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Geological and geomorphological conditions of landslide development in the Wisła source area of the Silesian Beskid mountains (Outer Carpathians, southern Poland)

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The Silesian Beskid mountains (Outer Western Carpathians) are affected by landslides, many being large, of rocky character and with clearly visible relief. I provide a new morphostructural analysis of mountain relief and landslide development, based on detailed field mapping and spatial analysis of a digital terrain model based on LiDAR data. The index of landslide occurrence was calculated at 22.57%. The basic geometrical features of the landslides mapped may be related to the morphostructure of the study area. Factors influencing long and wide landslides include lithology, slopes relative to stratal orientation, and developmental trends, while wide landslides are of frontal type. Tectonic structures are important controls on landslide shape.

Key words: landslides, frontal landslides, lithological control, Silesian Beskid, Outer Carpathians.

INTRODUCTION

The influence of passive factors on the development of mass movements in mountain areas is one of the most interesting and important issues in understanding the geological conditions and nature of landslide movements (Zaruba and Mencl, 1969; Varnes, 1978; Guzzetti et al., 1996; Margielewski, 2001, 2004; Wójcik et al., 2006). The results of such studies, carried out with the use of classical methods and supported by modern possibilities of spatial analysis of mountain slopes, may help identify rock masses relevant to the planning of construction investments, or to the prevention of landslides.

In Poland, the area most prone to landslide development, and thus most affected by landslide processes, is the Outer Western Carpathians (Wójcik and Wojciechowski, 2016; Wojciechowski, 2019). It may host 90–95% of all landslides in Poland (Wójcik and Mrozek, 2002; Poprawa and Rączkowski, 2003).

The first inventory of landslides in Poland was made in the early 1970s (Bażyński and Kühn, 1971; Chowaniec et al., 1975). A detailed inventory of landslides on maps at 1:10,000 scale has been made since 2007 within the Landslide Counteracting System (SOPO) project (Grabowski et al., 2008). One of the first areas thus mapped was the Silesian Beskid. According to the SOPO database (mapa.osuwiska.pgi.gov.pl), 1019 landslides have been registered there since 2008. Many of these represent different types of rock slides of considerable size (e.g., Wójcik and Mrozek, 2002; Albrycht and Maleszyk, 2009; Lasoń et al., 2011; Wojciechowski and Lewandowski, 2011). Baumgart-Kotarba et al. (1969) indicated a significant influence of landslides on the evolution of relief of the Silesian Beskid. Ziętara (1964, 1968) pointed out that many broad landslides in the region of Skrzyczne Mountain have rectilinear escarpments, which may be fault-controlled, and he called these frontal landslides. Similar relationships in this area were observed by Wójcik and Nescieruk (1996).

An interesting area for studies of landslides and the influence on them of geological factors of bedrock and slope configuration is the source area of the Wisła River, situated on the western and north-western slopes of the Barania Góra Range (Fig. 1). Landslides in the Barania Góra region were noted by Szajnocha (1923). Macura (1956) suggested that the landslide of the "Czerwony Usyp" ("Red Pile") below Barania Góra is a glacial cirque. On the Detailed Geological Map of Poland at 1:50,000 scale – the Wisła sheet (Burtan, 1972) and its explanation (Burtan, 1973) – only 2 landslides were marked on the area studied, in the Biała Wisełka Valley and the Malinka Valley. In the landslide catalogues published by Bażyński and Kühn (1971) and Chowaniec et al. (1975), 33 landslides were registered in the area. Bober (1984) estimated the index of landslide occurrence (ILO) of the area at 0.93%. He also indicated that landslides occur most frequently in the Istebna Beds and the Godula Beds. In the study area, the influence of bedrock tectonic structures on the development of crevice caves, including caves in landslides, has also been demonstrated (Margielewski and Urban, 2000, 2003; Tomaszczyk, 2005; Margielewski et al., 2007; Pánek et al., 2010). According to

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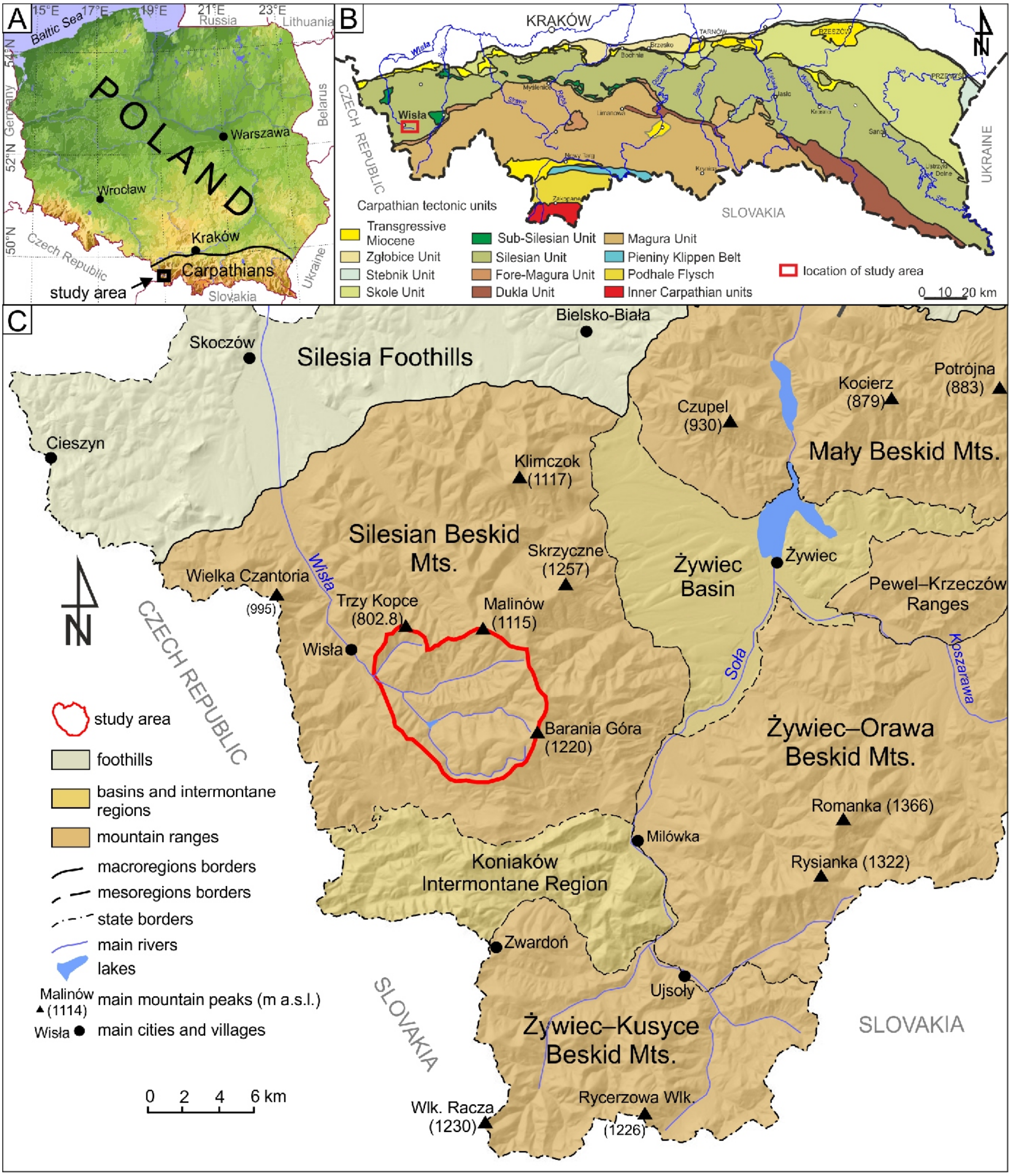

Fig. 1A, B – location of the study area within the Flysch Carpathians of Poland (after Żytko et al., 1989, Oszczypko et al., 2008; modified); C – Polish part of the Outer Western Carpathians (after Solon et al., 2018; modified)

Sikora (2018), the Biała Wisełka Landslide Complex represents a structurally controlled deep-seated landslide (*sensu* Hutchinson, 1995) or the result of rock slope deformation (*sensu* Hungr et al., 2014).

Landslide activation in the Carpathians has been linked to the humid periods with greater morphological activity in the Late Pleistocene and Holocene (Alexandrowicz, 1996; Starkel, 1997; Starkel et al., 2013). These events have been dated to more than 13,000 years (Margielewski, 2006) or 15,000 years ago (Wójcik, 2019) and several periods of increased activity have been demonstrated since then (Margielewski, 2002, 2006, 2018; Pánek et al., 2013; Szczygieł et al., 2019; Wójcik, 2019). A Late Glacial age of landslides has been indirectly indicated by the dating of calcite speleothems in caves in the study area. Dates from the Miecharska Cave in a landslide on the southern slopes of Malinowska Skała Mountain indicated the oldest ages: 15.45–13.45 ka (Upper Vistulian), and from Wiślańska Cave (to the N of the study area): 12.85–11.15 ka (Allerød/Younger Dryas; Urban et al., 2015).

This paper describes analysis of the determinants of landslide development involving passive factors, based on a detailed cataloguing of landslides in the Wisła River source area (Sikora and Piotrowski, 2013a, b).

LOCATION AND TOPOGRAPHY OF THE STUDY AREA

The study area (61 km^2) covers part of the Moravo-Silesian Beskid region in the Western Outer Carpathians, representing the Barania Góra Group of the Silesian Beskid (Figs. 1 and 2; Starkel, 1972; Solon et al., 2018). The study covered the northern and western slopes of the Barania Góra Range with intermediate mountainous relief (Klimaszewski, 1978). The area examined is enclosed between the main ridge of the Barania Góra Range in the south and east, the Równica Ridge in the north and the Zadni Groń Ridge in the west (Fig. 2A). The main ridge of the Barania Góra Range runs E–W in its southern part and N–S in its eastern part (Fig. 2). Repeated branching of the ridges and cutting of the slopes by many stream valleys determine the dominant trellis drainage pattern in this area (Fig. 2B; Klimaszewski, 1978).

The height difference between the lowest point in the study area (458 m a.s.l. on the Wisła Valley floor near Gościejów) and the summit of Barania Góra (1220 m a.s.l.) is 762 m, but differences in relative height on individual ridges are smaller (Fig. 2). These range from 200 m on the slopes of the Cienków Ridge to 450 m on the slopes of the main ridge of the Barania Góra Range. The slopes of the sub-parallel ranges and ridges include distinct, steeper sections (Fig. 2A). These are present mainly on the slopes with northern and northeastern exposure, and less frequently on the slopes descending to the south and south-west. On the top parts of the slopes, these topographic steps can reach several tens of metres of height. In the middle parts of the slopes, they are lower and often separated by flatter portions.

The main streams in the study area are the Czarna Wisełka and Biała Wisełka, whose waters merge to form the Wisełka which, after merging with the Malinka Stream, forms the Wisła River. In the northwestern part of the area, it is joined by the Gościejów Stream (Fig. 2B).

GEOLOGICAL STRUCTURE OF THE STUDY AREA

Geologically, the study area is located in the Outer Flysch Carpathians within the Silesian Nappe (Żytko et al., 1988; Oszczypko et al., 2008), within the Godula Sub-nappe (Silesian-Godula Sub-nappe; Nowak, 1927; Burtanówna et al., 1937; Paul et al., 1996). This is the area of the Silesian Beskid Block (SBB; Książkiewicz, 1953, 1972). The northern part of the block is underlain by the Silesian–Cieszyn Sub-Nappe and its southern part is overlain by the Fore-Magura and Magura nappes (Burtan et al., 1937; Burtan, 1973; Paul et al., 1996).

The study was conducted on the southern limb of the Szczyrk Anticline (with ENE–WSW oriented axis; Wójcik and Nescieruk, 1996; Nescieruk and Wójcik, 2017) in the southern part of the SBB, where monoclinal strata, inclined generally towards the SW at angles of 10–25°, dominate (Fig. 3; Sikora, 2022). The strata of the bedrock are crossed by numerous NW–SE-directed transverse and ENE–WSW-trending longitudinal dislocations, and to a lesser extent by faults oblique to regional fold structures (Fig. 3). The orientation of the faults relates to the joint systems recognized in the bedrock, where an orthogonal joint system (transverse T and longitudinal L, L' and L") predominates over an oblique joint system (S_R and S_L; Sikora, 2022).

The Upper Godula Beds (UGB) and the Lower Istebna Beds (LIB) are present in the study area (Fig. 3). The Upper Godula Beds (Santonian–Campanian; Burtan, 1973; Słomka, 1995) are exposed north of the Biała Wisełka Valley. They are represented by thin- and locally medium-bedded massive sandstones and thin-bedded mudstones (Fig. 3A; Burtan, 1972, 1973; Nescieruk and Wójcik, 2017). A characteristic feature of the sandstone and shale varieties of the UGB is their strong fracturing and densely-arranged separation along the bedding planes (Sikora, 2022).

