Geometry and topology of Polish Outer Carpathian digital elevation model interpreted lineament network in context of regional tectonics

Maciej Kania[1], Mateusz Szczęch[1]

[1]Jagiellonian University in Kraków, Faculty of Geography and Geology, Institute of Geological Sciences, Gronostajowa 3a, 30-863 Kraków, Poland

Correspondence to: Maciej Kania (maciej.kania@uj.edu.pl)

Abstract. The Polish part of the Western Outer Carpathians lineament network was analysed based on the GMTED2010 digital elevation model. Lineaments were identified in the visual screening of the hillshade model. To the best of our knowledge, no one has studied the geometrical properties of the network with relation to the topological ones. The NetworkGT QGIS toolbox was applied to identify the nodes and branches of the network, as well as to calculate the topology parameters. Our aim was to find differences between the western and eastern parts of the Western Outer Carpathians; therefore, the analyses were carried out in six sectors chosen based on the geographical subdivision in the geological context: three in the north, mainly the Silesian unit; and three in the south, mainly the Magura unit. We found general agreement of the identified network with the photolineament map; however, some of the photolineaments are not confirmed by digital elevation model (DEM). We found that the topological parameters of the networks change from west to east, but not from north to south. There are areas of increased interconnectivity, especially the Nowy Sącz Basin, where the lineament network may reflect a complicated system of cross-cutting deep-rooted fault zones in the basement.

1. Introduction

Remote sensing imagery is an important source of data in regional tectonics, and its importance has been growing in recent years. Since the 1970s, there have been multispectral satellite photos of the Earth surface applied mainly in mineral mapping (e.g. van der Meer et al., 2012), as well as in tectonic studies (e.g. Leech et al., 2003). The Shuttle Radar Topography Mission (SRTM) resulted in the first remote sensing digital elevation model of most of the continental surface of the planet, with immense potential for application in geology (Yang et al., 2011). Then, new superior resolution and quality models were created on both the global (satellite) and local scale (mainly airborne LiDAR scanning). Digital elevation models are especially useful in areas with lush vegetation. The application of LiDAR in the Carpathians' flysch-type mountains in geological interpretations was shown, for example, in Kania and Szczęch (2022).

Our previous study (Kania and Szczęch, 2020), based on the interpretation of the model augmented with field geological mapping (Szczęch and Cieszkowski, 2021), showed how a lineament network can be interpreted in topological and geometrical terms. This paper presents to up-scale DEM-based geometrical and topological analyses of a regional scale lineament network to find how this is reflected in the tectonic structure of the Western Carpathians. Previous studies of the Carpathian lineaments were mainly focused on lineament strikes distribution (e.g. Doktór and Graniczny, 1982, 1983; Doktór et al., 1985, 1990, 2002; Bażyński et al., 1986; Graniczny and Mizerski, 2003); therefore, we decided to add an interconnectivity aspect in terms of the topological parameters (Valentini et al., 2007; Sanderson and Nixon, 2015; Thiele et al., 2016), as a way of better understanding the structural problems. Our aim was to find, if and how the deep-rooted lineaments (fault zones) are influencing lineament network pattern on the surface. Our hypothesis was that these deep-rooted features are expressed in the network independently of the contemporary observed Carpathian nappes stacked structure. Most of the Carpathian-related studies are geographically organised in mountain arc parallel belts, reflecting the main tectonostratigraphic units, now forming nappes and being sedimentary basins during the Carpathian flysch depositions. We decided to keep this subdivision, although combining this with physiographical subdivisions into sectors with borders perpendicular to the Carpathian belt.

2. Previous research on the Polish Outer Carpathian lineaments

The fact that dislocation lines perpendicular to the Carpathian arc are related to the deep basement, and are significantly older than the Carpathians themselves, was postulated even before the remote sensing era (Teisseyre, 1907). The first modern attempts to interpret lineaments in the Polish Carpathians were based on the Landsat MSS imagery and Heat Capacity Mapping Mission satellite, and reported together with data from the whole territory of Poland on a photogeological map at 1:1 000 000 scale (; Bażyński et al., 1986; Graniczny and Mizerski, 2003). The main lineament systems of the Western Carpathians in the context of structural geology were shown by Doktór and Graniczny (1983) and Doktór et al. (1985). The results of satellite imagery lineament detections were then correlated with geophysical data proving relationships between the surface, neotectonic processes and deep Carpathian basement structure (Motyl-Rakowska and Ślączka, 1984; Doktór et al., 1990). Airborne radar data were applied in tectonic analysis of the Carpathians, resulting in 17 000 short lineaments that were the basis of the lineament density map (Doktór et al., 2002). The interpretation of SRTM hillshading visualisation was performed by Chodyń (2004) on the limited area in Beskid Wyspowy Mts. Comparison of Landsat MSS and SRTM data by Ozimkowski (2008) showed that whilst the main faults can be related to lineaments, there are still numerous lineaments without geological explanation. In the last few years LiDAR high resolution digital elevation models became available for the Polish Carpathians allowing more regional-scale lineament network analysis and their interpretation as fault-related features (Kania and Szczęch, 2020, 2022; Szczęch and Cieszkowski, 2021; Barmuta et al., 2021; Sikora, 2022)

3. Study area

The choice of the study area was based on the physiogeographical subdivision of Poland by Solon et al. (2018). The following macroregions were selected: the Western Beskidy Foothills, Western Beskidy Mts., Orawa–Podhale Basin, Mid-Beskidy Foothills and Mid-Beskidy Mts (Fig. 1). These five regions, with a total area of 17 437 km^2, cover most of the Polish part of the Outer Carpathians, excluding a small part of the Eastern Outer Carpathians located in Poland.

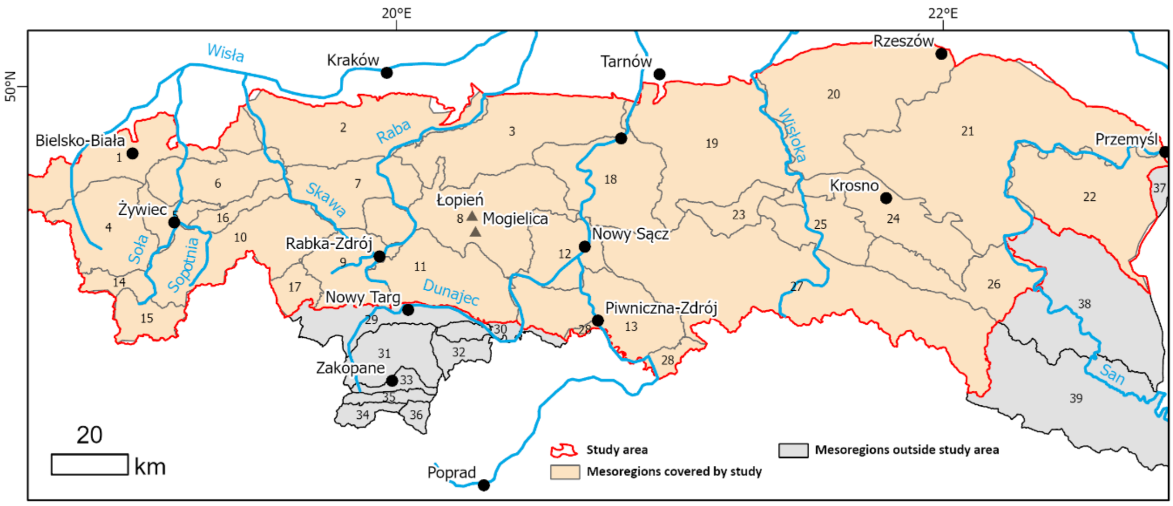

Fig. 1. Physiogeographical subdivision of the study area and adjancted parts of the Polish Carpathians based on Solon et al. (2018). Mesoregions covered by study: 1 – Silesia Foothills, 2 – Wieliczka Foothills, 3 – Wiśnicz Foothills, 4 – Silesian Beskid Mts, 5 – Żywiec Basin, 6 – Mały Beskid Mts, 7 – Makowski Beskid,

