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STRUCTURAL CONTROL ON MORPHOLOGY OF SOUTH-WESTERN SLOPE OF CHORNOHORA MOUNTAINS BETWEEN MT. HOVERLA AND MT. POP IVAN (EASTERN CARPATHIAN MOUNTAINS, UKRAINE)

Piotr KŁAPYTA

Jagiellonian University, Institute of Geography and Spatial Management, Gronostajowa 7, 30-387 Kraków, Poland;
e-mail: woytastry@gmail.com

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Abstract: The landforms of the Chornohora Mountains and related geomorphological processes are strongly controlled by geological structure. Detailed geomorphological mapping of the Chornohora Range yielded evidence of deep-seated gravitational slope failures on the south-western slopes. These slope deformations were structurally predisposed and linked to the dip of bedrock strata and their resistance to erosion, as well as to cracks and faults within the flysch formations. This paper presents structural factors controlling the morphology of relatively poorly recognized, dip-adjusted south-western slopes of the Chornohora Mts. between Mt. Hoverla (2,061 m a.s.l.) and Mt. Pop Ivan (2,022 m a.s.l.).

Key words: flysch, deep-seated gravitational slope failures, slope asymmetry, Chornohora Mts., Eastern Carpathians, Ukraine.

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INTRODUCTION

The Eastern Carpathian Mountains provided the background for pioneering works that looked at the relationship between landforms and geology and the role of tectonics and lithology in the development of relief (Rehman, 1895; Romer, 1909; Teisseyre, 1928; Świderski, 1934, 1952; Świdziński, 1953). The role of geology in the evolution and final shaping of the flysch Carpathian Mountains as a whole was reported in numerous papers (Rehman, 1895; Klimaszewski, 1946; Starkel, 1965, 1969, 2005).

With its well-developed glacial and periglacial landforms, the Chornohora Range played a crucial role in the geomorphological study of the Eastern Carpathian Mountains. Most of this work was carried out on the north-eastern slopes of the range (then in the province of Galizien), hence there is a much better understanding of the local landforms and their geological control on this area when compared to the south-western slopes, known as Transcarpathians (Kłapyta, 2006).

The earliest general comments on the morphology of the Chornohora Mts. date back to visits by Pol (1851, 1876), Paul and Tietze (1876), Siegmeth (1882), and Zapałowicz (1889), whereas Pawłowski (1915) wrote the first geomorphological synthesis of the glaciation of the Chornohora Range. Glacial relief has been the main topic of geomorphological research right from the beginning. The geomorphological investigation of the Chornohora Mts. was crowned by publications by Świderski (1932, 1933, 1937), including his major comprehensive study and a 1:25,000 geomorphological map of the north-eastern portion of the range. This study was the first reconstruction of the Chornohora glaciation by combining geomorphological mapping and palaeobotanical data of Kozij (1932), and was the first to differentiate between landforms and deposits of the Würm and Riss glacial stages, and of an older complex of deposits representing the Mindel stage. This publication was a pioneer geomorphological work of the genetic-chronological type, later to be applied by Klimaszewski (1988) in his study of the landforms of the Tatra Mts.

After the WW2, researchers looked at the stratigraphy and chronology of the last ice age using geomorphological criteria, such as the elevations of fluvioglacial terraces and terminal moraines (Cys', 1955) and the radiocarbon-dating of deposits found between stadial moraines (Miller, 1961, 1963; Trietiak & Kuleshko, 1982). Attempts were also made to link block tectonics with the development of glacial cirques, which were viewed as tectonically-predisposed cavities subsequently transformed by glacial and periglacial processes (Bashenina *et al.*, 1969).

The earliest fragmentary reports on glacial landforms and landslides on the south-western slopes are found in publications by Czirbusz (1900), Pawłowski (1915), and Vitásek (1923). After the WWII, researchers began noticing the considerable impact that the underlying structure had on the morphological difference between the south-western and north-eastern slopes. They concluded that the morphology of the south-western slope is typified by its lesser degree of glacier development and smaller number of glacial cirques. The asymmetrical cross-profiles of glacial cirques were attributed to their formation on slopes cutting through relatively less resistant rock layers and generally following the dip of strata (Miller, 1961, 1963, 1964). The geomorphological map of the Chornohora Mts. (Świderski, 1937) does not include the south-western slopes which remained poorly studied, except for a small number of notes in the post-war literature. Indeed, there is no comprehensive geomorphological study of the entire area that would take into account the asymmetry between the north-eastern and south-western slopes, which is a characteristic feature of the Chornohora Range, further highlighted by the differences in the Pleistocene glaciations (Pawłowski, 1936; Evans, 1977).

Thus, the aim of this study was to recognize the structural factors controlling the morphology of dip-adjusted south-western slopes of the Chornohora Mts. between Mt. Hoverla (2,061 m a.s.l.) and Mt. Pop Ivan (2,022 m a.s.l.) in comparison to the morphology of north-eastern, anti-dip slopes. To achieve this task, a geomorphological mapping was carried out at the scales of 1: 25,000 and 1:10,000 being complemented by an analysis of Landsat (30×30 m pixel size) and Aster (15 m pixel size) satellite images. Images from the Aster satellite proved particularly useful for the analysis of large-scale landforms, such as large landslides, which could not be mapped through fieldwork alone. Winter season images, with their strong shadows, graphically showed landslides, larger crevices, fissures and glacial cirques.

Geomorphological map allowed for the identification of glacial cirques and large structurally controlled landslides. Glacial cirques were defined as relatively depressed, arcuate in plane areas, located immediately below the crest, surrounded by very steep slopes, and more gently sloping floor with the presence of morainic deposits. Special attention was paid to the structure of landslides and their relation to the underlying geology. Strike and dip of bedrock strata were measured with the help of geological compass. GPS measurements were recorded in order to mark the landslide niches and fissure boundaries. Landslide morphology was identified as the complex of mass movement landforms with the area of concave niche and zone of mass accumulation beneath. In the Chornohora range, the mass accumulation zone consists mainly of rigid rock packets and sandstone debris colluvium.

This study has implications for landscape evolution in high mountain ranges, where the rock-controlled asymmetry of glaciation occurs, like for instance the Brecon Beacons range in Wales (Shakesby & Matthews, 1996; Jansson & Glasser, 2007), and where the structure of flysch strata controls the landform development above the timberline (e.g., Babia Góra Mts., Poland; Łajczak, 1995; Świdowiec Mts., Ukraine; Romer, 1906).