Locally, in the upper part of the UGB, the thick-bedded Malinów Conglomerates occur (Fig. 3B; Burtan, 1972; Nescieruk and Wójcik, 2017; Rylko, 2018) with a maximum thickness of 120 m and interbedded thin layers of mudstone (Burtan, 1973). The widest outcrops of the Malinów Conglomerates are located on the peaks of the Barania Góra Range in the eastern part of the study area (Fig. 3A).

Continuous outcrops of the LIB (Campanian–Maastrichtian; Burtanówna et al., 1937; Unrug, 1963; Burtan, 1972; Nescieruk and Szydło, 1993) are located in the southern and central parts of the study area and as an outlier in the northern part (in the Gościejów Valley; Figs. 2 and 3A). The LIB in the study area are mainly thick-bedded sandstones and conglomerates with bed thickness up to 4.5 m. In their bottom and top parts, there are beds and lenses of mudstone up to 12 m thick. The rocks of the LIB are poorly compacted and undergo intensive granular disintegration (Burtan, 1973).

The vertical contact between the LIB and the UGB is continuous. In the Biała Wisełka Valley, a sedimentary transition is observed, marked by intercalations of the respective lithological facies (Burtan, 1972, 1973; Nescieruk and Wojcik, 2017; Strzeboński, 2022).

The slopes underlain by these Upper Cretaceous flysch rocks have a cover of Quaternary landslide colluvia (with landslide packets of rocks of Cretaceous age), rock rubble and weathered clays with rock rubble, up to 3 metres thick (Burtan,

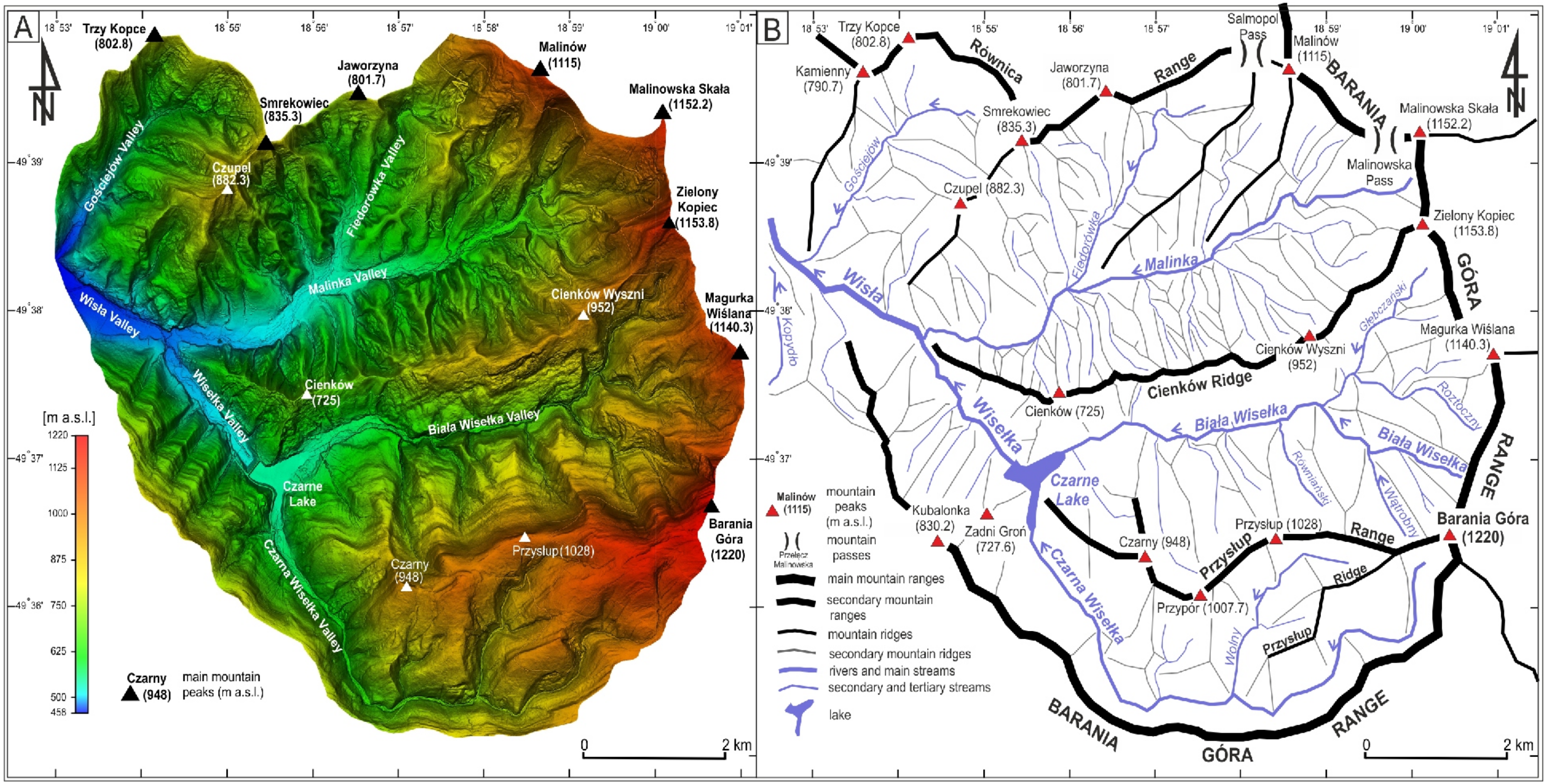

Fig. 2A – digital elevation model of the Wisła River source area from LiDAR data and B – stream network map of the study area

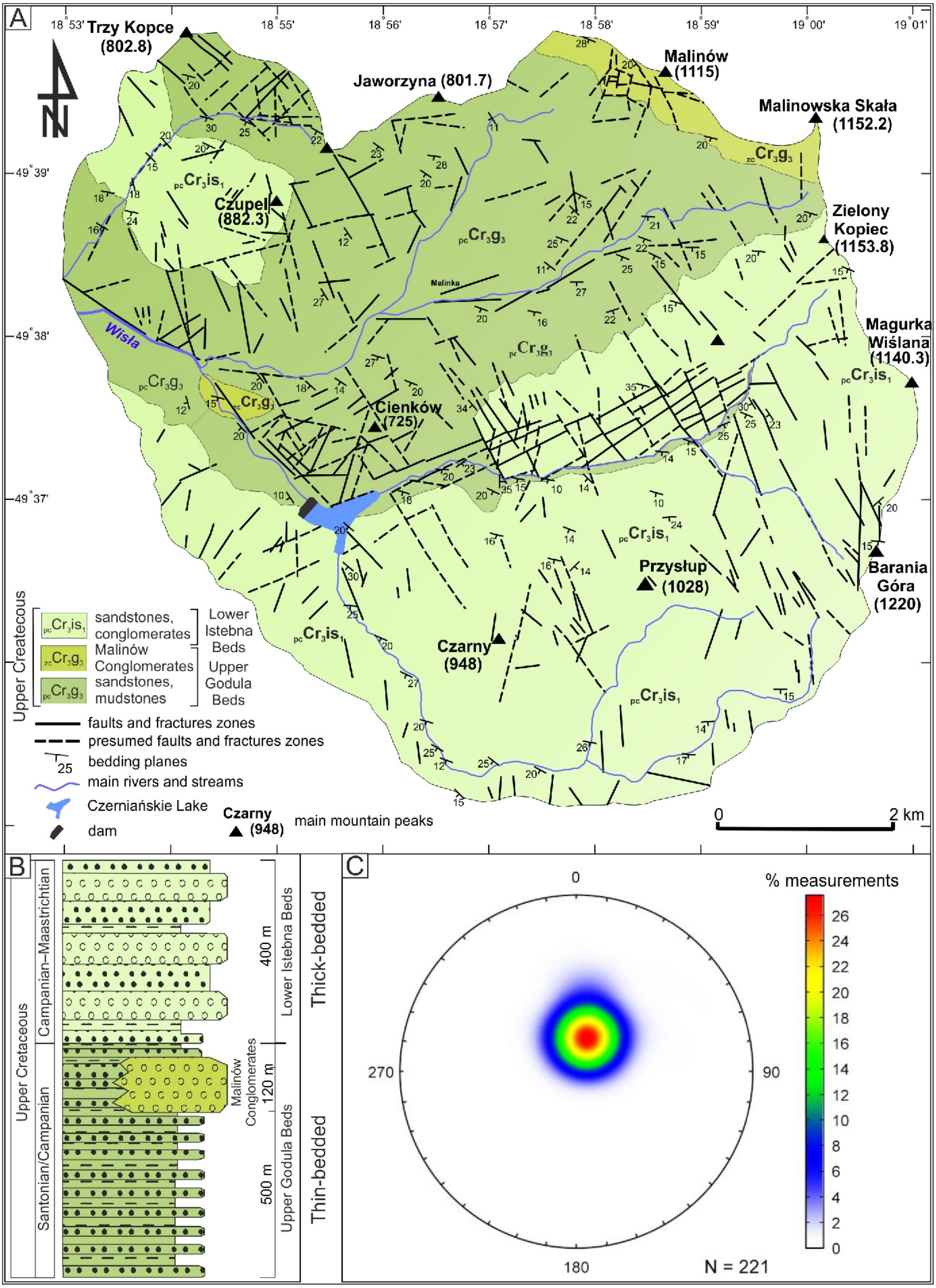

Fig. 3A – litho-structural map of the bedrock in the Wisła River source area (after Sikora, 2022); **B** – schematic lithostratigraphical profile of the study area; **C** – contour diagram of bedding plane orientations in the whole analysed terrain – equal area, lower hemisphere

1973; Nescieruk and Wójcik, 2017). The valley floors are rocky and in their lower sections covered with boulders and thin (several centimetres) gravel layers. Terraces are present along the valleys, appearing below the junction of the Biała and Czarna Wisełka, comprising rock bases covered with a thin gravel layers. The oldest terraces are connected with the Middle Polish Glaciation (Starkel, 1967). Below them, there is a terrace (Vistulian) built of gravels covered locally by slope deposits (solifluction and deluvial clays), connected with the Northern Polish Glaciations (Starkel, 1967, 2001). The lowest terraces within the valleys are Holocene. Locally on the slopes, in hollows and landslide depressions in the Wisełka and Czarna Wisełka valleys, peats occur.

MATERIALS AND METHODS

The studies on landslides were based on field mapping and laboratory analysis of the data obtained. The fieldwork comprised detailed delineation of landslides, slopes and other elements of landslide relief following Grabowski et al. (2008) and Ozimkowski et al. (2010). In the field, observations were made on landslide-affected slopes to determine the character of the landslide movements (Dikau et al., 1996; Crosta, 1996; Cruden and Varnes, 1996) and the type of colluvial material and its degree of disintegration. Attention was paid to the relief of landslide surfaces, the nature of landslide scarps, the presence of extensional fractures (trenches) and the occurrence of detached and toppled blocks and rock packages. In many forested areas, the topographic maps did not reflect the complexity of the relief caused by landslide processes. To interpret the landslides and clarify their boundaries, a Digital Elevation Model (DEM) with a resolution of 1 1 m from LiDAR data (Light Detection and Ranging) was used. The LiDAR-DEM was produced as a part of ISOK (Informatics System for the Protection of the Country from Extraordinary Dangers), available among the resources of the Head Office of Geodesy and Cartography (GUGiK). Its spatial analyses were carried out using GIS software such as Global Mapper, ArcGIS and ILWIS. The mapping results were compiled on a map at 1:10,000 scale.

Where entire slope surfaces were covered by landslides, attention was paid to the landslide boundaries. Usually, when landslides were clearly separated by side scarps or as landslide bodies displaced in different directions, they were marked as separate forms. Such landslides were classified into groups, but morphometrical analyses were carried out on individual forms. When defining the boundaries was not possible, the landslides were marked as a complex and analyses were carried out for combined areas. In the spatial analysis, the slope surfaces affected by landslides were taken into account, and in the geometric analysis, the shapes of individual forms within groups were taken into account. Landslide complexes were treated as single forms.

An analysis of slopes was also carried out based on LiDAR-DEM. Aspects were analysed in eight classes: N, S, E, W, NE, NW, SE and SW (Moellering and Kimerling, 1990; GIS World, 1991; Buckley, 2008), and slopes in 11 classes. The lowest class included slopes of <6°, slopes of 6–30° were included in classes of 3° increments, and the steepest slopes were included in 30–40° and >40° ranges. The resulting slope data was then analysed in each aspect class and compared with the orientation of bedding planes. After comparison with the orientation of the strata, it was possible to classify cataclinal, orthoclinal and anaclinal slopes (Powell, 1875).

