Geology of the Magura Nappe, south-western Gorce Mountains (Outer Carpathians, Poland)

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1. Introduction

The Magura Nappe, located in the Gorce Mountains, one of the mountain belts constituting the Polish Outer Carpathians, has not yet been fully investigated. Heretofore, no comprehensive study of lithostratigraphic units has been carried out there, nor have its lithostratigraphic boundaries been correctly defined or precisely drawn on geological maps. Definitions of some individual lithostratigraphic divisions have been left open to question; moreover, micropalaeontological studies have presented divergent views on the age of some deposits (Cieszkowski, 1992; Kaczmarek et al., 2016; Oszczypko-Clowes et al., 2018). Use of the formal names of selected lithostratigraphic divisions in the Krynica Subunit as proposed by Birkenmajer and Oszczypko (1989) is problematic, as these names are formally associated with the Beskid Sądecki range, where the development of some lithofacies differs from that in the Gorce. In previous research, the tectonics of the south-western part of the Gorce were not described in detail (Burtan et al., 1978a, 1978b; Watycha, 1975, p. 1976). Moreover, previous mappings have failed to reconstruct fold structures or faults. Also, the lower range tectonic units have not been properly distinguished in previous studies (Watycha, 1963; Watycha in: Burtan et al., 1978a, 1978b).

In the present study, the authors decided to conduct new, classical geological mapping. The main aim was the construction of a new geological map of the Magura Nappe deposits in the south-western part of the Gorce Mountains. The map was drawn up based on data obtained via accurate geological mapping performed at 1:10,000 scale and acquisition of geological content through the analysis of a high-resolution digital elevation model (DEM). This research delivers new tectonic and lithostratigraphic data of the study area. The criteria adopted for distinguishing various lithostratigraphic units during the fieldwork in the study area will be clearly described. One of the main results presented in the present paper is a geological map on a 1:25,000 scale, complete with geological cross-sections and lithostratigraphic logs ‘Main Map’. This research was primarily focused on Magura Nappe deposits. Great attention was paid during the construction of this map to the clarification of the boundaries of lithostratigraphic units. On the map, folds, faults, and thrusts are shown, as well as being detailed on the tectonic sketch (Figure 1). This significant progress in the identification of geological structures was possible thanks to the application of modern geographic information system methods based on a high-resolution digital elevation model (DEM) to the classical geological mapping methodology.
2. Geological setting

The Western Carpathians are subdivided into exter- nides (the Outer Carpathians) and internides (including the Central and Inner Carpathians; Golonka et al., 2018; Golonka, Pietsch, et al., 2019; Golonka, Waśkowska, et al., 2019; Golonka et al., 2020; Książkiewicz, 1977; Plaśienka, 2018), both distinctly bounded by the Pieniny Klippen Belt (Figure 2(A,B)). The recent geological structure of the Western Carpathians is a result of plate tectonics which led to a collision of the Central Carpathian, which is part of the Adriatic (Apulian) plate, with the northern European Plate (Golonka, Pietsch, et al., 2019; Golonka, Waśkowska, et al., 2019; Golonka et al., 2020). As part of a subduction process, the European Plate is sliding towards the south beneath the Adriatic (Apulian) Plate (Golonka, Waśkowska, et al., 2019; Golonka et al., 2020). In this location, the Outer Carpathians formed an accre- tionary wedge thrust onto the European Plate. The geological deep structure of the Polish Carpathians is presented on a cross-section along the main geotra- verse between Kraków and Zakopane (Figure 2(A, B)), constructed on the basis of data coming from deep boreholes (up to 5000 m) and seismic data recorded in the last four decades of the twentieth century (e.g. Golonka et al., 2005, 2018, Golonka, Pietsch, et al., 2019; Marzec et al., 2019; Sikora et al., 1980).