GEOLOGICAL STRUCTURE

The Chornohora Mts., as part of the Outer Eastern Carpathians, is built up of Cretaceous–Palaeogene flysch formations (Fig. 1). The Ukrainian segment of the Eastern Carpathians is composed of several overthrust nappes with secondary thrusts, folds, slices, and transversal tectonic elevation and depression zones (Teisseyre, 1928; Świderski, 1952; Tołwiński, 1956; Mihailescu, 1963; Starkel, 1965, 1969). These tectonic structures emerged as the Moldavide accretionary wedge in the early and middle Miocene (Mihailescu, 1963; Żytko, 1999) following a collision between the rigid East European Platform and the Tisza and Dacia terranes (Żytko, 1999; Necea *et al.*, 2005). The Eastern Carpathian folding (20–9 Ma BP) was accompanied by lateral migration of a lithospheric block from the Eastern Alps towards the NE and SW (Decker & Peresson, 1996). As a result of different kinematics of the folding, there are clear differences in the age and evolution of tectonic structures compared to those of the Western Carpathians (Starkel, 1969, 2005; Decker & Peresson, 1996).

The compact and broad ranges of the Chornohora Mts. are built by a series of resistant sandstones separated by narrow zones composed of schists (Fig. 1). The Chornohora Mts. is a tectonic block surrounded by large faults (Jahn, 1992). Bashenina *et al.* (1969) divided the Eastern Carpathian Mountains into numerous horsts, flexures and grabens, and identified the Chornohora Mts. as the highest uplifted isometric block bound by deep longitudinal and transverse fault zones.

The Chornohora Range's structure consists of three nappe units: Chornohora, Dukla and Porkulets (Nowak, 1927; Guzik, 1957; Zahulska, 2003; Ślączka *et al.*, 2005) (Fig. 1). The Chornohora unit consists in turn of two tectonic and facies sub-units: the outer Skupowa sub-unit and the inner Chornohora proper sub-unit (Guzik, 1957). There are three rock complexes within the Chornohora unit of different age and resistance: the oldest, Lower Cretaceous thin-bedded formations of black flysch belonging to the Shipot beds (Barremian–Albian), the younger, spotted schists and marls of the Porkulets beds (Cenomanian–Turonian), and the Upper Cretaceous, thick- and thin-bedded Chornohora sandstone and conglomerate (Świderski, 1937; Guzik, 1957; Zahulska, 2003; Rogoziński & Krobicki, 2006) (Fig. 1). Within the Chornohora Mts., the Porkulets nappe (also known as the Burkut nappe) mainly consists of thick-bedded sandstone and conglomerate of the Chornoholova beds (Campanian–Eocene), and of the grey and spotted schists of the Porkulets formation (Nowak, 1927; Rogoziński & Krobicki, 2006). In the Chornohora Mts., the Porkulets unit reaches farther in the foreland than in the neighbouring regions and forms a unique Petros tectonic

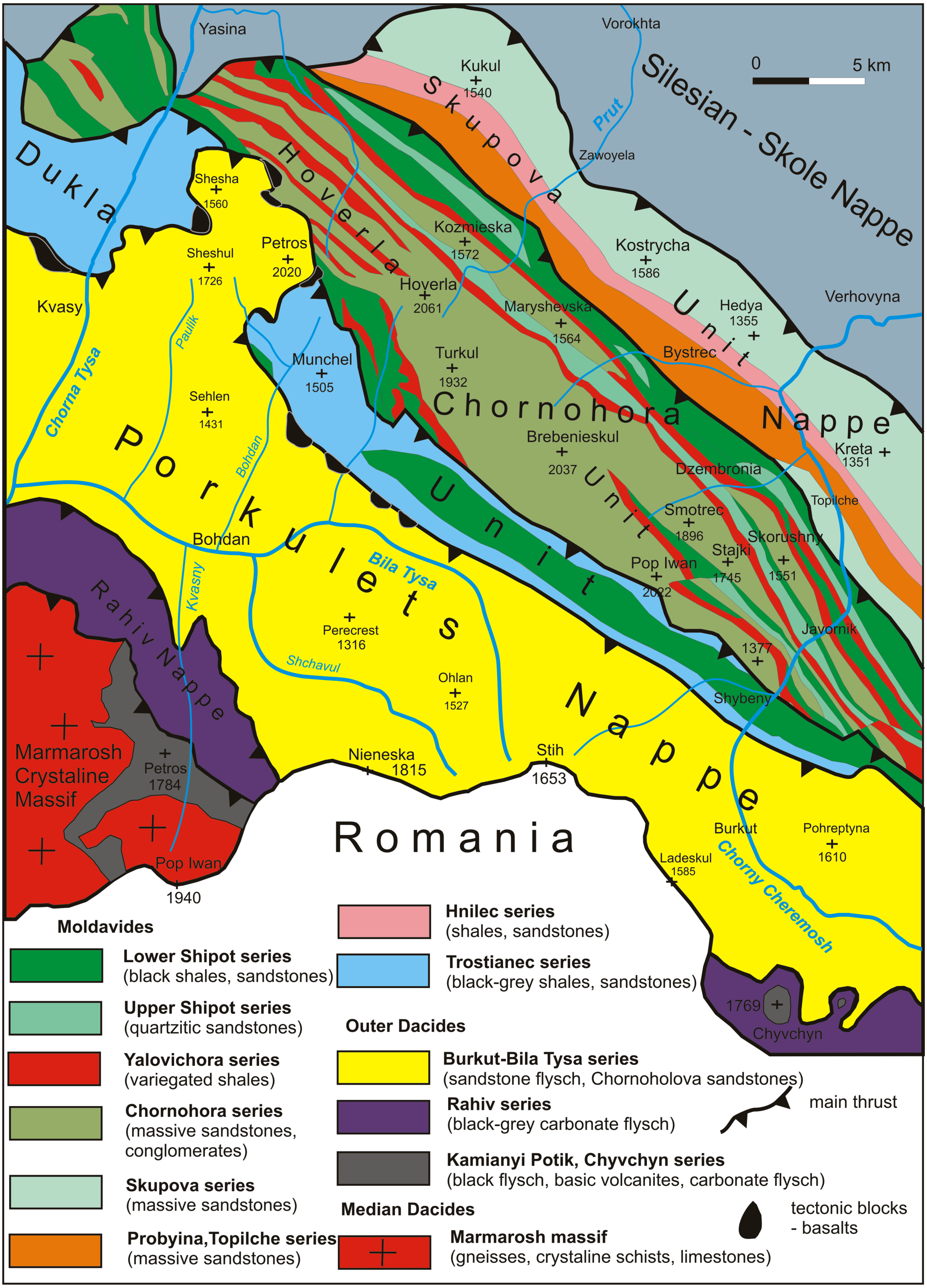

Fig. 1. Geological sketch-map of the SE part of the Ukrainian Carpathians, based on Shakin *et al.* (1976) and Oszczypko (2004)

