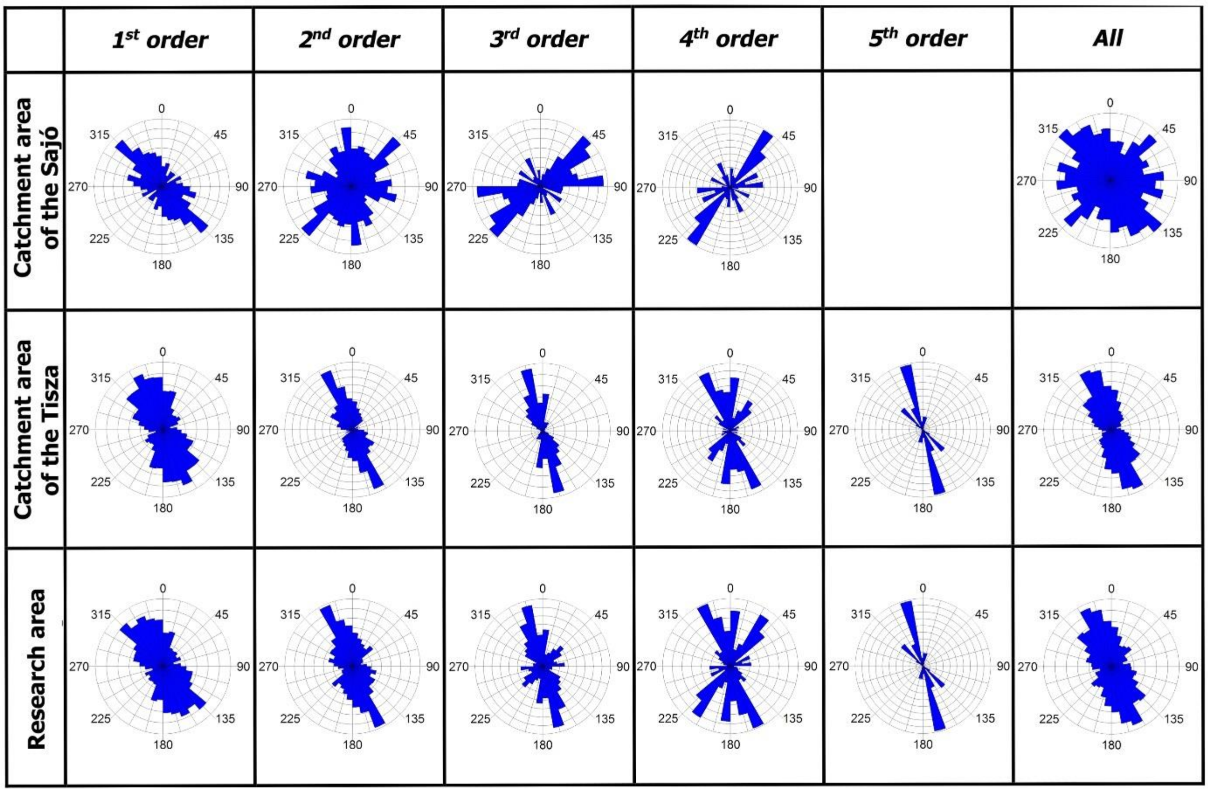

Fig. 5. Drainage network direction of the Bükk area.

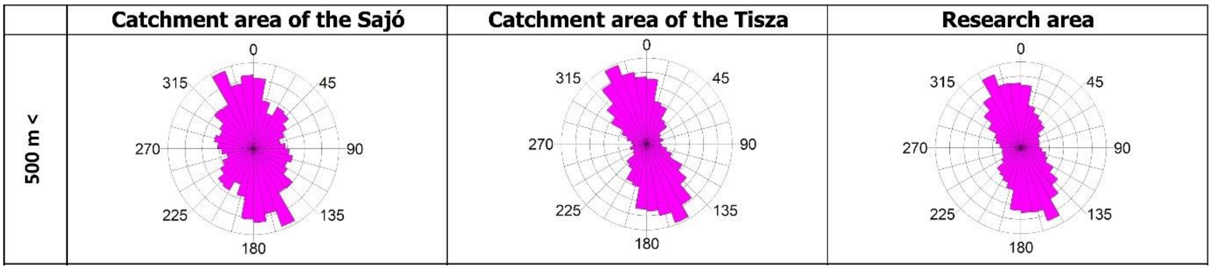

Fig. 6. Lineament network directions of the Bükk area.

Conclusion

In highly tectonised areas, the analysis of drainage characteristics and the linear features' effect on the evolution of landforms is a well-known method to identify faults (e.g. Centamore et al., 1996; Al-Rawashdeh et al., 2006; Ruszkiczay-Rüdiger et al., 2007, 2009; Siddiqui et al., 2015; Radaideh et al., 2016). In Fig. 7, it can be seen that in the Sajó catchment, the direction of lineaments does not coincide with the direction of the valleys and the structural elements, nor the dominant aspect. In the Tisza subunit, the orientation of the main structural features notably differs from the direction of the other 3 factors.

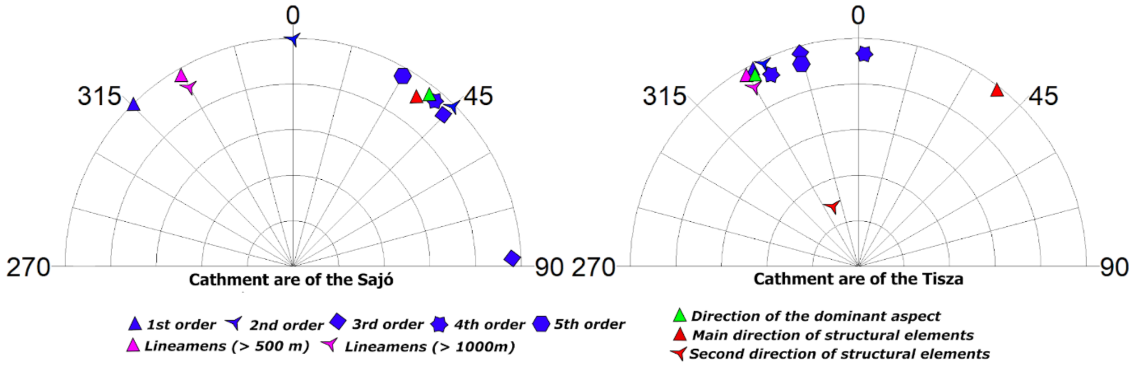

Fig. 7. Direction of the linear elements.

This result can be explained in three possible ways: The first explanation is that the applied method does not provide reliable results on areas with complex geological settings. The second explanation is that the regional structural processes may affect the evolution of the drainage network and the dominant aspect. The third explanation is that there may have been unknown structural elements that can affect the recent geomorphological settings and processes in the research area. The results of recent studies (Szalai et al., 2002; Demeter & Szabó, 2009; Pecsmány & Vágó, 2020; Pecsmány et al., 2021b) assume that there may have been diagonal and cross faults, striking perpendicular to the main faults. In our opinion, our results support those findings. In the Sajó area, the NNW-SEE direction of lineaments may be caused by unmapped geological structures, while in the Tisza area, the direction of main valleys may be related to these faults. Our results draw attention to the fact that there might be other factors (e.g., resistance to denudation of different rock types, microclimate) that affect the geomorphological processes, which have not been taken into account so far. Our recent research was based only on directional statistical examinations; further geological and geophysical analyses are required to prove the existence of these hypothetical morphotectonic features.

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