The Central Carpathians constitute a prolongation of the Eastern Alps (which, taken together, form part of the ALCAPA tectonic plate; e.g. Golonka et al., 2020; Plaśienka, 2018), built of Permian–Cretaceous deposits covering an older crystalline bedrock composed mainly of granitoids and metamorphic rocks. At the end of the Late Cretaceous, folding and thrust- ing resulted in the creation of a system of nappes. Later, during the Palaeogene, a period of uplifted and eroded orogeny was entered by transgression. This resulted in the sedimentation of several thou- sands of metres of deposits, mainly turbidites (Soták et al., 2001). In general, this post-orogenic sedimentary cover is known as the Central Carpathian Palaeogene.

The Pieniny Klippen Belt (PKB) is a narrow tec- tonic unit extending from Austria to Romania, along the boundary between the Central and Outer Carpathians (Birkenmajer, 1986; Golonka et al., 2015, 2018; Golonka, Pietsch, et al., 2019; Golonka, Waśkowska, et al., 2019; Golonka et al., 2020; Książkiewicz, 1977; Plaśienka, 2018). The Mesozoic–lower Cenozoic sedimentary rocks of the PKB were deposited in the
 palaeogeographic realm of the Alpine Tethys. During the Late Cretaceous–Palaeogene, the sedimentary cover was deformed by orogenic deformations and became part of the accretionary prism formed in front of the advancing ALCAPA (Central Carpathians) and subsequently incorporated into the Outer Carpathians in the Miocene orogenic phase (Golonka, Waśkowska, et al., 2019). Generally, the PKB is analogous to the klippen zones in the northern Alps of Eastern Austria.

The Outer Carpathians, built mainly of thick flysch successions (up to 6000 m), are also known as the Flysch Carpathians (e.g. Golonka et al., 2005; Golonka, Waśkowska, et al., 2019; Golonka et al., 2020; Książkiewicz, 1977; Ślązka et al., 2006). Their origin is connected with the geological evolution of the northern part of the Alpine Tethys, where several sedimentary basins, separated by ridges, were formed. During the Late Jurassic–Early Miocene, these basins were filled mainly with deep-sea sediments deposited by turbidity currents. The northward movement of the Central Carpathian Plate and the underriding of the European Plate beneath it led to the development of an accretionary wedge and reorganisation of the Outer Carpathian basins during the synorogenic stage. Deposits filling basins were folded and detached from their basement in the Miocene. These deposits formed a sequence of nappes bounded by thrusts.

Figure 2. Location of the research area: (A) map of the Outer Western Carpathians in Poland (after Cieszkowski et al., 2017); (B) cross-section A–B through the Western Carpathians (Zakopane–Cracow line after Golonka et al., 2019, simplified). Map presents the polish sector of the Western Carpathians (after Cieszkowski et al., 2017). There are marked the main Carpathians tectonic units with the location of the research area (red box) and with the line of the cross-section Cracow–Zakopane, which is added below the map. The cross-section presents the nappes structure of the Outer Carpathians and their basement, as well as contact with Central Carpathians.
Together, they overthrust the consolidated North European Plate, consisting of Precambrian, Palaeozoic, and Mesozoic rocks. The platform was underridden beneath the Outer Carpathian Plate. In the subduction processes the ridges collapsed; as a result, only basal deposits were preserved in the nappes. In front of the Outer Carpathian orogenic belt thrusting over the North European Platform, the Carpathian Foredeep, filled with Miocene molasses, was formed (Golonka, Waszkowska, et al., 2019; Śłaczka et al., 2006).

The Magura Nappe, the largest tectonic unit in the Polish and Slovakian sector of the Outer Carpathians, tectonically adjoins the PKB (e.g. Golonka et al., 2015) to the south, bordering on the Inner Carpathians (Figure 2), and overthrusts northwardly the Dukla, Fore-Magura, and Silesian Nappes. Within the Magura Nappe, four facies-tectonic zones (subunits) can be distinguished (Koszarski et al., 1974). The thicknesses of their sedimentary successions range between 2000 and 5000 m. The Krynica and Bystrica Subunits occur in the Gorce Mountains. The former is spread over the southern and central parts of the studied area, whereas the Bystrica Subunit occupies only a narrow fragment in its northern part. Near the western border of the research area is the Kraków–Zakopane geological cross-section representing the deep geological structures of the Carpathians and their consolidated basement between the emergence of the European Platform in Kraków and the Inner Carpathians in the Tatra Mountains (Cieszkowski, 2006; Golonka et al., 2005, 2018; Golonka, Pietsch, et al., 2019; Marzec et al., 2019; Sikora et al., 1980).