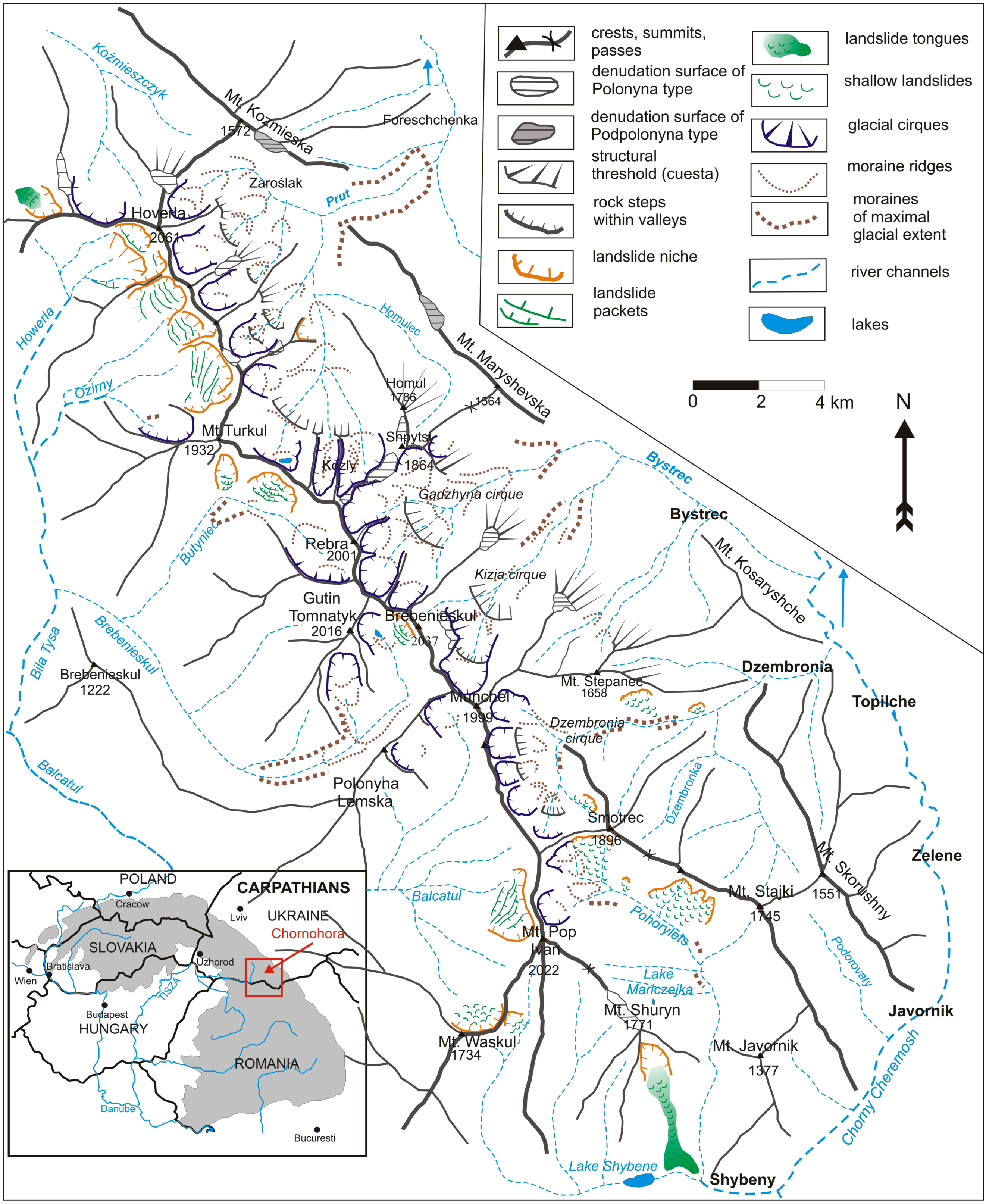

Fig. 2. Map of the Chornohora landforms between Mt. Hoverla and Mt. Pop Ivan (according to Świderski, 1937 and the author)

peninsula (Fig. 1). An olistostrome zone identified in front of this unit, consists of volcanic rock olistolith (basalt and melaphyre lava) and organic-detritic limestones that are clearly marked in the relief in the form of klippes (Goldschlag, 1914; Rogoziński & Krobicki, 2006).

The Chornohora Range is located in one of the three regional zones of tectonic elevations, identified in this part of the Carpathian Mountains (Tołwiński, 1950; Jahn, 1992). The elevation of the Pokutt'a Carpathian ranges (also known as Podil'a Carpathians) cuts across all other geological structures of the Eastern Carpathians at a right angle, from the Pokutt'a Beskidy Mts. range in the NE, through the Chornohora Mts., to the Marmarosh Massif in the SW (Tołwiński, 1950). The elevation was first identified by Teisseyre (1928), who analysed the summit surface of the Carpathians and identified zones of transversal tectonic elevations and depressions, which he regarded as dislocations of the piedmont that continued under the Carpathian Mountains and influenced their tectonic structures. The Shopurka fault, a deep regional tectonic fault zone separating the Tisza and Dacia terranes, played an important role in the development of the Chornohora's tectonic structures. It is a north-eastern continuation of an important fault in this part of the Carpathians (Żytko, 1999). The fault zone constitutes the western boundary of the Chornohora unit and an important regional tectonic boundary that separates the Chornohora Range from the Świdowiec mountain group. The fault zone trends NE–SW at the western foot of Mt. Petros and Mt. Sheshul and down the Tisza valley, where it controls the course of the gap reach of that river (Fig. 1).

GENERAL CHARACTERISTICS OF THE CHORNOHORA LANDFORMS

The Chornohora Mts. are one of the main ranges of the Eastern Carpathians (Fig. 2). Culminating at more than 2,000 m a.s.l., it is the highest Carpathian range built of flysch formations. In terms of physico-geographical regions, it is part of the Polonyny Beskidy Mts. (Kondracki, 1978), and in geomorphological terms it forms part of the Poloniny-Chornohora Carpathian Mountains (Rud'ko & Kravchuk, 2002). The main ridge running between Mt. Hoverla (2,061 m) and Mt. Pop Ivan (2,022 m) is a section of the main Carpathian watershed that separates the basins of the rivers Prut and Cheremosh from that of the Tisza River. The Chornohora Mts. form a high-mountain terrain, when assessed on the basis of geoecological criteria (Troll, 1973). The morphogenetic cryo-nival zone is located above the climatic timberline, which is situated at 1,600 m a.s.l. (Środoń, 1946). The highest parts rising above 1,850 m a.s.l. belong to the Alpine zone, characterized by the greatest intensities of aeolian deflation, gelifluction and nivation processes (Hradecký *et al.*, 2001).

