S T U D I A G E O M O R P H O L O G I C A C A R P A T H O - B A L C A N I C A
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PROCESS – FORM RELATIONSHIP IN THE STOŁOWE MOUNTAINS TABLELAND (CENTRAL EUROPE) – AN EXAMPLE OF STRONG LITHOSTRUCTURAL CONTROL ON GEOMORPHIC SYSTEMS OF MEDIUM-ALTITUDE MOUNTAINS

Abstract. The Stołowe Mountains are a stepped tableland within the Sudetes range, which otherwise represents valley-and-ridge fluvio-denudational relief. Reasons for the distinctiveness of the Stołowe Mountains are lithostructural and related to the presence of a nearly flat-lying clastic sedimentary sequence, with massive sandstone beds separated by fine-grained rock complex. Consequently, the geomorphic system of the area is distinctive too. Lacking long-term measurements of process rates, this paper attempts to provide qualitative characteristics of this system. Under contemporary conditions slope-channel connectivity is very limited and coupling between the two subsystems is episodic at most. Due to low gradient surface processes on extensive plateaus are of very low efficacy, whereas escarpments tend to disintegrate in situ rather than are subject to frequent rock slope failures. Subsurface processes of sand grain detachment, joint-guided transport and removal away from the rock massif play an important part. Rock control in the broad sense is so pervasive that it is nearly impossible to identify with confidence inherited landforms, whether from the Pleistocene or late Neogene.

Keywords: mountain geomorphology, sandstone geomorphology, escarpment, geomorphic system, Sudetes

INTRODUCTION

Mountain geomorphic systems are often analyzed in terms of a process cascade conditioned by altitudinal differentiation within mountainous drainage basins (Slaymaker, Embleton-Hamann 2009, 2018; Beylich et al. 2013; Heckman, Schwanghart 2013). This approach is most evident in high mountains where several altitudinal belts typified by different climatic and ecological characteristics may be distinguished (Troll 1973; Starkel 1980; Caine 1984; Slaymaker, Embleton-Hamann 2009). Consequently, each of these belts represents a separate geomorphological environment, with distinctive, although not necessarily unique, landforms, form–process relationships and slope-to-channel coupling (connectivity). Moreover, the cascade nature of the system dictates that each consecutively lower belt does not only hosts landforms and process domains specific to itself, but is also moulded in response to mass movement and fluvial processes initiated in higher belts, although the issue of connectivity must not be ignored. Finally, the factor of inheritance plays a prominent role and explains the presence of disequilibrium glacial and periglacial landforms well below the current lower altitudinal limits of these process domains.

Among the mountain areas where such a system approach has been championed are the Tatra Mountains in southern Poland/northern Slovakia (Kotarba 1984; Kotarba et al. 1987). A. Kotarba and L. Starkel (1972) contrasted the complexity of the denudational system of the Tatra Mountains – a part of the Inner Carpathians, with an apparently much simpler system of the Outer Carpathians, built of sedimentary flysch rocks and only locally exceeding the altitude of the timberline. The system approach was subsequently transferred to the Karkonosze Mountains in the Sudetes range (SW Poland/N Czechia), which are an example of a transitional mountain environment, with some high mountain characteristics but otherwise being typical medium-altitude, forested mountain range (Migoń 2008a; Kotarba, Migoń 2010). Within the montane forest belt J. Bieroński et al. (1992) identified three spatial domains: the most extensive hillslope domain with regolith-covered slopes, inherited glacial erosional domain with rock slopes in cirques, and the valley floor domain. In their view, the most significant processes active in these domains are slope wash, cryogenic processes and nivation in the former, debris flows, snow avalanches and nivation in cirques, whereas valley floors were mainly seen as transport corridors, with rather subordinate role of either erosion and deposition. Even admitting that the view of J. Bieroński et al. (1992) was more intuitive than based on systematic measurements, and that the role of extreme hydrometeorological-geomorphic events was insufficiently addressed as shown subsequently (Migoń et al. 2002; Migoń 2008b; Pawlik et al. 2016), the emphasis on a limited suite and low efficacy of superficial processes within the generally coupled hillslope-fluvial system, unless anthropogenically disturbed, seems adequate to characterize forested, low- to medium-altitude mountains of Central Europe, especially in crystalline basement rocks (Kotarba, Migoń 2010).

In this paper the focus will be on a sedimentary tableland of the Stołowe Mountains – a plateau-like terrain in the inner part of the Sudetes (Fig. 1). Its stepped morphology represents a type of relief very different from the ridge-and-valley morphology of other mountain groups in the Sudetes or Outer Carpathians. Consequently, the main aim here is to explore the characteristics of this distinctive morphological system to see whether it fits the common perception of geomorphology of low- to medium-altitude mountains or is a notable exception. Since sedimentary tablelands extend further west into Czechia and Germany, the relevance of this study is not limited to the Stołowe Mountains but its implications may be wider.

STUDY AREA

The Stołowe Mountains are a tableland c. 20 km long and 4–8 km wide, underlain by nearly flat-lying beds of mainly sandstones and mudstones of Cretaceous age (P u l i n o w a 1989; K a s p r z a k, M i g o ń 2015). They show a distinctive stepped relief, with a group of mesas and remnant plateaus rising above an extensive main plateau, which in turns terminates with a prominent escarpment in the north-east that connects with the undulated foreland cut across older, Permian sedimentary rocks. In the south-west, the morphological contrast with the highly dissected granite terrain is striking (Fig. 1). The altitudes of the mesas and plateau tops exceed 900 m a.s.l., whereas the altitude of the main plateau decreases from c. 750 m a.s.l. in the west to 550–600 m a.s.l. in the east, consistent with the southeastward inclination of Cretaceous beds. These planar elements of relief are truly remarkable and the slope inclination class 0–5° occupies more than one third of the core area of the Stołowe Mountains (K a s p r z a k, M i g o ń 2015). The north- and south-bounding escarpments as well as the marginal slopes of the mesas and remnant upper plateaus are 150–300 m high and show distinctive concave slope profiles over long distances.