RESULTS OF SLOPE AND ASPECT ANALYSIS

The study area is dominated by slopes dipping within the 9–24° gradient range (Fig. 4). These account for nearly 43% of the total slope area, with slopes in the 15–18° class standing out, covering 8.55 km^2. Slopes in classes 12–15° (8.23 km^2) and 18–21° (7.78 km^2) occupy a slightly smaller area. Slopes in these classes are commonly found in the middle and upper parts of the slopes, and in the Czarna Wisełka Valley in the lower parts of the slopes. On the slope map (Fig. 4A), steepness stands out, occupying nearly 10% of the total area of the study area. These are slopes in the range of 30–40° (4.98 km^2; 8.18% of the terrain area), accompanied by slopes greater than 40° (0.87 km^2; 1.42% of the terrain area; Fig. 4B). These are marked as distinct steps, several tens of metres high, which extend over several hundred metres, ranging up to 6 kilometres long. Steep gradients are characteristic of the upper parts of the slopes. These most often occur on northern, northeastern and eastern slopes (Fig. 4A) and their strike is usually close to ENE–WSW. They occur, for instance, on the slopes of the Przysłup Range and the Cienków Ridge (Figs. 2 and 4). On the map of the southeastern slopes of Malinów Mountain, an extensive steep surface sloping SE stands out (Fig. 4A). Steep and very steep sections of slopes also occur on the south, south-west, west and north-west slopes. The steepness of these slopes is usually marked as very narrow strips, sometimes several hundred metres long. Their trend is close to ENE–WSW or NW–SE. In places, they run across the slope (Fig. 4A). Steep and very steep slopes are also typical of erosion slopes of narrow streams, with heights of up to several metres, e.g. in the Gościejów, Biała Wisełka and Czarna Wisełka valleys. They also occur in places where landslides occur.

The steepness marked on the slope map is related to the topographic elements and tectonic structures of the bedrock. In addition, the steepness is emphasized by the difference in the resistance of rocks to erosion. Structural thresholds on obsequent slopes (northern slopes of the Przysłup Range, Barania Góra and the Cienków Ridge; Fig. 4A) are parallel to frontal surfaces of inclined beds and largely refer to the strike of the L and L' joint sets (ENE–WSW and NE–SW; see Sikora, 2022). The rectilinear trend of these thresholds is disrupted by transverse faults consistent with the NW–SE trend of the T joints set. Tectonic elements are also reflected in the development of steep slopes and fractures on the consequent slopes. As regards the orientation of joints, most of the L, L', L" sets (ENE–WSW, NE–SW and NNE–SSW) are related to longitudinal escarpments and trenches (southern and southwestern slopes of the Przysłup Range, Cienków Ridge and Równica Range; Fig. 4A). Transverse to them, the strike of topographic steps developed parallel to joints of the T-set. Some escarpments and trenches developed also as a result of secondary displacements along fault surfaces (composite scarps; Dadlez and Jaroszeski, 1994).

Flat and very weakly sloping terrains (0–6°) are found in the bottoms of the river and stream valleys and on the mountaintops (Fig. 4B). The total area of flat and very gently sloping slopes is 3.99 km^2, which is only 6.56% of the land area (Fig. 4B). Weakly sloping surfaces (6–9°), occupy an area of 4.35 km^2, or 7.14% of the total area of the study area. They are most frequently found in the middle parts of the slopes, in the Czarna and Biała Wisełka valleys. They occupy the largest areas on slopes oriented towards the south or south-west (Fig. 4A).

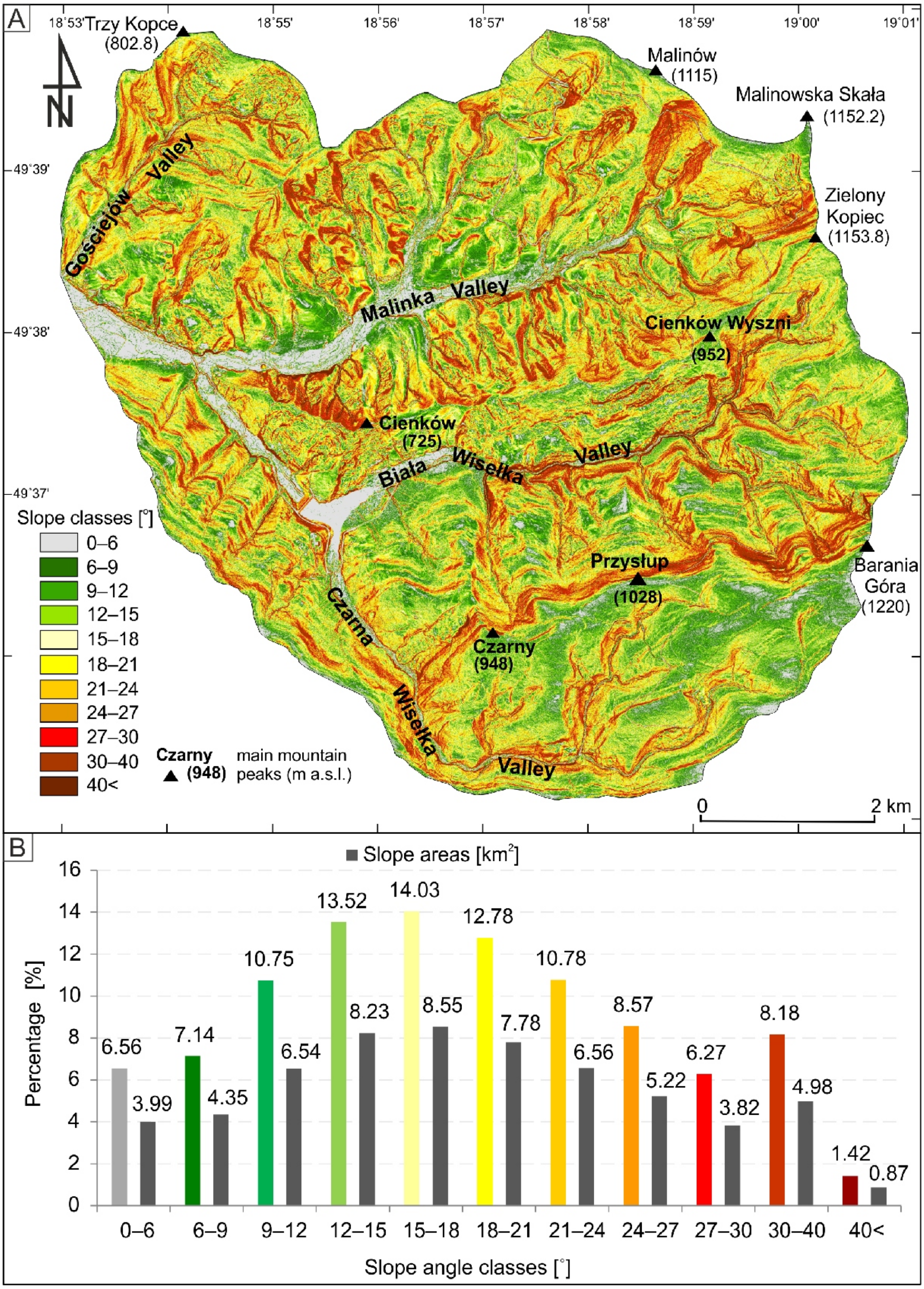

Fig. 4A – slope map of the study area and B – distribution of slope in classes

The dependence of the terrain relief on the structure of the bedrock is also reflected in the directions of slope inclination. In the study area, the slopes are mostly inclined towards the SW, S and W (Fig. 5). The areas of these slopes are 10.89, 9.56 and 9.55 km^2 respectively, which corresponds to 17.85, 15.68 and 15.65% of the total area (Fig. 5B). Slightly fewer slopes face NW: 8.76 km^2, accounting for 14.36% of the area. The slopes described above far outweigh the slopes facing E, NE, and SE with areas of 3.89 km^2 (6.38%), 5.36 km^2 (8.79%), and 5.47 km^2 (8.97%).

Southern, southwestern and western orientations of the slopes are characteristic of the major part of the study area, especially its northern and southern parts (Fig. 5A). These are the slopes of the Równica Range, the northern part of the Barania Góra Range located within the study area and in Czarna Wisełka Valley. The exception is the southwestern part of the area, where east-facing slopes prevail, and the extreme northwestern part with slopes oriented mainly towards the south-east (Fig. 5A). High variability of slope directions is observed in the central part of the area (Cienków Ridge and Przysłup Range). However, north-western, northern and north-eastern slopes dominate there.

ASYMMETRY OF MOUNTAIN RIDGES

The mountain ridges located in the study area are characterised by a clear asymmetry (Fig. 6A), as the direction of slope inclination is determined by the monoclinal structure of the bedrock. The dominant SW, S and W orientation of the slopes is related to the dip direction of the bedding planes (Sikora, 2022). Consequent slopes are mostly inclined at similar angles to the dip of rock strata (9–18°); in terms of structural classification, they are cataclinal slopes (Powell, 1875). They range from 153–243° and cover 33% (20.21 km^2) of the area in the study area (Fig. 6A). The NE, N and E oriented slopes relate to the frontal surface of inclined strata and they are obsequent (anaclinal). They range from 333–63° and cover 22% (13.23 km^2) of the site area. Their surfaces are steeper and they are often very steep (24–89°). Insequent and therefore orthoclinal slopes form 45% of the land area, with an uneven distribution. 30% (18.44 km^2) of the slopes are oriented in the range 244–333°, and 14% (9 km^2) of the slopes are oriented at 64–152° (Fig. 6A).

The asymmetry of slopes caused by the monoclinal structure of the geological basement manifests in the topography in the form of isoclinal slopes (cuestas; Cruden, 2003). In the study area these are the cuestas of Cienków and Barania Góra (Fig. 6B). Escarpments of these cuestas are visible on the slope map (Fig. 4A) on the upper parts of the slopes in the form of long, sub-latitudinally running steps emphasized by higher resistance of the LIB sandstones and conglomerates. The cuestas are divided by the subsequent Biała Wisełka Valley and the Malinka Valley (Fig. 6B).

RESULTS OF LANDSLIDE MAPPING

In the study area, 183 landslides (total landslide number – TLN) were mapped (Fig. 7). In area they range from 0.00032 to 2.243 km^2 (Fig. 8). In total, they cover an area of 13.75 km^2 (total landslide area – TLA) and the ILO index is 22.57%. The study area is dominated by small and medium landslides with areas ranging from 0.005–0.1 km^2. Landslides with areas of 0.01–0.05 km^2 have the largest share of the population (Fig. 8). Sixty-two landslides belong to this class and they represent 33.88% of the TLN. The next largest group are landslides in the class 0.05–0.1 km^2 (33 landslides accounting for 18.03% of the TLA) and landslides in the class <0.005 km^2 (32 landslides accounting for 17.49% of the TLN).

The analysis shows that the landslide character of the slopes in the study area is not defined by the number of landslides, but by the areas occupied by landslides. There are 14 landslides in the 0.2–0.5 km^2 class and they occupy 4.05 km^2, while in the class >0.5 km^2 there are 2 landslides which occupy the area of 2.88 km^2; their areas constitute nearly 50% (29.45% and 20.93% respectively; Fig. 8) of the TLA. The Biała Wisełka Landslide Complex (BWLC; Sikora, 2018) stands out among all the forms, accounting for 16.31% of the TLA (2.243 km^2; Fig. 7).

Large landslides often co-occur on a single slope. They then have common boundaries and form groups which cover considerable slope areas. Landslide groups are found in the Gościejów Valley (Gościejów Landslide Group), south-west of Smrekowiec Mountain (Kadłub Landslide Group), on the western slopes of Malinów Mountain (Malinów Landslide Group), on the western and southern slopes of Cienków Mountain (Czarna Wisełka Landslide Group and Cienków Landslide Group) and in the Wątrobny Valley (Kaskady Rodła Landslide Group; Fig. 7).

The largest number of landslides (63) are developed on south-western slopes, i.e. 34.5% of the TLN (Fig. 9). Fewer landslides are located on the southern (26), western (25) and north-western slopes (28), accounting respectively for 14.2%, 13.7 and 15.3% of the TLN. The remaining slopes comprise not more than a dozen landslides and only 2 landslides were recognized on the eastern slopes (Fig. 9). The higher landslide count on southwestern and southern slopes was also reflected in the analysis of landslide sizes, accounting for almost 73% of the TLA in the study area (44.38 and 28.45%, respectively). Landslide areas on the remaining slopes vary from 0.12 to 6.8% of the TLA (Fig. 9).

Most of the landslides studied (85) occupy entire slopes: 10.32 km^2 or 78.75% of the TLA in the study area (Fig. 10). Fifty-eight of them span more than 100 m (of which 13 span more than 200 m). Eleven landslides covering the middle and lower parts occupy 0.86 km^2 (6.23% of the TLA). They also reach significant spans of 100–230 m (Fig. 11). Similarly large and medium spans (50–200 m) are characterised by landslides occupying only the upper parts of the slopes. There are only 13 forms with a total area of 0.50 km^2 (3.63% of the TLA; Fig. 10). A large population of 61 landslides is developed on the lower parts of the slopes and these occupy 1.34 km^2 (9.72% of the TLA; Fig. 10). The spans of landslides in this group are the smallest. They generally reach 50 m, more rarely reach 100 m, and only occasionally >100, up to 146 m (Fig. 11). Landslides located in the middle parts of the slopes (13 forms) occupy only 0.23 km^2 (1.67% of the TLA; Fig. 10). Their spans vary but are usually in the 50–100 m range (Fig. 11). On the scale of the whole population, there is a strong positive linear relationship between the area of landslides and their spans, as shown by the trend line (Fig. 11). The Pearson's correlation coefficient (*rxy*) is 0.917. This relationship dissipates with increasing landslide size.