8 – Wyspowy Beskid, 9 – Orawa-Jordanów Foothills, 10 – Żywiec-Orawa Beskid Mts, 11 – Gorce Mts, 12 – Sącz Basin, 13 – Sącz Beskid Mts, 14 – Koniaków Intermontane Region, 15 – Żywiec-Kysuce Beskid Mts, 16 – Pewel-Krzeczów Ranges, 17 – Orawa Interfluve, 18 – Rożnów Foothills, 19 – Cięzkowice Foothills, 20 – Strzyżów Foothills, 21 – Dynów Foothills, 22 – Przemyśl Foothills, 23 – Gorlice Basin, 24 – Jasło-Krosno Basin, 25 – Jasło Foothills, 26 – Bukowiec Foothills, 27 – Low Beskid Mts, 28 – Poprad Foothills; mesoregions outside the study area: 29 – Orawa-Nowy Targ Basin, 30 – Pieniny Mts, 31 – Fore-Tatra Foothills, 32 – Magura Spiska Mts, 33 – Sub-Tatra Depression, 34 – Western Tatra Mts, 35 – Reglowe Tatra Mts, 36 – High Tatra Mts, 37 – Hermanowice Submontane Region, 38 – Sanocko-Turczańskie Mts, 39 – Bieszczady Mts.

3.1 Geological setting of the study area

The research area is located in the Polish sector of the Western Outer Carpathians (Mahel', 1974; Książkiewicz, 1977; Ślączka et al., 2006; Fig. 2). It contacts tectonically with the Pieniny Klippen Belt from the south, which is a border between the Outer and the Central Carpathians (Książkiewicz, 1977; Plašienka, 2018; Golonka et al., 2019, 2021). The basement under the Western Outer Carpathians is formed of two blocks: Brunovistulicum and Małopolska Massif, which are separated by major tectonic zone: Kraków – Lubliniec Fault (Fig. 2B) Żaba, 1999; Żelaźniewicz, 2011), cut by numerous other deep rooted lineaments (Doktór, 1985). The Outer Carpathians are built mainly of flysch deposits, whose thickness is approximately 6 000 m, and thus they are also referred to as the Flysch Carpathians (Książkiewicz, 1977; Golonka et al., 2005, 2021; Ślączka et al., 2006;. These deposits are Late Jurassic–Early Miocene in age and are mainly deep-sea sediments deposited by the gravity flow in the several sedimentary basins of the Northern Tethys, separated by ridges (Książkiewicz, 1977; Golonka et al., 2005, 2021; Ślączka et al., 2006). The thrust of the Central Carpathians block to the north on the European Platform blocks — the Brunovistulicum and Małopolska Massif (Żaba, 1999) — led to the forming of the synorogenic stage accretionary prism. The sediments deposited in the basins were folded and thrusted one upon another, creating the sequence of the nappes in the Miocene. Going from the south there are the Magura Nappe, Dukla Nappe, Fore–Magura group of nappes, Silesian Nappe, Sub-Silesian Nappe and Skole Nappe (Mahel', 1974; Książkiewicz, 1977; Golonka et al., 2005, 2019; Ślączka et al., 2006). The deposits of the Outer Carpathians are overthrust on the Miocene molasses filling the Carpathian Foredeep, which was deposited on the front of the Outer Carpathian orogenic belt thrusting over the North European Platform (Ślączka et al., 2006; Oszczypko, 2006).

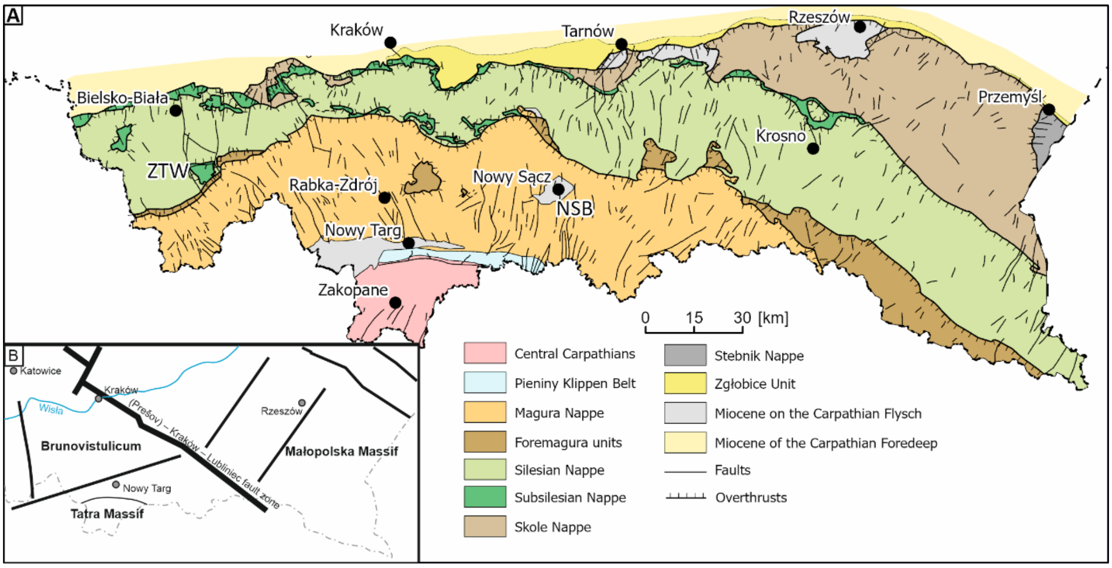

Fig. 2. A: Generalised geological map of the Polish part of the Carpathians based on Cieszkowski et al., 2017 and cited there, faults after Lexa et al., 2000. B: .Main tectonic units under the Carpathians, after Żelaźniewicz et al., 2011.

3.2 Analysis of the sectors

We used the morphometry subdivision of Poland (Solon et al., 2018) to define the area, based on the subprovinces of the Western Outer Carpathians in the area of Poland and a small band of Northern Subcarpathia subprovince to the border of the Carpathians in the geological meaning (Carpathian overthrust on the Foredeep sediments), according to Lexa et al. (2000). The subdivision of the outer Carpathian belt is mostly used in the geology basis on the tectonostratigraphic units (nappes). This subdivision, however, does not allow differences in lineament systems parallel to the belt to be caught. The newly proposed morphostructural subdivision of the Western Carpathians (Minár et al., 2011) is another approach that compiles geological and morphological features. The Polish part of the Western Carpathians is subdivided into the following subregions (number according to the paper cited): (3f) Moravian–Silesian Beskid, (3a) Beskid Żywiecki–Gorce, (3b) Beskid Sądecki–Levočské vrchy, (5a) Beskid Wyspowy, (5b) Low Beskid and (6) North Foreland. The last subregion spans all the length of the northern Carpathian boundary between the Orava and San rivers. We decided to compile the geological subdivision with the morphological one (Solon et al., 2018), which also comprises a subdivision of the outermost units, into five sectors (Fig. 3, Tab. 1). The only change was including Mount Ciecień in Beskid Wyspowy into the Central Silesian sectors, as this massif, unlike all other Beskid Wyspowy culminations is built of Silesian series deposits (Burtan, 1974).