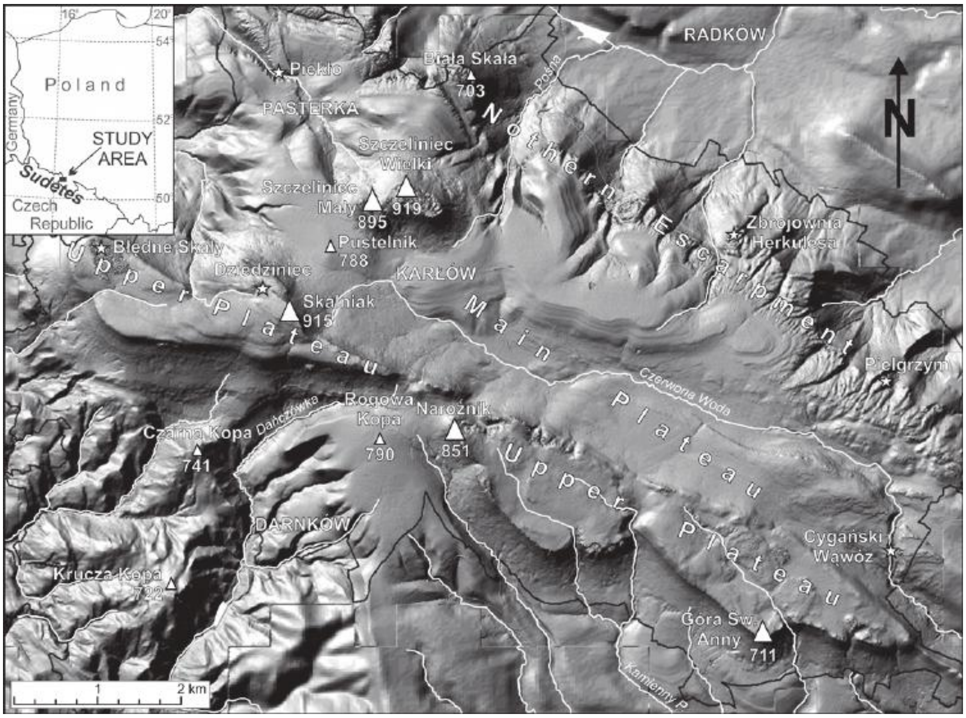

Fig. 1. Main relief features of the Stołowe Mountains tableland and location of sites referred to in the text. Shaded relief model courtesy of M. Kasprzak, based on LiDAR data made available by the Stołowe Mountains National Park

The Cretaceous succession beneath the tableland is c. 300 m thick and spans the period from late Cenomanian to late Turonian, possibly early Coniacian, hence c. 6 Ma. In the vertical profile three main sandstone horizons occur from bottom to top: glauconitic sandstone and conglomerates at the base of the succession (c. 15 m thick), medium- to coarse-grained arkosic sandstones in the middle (c. 80 m thick), and quartz sandstones capping the sequence (c. 50 m thick) (Jerzykiewicz 1968; Wojewoda 1997). Several minor (up to 15 m thick) sandstone bodies occur between the middle and the upper major sandstone horizon. Regular orthogonal jointing is typical for the Cretaceous sandstone, although joint spacing varies from less than 1 m to more than 10 m (Duszyński, Migoń 2015). Some sandstone lithosomes, especially the middle arkosic sandstones, wedge out in the south-westerly direction, accounting for the general asymmetry of the tableland which shows higher relative relief in the north. Between the sandstones various fine-grained rocks occur, mainly mudstones and siliceous marls, with the subordinate presence of calcareous sandstones, claystones, spongiolites and gaizes (Rotnicka 1997; Wojewoda 1997). Their common feature is poor permeability which contrasts with good permeability of the sandstones themselves due to both primary and secondary porosity (Kowalski 1983).

Post-depositional tectonic deformation of the Cretaceous beds was limited in the area of the present-day Stołowe Mountains plateau (as opposed to the nearby Kudowa Basin where considerable deformation has taken place, see J. Wojewoda 2009). Nevertheless, both large-scale and more local tilting are evident and reflected in the decreasing altitude and consistent sloping of the main plateau to the east, as well as southerly and south-easterly inclination of the upper plateau. Vertical bands of densely jointed, locally crushed rock, 0.5–2 m thick, provide evidence of brittle deformation that affected Cretaceous strata and focus enhanced weathering and rock disintegration (Pulinowa 1989). However, no unequivocal proofs of significant vertical fault displacements subsequent to the origin of the main features of the present-day relief exist.

MAJOR LANDFORMS

PLATEAUS

One of the most distinctive geomorphic features of the Stołowe Mountains is the presence of extensive surfaces of low gradient (Figs. 2, 3). They form the top parts of the remnant plateaus, mesas and midslope benches and occur at three altitudinal levels. The upper one is represented by the Skalniak and Narożnik massifs as well as the twin mesa of Szczeliniec Wielki and Szczeliniec Mały. They rise to the maximum height of 915 m a.s.l. , 851 m a.s.l., 919 m a.s.l. and 895 m a.s.l., respectively. Top surfaces of the former extend in the WNW-ESE direction at a distance of c. 4 and 6 km respectively, reaching the width up to

Fig. 2. Representative view of stepped tableland morphology. From left to right: footslopes in Permian sedimentary rocks, sinuous Northern Escarpment (note a quarry), Main Plateau, mesas of Szczeliniec Wielki and Szczeliniec Mały as outliers of the Upper Plateau

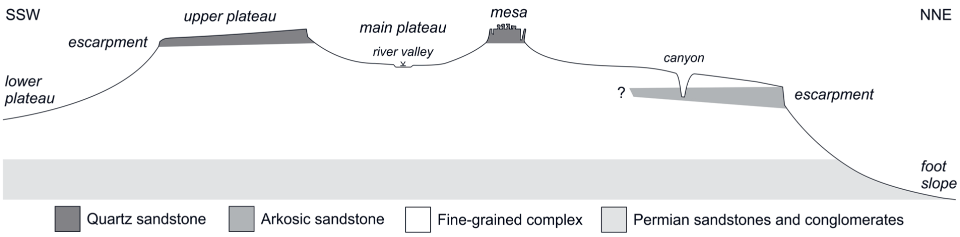

Fig. 3. Schematic cross-section of the Stołowe Mountains, showing the relationship to geology

1 km. The planar top surfaces of Szczeliniec Wielki and Szczeliniec Mały are much smaller – the former is c. 630 x 325 m, whereas the latter is 350 x 180 m. Some 100–150 m beneath the top surfaces of the remnant plateaus the middle storey of the Stołowe Mountains occurs. The so-called Main (or Central) Plateau is a planar or gently undulating surface constituting the dominant landform of the entire tableland. It extends over a distance of 16 km in the NW-SE direction, gently dropping to the south-east. The third morphological level of the Stołowe Mountains is present at elevations 500–600 m a.s.l., below the prominent escarpments.

The remnant plateaus of the upper level of the Stołowe Mountains are not uniformly inclined. The northern part of the Skalniak plateau is locally dipping to the south, in such places exceeding the inclination of 10–12°, generally consistent with the dip of Upper Turonian sandstone cap (P u l i n o w a 1989). An analogous feature may be found within the Narożnik massif. There, the north-western part of the plateau surface is distinctively sloping towards south-east. In both cases tectonic tilting seems to be the most likely reason. In other localities the morphology of Skalniak and Narożnik top surfaces is rather monotonous and characterized by low inclinations, typically below 5°. The Szczeliniec Wielki and the Szczeliniec Mały are typified by a starkly different relief which will be a subject of discussion later on.