Most of the landslides in the study area have clearly developed, ten or even several tens of metres high, main scarps and locally minor and lateral escarpments (Fig. 7). The escarpments of landslides are usually rectilinear over a considerable area (up to several hundred metres) and are accompanied by extensional fissures. Landslides and their colluvia are characterized by complex relief, in places with very numerous secondary escarpments, trenches, hollows, flattening and landslide ridges (Fig. 12A, B). Rock blocks are present on the surface of some landslides and caves have developed in the main body of

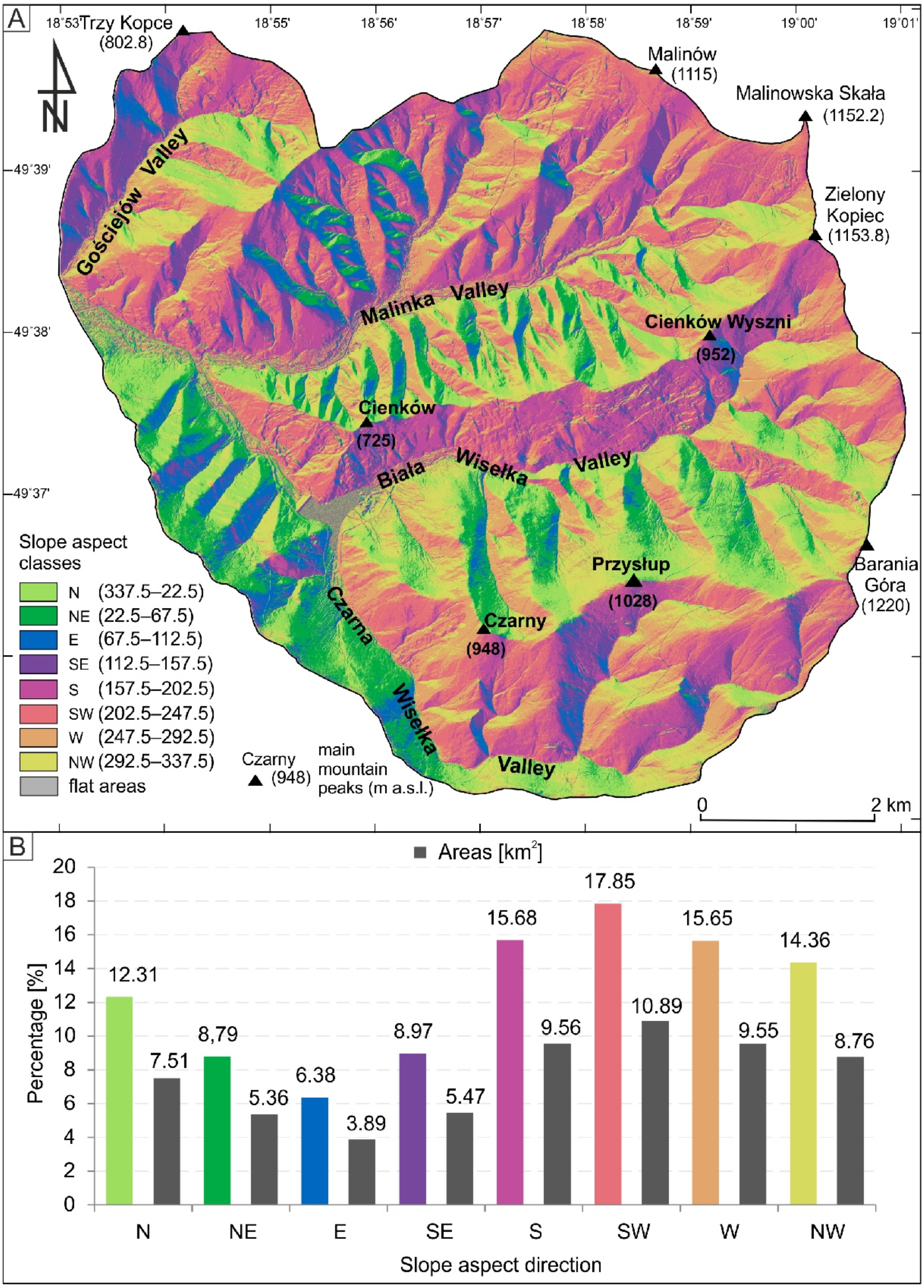

Fig. 5A – aspect map of the study area and B – slope distribution by direction

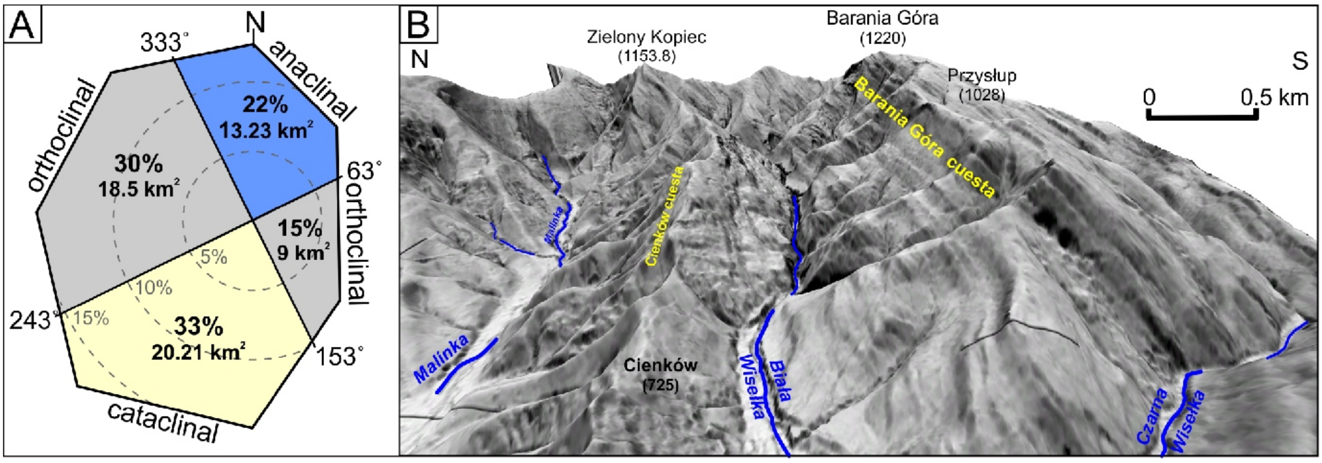

Fig. 6A – structural classification and orientation of slopes in the Wisła River source area and B – DEM of the Barania Góra and Cienków cuestas

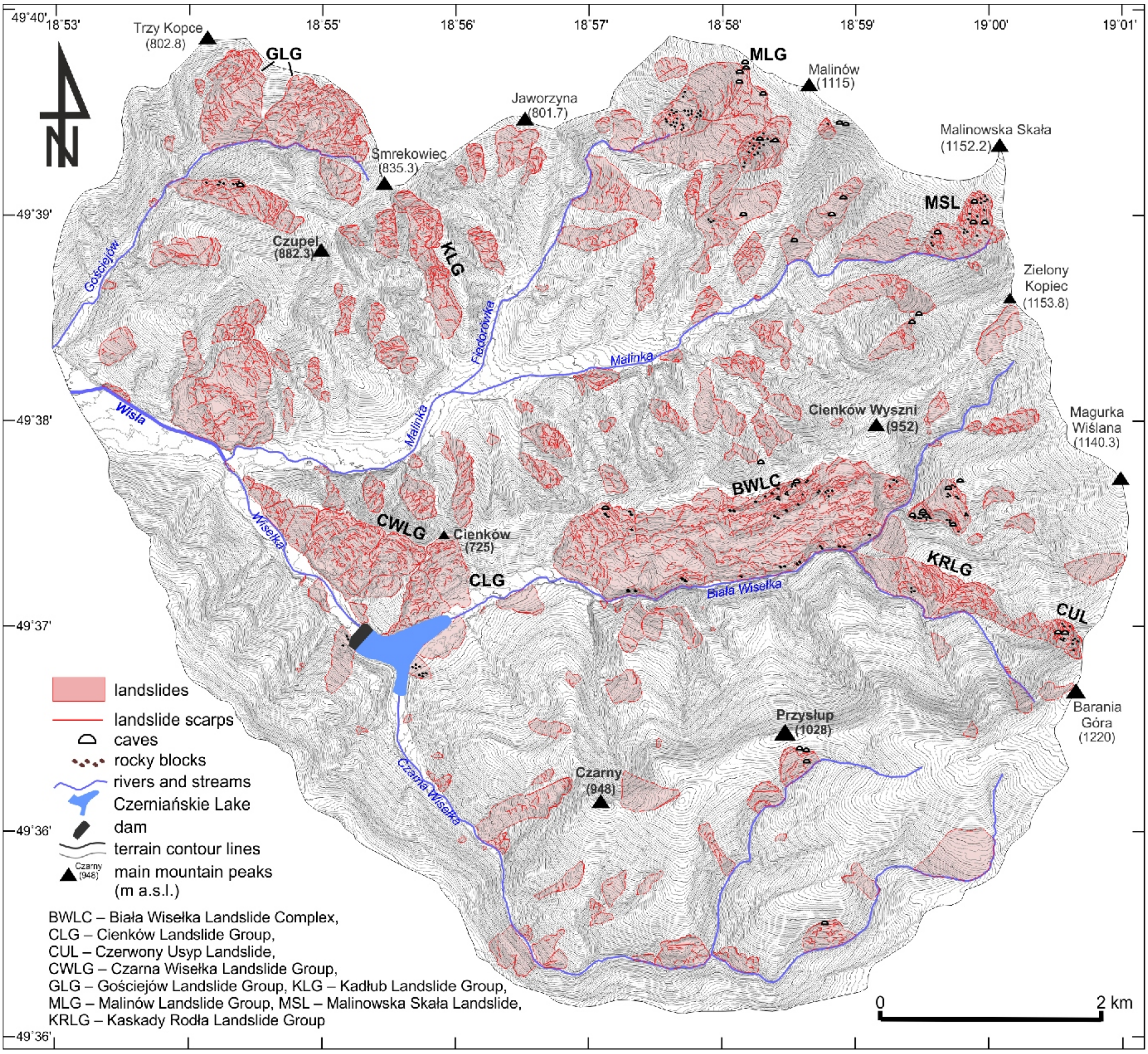

Fig. 7. Landslide map of the Wisła River source area (after Sikora and Piotrowski, 2013a, modified)

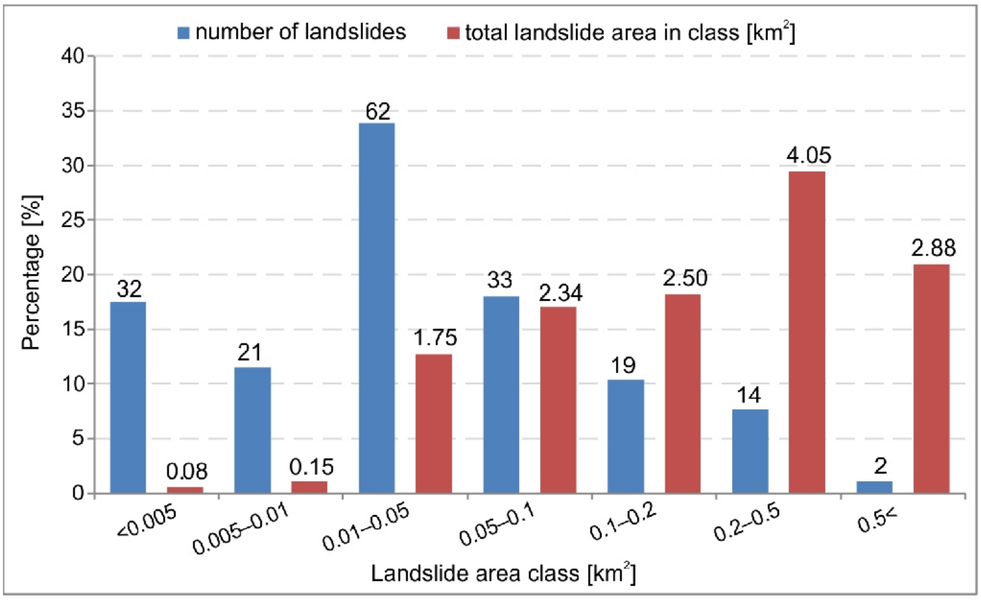

Fig. 8. Distribution of the numbers of landslides in the study area by their size

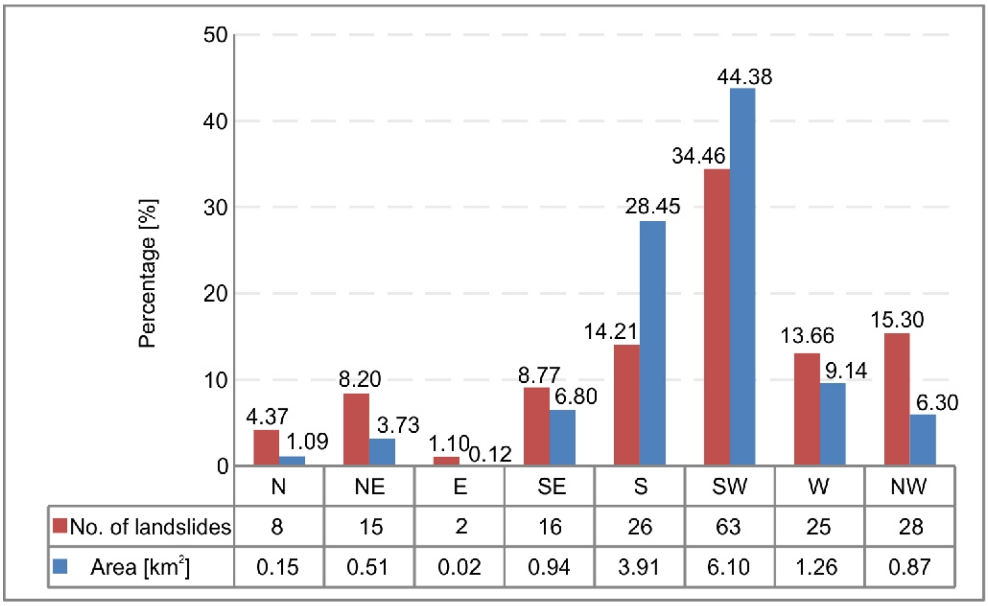

Fig. 9. Landslide distribution relative to slope orientation in the study area

the landslides (Fig. 7; Szura, 2007). Caves (35) were marked based on data from the portal "Jaskinie Polski' (geologia.pgi.gov.pl/jaskinie/). The above information suggests that most of the landslides represent rock slides. Only some, usually very small, landslides can be classified as debris slides (Fig. 12C, D). The landslide toes in the study area are generally distinct; locally they reach 10 or even more than 20 m in height (Fig. 13A).