3. Methods
3.1. Methods and data

The geological map of the south-western part of the Gorce Mountains presented here was constructed on the basis of accurate geological investigations, using traditional methods of geological field mapping coupled with the interpretation of a high-resolution digital elevation model (DEM). DEMs are successfully used in geological research (Cieszkowski et al., 2017; Lo et al., 2021; Starzec et al., 2018). The field work, which enabled direct observations of outcrops, was carried out in 2015–2018. Subsequently, studies were made on the flysch deposits and on the lithological and sedimentological features of the mapped deposits, in order to better define the stratigraphic boundaries between the several lithostratigraphic units. The mapped tectonic units were also analysed. In locations without outcrops, we attempted to identify the lithostratigraphic units by means of a study of the composition of weathering covers. In places with no outcrops, as well as in inaccessible areas, remote sensing methods were of particular importance. In such cases, stratification, lithostratigraphic boundaries, faults, and fractures, thrusts, fold structures, and geomorphological forms were clearly visible where they existed in places with thin and undisturbed weathered covers (Figures 3 and 4; Kania & Szczęp, 2020).

3.2. DEM analyses

The high-resolution digital elevation model (DEM) was based on airborne laser scanning (ASL). The standard for this ASL data was an average density of 4–6 points/m². The working resolution of the DEM was 1 m; the root mean square error of height was <15 cm (Wężyk, 2015). The advantage of this type of DEM is its capacity for the observation of the morphology of terrain without vegetation.

During a preliminary study, research methods based on a DEM applicable to geological research were selected. Firstly, long, linear forms in slope morphology, i.e. step-like forms (variations in slope inclination; Figure 3), were related to the stratifications of sandstone-shale deposits or more resistant sandstone layers. Secondly, changes in features such as the density, thickness, and height of the above-mentioned linear forms were associated with various levels of resistance to the erosion of the rock formations and dipping of layers. These observations enabled easier, faster interpretation of the boundaries of each rock formation over long distances (Figures 3 and 4), despite a lack of outcrops in many places. These methods were important e.g. in the correction of the Krynica Subunit trace of the thrust.

In the research, the authors used the lineament method, as well as observations of breaks in the mentioned linear forms visible on the materials from the DEM (Figure 3). In the current study, we accepted the definition of lineament given by O’Leary et al. (1976) as a linear form in morphology occurring over considerable distances with a high probability of association with a geological structure. Based on the DEM research, a network of lineaments was obtained and referred to potential faults. Based on the DEM analysis, the detected lineaments were randomly tested in the field in order to validate the hypothesis. Field testing allowed us to confirm most of the interpreted lineaments as faults; the latter faults were identified by the occurrence of such forms as fault throws, fault-drag related folds, fractures, melange zones, tectonic breccias, cataclasites, and microbreccias. Many of the identified faults on the DEM would have been impossible to detect based on the field mapping investigations alone. The use of DEM-based methods enabled the
detection of faults, making it possible to revise and correct fault strikes identified in the field.