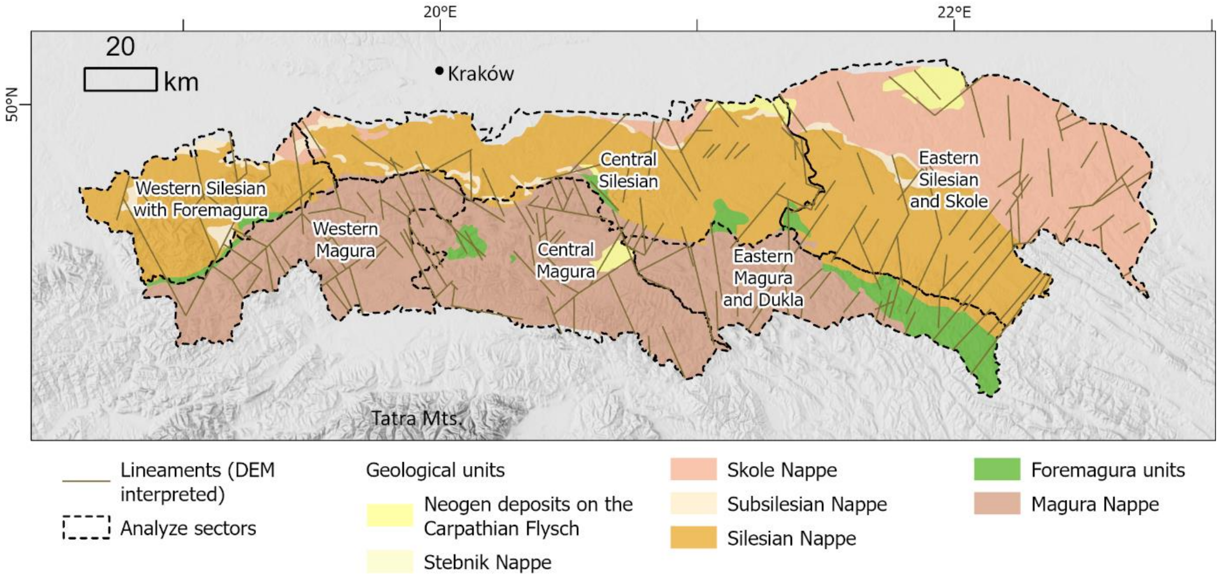

Fig. 3. Sectors defined based on the physiogeographical (Solon et al., 2018) and tectonic subdivisions (Golonka et al., 2021) of the study area (Western Outer Carpathians in Poland).

Tab. 1. Analyse sectors

Analyse sectors name;	**Symbol**	**Mesoregions covered according to** Solon et al., 2018
Western Silesian with Foremagura	WS	Silesian Beskid Mts., Żywiec Basin, Silesia Foothils, Mały Beskid Mts.
Central Silesian	CS	Wieliczka Foothils, Wiśnicz Foothils, Beskid Wyspowy Mts – only the Ciecień ridge, Rożnów Foothils, Ciężkowice Foothils, Gorlice Basin
Eastern Silesian and Skole	ES	Przemyśl Foothils, Jasło-Krosno Basin, Strzyżów Foothills, Dynów Foothils, Jasło Foothils, Bukowiec Foothills
Western Magura	WM	Orawa-Jordanów Foothills, Orawa Interfluve, Koniaków Intermontane Region, Żywiec-Kysuce Beski, Pewel-Krzeczów Ranges, Makowski Beskid, Żywiec-Orawa Beskid
Central Magura	CM	Sącz Beskid Mts., Sącz Basin, Wyspowy Beskid (without Ciecień Ridge), Gorce Mts.
Eastern Magura and Dukla	EM	Low Beskid Mts.

4. Digital elevation model

The Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010; see Danielson, 2011) 7.5 arc-second product was chosen as a work base. The model is a compilation of different raster-based elevation sources, based mainly on SRTM digital terrain elevation data. The resolution is ca. 0.0021°/pixel, which means ca. 233 m/pixel.

This was found to be sufficient, while the working scale during lineament detection was 1:150 000. As the shading azimuth can influence the results, the working imagery was multidirectional hillshade (Nagi, 2022.

5. Methods

5.1 Multiple cover lineament detection

The manual method of lineament extraction was applied for two reasons. First, it is the simplest, low cost and widely used method. The second reason is that it creates a basis for further work, based on automated extraction. However, the method used is prone to some operator-related bias (Scheiber et al., 2015; Ehlen, 2004). Thus, to reduce this bias the lineaments were extracted by two operators working independently, in three sessions, separated by intervals of several months. After each session, the results were analysed and a network of common features was created. Lineaments marked by both operators were merged into single feature. Lineaments marked by only one operator were removed. The last stage was creating a concise network of lineaments based on the results of the three sessions.

5.2 Network analysis

A network can be described by scale-independent topological characteristics, based on the case of a line network on graph theory. The network (graph) is formed by nodes (end or intersection points) connected by lines (Sanderson and Nixon, 2015; Mukherjee, 2019). The line can be formed by one or more branches connected by nodes. The node can be isolated (I type), an embranchment (Y type) or an intersection (X type), where the latter two types are connecting nodes. Thus, the branch can connect two I type nodes (I–I branch), isolated and connecting nodes (I–C branch, which can be I–Y or I–X) and two connecting nodes (C–C branch, which can be X–X, X–Y or Y–Y). The proportion of nodes and branch types can be analysed as tertiary systems that characterise the properties of the network, especially its interconnectivity (Procter and Sanderson, 2018; Sanderson and Nixon, 2015; Sanderson et al., 2018).

The spatial variation of the topological parameters of the network was analysed with the following aspects: (1) regular, in a 5x5 km grid; and (2) within sectors based on the mesoregions of physiogeographical subdivision, according to Solon et al. (2018) and the main tectonic units (Fig. 3 Tab. 1).

The NetworkGT Qgis toolbox (Nyberg et al., 2018) was used as a tool in the topological analyses. The lineament network was checked and repaired with NetworkGT tools. An additional stage was the manual correction of some features to eliminate all non-defined types of nodes, as well as some extremely short (ca. 500 m or shorter) features. The topological parameters were analysed in three modes: the whole network; the sectors defined; and in a regular, 5x5 km grid with 10 km search radius.

The Rayleigh test of semicircular distribution test was performed with the EZ-ROSE spreadsheet (Baas, 2000), and circular statistics were calculated with the SciPy stats module (The SciPy Community, 2022).

6. Results

6.1 Network geometry

The azimuths of the lineaments in all the analysed sectors show a multimodal distribution. Thus, the directions were separated into sets, in a way that gives low values of circular variance. The angular ranges of all the sets are presented in Tab. 2. For all sets, except for set 2 in the Eastern Magura (EM) sector and set 2 in the Western Silesian (WS) sector, the distribution is not uniform, as checked with the Rayleigh test (Baas, 2000). The two sets not checked were not numerous enough to be representative.