The oldest landslides have blurred, indistinct relief (Fig. 13B, C), although the blurred relief may have been caused by anthropogenic activity. Such changes were observed on the surfaces of many landslides, e.g. the central part of the landslide in Figure 13B. Many large landslides have varied relief and secondary displacements can be distinguished within them (Fig. 13B, D). Reactivation of rocky scarps of landslides has been inferred based on observations of toppled rock blocks and packages (Fig 14). The topplings are the youngest events that can currently be recorded within the landslides studied, but they are local in scope. Some blocks lean against the trunks of trees several years old, making it possible to approximate date the displacement (Fig. 14A). The oldest detached blocks are overgrown with several decades-old trees (SW slope of Malinów Mountain; Fig. 14B, C). In other cases the blocks are "bare", suggesting relatively recent detachment from the scarps. Rock debris on the Malinów Mountain slopes also documents the degradation of the permafrost on the slopes of the Silesian Beskid in the Late Pleistocene (Fig. 14D; Golonka and Wójcik, 1978; Wójcik, 1997, 2019; Ryłko, 2019). Contemporary reactivation of landslide segments occurs within landslide fronts as a result of erosional undercutting by stream waters.

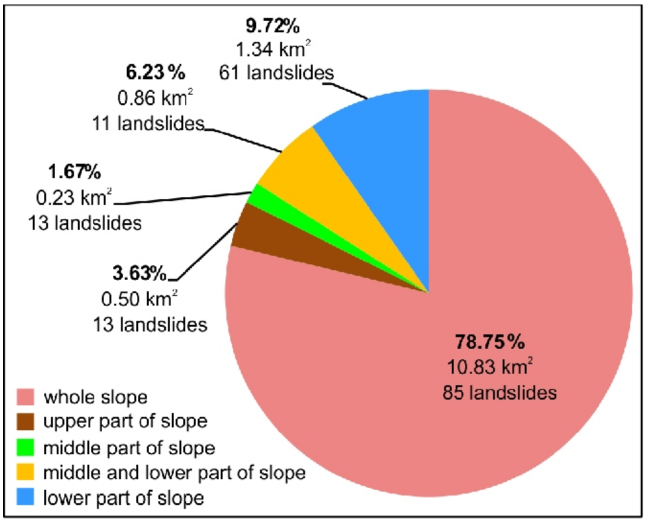

Fig. 10. Distribution of landslides in the study area by their location on the slopes

RELATIONSHIPS BETWEEN LANDSLIDE OCCURRENCE AND LITHOLOGY OF THE BEDROCK

The distribution of landslides in the study area is not uniform (Fig. 7). The part of the area situated to the north of the Biała Wisełka River Valley is most affected by landslides both in terms of the number of landslides and in the total area covered by landslides. There are 113 landslides, with a total area of 10.73 km^2 (ILO: 32.72%). Among these, there are the largest mapped landslides (e.g., Biała Wisełka Landslide Complex) and groups comprising several landslides (Fig. 7). Seventy landslides were mapped on the south side of the Biała Wisełka Valley with a total area of 3.02 km^2 (ILO: 10,74%).

The distribution of landslides on the geological map (Fig. 15) shows that the landslide character of the different areas relates to the geological structure of the bedrock. The Upper Godula Beds constitute the bedrock of 92 landslides with a total area of 6.63 km^2 (48.25% of the TLA; Fig. 16). Landslides have developed mainly within the sandstones and shales of the UGB: 82 landslides with an area of 5.27 km^2 (38.30% of the TLA). Sandstones and shales of the UGB and Malinów Conglomerates underlie 6 landslides with a total area of 1.30 km^2 (9.045% of the TLA). Only 3 landslides with a total area of 0.07 km^2 (0.48% of TLA) developed exclusively on the Malinów Conglomerates (Fig. 16). Within the LIB there developed 77 landslides a total area of 3.48 km^2 (25.35% of the TLA; Fig. 16).

A special case is when landslides developed on slopes where thick-bedded units overlie thin-bedded strata. The largest landslides and landslide complexes have developed in these areas, where numerous trenches, slid-packed and toppled rock blocks are present in the colluvium. In this group, there are 14 landslides covering the area of 3.63 km^2 (34.92% of the TLA; Fig. 16).

The above data indicate that the development of mass movements is favoured by the presence of thin-bedded bedrock facies, especially the UGB. Landslides developed on them (103 forms) occupy a total area of 10.19 km^2 (74.16% of the TLA).

RELATIONSHIPS BETWEEN LANDSLIDES, STRATAL ORIENTATION AND SLOPE EXPOSURE

The distribution of landslides on the slopes and the directions of their displacements relate to the character of the bedrock strata, which are inclined mainly towards the SW and SSW (Fig. 17A). This shows that the orientation of rock strata not only influences the nature of slopes in the study area but also determines the size of landslides and the main directions of their movement. The largest area, 6.49 km^2 (47% of the TLA), is occupied by colluvium comprising landslides displaced towards the SW (Fig. 17B). The second group consists of areas of landslides displaced towards the S (3.71 km^2, 27% of the TLA) and next are surfaces displaced towards the W (1.45 km^2, 11% of the TLA). Areas slid in the other directions comprise no more than 0.82 km^2 (6% of the TLA).

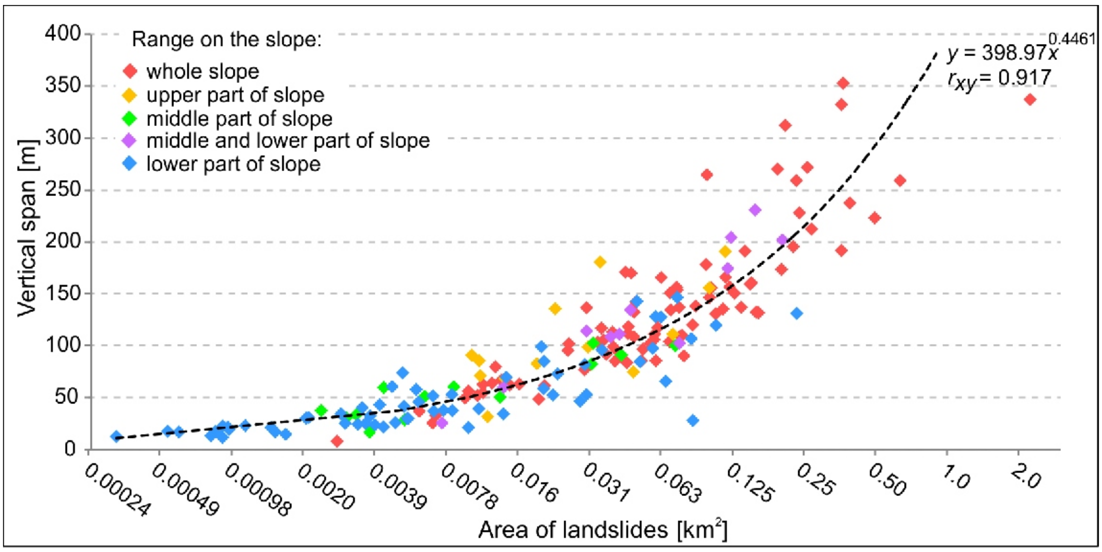

Fig. 11. Distribution of landslide spans by their size and location on the slope

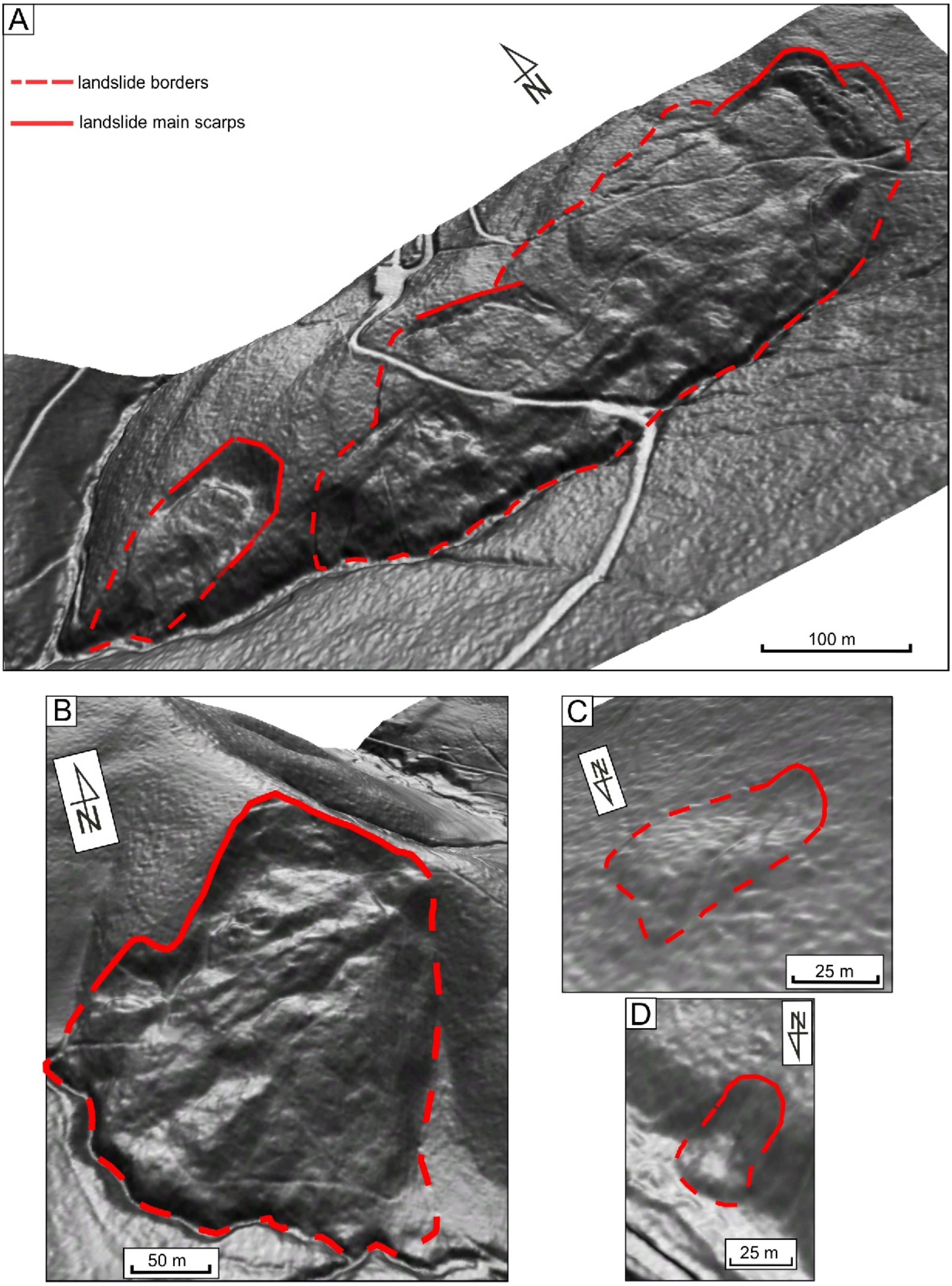

Fig. 12A – landslide in the Biała Wisełka Valley with rectilinear scarps and colluvial trenches on the LiDAR-DEM; B – landslide in the Fiedorów Valley with a high (up to 15 m) main scarp, several minor scarps and a few colluvial trenches; C, D – small landslides in weathered soils on the slopes of the Czarna Wisełka Valley