The planar surfaces of the upper plateaus and mesas are all underlain by the same quartz sandstone which acts as a resistant caprock. In each locality the sandstone series lies horizontally or is gently dipping (generally less than 10°). At least four morphological types of plateau surfaces may be distinguished in the Stołowe Mountains (Duszyński et al. 2016). These are: (1) nearly level surfaces locally covered by regolith, with almost no rock outcrops, (2) ruiniform relief limited only to marginal parts of the plateaus, (3) ruiniform relief covering the entire plateau surface and (4) the chaos of blocks and boulders instead of intact rock.

The first type characterizes the largest portion of the area as it is present within the most extensive Skalniak and Narożnik plateaus. Not only bedrock outcrops are sporadic, but the amount of blocky material littering the surface is very limited, too. However, in both cases there exist sections of plateaus which are typified by the presence of rock outcrops in the marginal parts. In such situations *in situ* bedrock compartments may extend up to 50 m inward. Ruiniform relief – a natural feature of sandstone terrains characterized by the presence of open clefts, wide corridors and passages as well as the groups of isolated towers, spires and pinnacles – is very rare, but locally diversifies the morphology of Skalniak and Narożnik plateau surfaces. The best example is Dziedziniec (*Courtyard*) locality near the highest spot of Skalniak. It is a distinctive group of sandstone outcrops that form wide passageways and a rock labyrinth, with all corridors following the primary bedrock discontinuities (Duszyński, Migoń 2017).

An extensive group of sandstone outcrops is present only within the westernmost portion of Skalniak plateau. The so-called Błędne Skały is a rock labyrinth that occupies an area of c. 400 x 200 m (Fig. 1). It rises abruptly from the soil-covered top surface and appears as a regular set of bedrock compartments cut by a network of joint-aligned corridors (15–20°, 85–90° and 130–135°). No similar landform assemblage is present anywhere else in the whole tableland.

The summit surfaces of Szczeliniec Wielki and Szczeliniec Mały are characterized by a completely different morphology. The mesas are entirely covered by ruiniform relief, with spectacular examples of wide joint-guided corridors, isolated tor-like blocks and residual boulder accumulations. The 'rock city' of Szczeliniec Wielki (Czeppe 1949; Migoń, Kasprzak 2015) reaches the height of up to 30 m and occupies the total area of c. 17 ha. Unlike anywhere else its marginal parts are characterized by the presence of deep open clefts (the famous Piekiełko and Diabelska Kuchnia) which follow one of the dominant joint sets (130°). The eastern portion of Szczeliniec Wielki is a huge accumulation of loose blocks of sandstone stacked one upon another (Migoń, Kasprzak 2015). They are separated from the rest of the top surface by a clear topographic step, c. 20 m high.

The Main Plateau of the Stołowe Mountains is underlain mainly by the complex of less resistant fine-grained rocks (calcareous mudstones, calcarenites and claystones) (Fig. 3). To the east arkosic sandstones crop out, too (Wojewoda et al. 2011). The boundaries of the intermediate level of the Stołowe Mountains are not as clearly defined as those of the upper plateaus. In the west the Main Plateau is truncated by a sinuous escarpment in the south whereas in the north it is connected via a narrow neck with the backslope of a cuesta that extends further to the north-west. It continues in the south-east direction, with the valley of Czerwona Woda river acting as a morphological axis. Minor escarpments occur within the eastern part of the Main Plateau, related to the local occurrence of sandstone inliers within the fine-grained series.

MESAS

Only two mesas occur in the Stołowe Mountains – Szczeliniec Wielki and Szczeliniec Mały (Fig. 1). They represent an example of a twinned landform, being separated from each other only by a shallow pass. Both are capped by a sandstone layer which is up to 80 thick. Its middle portion of 40 m high acts as a vertical or close to vertical rock face. Sandstone walls are crowning both mesas, forming spectacular cliff lines, especially in the north and south. In plan view the cliffs follow the dominant joint directions – 30° and 120° and therefore in all those places where they are intersecting the cliff, the rock wall shows a distinctive zig-zag course. However, the cliffs of Szczeliniec Wielki and Szczeliniec Mały are highly diversified along their lengths. Next to very high and solid rock faces there occur highly disintegrated sandstone outcrops. In such localities the intact rock face is replaced by tilted blocks separated from each other by widened corridors or huge boulder accumulations filling distinctive slope depressions.

Further down the slope vertical cliffs give way to a concave slope section truncating less resistant layers of mudstones and claystones. Middle and lower slopes are littered with allochthonous sandstones boulders of substantial dimensions (those exceeding 5 m are common) that extend to the nearly level footslope section, some 300–450 m away from the rock faces (Duszyński, Migoń 2015). The lowermost part of the slope subtly connects with the Main Plateau.

ESCARPMENTS

Escarpments bounding the plateaus belong to the most prominent features of the Stołowe Mountains tableland (e.g. Dumanowski 1961; Pulinowa 1989; Migoń 2008b; Migoń et al. 2011) (Figs. 2, 3). The vast majority of them is associated with the presence of sandstone capping of substantial thickness and this causal relationship was noted as early as the late 1950s (Rogaliński, Słowiok 1958). The escarpments are developed within both the quartz sandstone of the upper plateaus as well as arkosic sandstone outcropping within the northern margin of the Stołowe Mountains. In both cases rock walls in the uppermost slope section are common. They reach up to 30–40 m high, but such impressive sections are limited only to a few localities – Szczeliniec Wielki, Szczeliniec Mały and some parts of the northern escarpment (Biała Skała, Zbrojownia Herkulesa and Pielgrzym). More often rock faces are 10–20 m high. There are also sections of cliff lines where the rock wall is not present at all and in fact, more than 50% of escarpments bounding the upper plateau level partly or entirely lack the rock face (Duszyński et al. 2016). Instead, rock spurs separated by extensive accumulations of joint-bounded boulders as well as convex sections covered by loosely lying blocks occur. A large part of the southern escarpment of Skalniak is completely rock wall free.