3.3. Geological map construction

Field mapping of the southwestern part of the Gorce Mountains was performed at 1:10,000 scale and greater, while the final product was returned at a 1:25,000 scale (Figure 4). Field data have been integrated with interpretative geological facts based on DEM analysis. Some geological features interpreted with DEM were compared with real conditions in the field and, conversely, some field findings were checked via DEM. This procedure eliminated many errors and significantly improved the accuracy of the map. With this approach, strike and dip measurements were eliminated in some locations (e.g. within landslides), especially where dips may have been rotated by landslides rather than by fault activity. Additionally, in many inaccessible locations or in sites covered by soil and younger sediments, if stratification was visible as the previously mentioned step-like forms, DEM enabled lithostratigraphic boundaries and thrusts to be drawn with great accuracy. As mentioned, the DEM studies and the applied lineament method enabled the identification of numerous new faults not described or marked on previous geological maps. Based on the completed map, geological cross-sections and a tectonic sketch were constructed.

4. Geological mapping results

In the study area, four Campanian–Lower Miocene lithostratigraphic formations were distinguished in the Krynica Subunit. The youngest (Lower–Middle Miocene) deposits of the Krynica Subunit are exposed close to, but out of, the study area (Cieszkowski, 1992).

Older Cenomanian–Campanian deposits were drilled through by the Obidowa IG-1 deep borehole, located in Rdzawka (2 km west of the research area) and coincident with the Kraków–Zakopane cross-section.

4.1. Sedimentary succession of the Krynica Subunit

In the studied area, the Campanian–Lower Miocene sedimentary succession of the Krynica Subunit is relatively poorly differentiated. The Upper Cretaceous–Palaeocene Ropianka and Eocene Beloveža formations stand out clearly in lithological terms (Figure 5). The overlying the Eocene–Oligocene Magura Formation and Upper Eocene–Oligocene Malcov Formation consist mainly of thin- and medium-bedded siliciclastic turbidites, although they include intercalations of Magura-like lithotype sandstones as well. The total thickness of these formations is in the range of 3500–4000 m.

The Ropianka Formation (Campanian–Palaeocene) is represented by thin- and medium-bedded sandstone-shale alternations, developed as classic turbidites (Figure 6(A)). Fine- or medium-grained muscovitic sandstones are intercalated with grey and greenish-grey, more or less marly shales. These deposits are interbedded with packages of thick-bedded sandstones and conglomerates (Figure 6(B)); the thickest, well exposed in the Obidowiec Ridge, reaches approximately 120 m.

The Beloveža Formation (Lower Eocene) is represented by thin- and/or medium-bedded shale-sandstone turbidites, very rich in trace fossils. Light grey calcareous sandstones are intercalated with bluish-grey marly shales in proportions of 2:1 or 1:1. Within these, deposits occur called the Krynica Sandstone Member, 30–40 m thick and represented by thick-bedded sandstones and conglomerates, similar to those known from the Magura Formation.
Figure 4. Part of the here-presented geological map illustrating observation points measured in the field. A: before generalisation; B: after generalisation. There are two images showing a fragment of the geological map. In the figure A, the documentation map with the observation points of the dip and strike bedding measured in the field is presented. The image B presents a geological map with the dip and strike bedding after generalisation.

Figure 5. Lithostratigraphical logs of the Krynica Subunit constructed on the base of cross-sections presented on the geological map. There are five pictures of the lithostratigraphical logs of the Krynica Subunit constructed on the base of cross-sections presented on the geological map.
The Magura Formation (Lower Eocene–Lower Oligocene), although characterised by great thickness, is dominated by thick-bedded sandstones of the ‘Magura sandstone’ lithotype (Figure 5), and subordinately by conglomerates. The sandstones are more or less calcareous, bluish-grey or grey in colour, or yellowish-grey when weathered. One feature that allows researchers to clearly distinguish sandstones and conglomerates embedded in the Magura Formation is the presence of red and pink grains (i.e. pink quartz and feldspars, red quartzitic sandstones, and porphyry-like volcanic rocks – see Figure 7(B)).