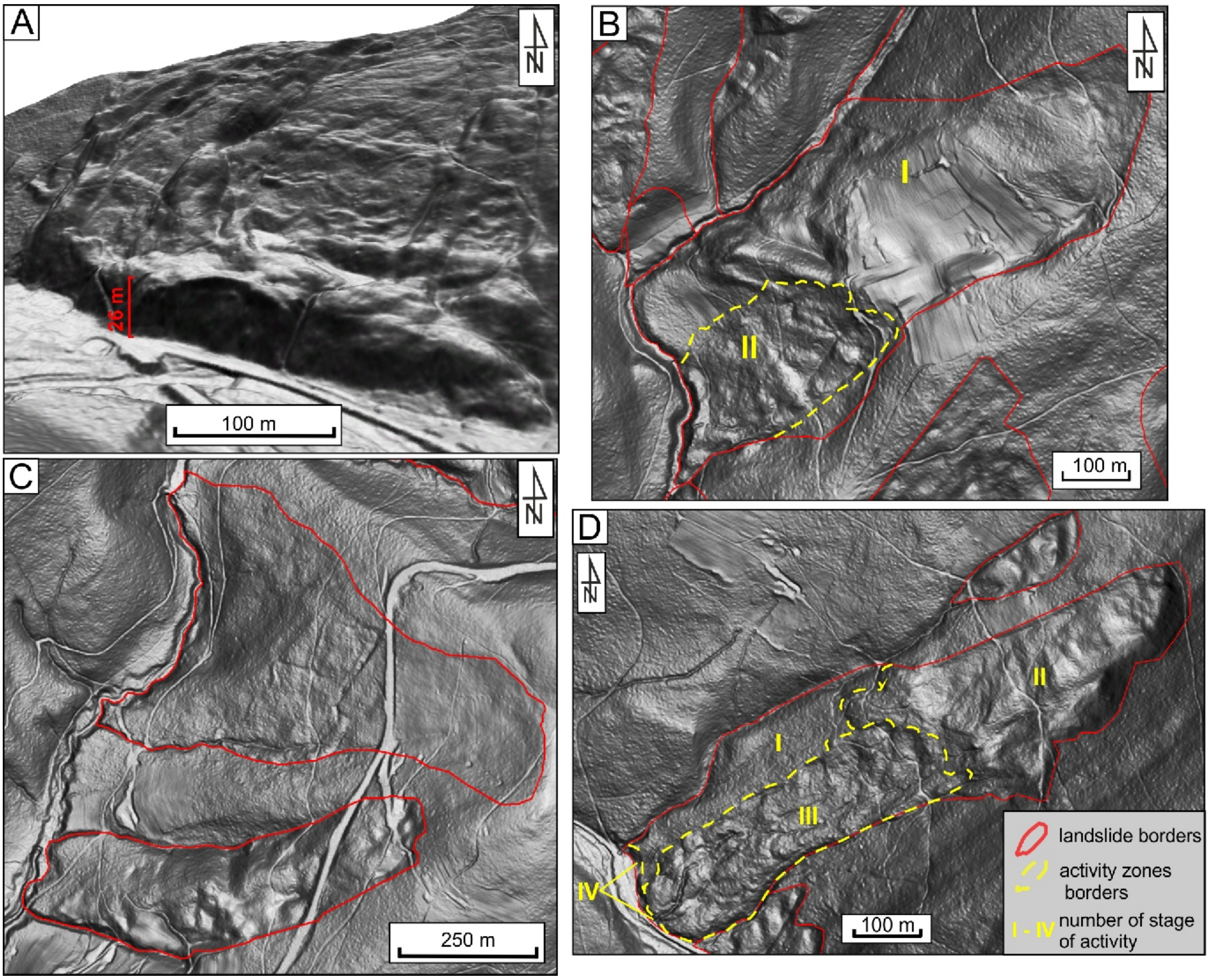

Fig. 13A – landslide on the SW slopes of Cienków Mountain with clearly visible relief and high (up to 26 m) toe; B – landslide in the Malinka Valley with different visible relief, the central part of the colluvium has been changed by anthropogenic activity; C – landslides in the Fiedorów Valley with different exposed colluvium relief; D – multi-stage relief of the long landslide on the SW slopes of Czarny Mountain

Displacements consequent or insequent to the orientation of the strata account for 87% of the TLA in the study area (Fig. 17C). Consequent landslides account for 38% (5.24 km^2) and insequent landslides for 49% (6.71 km^2). Only 4% (0.68 km^2) of the TLA comprise surfaces displaced subsequent to the stratal alignment.

The dependence of landslide development on the orientation of the bedrock influences the vertical span of landslides, which varies from 8 to 353 m. Nearly 52% of landslides (96 forms) reach spans of 50–150 m, and 20% (37 forms) exceed 150 m (Fig. 18). Although this parameter depends on the relative height of the slopes in the study area (200–450 m), the largest spans between the slope and the base of the face (200–353 m) are reached by landslides developed consequently and insequently to the layering (Fig. 19). Spans of landslides developed obsequent and subsequent with displacement directions towards the N, NE and E, rarely exceed 150 m. The relationship between landslide spans and sizes with displacement directions is described by the linear correlation found earlier (with a Pearson coefficient of 0.92; Fig. 19). A similar graph in Figure 18 shows that both parameters depend on the direction of landslide displacements.

LANDSLIDE GEOMETRY

Analysis of landslide shapes based on the ratio of their width to length (shape factor: W/L) showed that wide forms predominate over long forms (Fig. 20A). Areas occupied by wide landslides with W/L>1.1 occupy 54% of the TLA (82 landslides), and long landslides with W/L<0.9 occupy 35% of this area (86 landslides), and isometric landslides with L~W:1.0+/-0.1 form 11% of the TLA (15 landslides).

The width of landslides in the study area varies depending on the arrangement of landslides relative to the bedrock and its lithology. Among the landslides developed consequently and insequently to the bedding orientation, the largest areas are occupied by wide forms (23.39% and 29.30% of the TLA, respectively), although locally long forms are more numerous (Fig. 20B). Wide and long forms in landslides developed obsequently and subsequently to the bedding planes occupy similar areas: 3.24, 3.61, 2.66 and 2.25%, of the TLA, respectively. Landslides formed with complicated bedding relationships are long and occupy 2.55% of the TLA. Isometric forms are frequent for the innsequent landslides and occupy 3.01% of the TLA. This type of form is also represented by obsequent

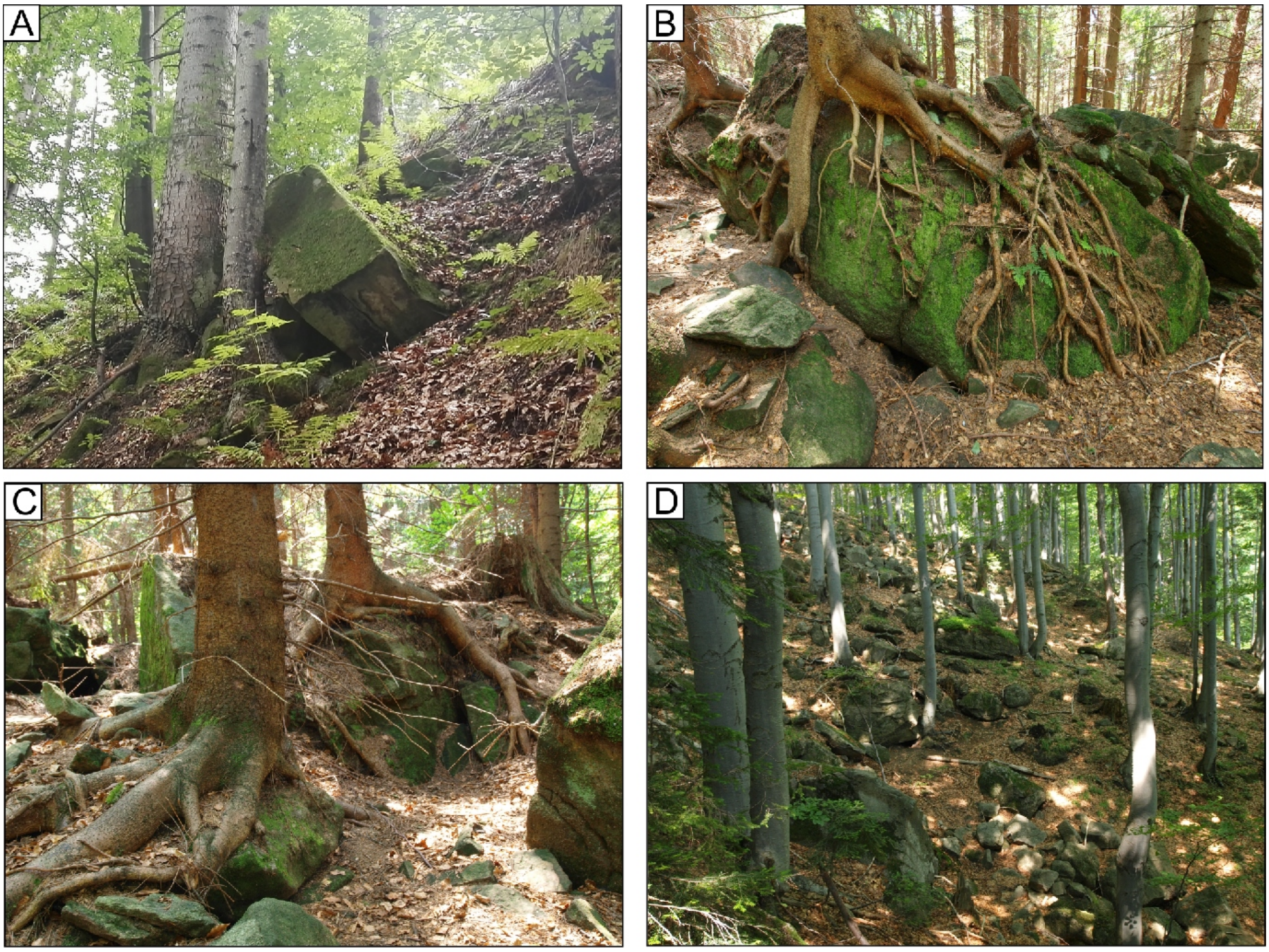

Fig. 14A, B – blocks of the Malinów Conglomerates in the landslide colluvia on the SW slopes of Malinów Mountain; C – field of blocks on the SW slope of Malinów Mountain produced by Pleistocene permafrost conditions; D – toppled and rolled block on a tree trunk, the lower part of the Biała Wisełka Landslide Complex

landslides (0.97% of the TLA) and less frequently by consequent landslides (0.03% of the TLA).

The thick-bedded sandstones and conglomerates of the LIB are predisposed to the development of wide landslides (Fig. 20C). Wide forms within them occupy 66.28%, long forms 24.29% and isometric forms 9.43% of the landslide area. The share of wide and isometric forms increases where the LIB are underlain by the thin-bedded UGB. Wide landslides then account for 73.68%, long landslides 8.39% and isometric landslides 17.93.% of the landslide area. Wide forms also account for 42.20% of the landslide area developed exclusively in thin-bedded sandstones and shales of the UGB and long forms occupy a little more: 46.70%. Isometric forms in the UGB occupied 11.10% of the landslide area (Fig. 20B). Of the 3 landslides developed within the Malinów Conglomerates, two are broad (71.45% of the area) and one is long (28.55% of the area), with no isometric landslides in this group. Although the development of wide landslides correlates with the occurrence of thick-bedded rocks, different results were obtained when landslides were founded on thick-bedded Malinów Conglomerates underlain by sandstones and UGB shales. In this case, more (6) landsides are long (89.49% of landslide area) than wide (10.51% of landslide area) while isometric landslides are absent. This is because the side scarps of these landslides strike along faults, elongating the landslide geometry (Fig. 15). Elsewhere, several long and large landslides can occur side by side on a slope creating, in effect, a wide landslide area (e.g., the SW slope of Malinów Mountain; Fig. 7).

The relationship between the width and length of landslides is quite strong, as indicated by the trend line and the value of Pearson's correlation coefficient (*rxy*) equal to 0.72 (Fig. 21). The landslide shapes change with increase in their area and this is influenced by the lithology of the bedrock. Up to a size of ~200 200 m, landslide shapes are generally concentrated near the isometric axis (Fig. 21). The lower ranges of the interval described are dominated by long landslides, developed mostly in the LIB. In the middle range of the interval, the proportion of long landslides developed within the UGB increases and wide landslides appear. Landslides developed in the LIB are situated close to the isometric axis or on it; in two landslides these rocks are underlain by the UGB. Landslides developed only in Malinów Conglomerates are also located close to the axis (Fig. 21). In the upper range of this interval landslides in the UGB are wide and significantly off the isometric axis. Close to it are landslides in the LIB.