Both P. Migoń (2008b) and M. Kasprzak and P. Migoń (2015) underlined the diversity of cliff lines in plan. The most striking difference is between the northern and southern escarpments (the latter understood as the southern slopes of Skalniak and Narożnik plateaus). The northern margin is highly sinuous and characterized by the presence of 14 amphitheatres incised into the escarpment, first emphasized by M.Z. Pulinowa (1989) who described them under the name of 'sapping cirques'. The rock faces within the recesses are also diversified. They are partly dissected and M. Kasprzak and P. Migoń (2015) reported as many as 29 ravines, many of them truncated at the cliffs. The southern escarpment is very little varied. Its sections follow straight courses, with no amphitheatres at all. At a distance of 10 km only eight box- or v-shaped valleys and two shallow troughs are present (Kasprzak, Migoń 2015). However, rock walls of the southern escarpment show some morphological diversity. According to J. Remisz (2008), it is possibly the result of varied density of fractures.

The escarpment slopes were long considered rather simple in the longitudinal profile, with a rock wall in the uppermost part, concave middle slope section termed as debris slope and a wash slope beneath (Dumanowski 1961, 1967; Rogaliński, Słowiok 1958). In fact, the morphology of slopes truncating less resistant strata is much more complex, with occasional mid-slope benches and risers (Migoń, Zwiernik 2006; Kasprzak, Migoń 2015; Duszyński et al. 2017). All escarpment slopes of the Stołowe Mountains are covered by boulders of various size and density. They are allochthonous, caprock-derived material.

FOOTSLOPE SURFACES

If no escarpments of lower morphological levels connect with the slopes of the plateaus situated above (as it is in the case of north-eastern section of Szczeliniec Wielki) or no river incision occurs (the example of a part of the southern escarpment of Skalniak), the lower slope segments of escarpments give way to level or nearly level footslope surfaces. They are all cut in less resistant strata – the complex of mudstones and claystones within the surfaces surrounding the upper plateaus and the weak sandstones and conglomerates of Permian age beneath the northern escarpment. Footslope surfaces in the Stołowe Mountains are rather monotonous, with only shallow and infrequent linear depressions parallel to the general slope inclination and locally present pit-and-mound microtopography due to tree uprooting. The most distinctive feature of footslope surfaces is related to the presence of material of allochthonous origin – the caprock-derived sandstone boulders. The boulders extend over large distances – the most distant ones are situated up to 1 km from the rock faces (Duszyński et al. 2017). They can be found on flat surfaces and usually attain considerable size, even 15 m long. Many boulders have tabular shapes, nearly 10 m long but even less than 1 m high (Duszyński, Migoń 2015).

CANYONS

Canyons belong to the most spectacular examples of river incision in the Cretaceous tableland and cuesta landscapes of the Middle Sudetes, but only two such landforms occur in the Polish part of the tableland (Fig. 1). One is Piekło valley in the vicinity of Pasterka village. It is a deeply incised valley with vertical escarpments on both sides. Its maximum depth is 30 m. The canyon extends over a distance of c. 700 m in the SE-NW direction and further down the valley widens. The second example is Cygański Wąwóz (= Gypsy Gorge) in the eastern part of the Main Plateau. The canyon formed by the Czerwona Woda river is about 300 m long and reaches the depth of 30–40 m. Both canyons have developed within the intermediate level of the tableland, cutting more resistant sandstone series.

PROCESSES

WEATHERING

Despite the popular interest in bizarre rock formations of the Stołowe Mountains tableland, weathering mechanisms acting upon sandstone outcrops are poorly understood. However, the main pathway of superficial weathering is grain-by-grain breakdown, leading to detachment of individual quartz grains. Disintegration occurs preferentially along horizontal partings, especially near the ground surface, producing overhangs which are locally a few metres long and usually up to 1 m high. They may extend slot-like into the rock walls for 1 m or more. Basal overhangs are best developed in the rock labyrinth of Błędne Skały. Their association with standing water pools and boggy ground suggests that wetting and drying may play an important part in rock breakdown. In other places granular breakdown appears more localized, producing isolated cavities which enlarge laterally and may coalesce to form horizontal strings of hollows resembling tafoni. Increasing rock porosity favours granular disintegration as testified by distinct rock wall recesses coinciding with layers of porous, poorly sorted sandy conglomerates. Sandy sheets on the floors of overhangs and around the outcrops are products of granular disintegration. Rock surfaces between the partings are protected from weathering by surface crusting. Its visual manifestation is darkened colour and the crusts are a few millimetres thick. No mineralogical work has been carried out on these features in the Stołowe Mountains and one can only hypothesize that they are similar in origin and composition to surface crusting developed on sandstone outcrops in the Carpathians (Alexandrowicz, Pawlikowski 1982) or in the other parts of the Bohemian Cretaceous Basin (Cílek, Langrová 1994; Adamovič et al. 2011), to contain significant amounts of gypsum and potassium alum.

Contemporary weathering within low-gradient surfaces occurs within regolith and contributes to the origin of soils. Depending on bedrock, pathways of pedogenesis vary (Kabała et al. 2011). Leptosols and Podzols form over sandstones whereas Cambisols and Luvisols are typical soils for mudstones and marls. Poor permeability of fine-grained rocks and minimal slope inclination favours ground waterlogging and the development of peat bogs. Gleysols and Histosols evolved in such locations although widespread drainage of peatbogs in the 19th and early 20th century resulted in soil desiccation and change towards Hemic Histosols and Stagnic Podzols. Certain specific features of bare sandstone surfaces, resembling different types of karren (sensu Gines et al. 2009), suggest that they formed under the soil and vegetation cover through biochemical etching and have become exposed after the soil cover was eroded away.

SUBSURFACE EROSION AND RELATED DEPOSITION

Since more than 60 years ago subsurface erosion has been considered the crucial geomorphic agent in the evolution of the Stołowe Mountains tableland. For long time its action was linked solely with the undermining of rock faces and the resultant subsidence and collapses (Czeppe 1952; Dumanowski 1961; Pulinowa 1989). Recently, however, it was realized that underground water flow rarely leads to initiation of catastrophic episodic mass movements; rather, its main role is to remove sandy detritus from inside the caprock (Duszyński et al. 2016). According to this new evidence-based concept, rainwater percolates effectively through highly porous and permeable sandstone beds, making use especially of a regular system of joints. The sandstone is underlain by a complex of poorly permeable mudstones and claystones and hence, water is not able to penetrate further down after reaching the lithological contact. As a result, it flows directly towards the slope surface, carrying detached grains of sand and removing them outside the sandstone caprock. The process, termed by F. Duszyński et al. (2016) as 'underground erosion', is most effective in the marginal parts of sandstone plateaus and mesas and explains why their morphology is often characterized by distinctive ruiniform relief, with widened corridors