The presence or absence of intercalations of other lithological types of deposits between thick-bedded sandstones enabled the distinction of three lithostratigraphic members within the Magura Formation (Figure 7(A)). The Piwniczna Sandstone Member (Lower–Middle Eocene) is represented by thick-bedded sandstones, conglomeratic sandstones, and conglomerates intercalated with thin- and medium-bedded shale-sandstone packages, developed as Beloveža Formation-like facies (Figure 7(C)). The thick-bedded sandstones deposits of the Kowniec Member (Middle–Upper Eocene) are characterised by the occurrence of layers of coarsely cleavable, calcite-free, green mudstones, thin-bedded shale-sandstone packages, and single intercalations of thick-bedded, massive grey, marly turbidites known as Łącko Marls. The Poprad Sandstone Member (Upper Eocene) is built almost entirely of thick-bedded Magura sandstones (Figure 6(B)) and reaches 1000–1200 m thickness in the Gorces (Figure 5).

The Malcov Formation (Oligocene–Lower Miocene) consists of medium- and thin-bedded sandstone-shale deposits, nearly all calcareous (Figure 8(C)). Occasional intercalations of massive green shales or grey-yellowish and bluish soft marls occur, sometimes as much as several metres thick. Moreover, a substantial part of this formation comprises packages of medium- and thick-bedded Magura sandstone-like lithotype. At the top of the formation, these thick-bedded sandstones constitute the Waksmund Sandstone Member.

4.2. Sedimentary succession of the Bystrica Subunit

North of the studied area, the most complete profile of Cenomanian–Oligocene deposits of the Bystrica Subunit crops out (e.g. Burtan et al., 1978a, 1978b; Szczęk et al., 2016). In the studied area, the Bystrica Subunit is represented solely by the Magura Formation (Middle Eocene–Oligocene), compounded of several members (according to Cieszkowski, 2006; Oszczypko, 1991; Szczęk et al., 2016). The Maszkowice Sandstone Member (Middle Eocene) is represented by the thick-bedded ‘Magura sandstone’ lithotype, with rare intercalations of thin-bedded sandstone-shale deposits similar to those of the Beloveža Formation. The Mniszek Shale Member (Middle Eocene) is built only of thin- and medium-bedded sandstone-shale deposits similar to those of the Beloveža Formation. The lower part of this member is marked by the occurrence of several metre-thick variegated shales. Above this is the Trusiówka Member (Upper Eocene), represented by a thick-bedded ‘Magura sandstone’ lithotype intercalated occasionally by dark grey to grey shale or sandstone-shale deposits similar to those of the Beloveža Formation. The youngest Poprad Sandstone Member (Upper Eocene–Oligocene) is similar to the Poprad Sandstone Member from the Krynica Subunit; however, the grains in the thick-bedded sandstone are usually finer.

4.3. Quaternary deposits

In the research area, Quaternary deposits are represented mainly by fluvial deposits accumulated in narrow, deeply indented V-shaped valleys. The thickness of the fluvial deposits is from 0.5 to 5 m.
Only in the southernmost part of the research area in the Orava-Nowy Targ Basin does the thickness of the quaternary deposits grow to about 10 m (Watycha, 1976). These deposits are represented mainly by gravels, with sands and muds built from fyls material also occurring. In the Orava-Nowy Targ Basin, pebbles of the Tatra material dominate in the gravel composition. To the west of Nowy Targ, about 4 m thick of yellow alluvial clay was accumulated on the fluvial material (Watycha, 1978). On the clays, a raised bog was developed.

The slopes in the Gorce Mountains are covered with a thin watershed, the thickness of which ranges from 0.25 to 2 m, occasionally thicker. The common forms in the studied area are landslides. These forms have dimensions of about 200 × 300 m but the biggest landslides located on the southern slopes of Mt Kudłoń have dimensions of 2 × 1 km.