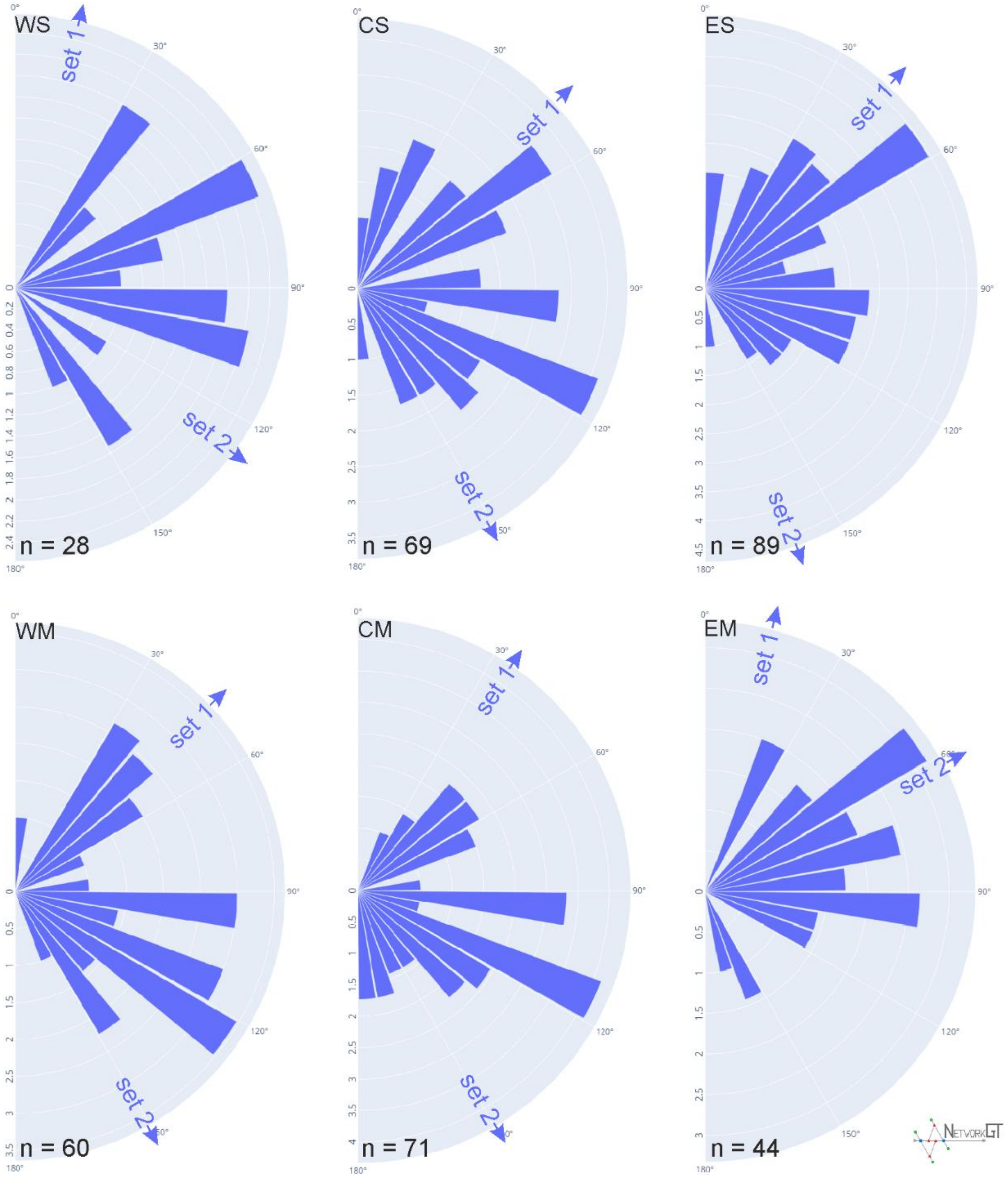

Fig. 4: Rose diagrams of the analysed networks in the analytic sectors; upper row: Western Silesian sector with Foremagura (WS), Central Silesia (CS), Eastern Silesia with Skole (ES); lower row: Western Magura (WM), Central Magura (CM), and Eastern Magura with Dukla (EM). Arrows mark the mean azimuth for the sets defined in Tab. 2.

Tab. 2. Azimuths of the lineaments in the analyse sectors

Analyse sector	Set	Azimuths range	n	Circular statistics			The acute angle between sets means
				Mean	Std. dev	Variance	
CS	1	0 – 100	15	46.5	14.2	3.5	75.5
	2	100 – 180	13	151	16.6	4.8	
CM	1	0 – 80	17	34.1	13	3	63.9
	2	80 – 180	51	150.2	21.5	8.1	
EM	1	45 – 75	41	62.1	7.5	1.0	47.7
	2	0 – 45 75 – 180	3	14.4	26.7	12.5	
ES	1	0 – 100	59	42.7	19.7	6.8	62.1
	2	100 – 180	28	160.6	14.7	3.8	
WM	1	0 – 100	20	46.5	14.2	3.5	75.5
	2	100 – 180	40	151	16.6	4.8	
WS	1	0 – 60 150 – 180	23	13.6	23.3	9.5	66.2
	2	60 – 150	5	127.4	8.9	1.4	

The orientation of lineaments in all sectors, as well as the circular mean azimuth are shown in Fig. 4. In sectors Central and Eastern Silesian (CS, ES) and Central and Western Magura (CM, WM) the set 1 mean is located between 34° and 47°, marking a dominant SW–NE strike of lineaments. In the Western Silesian sector (WS), set 1 is oriented more to the north (14°). In all sectors above, there is a second set with a NW–SE trend, mostly oriented at 150–160°, but in the Western Silesian sector case the mean azimuth is lower (127°), as in the case of the first set. The last sector, Eastern Magura and Dukla, is different. There is one dominant set with azimuth 62°, and the second set is poorly represented and oriented northward. The angle between the two sets varies in the 62–76° range, except in the Eastern Magura and Dukla sector where it is only 48°.

6.2 Network topology

In the study area, 305 lineaments were marked in total. These features comprise 432 nodes. Of this count, 58% are I nodes, 19% are E nodes, 18% are Y nodes and 5% are X nodes. The network contains 338 branches, within which 49% are C–I type branches, 29% are C–C branches and 22% are I–I branches marking completely separated lineaments. Topological parameters are shown in Tab. 3.

Tab. 3. Topological parameters of the network in analyse sectors

	Western Silesian with Foremagura	Central Silesian	Eastern Silesian and Skole	Western Magura	Central Magura	Eastern Magura and Dukla	Whole area

	WS	CS	ES	WM	CM	EM	
No. of nodes (I+X+Y)	19	68	101	47	67	40	383
I nodes	8	51	76	26	48	36	293
X nodes	1	6	6	3	6	2	19
Y nodes	10	11	21	18	15	2	71
E nodes	22	38	49	46	61	52	-
C-C connections	11.5	14.5	18.5	21.0	33.5	3.0	77.0
C-I connections	8.5	28.5	35.5	22.0	25.0	11.5	131.0
I-I connections	1.0	11.0	23.5	3.0	14.0	10.5	81.0
No. of branches	21.0	54.0	77.5	46.0	54.5	25.0	291
No. of lines	9.0	31.0	48.5	22.0	31.5	19.0	182
No. of connections	11	17	25	21	19	4	90
Connects per line	2.44	1.10	1.03	1.91	1.21	0.42	0.99
Connects per branch	1.62	1.06	1.02	1.43	1.12	0.56	0.99
Dim.less intensity	1.21	0.87	1.21	1.65	1.33	2.06	0.75
Av. Degree of network	2.21	1.59	1.53	1.96	1.63	1.25	1.52

The highest dimensionless intensity parameter is in the Eastern Magura and Dukla sector (2.05) and the lowest in the Central Silesian (0.87). On the other hand, the Eastern Magura sector is characterised by the lowest connections per branch (0.56) or the average degree of network (1.25) due to its form of mainly parallel features, with only 12% of the branches of connecting type (C–C). The best interconnectivity is observed in the Western Silesian sector with 1.62 connections per branch and an average degree of the network of 2.21. This is an effect of the presence of the Żywiec Basin block-system in the central part of the region.

The difference between these two (Eastern Magura and Western Silesia) sectors can be clearly visible on the ternary diagrams (Fig. 5) presenting the relationships of the nodes and branch types. In the Western Silesian sector, there is a high ratio of Y type nodes (52% of non-E-type nodes) and only one I–I branch.