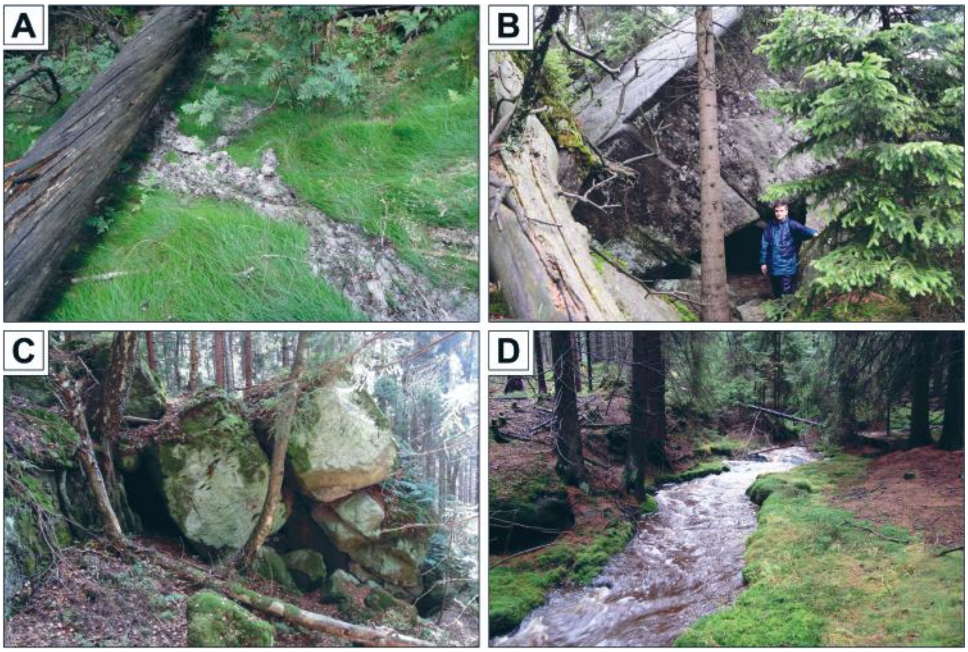

Fig. 4. Evidence of geomorphic processes in the tableland: A – fresh sandy deposition over grass during extreme precipitation events; B – toppled sandstone column (note c. 45° dip of bedding planes); C – irregular boulder accumulation within an escarpment; D – Czerwona Woda stream at nearly bankfull discharge

and rock labyrinths, isolated tor-like sandstone compartments or by the presence of huge accumulations of joint-bounded boulders lying one-upon-another. Long-term action of underground erosion leads to *in situ* disintegration of cliff-lines along discontinuities.

The direct geomorphic evidence of underground erosion and sand removal is the presence of sandy accumulation beneath the cliff lines. It often takes the form of cones supported by rock wall from one side, but chaotic sheets or irregular paths of sand may also occur (Fig. 4A). No matter what their morphology is, all depositional forms are situated at the outlets of vertical fissures in rock walls, indicating that the interior of the sandstone slab is the source of mineral material. The removal of sandy detritus outside the caprock is known from localities elsewhere (e.g. W r a y 2009), but in the Stołowe Mountains tableland the cones have been mentioned for the first time by P. M i g o ń et al. (2011), whereas their first quantitative study is by F. D u s z y ń s k i et al. (2016). Volumetric calculations revealed that the total amount of sand that was removed from the sandstone cap of the upper level of the Stołowe Mountains and is now stored in the cones is close to 1000 m^3. This number should be considered as significant, taking into account that sandy cones are probably ephemeral forms (D u s z y ń s k i et al. 2016). Fresh sandy accumulations appear during or immediately after heavy rainstorms, suggesting that the removal of sand is limited to a few events throughout the year.

The removed grains of sand are further transported towards the middle and lower slope segments, where they form thick slope covers (Waroszewski et al. 2015; Duszyński et al. 2016). Their thickness might even reach 3 m or more and systematically decreases downslope. Using ERT survey F. Duszyński et al. (2016) estimated the total volume of allochthonous sandy covers within the escarpment slopes of the upper level to be as high as 22 x 10^6 m^3. The value is only one order of magnitude smaller than the total volume of the remaining sandstone cap of the upper level of the Stołowe Mountains, indicating the effectiveness of the process of underground erosion (Duszyński et al. 2016).

Subsurface evacuation of material has visible effects in the morphology of the upper slope segments and marginal parts of plateaus and mesas. The rock faces are often disintegrated to such a degree that they no longer form continuous cliff lines. Rather, chaotic boulder accumulations separated by short sections of degraded walls are present. The loss of material from beneath also results in the lack of support for more resistant sandstone compartments. As a consequence, the blocks tilt in various directions, sag into widened corridors or topple (Fig. 4B). The latter case is best represented by Piekiełko and Diabelska Kuchnia open clefts in the northern part of the mesa of Szczeliniec Wielki.

MASS MOVEMENTS

Mass movements have commonly been considered the dominant surface processes involved in parallel escarpment retreat in the Stołowe Mountains (e.g. Dumanowski 1961; Pulinowa 1989; Migoń 2008b; Duszyński, Migoń 2015). Both specific hydrogeological conditions (Czeppe 1952; Dumanowski 1961; Pulinowa 1972, 1989) as well as high relief energy (Rogaliński, Słowiok 1958) have been pointed out as natural factors predisposing the occurrence of rock mass failures. Various examples of slope instability have been mentioned in the context of the Stołowe Mountains: toppling failures (Dumanowski 1961; Pulinowa 1989), landslides (Pulinowa 1989), block slides (Pulinowa 1972) or even rock avalanches (Zgorzelski 1995). However, rock falls and collapses of the entire rock face segments were considered most often, with the lower scarp slope segments typically named as ‘debris slopes’ (Rogaliński, Słowiok 1958; Dumanowski 1967). The reasons why catastrophic mass movements within the caprock gained such emphasis in the Stołowe Mountains appear at least fourfold. First, extensive sandstone block fields are the most prominent feature within the middle and lower escarpment slopes (Fig. 4C). They were *a priori* linked with rock fall events (e.g. Łoziński 1909). Second, and related to the first, vertical cliffs in the uppermost slope sections were seen as the obvious source of blocky material beneath. Third, the most influential studies were conducted solely within the mesa of Szczeliniec

Wielki (Dumanowski 1961; Pulinowa 1972) where some spectacular examples of toppling are indeed present (Piekiełko and Diabelska Kuchnia open clefts). Fourth, rock mass failures were commonly described from tablelands all over the world (e.g. Schumm, Chorley 1966; Howard, Kochel 1988), offering a ready and apparently appropriate explanation how escarpments retreat in the Stołowe Mountains as well. The opinion about the crucial role of mass movements was thus an assumption rather than a systematically examined problem. In fact, apart from one minor event from the Czech part of the Stołowe Mountains in 1921, no large-scale mass movements have been recorded in historical times (Duszyński, Migoń 2015).