4.4. Tectonics

Two tectonic units occur in the investigated area in the Krynica Subunit: the Turbacz and the Kudłoń Thrust Sheets (newly distinguished by the authors) (Figure 1). Also, the ‘Peri-Klippens Fold Zone’ thrust sheet divided by Watycha (1975, 1976) in the southern part of the study area was included in the Turbacz Thrust Sheet. The authors of this publication (Watycha, 1975, 1976) identified a normal sedimentary transition between the Magura and Malcov formations at the site of the alleged thrust. What is more, recent micropalaeontological dating (Cieszkowski, 1992; Cieszkowski & Olszewska, 1986; Kaczmarek et al., 2016; Oszczypko-Clowes et al., 2018) showed that the deposits described by Watycha (1975, 1976) as Cretaceous deposits of the Ropianka Formation, located in the frontal part of the ‘Peri-Klippens Fold Zone’, are by contrast younger and referable to the Oligocene-Miocene deposits of the Malcov Formation. The Turbacz Thrust Sheet overthrusts the Kudłoń Thrust Sheets; both overthrust the Bystrica Subunit, represented here by the southernmost structural element of the Tobolów Thrust Sheet.

The sedimentary deposits of the Krynica Subunit are folded and cut by numerous faults. The folds, with the exception of the Rdzawka-Ponice Anticline (Figure 1), are characterised by rather small amplitudes in the studied area. Most are mesoscopic folds, and it is difficult to track the traces of their axes over great distances. Only some are macroscopic folds with axes that can be traced for a long distance (e.g. the Sieniawa Syncline, the Pyżówka Anticline, and the Rdzawka-Ponice Anticline – Figure 1).
Numerous transverse and oblique faults – usually strike-slip or oblique-strike – with various lengths, throws, and strike orientations occur in the study area. Two zones with differently oriented fault strikes can be oriented: a western sector, dominated by faults with strikes NNW–SSE and NNE–SSW, and an eastern sector, with dominating strikes oriented NNW–SSE, NNE–SSW, and NE–SW (Kania & Szczęch, 2020). Occasionally ENE–WSW fault strikes have also been observed. Some faults form complex dislocation zones 5–10 km long, or even longer. Examples are the dextral strike-slip of the Waksmund-Ponice Fault Zone (Figure 1), which is oriented NNW–SSE and extends to the Skawa River Fault Zone, also cutting across other subunits of the Magura Nappe (Książkiewicz, 1977); the dextral strike-slip of the Orava Fault Zone with the Lepietnica Fault, extending NE–SW; or the meridian Ostrowsko-Maniowy Fault Zone.
Fault Zone which is the oblique fault system, of unclear kinematics (Figure 1).

5. Discussion

The main problems identified during the work on the south-western part of the Gorce Mountains concerned the course of lithostratigraphic boundaries and the definition of lithostratigraphic units as well as tectonic structures.

Tracing the boundaries on the map between the various lithostratigraphic units of the Krynica Subunit on the map in the studied area was difficult. The identification of lithostratigraphic members of the Magura Formation was particularly difficult, due mainly to the dominance of thick-bedded ‘Magura sandstones’ lithotypes; only the inherent thin inter-beddings of other lithotypes enabled individual members to be distinguished (Burtan et al., 1978b; Watycha, 1975). DEM projections were very useful in plotting unit boundaries, improving the results from field-only evidence.

In formalising the lithostratigraphic nomenclature of the Krynica Subunit sedimentary succession, Birkenmajer and Oszczypko (1989) distinguished the Upper Cretaceous–Palaeocene deposits, previously known as ‘the Szczawnica beds’, under the formal name ‘the Szczawnica Formation’. Chrustek et al. (2005), among others, conducted in-depth studies on the Szczawnica Formation. According to the latter authors, the lithologic and sedimentary features of this unit do not differ from those of the Ropianka Formation, which is widespread in the Bystrica and Rača subunits (e.g. Książkiewicz, 1977; Oszczypko, 1991; Oszczypko, Malata, et al., 2005). Oszczypko-Clowes et al. (2018) stated in their research that parts of the deposit incorporated in the Szczawnica Formation, even within its stratotype area, are much younger, dating from the Miocene. However, in our opinion, the traditional name of the Ropianka Formation should be reverted. This allows for better fulfilment of the Stratigraphic Code, providing better consistency.