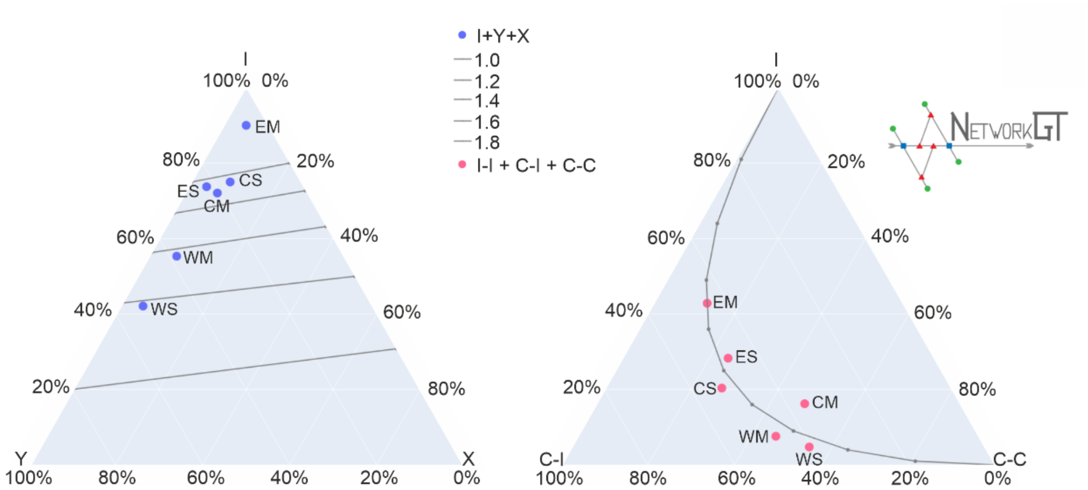

Fig. 5: Ternary diagram presenting nodes (left) and branches (right) proportions in the analyse sectors.

The parameters of all the other sectors fall between the Eastern Magura and Western Silesian sectors. The Western Magura sector has quite good interconnectivity with a similar type of Eastern Magura blocky network.

Another approach to analysing topology is to use a sampling regular grid. The results are shown in Fig. 5 as maps of connections per branch number, 2D network intensity and dimensionless intensity.

It can be seen we have two relatively large regions with a high value of connections per branch parameter . The first one is in the Western Silesian and partially Western Magura sectors, that is, the Żywiec Basin area, but from the geological point of view it is also a narrow zone of Foremagura units occurring between the Silesian and Magura nappes. Moreover, the Subsilesian unit tectonic window occurs in this area.

The Nowy Sącz Basin (eastern part of the Central Magura sector in the subdivision used here) is the next region with a high number of connections per network branch. The lineament system in this area surrounds a zone of Neogene deposits lying on the Carpathian flysch and filling the intramountain Nowy Sącz Basin.

The 2D intensity map shows that the Nowy Sącz Basin is characterised in general by a higher intensity than the Żywiec Basin. There is also a general trend of higher intensity in the western part of the Carpathians (especially the Western Magura and Central Magura sectors) than in the eastern part (Eastern Magura and Dukla).

In terms of dimensionless intensity parameter there are two regions with significantly high values: the south-eastern part of the Wiśnicz foothill, which is in the Central Silesian sector, and the eastern parts of the Beskid Niski Mts. and Bukowiec foothill in the Eastern Magura and Eastern Silesian sectors, on the geographical border of the Western and Eastern Carpathians.

7. Discussion

7.1 Different lineament identification approaches

There are 110 photolineaments marked on the photogeological map of Poland in the studied area (Bażyński et al., 1986). In the same area of the geological map of the Carpathians, Lexa et al. (2000) marked 2 325 features described as a fault or assumed fault. In many cases, our lineament system seems to be concordant or complimentary to Lexa et al.'s (Fig. 6). In some cases, the features marked as faults are rather thrust lines, as per the Fig. 6a example. The photolineament system is in general concordant with the DEM-interpreted system.

Visual inspection of the compiled lineaments map (Fig. 7a) shows that the especially NE striking lineaments of the Eastern Magura sector are consistent with each other. Moreover, the system framing the Żywiec tectonic window is well visible in both sets. On the other hand, there are some photolineaments that are not recognisable on the DEM, and in fact also hardly visible on the modern orthophoto map. The most prominent example are two straight, parallel lineaments striking the NNE in the central part of the study area, cutting its entire width. These features seem to cut Gorce Mts.; this is not confirmed by our other studies (Kania and Szczęch, 2020; Szczęch and Cieszkowski, 2021). Further to the north, these two lineaments are delimiting massifs of the Beskid Wyspowy Mts. (Mogielica, Łopień). These massifs are in fact particularly visible on the aerial photo, as rather isometric 'islands', and are formed by core parts of the synclines (Wójcik et al., 2009). On the other hand, some lineament systems well visible in DEM are not marked on the photolineament map, as per the case of the system north of the Nowy Sącz. That shows how these two methods can in fact be recognised as complementary approaches to the lineaments' identification.

The system from the map by Lexa et al. (2000) shows confirmed and inferred faults, which is why it is not fully compatible with lineaments; the lineaments, even when mainly tectonic related, are in fact a broader term (O'Leary et al., 1976). Especially, these data, despite being a very rich collection of features are not applicable for topological analyses: most of the features are short and isolated even when forming a network. Nevertheless, these data include faults that are identified with geological criteria that are not visible in the remote sensing (at least at the scale applied in this paper or by Bażyński et al., 1986 photolineament map. These data are augmenting each other, which is highly visible in the Piwniczna Zdrój area, where DEM interpreted that the NNW striking lineament along the Poprad River Valley (not present in the photolineament set) is flanked with a set of N or NNE striking faults, which we have not identified on the DEM.

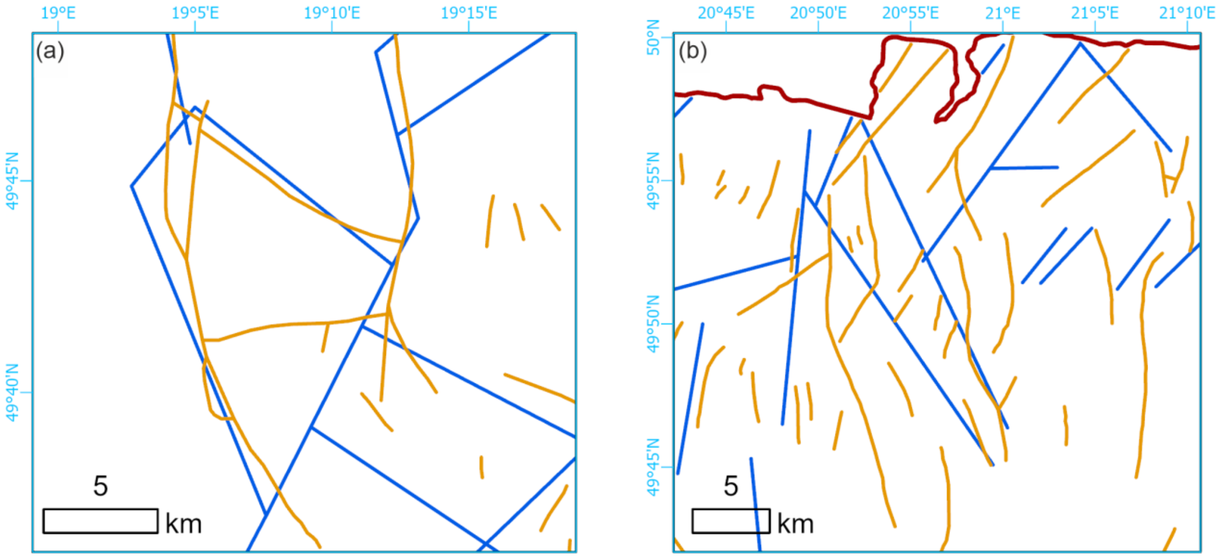

Fig. 6. Comparison of lineament system detected from the GMETD model (blue) and faults by Lexa et al., 2000 (brown). (a) Żywiec Basin area, (b) fragment of the Zakliczyn – Olszyny fault zone.