According to the latest research, rock mass failures play a minor role in the contemporary geomorphic evolution of the Stołowe Mountains (Duszyński, Migoń 2015; Duszyński et al. 2015). This radical change of view was supported mainly by observations of allochthonous sandstone boulders covering the lower escarpment slopes. Huge boulders, with the length reaching up to 10–15 m, are located in the nearly level footslope sections, hundreds of meters away from the rock faces, which is difficult to reconcile with rock fall origin. The results of computer simulations showed that the maximum rock fall run-out zones are 2–3 times shorter than the actual position of boulders (Duszyński, Migoń 2015). Furthermore, Schmidt hammer tests revealed that compressive strength of boulders systematically decreases down the slope, indicating an increasing degree of weathering, which in turn suggests that the most distant boulders have longest lifetimes. This increase of age with the distance from rock faces is hardly consistent with the rock fall origin.

On this basis, as well as the observations of highly disintegrated rock faces, F. Duszyński and P. Migoń (2015) proposed an alternative scenario of escarpment evolution in the Stołowe Mountains. The *in situ* disintegration model assumes that rock mass disintegrates grain by grain along the discontinuities (this idea was further developed by F. Duszyński et al. 2016). In this way once solid cliff lines become a mess of joint-bounded boulders. Their further transport down the slope is apparent rather than real as they occupy lower and lower topographic positions while the escarpment recesses and the surface is lowered. This hypothesis emphasizes the dominant role of non-catastrophic processes in the evolutionary pathway of the Stołowe Mountains.

Nonetheless, due to the availability of high-resolution LiDAR data local occurrences of rotational and translational landslides have been recognized recently (Migoń, Kasprzak 2011; Migoń, Kasprzak 2012; Migoń et al. 2013; Duszyński et al. 2017). They are limited to the middle and lower scarp slope segments built of fine-grained rocks and never involve the caprock. Although these landslides were recognized within eight localities only, their role should be considered as significant. Firstly, they re-model simple, concave longitudinal profiles of the escarpments, giving them more complicated, tread-and-riser morphology (Duszyński et al. 2017). Secondly, the sliding mass is able to transport

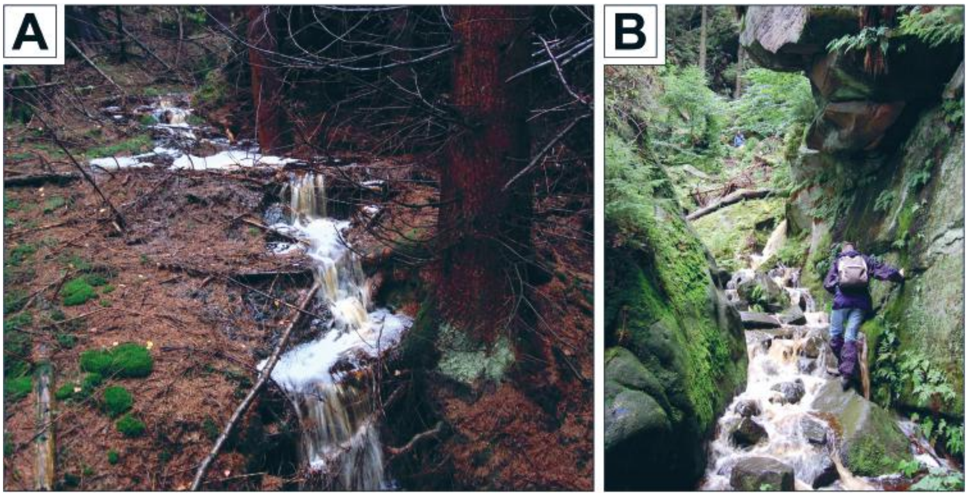

Fig. 5. Extreme hydrological events in the Stołowe Mountains: A – overland flow within a shallow trough near the plateau margin; B – episodic flow in a ravine incised into the Northern Escarpment

allochthonous sandstone boulders over substantial distances (D u s z y ń s k i et al. 2017). Third, the resultant landslide morphology degrades with time, leaving only residual boulders in the ultimate stage. Thus, it may be hypothesized that more landslide events may have taken place but the clear morphological evidence disappeared.

FLUVIAL PROCESSES

Fluvial processes appear not to be very significant in the tableland which is due to several reasons combined. First, significant amount of rainfall infiltrates into permeable bedrock and supplies groundwater resources. Second, part of it is stored within peat bogs and marshy ground, being released rather slowly to the drainage network. Third, the tableland of the Stołowe Mountains occupies watershed position and therefore discharges are very low. Fourth, topographic gradients are very low over much of the Stołowe Mountains, whereas steep escarpments coincide with the well-jointed sandstone bedrock, intercepting surface runoff. Thus, valleys crossing the northern escarpment are normally dry and carry watercourses only during and immediately after heavy rains (Fig. 5). Spring-related erosion (spring sapping) hypothesized by M.Z. P u l i n o w a (1989) to be very important in shaping amphitheatres within the northern escarpment is probably considerably reduced nowadays due to groundwater intake.

The longest streams draining the plateau levels, Czerwona Woda, Kamienny Potok and two others, were analysed in detail from geomorphological perspective by M. W i t e k (2013, 2015). Two types of channels were identified. Except for the longest Czerwona Woda, sluggish plateau reaches are very shallow, with indistinct low banks (<0.5 m), occasional dams from fallen tree logs, and no evidence of significant erosion. Longitudinal gradients increase within escarpments but the work of rivers is mainly to wash away fine sand, leaving the boulder lag in channels. Nothing suggests that these boulders, some up to 2 m long, are ever transported although they may change positions due to removal of sand from beneath. Channel morphology of the Czerwona Woda creek indicates moderate lateral erosion and bank undercutting in the meandering reach, whereas bedforms show slow transport of sand, accelerated during higher discharges (Fig. 4D).

Perhaps the most significant observation about the contemporary fluvial system is that it is nearly completely decoupled from the slope domain. In particular, slopes of the remnant mesas on the plateau and steep southern and northern escarpments do not connect to any sizeable watercourses and there is no undercutting. Thus, any activity within rock faces or intermediate slope segments has no effect on the fluvial system.

GEOMORPHIC SYSTEM OF A TABLELAND – A TENTATIVE SYNTHESIS

At the outset of the discussion it needs to be remarked that the evaluation of the contemporary geomorphic system – understood as the one characterizing most of the Holocene, i.e. the period with dense forest vegetation over the plateau surface and the escarpments – of the Stołowe Mountains tableland is almost entirely qualitative, based on process-from-form reasoning, negative rather than positive evidence (i.e. the lack of events is as significant as their presence), and consideration of morphometric characteristics of relief provided by M. Kasprzak and P. Migoń (2015). Quantitative approach to contemporary processes in the study area was attempted by M.Z. Pulinowa (1989) in respect to chemical and mechanical denudation but the results came from short-term measurements in a limited number of localities, hence they are difficult to extrapolate over the entire region. Monitoring of rock wall stability and movements yielded results which indicate some joint opening (Cacoń, Košták 1976; Cacoń et al. 2008), potentially leading to rock fall, but for most part they are not very conclusive in the context of long-term pathways of rock slope development.