In the research area, the possibility of the Beloveža Formation being distinguished is due to the fact that it occurs here in the northern, most distal part of the Krynica Subunit, preserved in the northern limb of the Rdzawka-Obidowiec anticline. In the more internal zones of the Krynica Subunit, also in the southern limb of the previously mentioned Rdzawka-Obidowiec anticline, this formation is replaced by the deposits of the Piwniczna sandstone member, which is a result of the overlapping facies. The relationship between the Beloveža Formation and the Piwniczna sandstone member may emphasise the occurrence in the Piwniczna sandstone member intercalations of the thin-bedded packets of sandstone-shale deposits of the Beloveža Formation lithotype.

Studies carried out in the SW part of the Gorce proved the importance of correct micropalaeontological dating of lithostratigraphic divisions. Inaccurate micropalaeontological dating of flysch deposits can lead to significant errors, even in the interpretation of tectonics, as exemplified by the distinction by Watycha (1975, 1976) of the thrust sheet called the Peri-Klippen Fold Zone.

The detrital material characterising the studied lithostratigraphic units was derived from turbidity currents and deposited in the proximal and, partly, central sector of the southern Magura Basin (Oszczypko et al., 2015, 2016). The material was sourced from an emergent ridge bordering the basin to the south and formed an extensive submarine lobe system (Dirnerová & Farkašovský, 2018; Oszczypko, Oszczypko-Clowes, et al., 2005).

The style of fold tectonics in the Krynica Subunit may be caused here by the dominance of thickly-bedded sandstones. These massive sandstones characterise about 2000 m of the Magura Formation (Figure 5) and their presence reduced the susceptibility to produce classic folded deformations, known from other areas in the Magura Nappe (e.g. Książkiewicz, 1977). The dense network of faults is compatible with the general Western Carpathian system (Kania & Szczech, 2020).

The authors noted that the layers of the Krynica Subunit were characterised by relatively steep dips. Additionally, this subunit included zones of overturned layers dipping to the north. Here, this phenomenon is associated with a flower structure formed within a collision zone of tectonic plates (Cieszkowski, 2006; Golonka et al., 2005; Golonka, Pietsch, et al., 2019; Marzec et al., 2019). The structural basement of the Magura Nappe in the Gorce region forms the Grybów and Dukla Nappes, both drilled through by deep boreholes in the western periphery of the Gorce Mountains (Cieszkowski, 2006; Golonka et al., 2005, 2018; Golonka, Pietsch, et al., 2019). The analysis of boreholes and geophysics allowed us to estimate the thickness of the Magura Nappe, ranging between 2000 and 4000 m. A platform consolidated basement was identified here at depths ranging between 7000 and 9000 m.

6. Conclusions

A new detailed geological map of the south-western part of the Gorce Mountains, on a 1:25,000 scale ‘Main Map’, was produced after field mapping and analysis of a high-resolution DEM.

In the study area, two lower-range tectonic structures of the Krynica Subunit occur; the Turbacz Thrust Sheet and the Kudłoń Thrust Sheet.
Furthermore, the southernmost part of the Tobolów Thrust Sheet belonging to the Bystrica Subunit was mapped.

The outcropping sedimentary succession of the Krynica Subunit, reaching approximately 4000 m in thickness and largely or totally dominated by thick-beded sandstones, is represented by four formations, Late Cretaceous bedded sandstones, is represented by four formations, Krynica Subunit, reaching approximately 4000 m in mapped. Thrust Sheet belonging to the Bystrica Subunit was been distinguished. By contrast, the Bystrica is here models was conducted with the use of Relief Visualiza-

tion zones, which extend in some places beyond the study area.

Software

The geological map of the south-western part of the Gorces and cross-sections were prepared with the use of ArcMap 10.4. The analysis of digital elevation models was conducted with the use of Relief Visualization Toolbox, version 1.3 (Kokal & Somrak, 2019; Zakšek et al., 2011). The lithostratigraphic logs were created in CorelDRAW.

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