The overall relief of the Chornohora Mts. features a structural asymmetry between its north-eastern and south-western slopes (Fig. 2), a product of a lower erosion base on the south-eastern side and of the monoclinal dip of strata (Kłapyta, 2006). The asymmetry of gradient on opposing erosion slopes in the Carpathians is generally well known (Jahn, 1992). The southern slopes drop 100 metres lower (to 200 m a.s.l.) than their northern counterparts, have greater denivelation and in general higher-energy relief (Tołwiński, 1956; Jahn, 1992). The valley network on the southern side of the Carpathian Mountains consists of young, deeply incised V-shaped valleys of the Upper Tisza River system which evolved its contemporary form earlier than on the northern side (Slyvka, 2001). The asymmetry is manifested in differences between the main landforms, their potential energy, and predisposition on the two sides of the mountain chain. The south-western dip-slopes situated above the timberline are smoother and less dissected than the north-eastern slopes. The latter were formed by cutting across more resistant strata and tend to be steep and ragged around glacial cirques. This main structural asymmetry became additionally highlighted by the asymmetry of the Pleistocene glaciation (Pawłowski, 1936; Evans, 1977).

The great elevation of the Chornohora Mts. and their large north-eastern slope fragmentation (Romer, 1909) facilitated the development of large and relatively long mountain glaciers during the Pleistocene. The subsequent formation of glacial and periglacial relief followed the existing tectonic and lithological differentiations and a network of erosional dissections. On the north-eastern slopes, glaciers were up to 4–6.5 km long (Świderski, 1937). The Chornohora's glacial relief, with its well developed valley head cirques, rocky steps and moraines, provides a model example of glacial erosion and accumulation landforms in a flysch area. The cirques developed as a result of glacial erosion of fluvial valleys; they are filled with debris flow deposits and talus cones. Moraines in the cirque bottoms mark stages in the retreat of glaciers, while large peat bogs evolved in concave terrain forms (Korshikov & Pirko, 2001) providing an important source of information on the local palaeoenvironment (Kozij, 1932; Hnatiuk, 1988).

Due to relatively low resistance of flysch formations compared to crystalline rocks and the intense post-glacial erosion, the glacial relief of the Chornohora Mts. is devoid of glacial erosion features, such as glacial polish, striations and roches moutonnées or typical glacial troughs. Boundaries of the cirques are clearly aligned with rock-resistance zones. Resistant zones uncovered within the cirques manifest themselves in the form of structural thresholds and rocky steps.

The role of glacial transformation of the south-western slopes of the Chornohora Range between Mt. Hoverla and Turkul was the subject of debate over a long period of time (Zapałowicz, 1889; Siegmeth, 1882; Czirbusz, 1900; Pawłowski, 1915; Kłapyta, 2006). There is a strong morphological contrast between the well-formed moraines and steep rock or rock waste mantled slopes of the glacial cirques on the northern and north-eastern side, and the relatively shallow glacial cirques and landslide niches on the south-western slopes (Fig. 2).

The asymmetry of the Chornohora's glacial cirques (Fig. 2) is rooted in structural influences on the main features of preglacial morphology that were subsequently enhanced by climate-driven processes. The monoclinal attitude of beds promoted greater fragmentation of slopes in the headwaters of the Prut and Cheremosh rivers, and was conducive to the formation of numerous concave landforms in the upper parts of the valleys. The shaded headwaters provided opportunity for accumulation of snow blown from the south or south-west, or supplied by avalanches from collapsing cornices (Świderski, 1937; Evans, 1977). Palaeoclimatological research shows that the prevailing atmospheric circulation in Central Europe during the last glacial maximum (LGM) was from the south and south-west (Florineth & Schlüchter, 1998). Gradually sloping sections of the south-western side of the Chornohora Range pro-

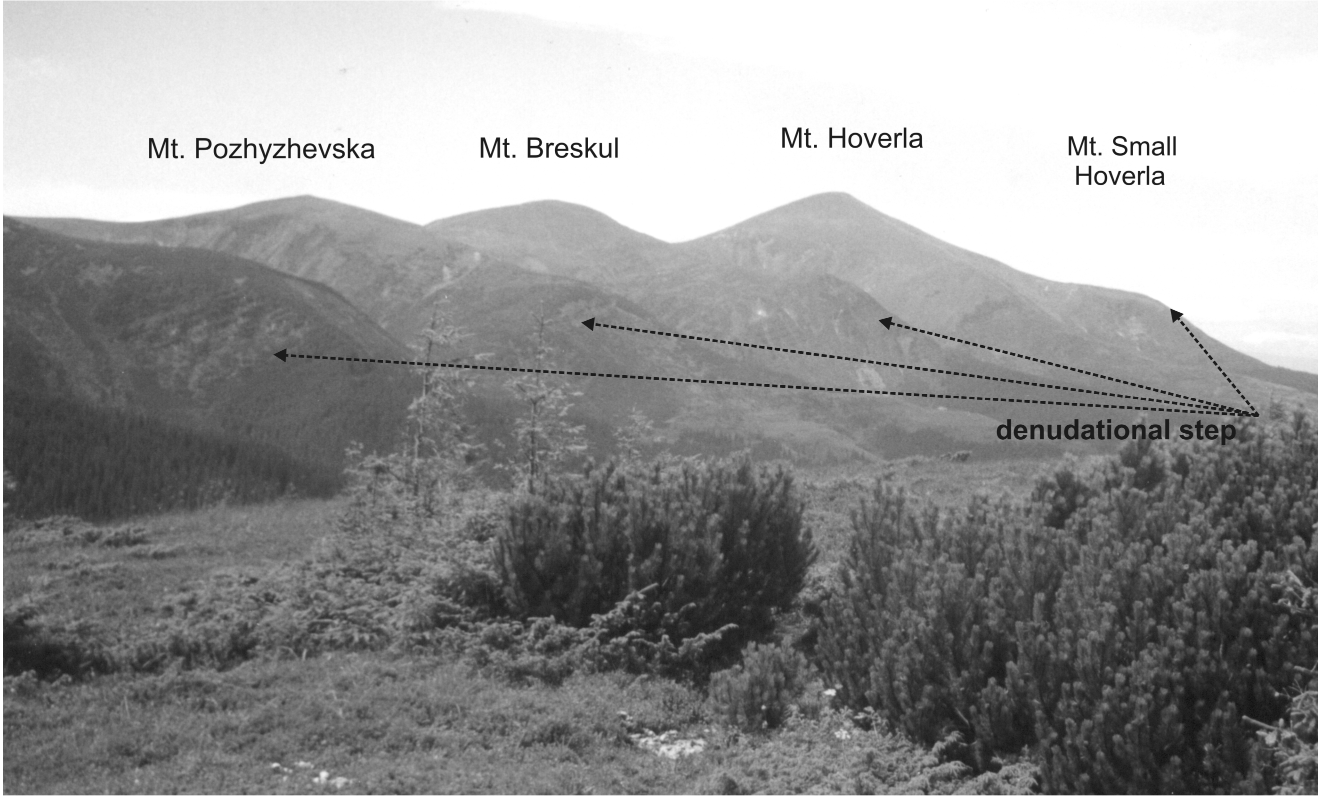

Fig. 3. NE slopes of Chornohora Mountains. A distinct denudational step (400 m high) links the heads of the highly resistant Chornohora sandstones and conglomerates, underlain by the low-resistant variegated shales of Yalovichora series. Note well developed set of valley heads of glacial cirques of the former Prut glacier system