There are five interrelated issues relevant to any attempts to produce a tentative synthesis of the contemporary geomorphic system of the Stołowe Mountains tableland. These are (i) connectivity, (ii) the role of gradual versus catastrophic processes, (iii) the relative role of different processes (i.e. ranking according to efficacy), (iv) inheritance, and (v) anthropic modifications.

The importance of connectivity in mountainous landscapes is increasingly emphasized in catchment-wide studies and in theoretical considerations (Harvey 2002; Fryirs 2013; Savi et al. 2013; Slaymaker 2017). Connectivity is achieved through the coupling of slope and channel subsystems, which in turn is both a feature of system's spatial organization, i.e. whether slopes and channels are physically connected, and a measure of system efficacy through time, i.e. how often and in which situations material actually moves from the slope to the channel. Thus, slopes and channels may be physically coupled and largely disconnected if no sediment transfer takes place across the slope/channel junction over long time.

At present, the tableland of the Stołowe Mountains appears as a landscape typified by extreme disconnectivity, both in space and time. There are very few places where steep slopes connect with river channels. This occurs in canyons, which are rare, and in ravines crossing the northern escarpment which remain dry for most of the time and having very small headwater catchments, do not carry much water capable of moving material forward. The situation encountered along the west-facing escarpment of the Rogowa Kopa, where ravines incise mudstone bedrock, and allochthonous sandstone boulders move downslope and accumulate in the valley bottoms (Parzóch, Migoń 2015), is probably exceptional. The typical situation for the Stołowe Mountains is the presence of wide, gently inclined footslopes which act as buffer zones and sites of long-term storage of material removed from the slopes. The recognition that superficial sandy sheets thin out downslope and wedge out before reaching the channels (Duszyński et al. 2016) is one example of disconnectivity. On the Main Plateau extensive peat bogs separate the slopes from channels, storing both water and sediment. Even if slopes are moderately steep, no ready transfer routes to connect with channels occur in a non-modified landscape, unless anthropogenic disturbance took place (Latocha 2014).

However, whereas disconnectivity is a distinctive feature of the contemporary geomorphic system, the stage in the past may have been different. Less vegetation in colder and/or drier periods of the Pleistocene would enhance sediment transport across the slopes and towards the channels, whether by surface wash or solifluction. This scenario was hypothesized by M.Z. Pulinowa (1989), who argued for very efficient periglacial mass transport, especially in the waning stages of cold periods. Unfortunately, in the absence of chronological markers the functioning of the Pleistocene/periglacial geomorphic system of the Stołowe Mountains remains a matter of speculations.

Despite occasional claims and intuitive opinions (Łoziński 1909; Zgorzelski 1995), catastrophic events seem to play a very minor role in the contemporary geomorphic system and are typified by very long recurrence intervals, even of duration beyond the time span of recording. Thus, only one case of rock fall and rolling down of debris was recorded in the entire 20th century and the volume of mass involved was small. Likewise, there are no reports about significant channel remodelling by floods which occur with very low frequency anyway. The only catastrophic events recognized beyond doubt are wind throws which contribute to regolith mixing, bedrock mining, origin of pit-and-mound topography and, in the aftermath, create conditions for accelerated surface wash (Pawlik et al. 2013). However, these are localized in space and if the sandstone plateau surfaces are affected, most airlifted material returns to pits (Pawlik et al. 2016). Otherwise, gradual, low rate processes of weathering and underground erosion take place, the latter involving sand grain detachment, transport along discontinuities and cone build-up. Subsurface erosion is then reflected in tilting and sagging of blocks which slowly adjust to the removal of support from beneath (Duszyński et al. 2016). Another gradual process identified in the tableland is slow creep of large boulders in specific topographic and geological circumstances (Duszyński, Parzóch 2017). These surface processes are supplemented by chemical denudation, probably important for mudstones/marls and sandstones alike (Pulinowa 1989) and possibly responsible for gradual slope lowering in fine-grained sedimentary series.

In the past attempts to recognize mountain denudational systems, geomorphic processes involved were categorized according to the relative importance or intensity. Thus, in the Tatra they were considered to be of high, medium and low intensity (Kotarba et al. 1987), whereas J. Bieroński et al. (1992) working in the Karkonosze Mts. took a restrictive approach and distinguished medium- and low-intensity processes only. The difference was meant to highlight diverse functioning of the high-mountain and medium altitude geomorphic systems in the temperate zone of Central Europe. In the Stołowe Mountains even categorization into medium and low intensity is debatable as most processes identified on the basis of form evidence appear to be invariably of low intensity. Consequently, ranking of processes according to their importance for the contemporary geomorphic system seems hardly feasible and would be highly speculative. Following M.Z. Pulinowa (1989) and F. Duszyński et al. (2016), and consistently with findings of J. Waroszewski et al. (2015), one may propose that subsurface erosion and chemical denudation, both largely "invisible", are more important than we think, but so far this is mainly an informed guess. Certainly, little support can be provided to claims that rock slope failures are important under current conditions.

The above considerations lead to the proposal that a significant part of the contemporary morphology of the tableland is inherited, although volumetric calculations of the amount of sand stored within escarpments of the Stołowe Mountains (Duszyński et al. 2016), integrated with data about the likely Holocene age of sandy sheets (possibly Subatlantic) (Waroszewski et al. 2015), suggest that inheritance may not be too distant. Old views that the gross features of the Stołowe Mountains might reflect arid conditions of the mid- of late Cenozoic, based on visual resemblances (Rogaliński, Słowiok 1958; Walczak 1968), are not tenable any longer. M.Z. Pulinowa (1989) was less keen to acknowledge the distant Tertiary inheritance but emphasized Pleistocene periglacial legacy, seeing it mainly in blocky talus widespread on escarpment slopes, the occurrence of ploughing blocks, the presence of 'block streams' filling the valleys incised into the lower slopes, and solifluction structures in slope deposits. However, unequivocal evidence that these features are indeed distinctively periglacial is missing and it is safer to assume that lithostructural control of processes in the tableland is so strong that these processes vary by rates rather than by type, sustaining the overall pathways of landform evolution. At the time of the most severe permafrost development subsurface processes of erosion and chemical denudation may have been significantly retarded but otherwise they were probably continually active.