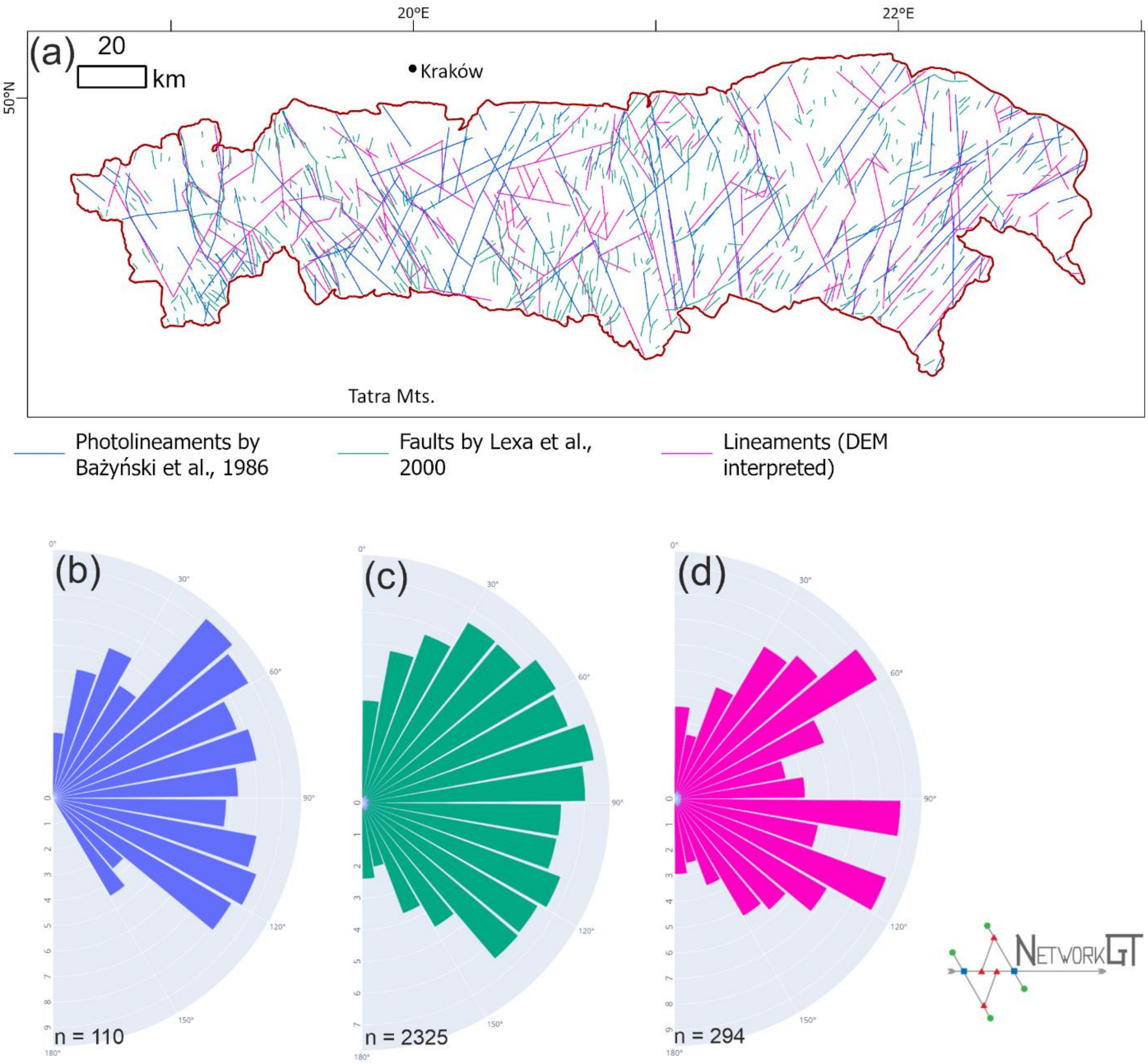

Fig. 7. Geometry of lineament networks in the Carpathians. (a) compilation map of lineaments by Bażyński et al., 1986, faults by Lexa et al., 2000 and lineaments interpreted from DEM in the presented paper. (b-d) rosediagrams of features azimuth in the whole study area from: (b) Bażyński et al. (1986), (c) Lexa et al., 2000 and (d) DEM interpreted.

When analysing the distribution of feature azimuth for the whole study area (Fig. 7b-d), it can be noted that the directions for the photolineament set (B) and DEM-interpreted set (D) are quite similar. What is noteworthy is the lack of azimuths greater than 150° in the photo set, which are present (albeit in a minority) in the DEM set. Furthermore, the photo set shows two maxima, at ca. 45° and 110°, whilst in the DEM set there are three maxima at ca. 50°, 100° and 110°. However, the dominating directions are not in fact distributed uniformly along the W–E span of the Polish Western Carpathians, which can be clearly seen in Fig. 7a where the domination of NE directions in the eastern sectors can be noticed, as well as the presence of two main directions in the western and central sectors.

7.2 Dominating directions of the lineament network

We observed a difference in dominating azimuths of lineaments between the western/central sectors (WS, WM, CS, CM) and eastern sectors (ES, EM) of the study area. The first ones are characterised by two distinct sets of lineaments (NNE or NE and SE), while the second has an SE set that is strongly reduced.

According to the general tectonic model of the Outer Carpathians (Unrug, 1980), the flysch deposits are cut by set sinistral strike–slip fault zones. These fault zones are arranged in a fan-like shape along the arc of the Carpathians, leading to the rotation of the set of nappes (Unrug, 1980; Graniczny and Mizerski, 2003). The observed trend of increasing importance of the NE direction to the east is consistent with this model. However, the more complicated geometry of the western part of the network may be related to the more complicated system of the deep-rooted fault zones in this part (see further discussion below).

7.3 Topological differentiation of the network

There are no topological analyses of the lineament networks for the Outer Carpathians. Our previous article (Kania and Szczęch, 2022) was focused on one mountain massif: Gorce Mts. From the tectonic point of view, this massif is quite homogenous, being located in the one tectono-facial unit (Magura unit) with some subunits within (Bystrica and Krynica subunits). Therefore, the paper focused mainly on different litostratigraphic units, showing how different types of lithology differ in topology terms.

Scaling the research into the Polish Western Carpathians shows that in general there are no differences in the network topology related to the tectono-facial units (Outer Carpathian nappes) since in general, all these units are similar in lithology (flysh packets). However, there are differences related to some irregularities in tectonics: especially, the intramountain basins are marked with increased network interconnectivity. The western part of the study area in general has a better developed network. Especially, the Eastern Magura differs from the rest of the sectors: the domination of one lineament direction results in low network interconnectivity, which is expressed by a high proportion of the I nodes and I–I branches (Fig. 5). We analysed Magura unit and part of the Dukla unit together; however, the interconnectivity in the Dukla Nappe (belonging to the Foremagura group) is stronger than in Magura, which can be related to the proximity of the Silesian unit overthrust.

The highest interconnectivity was observed in the Western Silesian sector. The area is characterised by a high proportion of Y nodes, and thus mainly by the presence of C–I or C–C branches (Fig. 5). In the geological context, it is related to the location of the Żywiec tectonic window, which exposes the Subsilesian unit.

However, the topological study shows that the tectonised zone is wider; the increase in connections per branch zone continues to the south along the Soła River and further, at least to the state border in the Beskid Żywiecki Mts.

7.4 Main large-scale, deep-rooted lineament systems of the Western Carpathians and their relation to DEM-interpreted lineaments

The following, well-known, large-scale lineaments reach the Carpathian basement cutting the Polish part of the Outer Western Carpathians (Doktór et al., 1985): Central Slovakia, Myjava, Muran, Štitnik and Przemyśl. There are also lineaments not named by Doktór et al. (1985), but striking parallel, approximately 10 km to the east from the Skawa fault zone (Cieszkowski et al., 2006). Fig. 8 presents the generalised positions of the lineaments.