vided a location for the accumulation of snow, which was then wind-blown across the ridge. Indeed, the considerable length of the glaciers (4–6.5 km) on the north-eastern side of the relatively low Chornohora range would suggest a high snow accumulation factor, and an area of supply larger than just the topographical limits of the cirques.

The lithological complexes of the Chornohora Mts. vary in their degree of resistance, thus influencing the shapes of the main landforms, especially in the zones of overthrust of main tectonic units. An example is provided by high denudational steps (400–500 m high) supported by very resistant lithological links to the face of the Porkulets and Chornohora unit overthrust, and the zone of Chornohora sandstones and conglomerates (Figs 1, 2, 3). The ridges are composed of strongly resistant complexes of the Chornohora beds of sandstone and conglomerate and the thick-bedded complex of Chornoholova sandstones.

The rock complexes in the Chornohora Mts. build a homocline, dipping at steep angles of 40–45° towards the SW. The main Chornohora ridge developed on the SW limb of a syncline built up of the Chornohora sandstone and conglomerate. The steep dips of the lithological complexes within folds are manifested in the topography in the form of

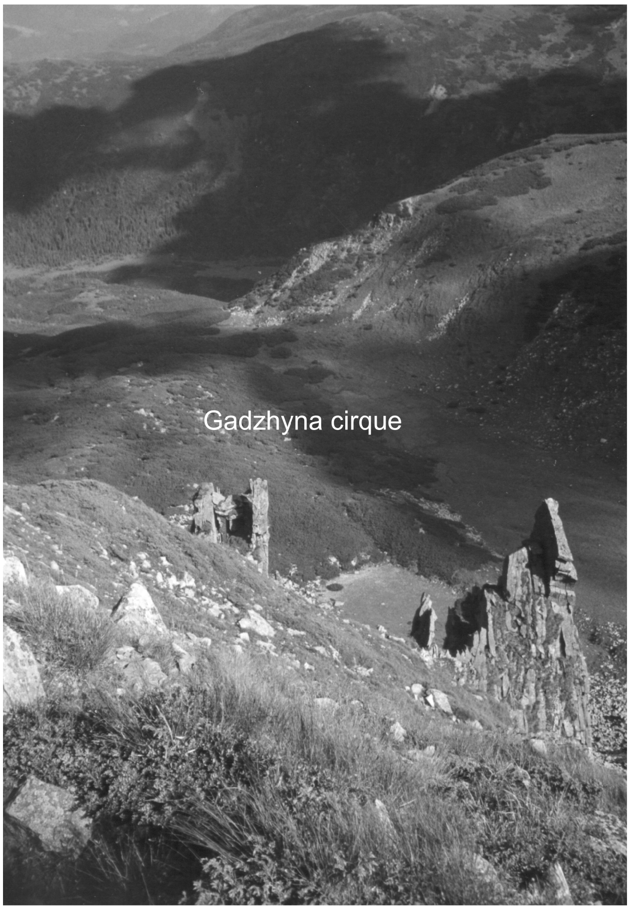

Fig. 4. Gadzhyna cirque. Rocky needles and spines near Shpytsi are associated with vertically dipping strata of the Chornohora sandstones