The human factor in the functioning of the geomorphic system of the Stołowe Mountains tableland was recently comprehensively addressed by A. Latocha (2014), with particular reference to agricultural use. She noted both considerable modifications of the natural geomorphic system due to land management as well as shifts in the intensity of slope-channel coupling/decoupling related to the history of management. Relict anthropic landforms such as road gullies provided connectivity and contributed to higher dynamics of the morphogenetic system. However, depopulation, spontaneous afforestation, disappearance or neglect of various anthropogenic features, typical for post-World War II period, resulted in decoupling of slopes and channels, increasing geomorphic stability. Except specific localities such as roads across steep terrain still used by forestry or heavily visited hiking trails, also within steep slopes, where enhanced erosion is recorded (Migoń et al. 2011; Owczarek, Kassa 2012), downslope transport of mineral material is negligible. In addition, numerous barriers of anthropogenic origin in the channels increase in-channel disconnectivity.

WHY IS THE GEOMORPHIC SYSTEM OF THE TABLELAND PECULIAR?

The concept of medium-altitude mountain geomorphic systems was developed in terrains typified by 'normal' fluvio-denudational relief, possibly with some inherited glacial component (Kotarba, Starkel 1972; Bieroński et al. 1992). Hence, ridge-and-valley topography is the norm, slopes are predominantly regolith-covered, potential connectivity exists, and steep-gradient streams are the main carriers of material, especially during extreme hydrometeorological events. In contrast to the Outer Carpathians or the Karkonosze, the geomorphic system of a tableland shows several distinctive characteristics (Fig. 6). First, the main features of relief are different and the ridge-and-valley topography is replaced by the stepped arrangement of planar surfaces, separated by concave escarpments crowned by nearly vertical rocky sections. Main drainage lines are rather far from the escarpments, within planar relief, and hence, valley forms are poorly developed. Second, this bears on connectivity between slopes and channels which is very poor or even non-existent. In the Stołowe Mountains neither the trunk stream of Czerwona Woda nor any of its tributaries drain steep escarpment slopes. Third, due to negligible gradient there are hardly contemporary mechanisms of surface transport through which regolith produced on plateaus could be transferred to streams. Fourth, even if valley forms exist in

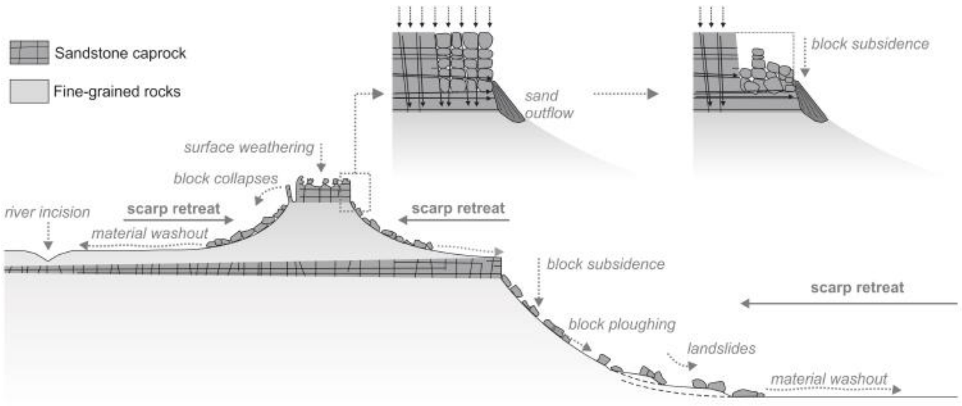

Fig. 6. Diagrammatic presentation of processes involved in the geomorphic evolution of the stepped tableland, including close-up to show mechanisms of in situ disintegration of cliffed escarpments

some places, they are either permanently dry or carry water only during very high intensity rainfall events, so that little fluvial erosion takes place. Fifth, the role of subsurface processes is important, with underground removal of sand via subterranean, joint-guided flow being a catalyst for slow-going disintegration of rock mass, sagging and tilting. Sixth, extreme geomorphic events, especially mass movements, play a very minor part in landform evolution, at least under the present-day conditions. Seventh, rock control in the broad sense is so pervasive that it is nearly impossible to identify with confidence inherited landforms, whether from the Pleistocene or late Neogene.

However, a cautionary note has to be issued. The tableland of the Stołowe Mountains cannot be considered entirely representative for sedimentary tablelands of Central Europe. Analogous plateaus exist in the northern part of Czechia (Adamovič et al. 2006, 2010) and while they share some characteristics with the Stołowe Mountains tableland, there are notable differences too. For instance, marginal parts of some of these plateaus are much more affected by mass movements, e.g. those of Přihražská plošina in the Bohemian Paradise where joint opening, block gliding, large-scale tilting and toppling, sandstone tower collapses and deep-seated slides are common (Rybář et al. 2006; Forczek 2009). In other places, e.g. on the Hruba Skála plateau, dolines are ubiquitous, indicating that subsurface removal of sand is much more efficient and differently organized than in the Stołowe Mountains (Balatka, Sládek 1971; Kùrková, Bruthans 2012). Bedding caves, rather uncommon in the Stołowe Mountains, are frequent in certain areas such as Klokočské skály, pointing to different disintegration patterns of rock cliffs (Vítek 1987). Finally, an extreme disconnectivity typical for the Stołowe Mountains will not typify areas showing higher fluvial dissection such as the canyonlands of Kokořinsko north of Prague (Balatka et al. 1969) or the Bohemian Switzerland (České Svýčarsko) (Vařilová 2016).

CONCLUSIONS

The Stołowe Mountains provide an example of a sedimentary tableland within the medium-altitude mountain range, otherwise built of crystalline, volcanic and deformed sedimentary series and hence, typified by ridge-and-valley topography, with localized remnants of elevated surfaces of low relief. Consequently, the contemporary geomorphic (denudational) system is distinctive and unlike 'classic' fluvio-denudational relief. Under contemporary environmental conditions, slope-channel connectivity is very limited and coupling between the two subsystems is episodic at most. Due to low gradient surface processes on plateaus are of very low efficacy, whereas escarpments tend to disintegrate in situ rather than are subject to frequent rock slope failures. Although this tableland is not karstic, subsurface processes of sand grain detachment, joint-guided transport and removal away from the rock massif play an important part. Extreme geomorphic events are almost unheard of, although this is not a universal feature of sandstone plateaus which elsewhere may be affected by rock falls and topples. Landform inheritance from the pre-Holocene period is difficult to demonstrate but this does not mean that the relief is so young and dynamic. Rather, it argues for the dominant role of lithostructural control on landforms and processes, regardless of changing environmental conditions.

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