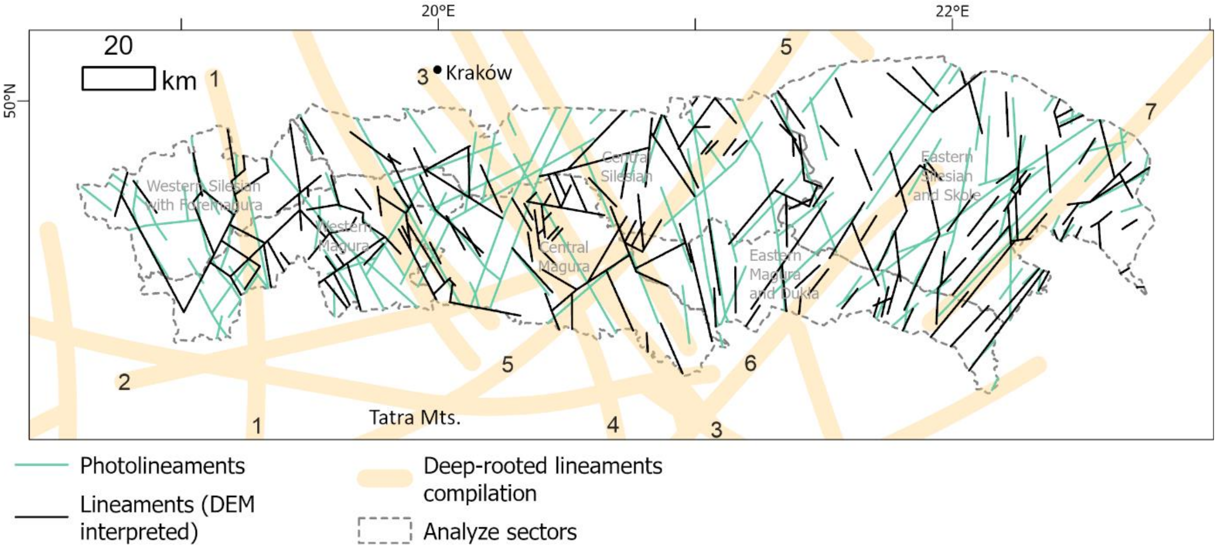

Fig. 8. Interpreted lineament system with photolineaments by Bażyński et al., 1986 as well as deep-rooted lineament compilation after Sikora, 1976; Zuchiewicz, 1984; Doktór et al., 1985. Important deep-rooted lineaments mark with numbers: 1 – Central Slovakia, 2 – Pericarpathian, 3 – Kraków – Prešov, 4 – Stitnik, 5 – Myjava, 6 – Muran, 7 - Przemyśl

The central Slovak line marks the eastern border of the Żywiec basin and marks the major fault zone well visible in the displacing Fore–Magura belt near Żywiec. Some of the lineaments belonging to the system can also be traced to the east, with some connecting NE–SW branches near the northern margin of the Carpathians.

The system of Muran lineaments in the discussed region is marked by a few short NE–SW lineaments in the eastern sectors of the Magura and Silesian units. The Myjava system, in fact one of the most prominent systems in the Carpathians, in the study area can be traced along the Nowy Sącz Basin, continuing to the north where there is a series of short lines parallel to the zone lineaments. The network interconnectivity increases in this area. The lineaments there lie in an extension of the Carpathian Shear Corridor, a large-scale strike–slip zone between Vienna and the High Tatra Mts. (Marko et al., 2017). Although the Štitnik system is unclear, some parallel or subparallel lineaments can be assigned to this zone. The Przemyśl lineament zone is identified as a set of long lineaments in the easternmost parts of the area, where the main features of NE–SW are possibly interconnected by shorter N–S lines, forming an interconnected, blocky, two-set system.

Another important deep-rooted linear structure, confirmed by a negative gravimetric anomaly is the Pericarpathian line, which runs along the Nowy Sącz–Nowy Targ–Kysucké Nové Mesto line (Zuchiewicz, 1984; Sikora, 1976), which runs similarly to the Myjava structure. The Kraków–Prešov lineament, which is an extension of the Kraków–Lubliniec fault zone and marks the border between the Małopolska and Brunovistulicum blocks of the basement (Żaba, 1999; Zuchiewicz, 1984). A system of lineaments is clearly visible along this line, mainly in the Magura Nappe; however, parallel photolineaments were marked even longer to the north (Bażyński et al., 1986).

These systems can be arranged in two sets: NNW, NW–SSE, SE striking (Central Slovakia, Skawa, Kraków–Presov and Štitnik); and NE–SE (Myjava and Pericarpathian, Muran and Przemyśl). That implies some points of system intersection, and in the area analysed such a place is in the Nowy Sącz region. This place is characterised by higher interconnection factors (Fig. 9), in relation to the surrounding area. Moreover, in terms of geomorphology, this is an intramountainous basin, being the only location where deposits are observed in the Magura Nappe Neogene.