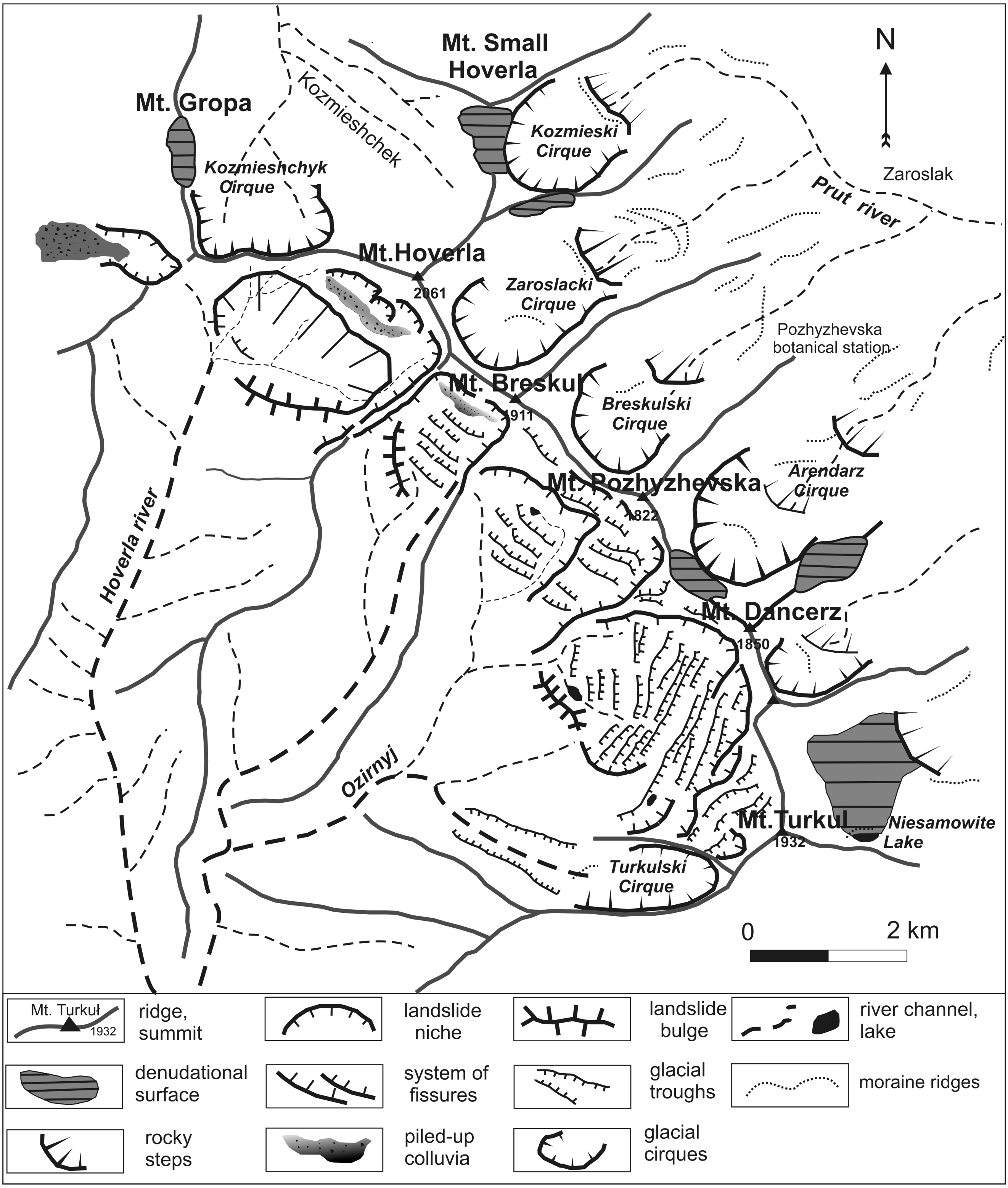

Fig. 5. Map of structural impacts on the Chornohora landforms between Mt. Hoverla and Mt. Turkul (according to the author). The landscape of the NE face is dominated by glacial features. Well developed glacial cirques are found in five headwater valleys of the Prut River. The landforms of the SW face are characterized by dominance of landslide forms, which developed through deep-seated gravitational displacements of rock blocks

monoclinal ridges, which either take the form of cuestas (Turkul, Dzembronia) or narrow hogback-type ridges (Mt. Hoverla, a ridge near Niesamowite Lake). Double ridges evolved where two lithologically resistant zones run parallel to each other (Brebenieskul, Munchel). Vertical strata are found in the central Chornohora Mts. between the area around the Niesamowite Lake and the Gadzhyna cirque. Selective erosion and denudation uncovered resistant strata,

Fig. 6. Mt. Hoverla. Hogback-type peak; note large landslide niches on the south-western slopes

producing spectacular rocky needles and spines near Shpytsi (Fig. 4), and narrow rocky ridges of the Velike and Male Kozly. The diversity of local landforms is linked with the alternating hard and soft complexes, which are formed in sub-parallel zones compatible with the patterns of tectonic structures. The vertical uplift of the Chornohora Mts. among other East Carpathian ranges was determined by its tectonics and lithology. Świderski (1933) links the high elevation of this range to an originally higher position of the Chornohora unit, compared to the lower-lying folded overthrusts and imbricated folds ("skibas") of the Eastern Carpathians.

MORPHOLOGY OF THE SOUTH-WESTERN SLOPE BETWEEN MT. HOVERLA AND MT. POP IVAN

The main geomorphic components of the south-western slope result from monoclinal attitude of beds. Dominant landforms include smooth slopes covered by a thick periglacial waste mantle, conforming to the dip of strata. Screes developed as a result of intense weathering and disintegration of hard sandstones and conglomerates. On more gently inclined slopes and ridges they form large screes, while on steeper slopes they form block streams. Due to differences in flysch lithology and tectonics, the screes of the Chornohora Range are smaller in size than those in the neighbouring Gorgany Range and are concentrated near rocky outcrops (Walczak, 1946; Bajtsar & Tretiak, 1998).

In the headwaters, the relief was transformed by landslides and in the central area between Turkul and Munchel, also by glacial and nival processes (Fig. 2). A longitudinal transect across the south-western slopes of the mountains reveals two sections with different gradients and landforms. The top section, rising above the timberline, is dominated by relatively gradual slopes linked with the dip of underlying beds, with large headwaters of polygenetic morphology. Below a break of slope dividing the two sections, steep slopes are carved by young and deep, V-shaped valleys that evolved when the landscape was rejuvenated during the Quaternary period.

LANDSLIDING ON THE SW SLOPES BETWEEN HOVERLA AND TURKUL MOUNTAINS

Mt. Hoverla is the highest peak of the Chornohora Mts. and the highest flysch peak of the entire Carpathian belt. This hogback-type peak is built up of steeply dipping Chornohora sandstones and conglomerates (Figs 1, 6). Mt. Hoverla rises 250–300 m, like a monadnock pyramid, above the Poloniny planation level found on Mt. Mala Hoverla (1,764 m) and on Mt. Plecy Hoverli (1,750 m) (Fig. 3). The N and NE slopes of Mt. Hoverla were re-shaped by glacial erosion: three cirques (Zaroślacki, Koźmieski and Koźmieszczyka) were carved within the headwaters, with steep rock and rock and waste mantle slopes and flat bottoms (Fig. 5). Thick periglacial screes developed on the slopes above the upper limit of the cirques.

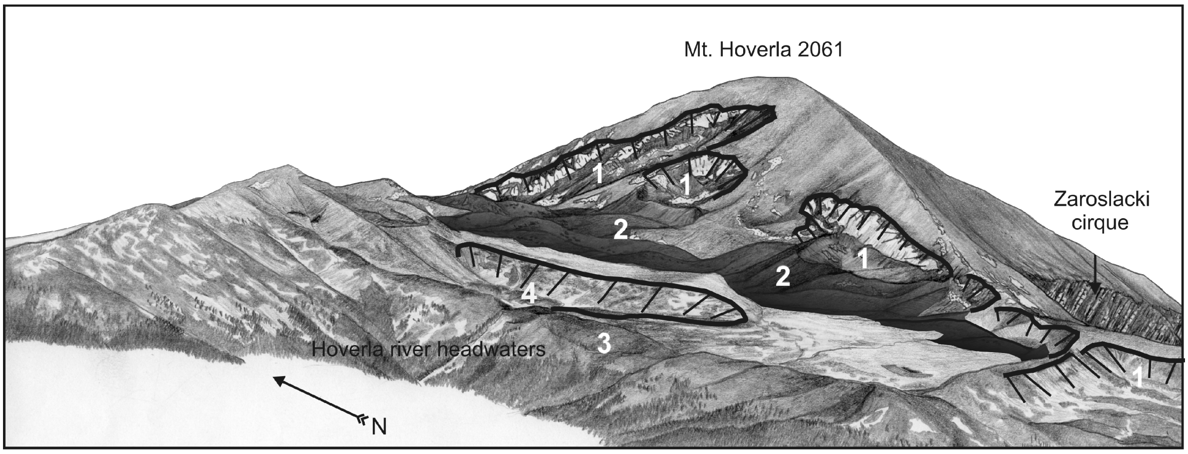

Fig. 7. A group of landforms resulting from landsliding on the SW slopes of Mt. Howerla (according to the author). A younger generation of sliding forms: 1 – niche with rocky slopes which are still affected by nivation processes, 2 – piled-up colluvial bulge. An older generation of sliding forms: 3 – landslide bulge, 4 – large rocky landslide niche within the headwaters of the Hoverla Stream