The dispersion of landslide shapes gradually increases to an interval of ~500 500 m. In this interval, landslides mainly in the LIB are located in or adjacent to the isometric axis. The majority of landslides in this compartment are wide. Occasionally, landslides in the UGB are located on the isometric axis. Long

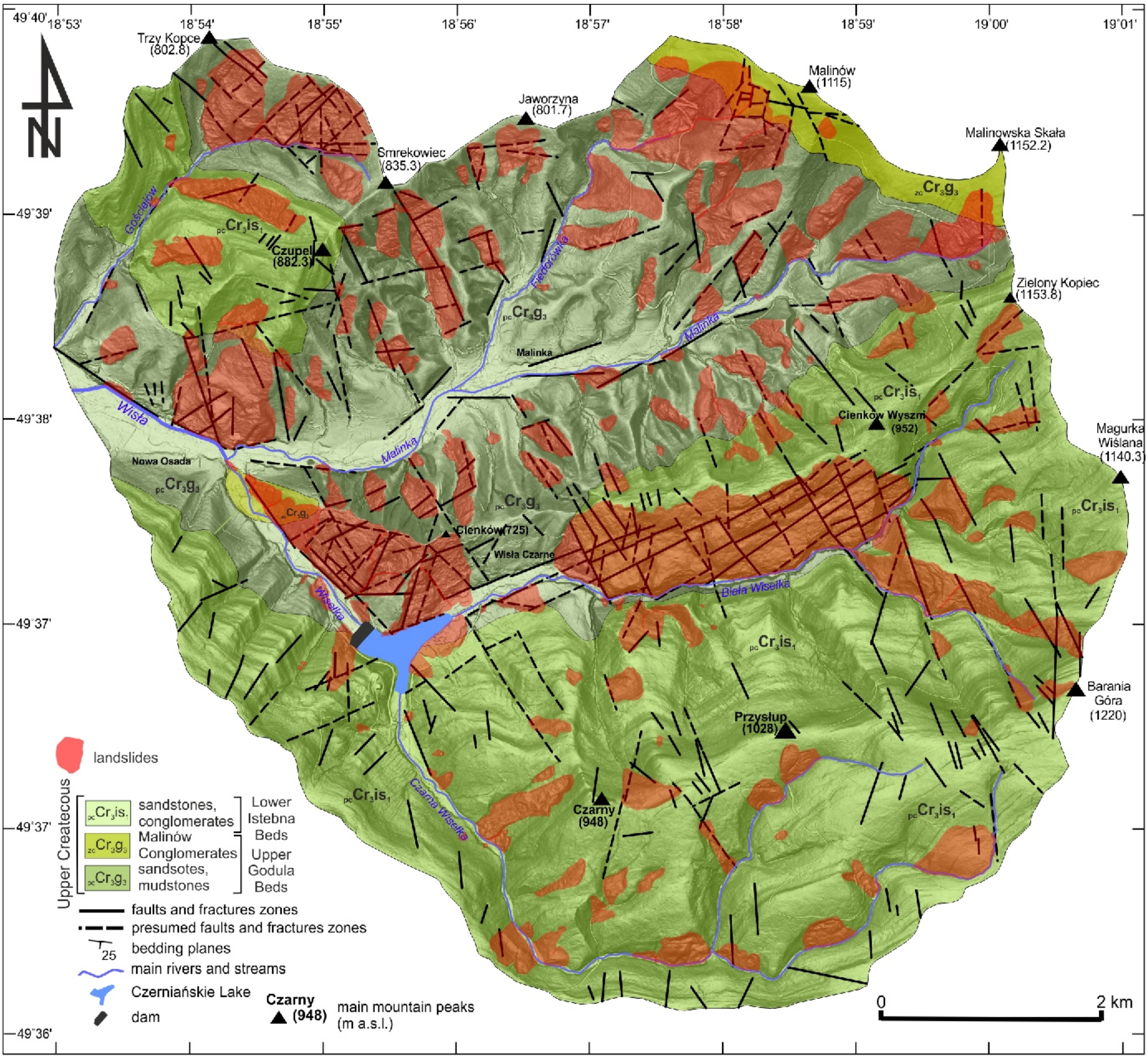

Fig. 15. Landslide areas on a litho-structural map of the study area

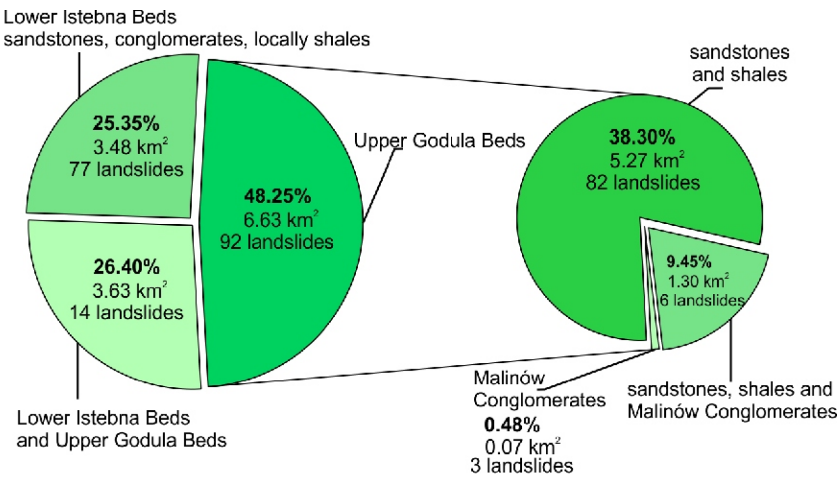

Fig. 16. Landslide distribution according to the lithology of the bedrock

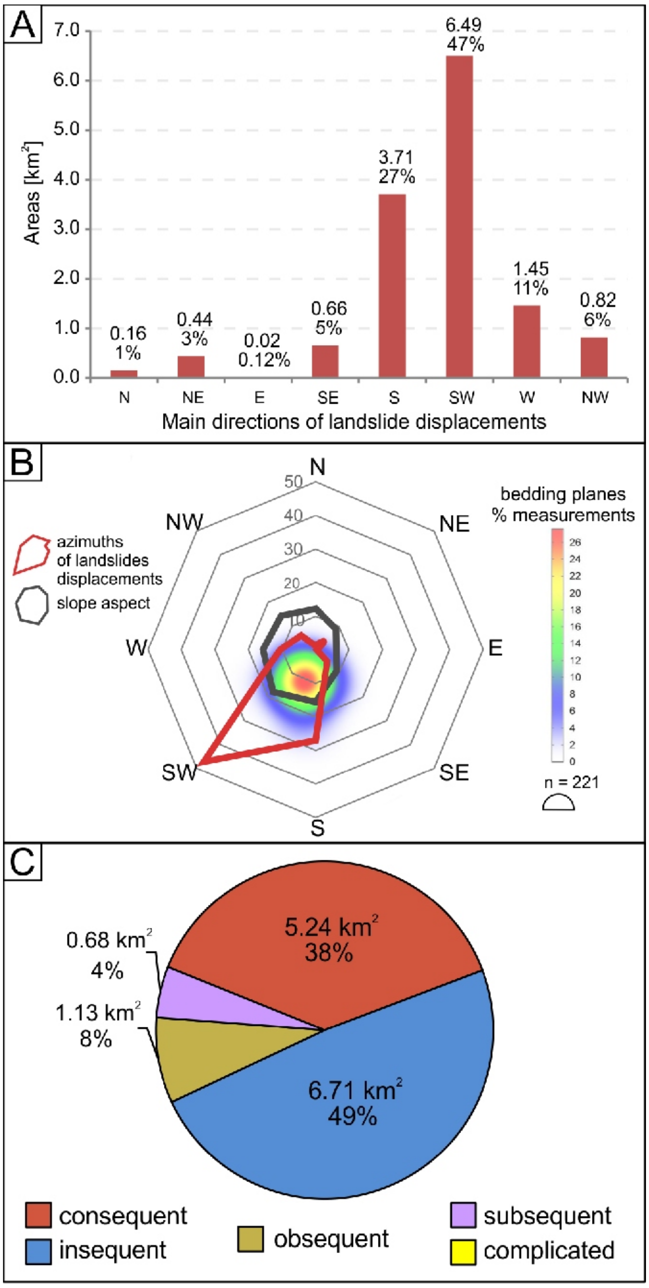

Fig. 17A – distribution of landslide displacements by their sizes; B – combined diagram of landslide sliding directions against relative to slope classification and bedding plane orientations; C – classification of landslide displacements by the orientation of bedding planes

forms also slightly predominate among landslides in this section. Landslides with both the LIB and the UGB as their base are located far from the isometric axis. In this group, the number of long forms slightly outweighs the wide ones (Fig. 21).

Above a size of 500 500 m, landslide shapes are highly dispersed. Long and wide forms occur within the thin-bedded rocks of the UGB, but the population moves away from the isometric axis. Long forms (including the longest among all the landslides) dominate where thin-bedded rocks are overlain by the Malinów Conglomerates. Most landslides in the LIB adopt broad forms. The same is true when they are underlain by thin-bedded UGB rocks.

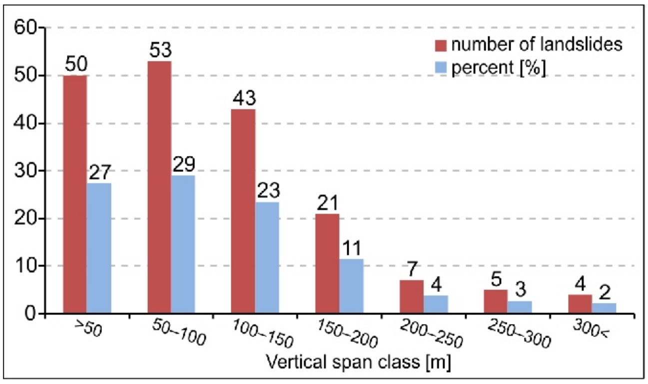

Fig. 18. Landslide distribution according to vertical span classes

The shape of landslides also changes with their size. Among very small landslides (up to 0.001 km^2), long landslides (W/L: 0.50–0.9) developed in the LIB (Fig. 22), and only landslides in thin-bedded rocks of the UGB (with W/L reaching 2.20) are wide. Among small landslides (up to 0.010 km^2), landslides developed only in the thin-bedded UGB rocks or only in the LIB show a large shape scatter (Fig. 22). In this interval, most landslides are long, especially in the LIB (W/L: 0.1–0.9). Landslides developed in the LIB underlain by the UGB are isometric (0.9–1.1).

The relationship is reversed in the medium landslide group (0.010 to 0.10 km^2). As the area increases, landslides in the UGB are more likely to be long (W/L: 0.4–0.8), while more wide (W/L:1.1–2.0) and very wide (W/L: >2.0) landslides appear among landslides in the LIB. Among the medium landslides, there is also the highest population of isometric forms. Landslides developed in the LIB/UGB configuration are either long or very wide. On the other hand, in the group of large landslides (0.1–0.3 km^2), these landslides are more often wide, similarly to forms developed in the LIB. Large landslides in the UGB tend to be long, as are landslides in the Malinów Conglomerates overlying the sandstones and shales of the UGB (W/L: 0.3–0.8). Only 1 landslide (Biała Wisełka Landslide Complex) is present in the interval of the largest landslides, i.e. those reaching sizes of >1 km^2, and it is developed in LIB/UGB bedrock (Fig. 22).

The analyses of the width-to-length ratio of landslides developed in the different rock facies described above indicated that the geometrical relationships are variable and, as these parameters change, the shapes disperse. Undoubtedly, the lithological factor indicated earlier plays a role in this. On the other hand, the analysis of the W/L ratio in relation to the size of landslides and relation to the lithology of the bedrock made it possible to discern the large variety of the geometry of forms and its variability with an increase in the area of landslides. An increasingly clear geometrical division of landslides into wide ones in the LIB and long ones in the UGB is then marked. If this dependence was dictated only by the lithological factor, this division would be the same and equally clear within the smaller forms. Therefore, the geometry of landslides developed in particular rock facies seems influenced by additional factors related to the tectonics and structure of the geological basement.