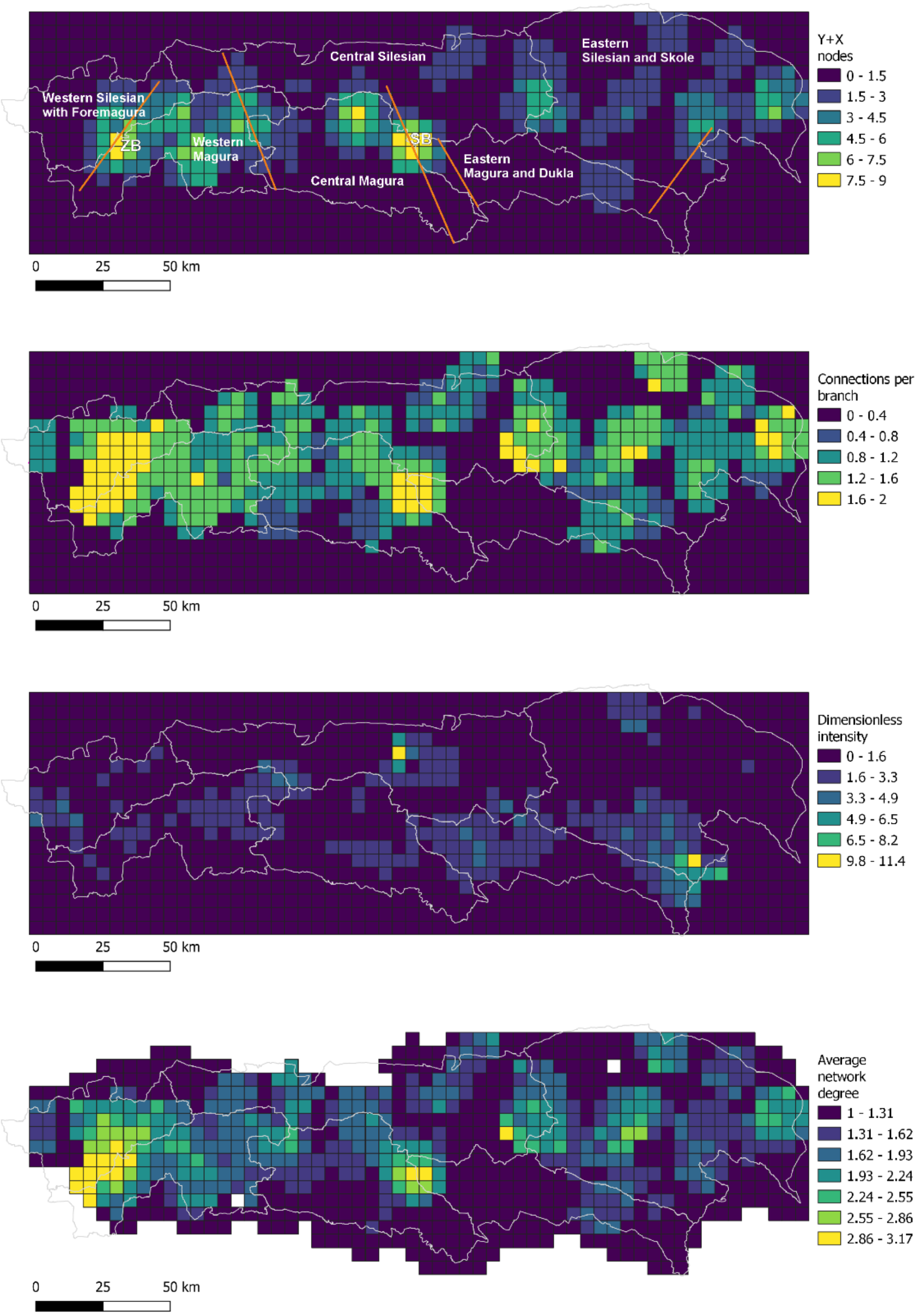

Fig. 9. Topological parameters of the lineament network, from up to down: connecting nodes number, connections per branch number, dimensionless intensity factor, and average network degree. ZB – Żywiec Basin (Żywiec tectonic window), SB – Nowy Sącz Basin, lines on X-Y nodes map are main faults.

The Central Slovakian system strikes along the east border of the Żywiec Basin and Żywiec tectonic window, where the Subsilesian Nappe is exposed. We also marked a major lineament there, which is not present on the photolineament map (Bażyński et al., 1986) or the database of the Western Carpathian Geological Map (Lexa et al., 2000). The lineament (in the central part, the Soła River Valley) cuts the Magura Nappe, the Foremagura zone with Magura overthrust and the Silesian Nappe. This structure is one of the edges of the rhomboidal block, in which the Żywiec Basin has been developed. The generally increased degree of network interconnection (Fig. 10) and the intensity of the network in this area can be an effect of the interaction between the central Slovakian system with the Soła lineament and all the lowered block edges.

The cross-cutting relations of the Myjava lineament and the Štitnik lineament, whose continuation can be the Dunajec fault system, are reflected in the bimodality of lineaments. The dominating maximum in the central Magura sector, at approximately 120°, is similar to the Štitnik lineament; however, the Myjava lineament is reflected there by just a few dominating lineaments, which are relatively long. Moreover, the Pericarpathian lineaments are also known in this region. This structure, reflected in the sedimentary cover as the Dunajec fault zone, is also confirmed by a negative gravimetric anomaly (Zuchiewicz, 1984; Sikora, 1976). Another deep structure cutting this area is the Kraków–Prešov fault, which is an extension of the Kraków–Lubliniec fault zone under the Carpathians active to the Quternary (Żaba, 1999). All these deep cross-cutting features result in an increased degree of the network connectivity observed on the surface. Then, the blocky structure allowed the formation of an intramountain basin, filled with Neogene sediments.

Topological analysis also suggests that the well-known Skawa fault zone (Zuchiewicz et al., 2009; Unrug, 1980) is in fact the western-most part of the wider zone of increased network interconnectivity, extending ca. 10–20 km to the west of the Raba River. The final interpretation of correlation of lineaments increased interconnectivity areas with tectonic structures of the area is shown on the Fig. 10.

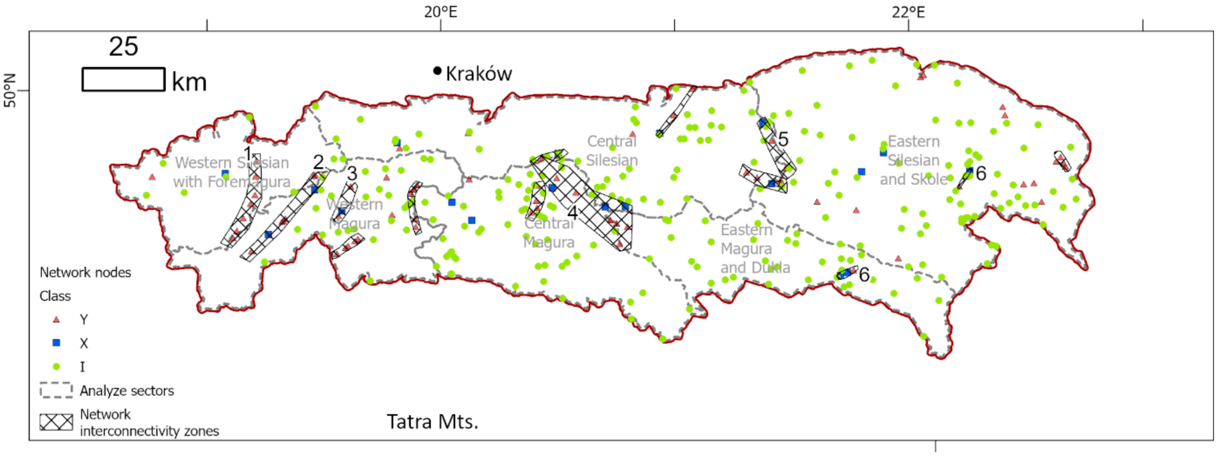

Fig. 10. Network nodes and zones of interconnectivity and their interpretation in context of Outer Carpathians Nappes (surface) and basement (deep) tectonics. 1 – Soła fault zone (surface), Central Slovakia lineament (deep), 2 – fault system along Sopotnia Valley, 3 – Skawa fault zone (surface), 4 – Nowy Sącz Basin (surface), Kraków – Prešov, Myjava and Štitnik lineaments (deep), 5 – faults along Wisłoka Valley (surface), 6 – Muran lineament (deep).

The other aspect of the fault system of the Carpathians is occurrence and migration of the mineral waters. The area to the south of the Nowy Sącz there is a well-known region of CO_2-rich mineral waters occurrence with renowned spa sites. These waters are associated with fault zones, often the deep one, penetratiting to the crystalline basement of the Carpathians (Oszczypko and Zuber, 2002; Zuber and Chowaniec, 2009; Ciężkowski et al., 2010). Its noteworthy, that this region is located on the crossing of two major deep-rooted fault zones: Štitnik lineament and Myjava lineament (Fig. 8). Similarly, the deep faults can be patch of migration of hydrocarbons, especially if source rocks are related to the platform cover of Brunovistulicum and Małopolska Massif lying under the Carpathians. In fact, some of the Polish Carpathian gas deposits are related to the Mesozoic-Palaeozoic basement (Kotarba and Koltun, 2006). Thus, the analyse of the fault systems and their interconnectivity has the potential in study of both, hydrocarbon and hydrogeological systems.

7.5 Conclusions

The proposed data source and analysis method are complementary with other lineament analysis from the study area. The observed azimuths are in general concordant with the photolineament network; however, there are some structures that are not confirmed by DEM interpretation. The relationship between the DEM-interpreted data and geologically confirmed faults shows the usefulness of DEM as a data source in fault detection.

The dominating directions of the network are typical for the Western Carpathians, with a clear increase of the NE striking features proportion towards the east.

The topological properties of the lineament network in the Western Carpathians show E–W trends, but no clear S–N (perpendicular to the tectonic units) trends. This justifies the proposed subdivision of the Carpathians in the western, central and eastern sectors in addition to the tectono-facial subdivision. The eastern sectors are dominated by NE–SW trends and low interconnectivity, while the central and western sectors are more interconnected and characterised by cross-cutting relationships of two main lineament directions. The degree of network interconnectivity increases in areas with a lower morphology (intramountainous basins): the Żywiec Basin and Nowy Sącz Basin.

The geometry of the network, in general, reflects a system of deep-rooted lineaments. The cross-cutting area of the main deep lineaments is reflected in stronger network interconnectivity in the Nowy Sącz area.

CrediT authorship contribution statement: Maciej Kania: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. Mateusz Szczęch: Investigation, Writing – review & editing, Visualization.

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