Fig. 8. SW slopes of Mt. Hoverla. Distinct landslide slip surface, associated with steeply dipping sandstone beds of the Chornohora series

Fig. 9. SW slopes of Mt. Hoverla. Piled-up colluvial material accumulated below the landslide hollows in the form of a 30–50-m-high bulge

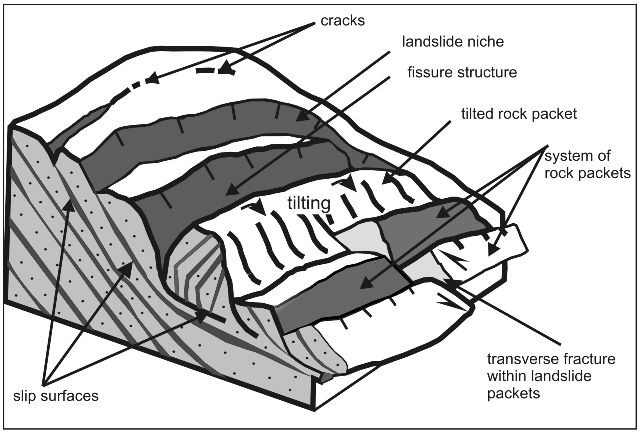

Fig. 10. A model of sliding forms on the SW slopes of Mt. Pozhyzhevska. The slope deformations developed as a result of displacement of rigid blocks along parallel slip surfaces. This process produced a 'step-like system' of fissures and rock masses. Transverse fractures are a result of variable movement rates between the rigid blocks

On the south-western side of the range, the slopes were re-shaped by large-scale mass movements (Figs 5, 7). The landslides of Mt. Hoverla are associated with the monoclinal pattern of bedrock strata and produced two distinct landforms of different age: the older and larger landslide within the headwaters of the Mt. Hoverla stream, and a younger generation of landslides on the mountain's south-western slopes.

The younger generation of landslide niches (Figs 5, 8) stand out clearly from the dominating landscape and contrast with the surrounding smooth and undistorted slopes. They represent classic translational landslides of block-glide type, where the slope blocks were detached along a bedding plane and were sliding down the slope, forming a jumbled pile of rock at the toe of the slide.

The three landslide niches have rocky walls and are recently subject to nivation processes, which are attested to by small nivation ramparts formed at the head of permanent snow patches. Slip surfaces appear within the landslide hollows in the form of solid sandstone beds, dipping steeply towards the SSW and SW at an angle of 30–40° (Fig. 8). The sandstone beds form characteristic rocky walls, 150–300 m long and 20–30 m high (Fig. 6, 8). Colluvial material consists mainly of sandstone boulders and solid rock packets, which are accumulated below the landslide hollows in the form of a 30–50-m-high wall (Fig. 9).

Landforms belonging to deep-seated gravitational slope deformations were identified on the slopes of Mt. Pozhyzhevska, Mt. Dancerz and Mt. Turkul (Kłapyta, 2006; Figs 5, 10). It is an area of complex morphology with dense network of crevices, landslide niches, and a system of fissures. Mass movement processes caused the formation of fracture systems, slumped bodies, and several generations of deep-seated slope deformations, accompanied by shallow landslides

The deformation on the slopes of Mt. Pozhyzhevska developed as a result of the displacement of rigid blocks along parallel slip surfaces (Fig. 10) that created a regular step-like system of fissures and rock masses forming rows of rock shelves (Fig. 11). These shelves are outcrops of thick, single or multiple beds intercalated by less resistant shales or marls. The dominant features in the uppermost section of the group of landforms originated due to rock sliding include cracks, crevices, landslide scars, and shallow fissures that frame the top side of the landslide hollow (Fig. 10). The displaced rock masses display breaks in bed continuity as a result of small-scale translational faults. Transversal cracks within the sliding rock masses originated due to varying rates and directions of movement between rigid blocks (Fig. 10). It is probable that cracks and faults within flysch formations played a major role in the development of landslide forms; these discontinuities compose a lineament perpendicular to the strike of beds and crossing the main ridge of the Chornohora Mts.

DISCUSSION

Detailed analysis of topographic and geomorphological maps and satellite images of the Chornohora Range yielded evidence of deep-seated gravitational slope deformation (DGSD) on the southern slopes of Mt. Pozhyzhevska, Mt. Dancerz and Mt. Turkul (Fig. 11). Deep-seated gravitational slope failures result from high-energy processes commonly occurring in alpine mountains and reported in the literature (Nemčok, 1982, 2007; Soldati *et al.*, 2004; Hradecký & Pánek, 2008). DGSD originated along a glacially over-steepened slopes (Madritsch & Millen, 2007), and in front of flysch nappes formed by rigid sandstones underlain by more plastic beds (Hradecký *et al.*, 2006). Flysch complexes are composed of alternating strata of contrasting strength. In the areas built of flysch, the geometry of deep slope deformation depends strongly of the internal bedrock structure and occurrence of cross-faults (Nemčok, 1982).

DGSD differ from landslides in having more than one slip surface and different mechanics of movement, with deformations occurring on multiple shearing surfaces (Tibaldi *et al.*, 2004). The resulting set of landforms can be divided into two subsets: split-ridges, landslide hollows, tension crevices and fissures in the upper slope section are known from the Alpine environment under a joint name of "*Bergzerreissung Phenomene*"; while in the lower sections of the slopes, large-scale bulging undulations are referred to as "*Talzuschub*" (Lotter *et al.*, 2001; Brückl & Mertl, 2006). Mountain areas built of alternating sequences of metamorphic schists, phyllites, and flysch tend to be particularly prone to this type of mass movement (Nemčok, 1982; Baron *et al.*, 2005). Faults and fissures found in flysch formations, as well as the patterns of rock strata have a strong bearing on landsliding. In flysch areas, these influences are crucial to the final shape of landforms originating from rock sliding, covering large areas up to several square kilometres and rock and waste-mantle formations up to 100 m deep. Inclinations of slope deformations in the West Carpathians are between 18° and 50° (Mahr, 2007).

The scale and complexity of these structures pose a considerable challenge to their correct identification and analysis. Such gravitational displacements alter the cross and longitudinal profiles of the slopes, as well as the course of the processes occurring along the entire slope profile. Research in the Western Alps demonstrated that large-scale deformations are found on slopes with relative drops between 500 and 1000 m (Tibaldi *et al.*, 2004). These deep-seated gravitational deformations were initiated on the convex slopes of young valleys.