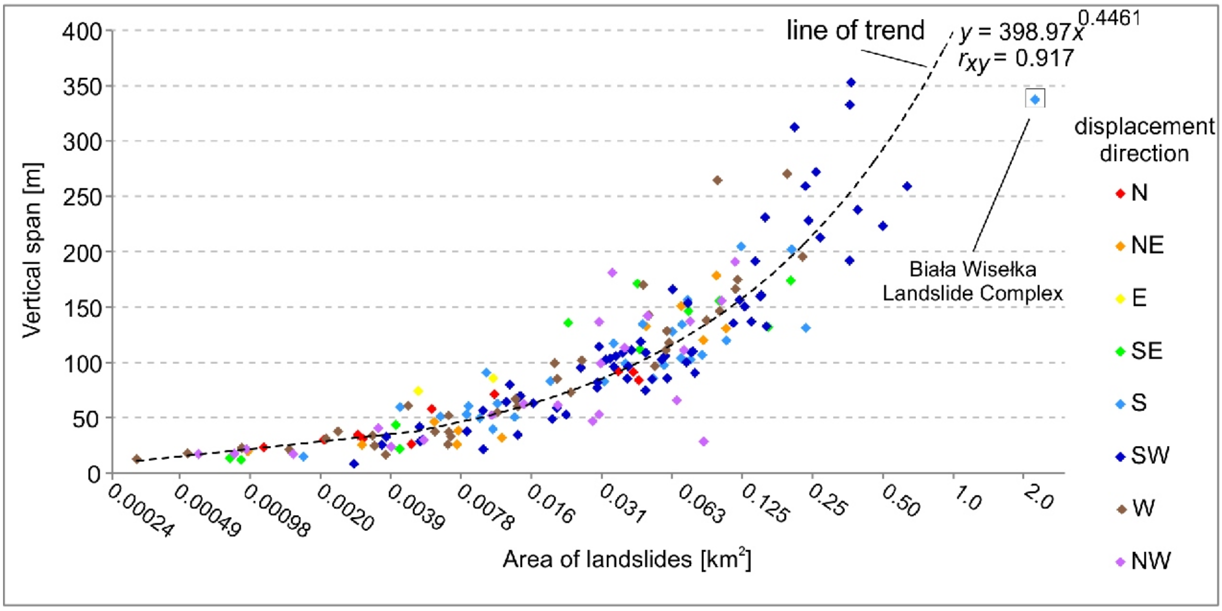

Fig. 19. Landslide vertical span distribution according to the distance and directions of displacement

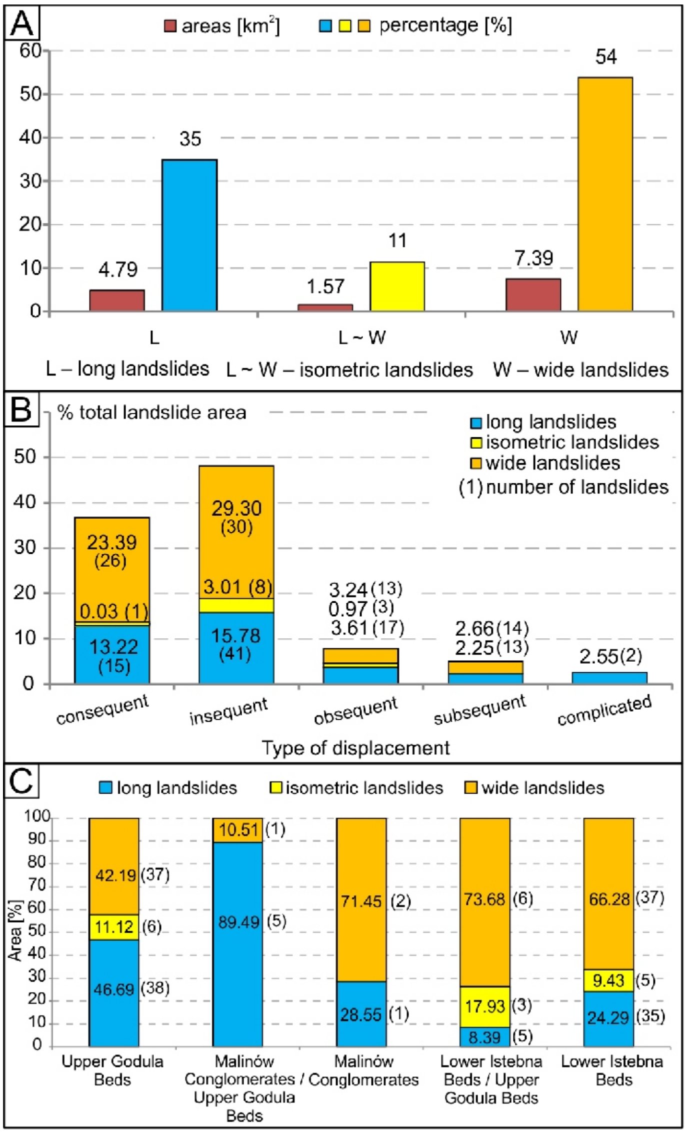

Fig. 20A – distribution of geometry of landslides by size;
B – displacement direction relative to stratal orientation;
C – lithology of the bedrock

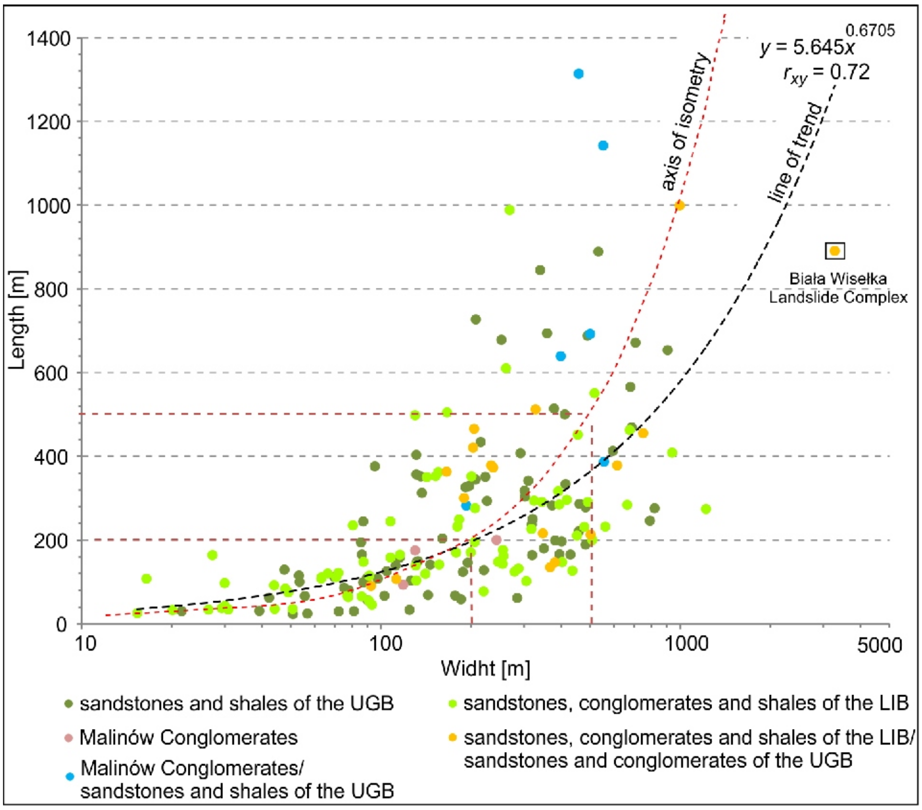

Fig. 21. Distribution of landslides relative to isometry axis and lithology of the bedrock

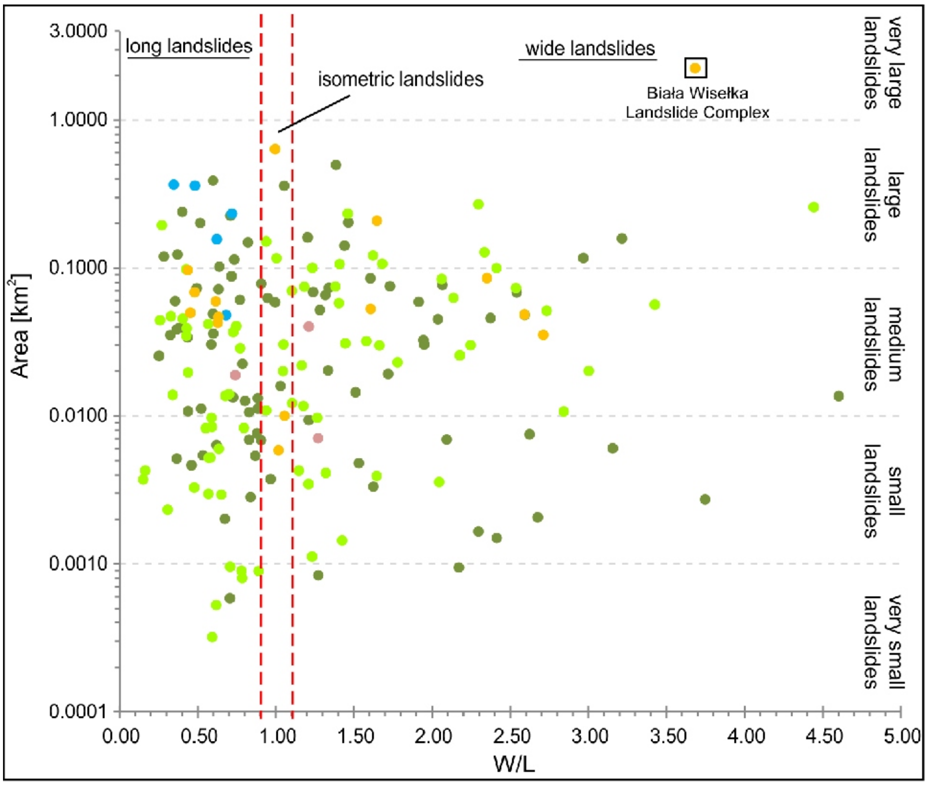

Fig. 22. Distribution of size class of landslides by W/L index and lithology of the bedrock

Explanations as on Figure 21

DISCUSSION AND SUMMARY OF RESEARCH RESULTS

In the study area, 183 landslides were identified covering 22.6% of the land area. The ILO index is ~2.5 times higher than the one indicated for this area by Bober (1984). The use of high-resolution DEM from LiDAR data for analysis of landslide terrains made it possible to more precisely establish the ranges of landslide areas in comparison with earlier maps and provide more accurate delineation of elements of landslide relief. Comparison of landslide shapes with the results of slope analysis based on LiDAR-DEM revealed geometrical relations between landslides, the litho-structural character of terrain relief, and the state of preservation of the rocks. Preliminary results showed a high correlation between landslide occurrence (especially of landslide groups) and the strike and density of the topolineaments (Sikora, 2017). According to the new structural data from the study area (Sikora, 2022), fault and fracture zones are reflected in the relief as numerous topolineaments. Similarly, many landslide scarps are marked on the LiDAR-DEM. Therefore, the application of topolineaments analysis is a promising perspective for further research on the relationships between landslide development and the structure of the bedrock.

The size of landslides registered varies, with nearly 79% of them occupying the whole slope area. Nearly 73% of the area occupied by landslides is located on slopes with southwestern and southern exposures, whose orientation refers to the dominant monoclinal arrangement of strata in the bedrock of the study area (Książkiewicz, 1972; Sikora, 2022). Thus, the largest share in mass movements (87%) is accounted for by landslides developed consequently or insequently to the strata orientation. These landslides also reach the greatest vertical span, which in the case of the largest forms can reach up to 350 m. The landslides are usually bounded by distinct, often rocky and rectilinear, escarpments, including lateral ones.

Wide landslides stand out in the maps and the analyses carried out showed that their occurrence depends on the lithology of the bedrock. Analysis of the geometry of landslides showed that these dominate over long forms (54% of landslide area in the study area) and are most typical of landslides occurring in a pattern consequent and insequent with the orientation of bedding planes. An important factor influencing the geometry of landslides is the formation and mutual arrangement of individual rock layers. Wide landslides, usually developed in thick-bedded facies of the Lower Istebna Beds, predominate where weakly fractured thick-bedded rocks are underlain by strongly fractured thin-bedded flysch of the Upper Godula Beds. Despite obvious differences in the anisotropy of the rocks, wide landslides have a significant share also in forms developed within the Upper Godula Beds.

Wide landslides include the largest ones documented in the study area. The results of these and previous analyses suggest that the wide Biała Wisełka Landslide Complex (Sikora, 2018), the largest in the study area, is conditioned by tectonic structures, seen in the strike of scarps reflecting the strike of fracture and fault zones. Moreover, the sizes and vertical span of many documented landslides suggest that they represent structurally controlled deep-seated types or in a few cases rock slope deformation like the Biała Wisełka Landslide Complex (Sikora, 2018). Many deep-seated landslides have been documented in the Czech Flysch Carpathians (Baroň et al., 2004, 2005; Pánek et al., 2011, 2019; Stemberk et al., 2017; Chalupa et al., 2018; Břežný et al., 2021) including landslides developed within monoclinal bedrock structure (Břežný and Pánek, 2017).

Therefore, individual wide landslides and wide landslide complexes and isometric forms conditioned by the bedrock structure represent frontal landslides *sensu* Ziętara (1964, 1968).

Thus, the presence of frontal landslides in mountainous areas may indirectly indicate the important role of the structure of the rock massif in the development of other landslides in adjacent areas (Ziętara and Bajgier, 1989; Bajgier, 1989; Wójcik, 1997; Margielewski, 2004; Sikora, 2017). Therefore, further research is needed towards a precise understanding of the structural condition of landslide movements in the study area. Only then will it be possible to trace mechanical and geometric changes within landslides and, consequently, to carry out landslide typology and classification. The data collected during the studies on the geometry of landslides, supplemented with the results of structural studies on landslides, make it possible to discern mechanisms affecting the relief of mountain slopes, and the dynamics and causes of mass movements in this part of Silesian Beskid.

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