A very complicated set of sliding forms was identified on the western and south-western slopes of Mt. Dancerz and Mt. Turkul (Figs 5). Below the shallow landslide hollows, there is a depressed area with a complex sliding morphology and a considerable degree of shattering and incorporating a system of regular fissures, landsliding crevices up to 4 m deep, and large-scale undulations. The shattered zone straddles the local watershed ridges with the fissures and crevices cutting across them (Fig 11). The discussed zone is limited to the south by a glacial cirque below Mt. Turkul, and to the north by the main ridge of the Chornohora Range, on the other side of which a large glacial cirque of Mt. Arendarz occurs. During the ice age and in postglacial time, the Chornohora cirques discharged large quantities of eroded rock masses.

Fig. 11. Mt. Pozhyzhevska and Mt. Dancerz SW slopes. Note deep-seated gravitational slope failures (*Bergzerreissung Phenomene*) with regular tension crevices and fissures in the upper slope section

Deep and large-scale landsliding stripped the upper sections of the south-western slopes of the Chornohora Range from large quantities of mass, and initiated rock and debris movement by secondary displacement. Today, the strongest morphogenetic effects of such movements are observed in secondary landslide hollows near the Chornohora ridges. The slopes also feature crevices and fissures known from the literature as the evidence of landforms developed due to brittle deformation of rock masses (Margielewski, 2001, 2004; Nemčok, 2007). Landforms linked to toppling and deformations in the existing rock masses suggest a continued gravitational instability of the slopes and that they are still adjusting to a new equilibrium profile (Hradecký & Pánek, 2008). Ziętara (1962, 1989) demonstrated in his studies of Mt. Babia Góra that gravitational deformations of hard sandstone complexes will continue as the most important process causing the retreat of mountain ridges.

The landsliding processes observed in the Chornohora Range are induced by bedrock structure, high potential energy of the relief, and heavy precipitation. The size and structure of the described landforms suggest multi-phase development of headwaters of the Hoverla River and Ozirnyj Stream. Deep-seated slope failures represent a very complicated system, and understanding their evolution and triggering mechanisms still remain unclear. Dating of large-scale gravitational deformations in the Carpathian Mountains linked these landforms with wet periods during the late Pleistocene and Holocene (Alexandrowicz & Alexandrowicz, 1999; Margielewski, 2002, 2004). It is suggested, however, that some large landforms in the Polish Western Carpathians could have developed earlier, even in the Pliocene (Łajczak, 2004). Climates regarded as conducive to the triggering of deep sliding in European mountains prevailed during the Late Glacial ice decay (12,500–11,500 cal BP), between the Atlantic and Subboreal periods (6,200–4,900 cal yrs BP) and during the climatic oscillations of the Little Ice Age (Soldati *et al.*, 2004). The accelerated frequency of mass movements in European mountains during the postglacial time is linked to a shallower ground water table, water saturation of the bedrock caused by greater precipitation, the melting of permafrost (Soldati *et al.*, 2004; Baron *et al.*, 2005), and neotectonics (Zuchiewicz *et al.*, 2002).

The morphology of the south-western slopes of the Chornohora Range is dominated by large structurally controlled landslides, both of rock and rock-and-waste mantle type, which can account for up to 70% of the slope area above the timberline (Fig. 5). The largest landslide features of the Chornohora Range were found on the south-western slopes of Mt. Hoverla, on the eastern slopes of Mt. Petrosul, on the western slopes between Mt. Breskul and Mt. Turkul, and on the western slopes of Mt. Pop Ivan (Hradecký *et al.*, 2001; Kłapyta, 2006) (Fig. 2). As an example, Świderski (1932) described the largest translational landslide of the Polish Beskidy Mountains that came down the southern slopes of Mt. Shuryn (Mt. Gropa) and blocked the Pohorylets River valley creating a temporary reservoir. Slip surfaces of these landslides are placed either on bedding surfaces (e.g. the consequent-structural landslide on the south-western slopes of Mt. Hoverla), or are related to crevices or cracks in hard lithological complexes (e.g. consequent landslides on Mt. Pop Ivan). The landslide hollows were reshaped by periglacial processes causing some researchers to mistake them for glacial cirques (Zapałowicz, 1889; Posewitz, 1893). In contrast, glacial cirques are deeper incised and their bottoms are filled with moraines and debris forms (protalus ramparts).

The relief of the Chornohora's dip-adjusted slope differs significantly from the morphology of the southern slope of the Babia Góra Mt. (1725 m a.s.l.) in the West Beskidy Mts., Poland. The Babia Góra Mt. is the highest elevated range of the Outer West Carpathians, and it is underlain by an asymmetric syncline, built mainly of thick-bedded Magura sandstones (Łajczak, 2004). Landform development of the Babia Góra Mt. is also strongly controlled by structural asymmetry, but dip-adjusted slopes of this massif are dominated by relatively shallow, broad landslide niches and rubble colluvium of the Magura sandstones (Łajczak, 2004; Hałat, 2006). These distinct differences are probably connected with the lower slope fragmentation and lower energy of relief within the southern Babia Góra slopes.

CONCLUSIONS

The main features of landforms of the Chornohora Range are associated with tectonic uplift of this section of the Carpathians, its tectonic style, and the occurrence of resistant complexes of the Chornohora sandstone and conglomerate. The characteristic asymmetrical morphology is of structural origin, as the lithological complexes built a homocline and the erosional base on the south-western side is lower than that on the north-eastern side. These structural factors were further reinforced by the Pleistocene glaciation. The different erosional regimes operating on either side of the main crests created strongly asymmetric ridges.

The slopes on the south-western face are characterized by a lesser degree of glacier development; they were reshaped by large-scale mass movements. The deformations were structurally predisposed, *i.e.* linked to the dip of strata and their resistance, as well as to cracks and faults within the flysch formations. The large-scale gravitational deformations were caused by mass movements comprising motions of rigid blocs along parallel slip surfaces. Formation of large-scale mass movements on the south-eastern slope of the Chornohora Mts. could be linked with the development of the Upper Tisza River headwaters and higher-energy backward erosion. The deep-seated large-scale sliding caused great changes to the relief, loss of large sections of the upper slope, and initiated secondary displacement of rock and waste mantle.

In contrast, the north-eastern, anti-dip slopes were strongly glaciated. The majority of valley head cirques are characterized by steep back walls and the bottoms filled with moraines, peat bogs, meltwater channels, landslide deposits and scree slopes.

The land relief of the Chornohora Mts. and its geological constraints are still little known and require more detailed studies, despite the long history of research. The Chornohora Range provides an opportunity for further research of climate-geological structure relationships in shaping a high mountain flysch massif, as well as for comparisons between the rates of glacial and nonglacial erosion on opposite slopes.

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