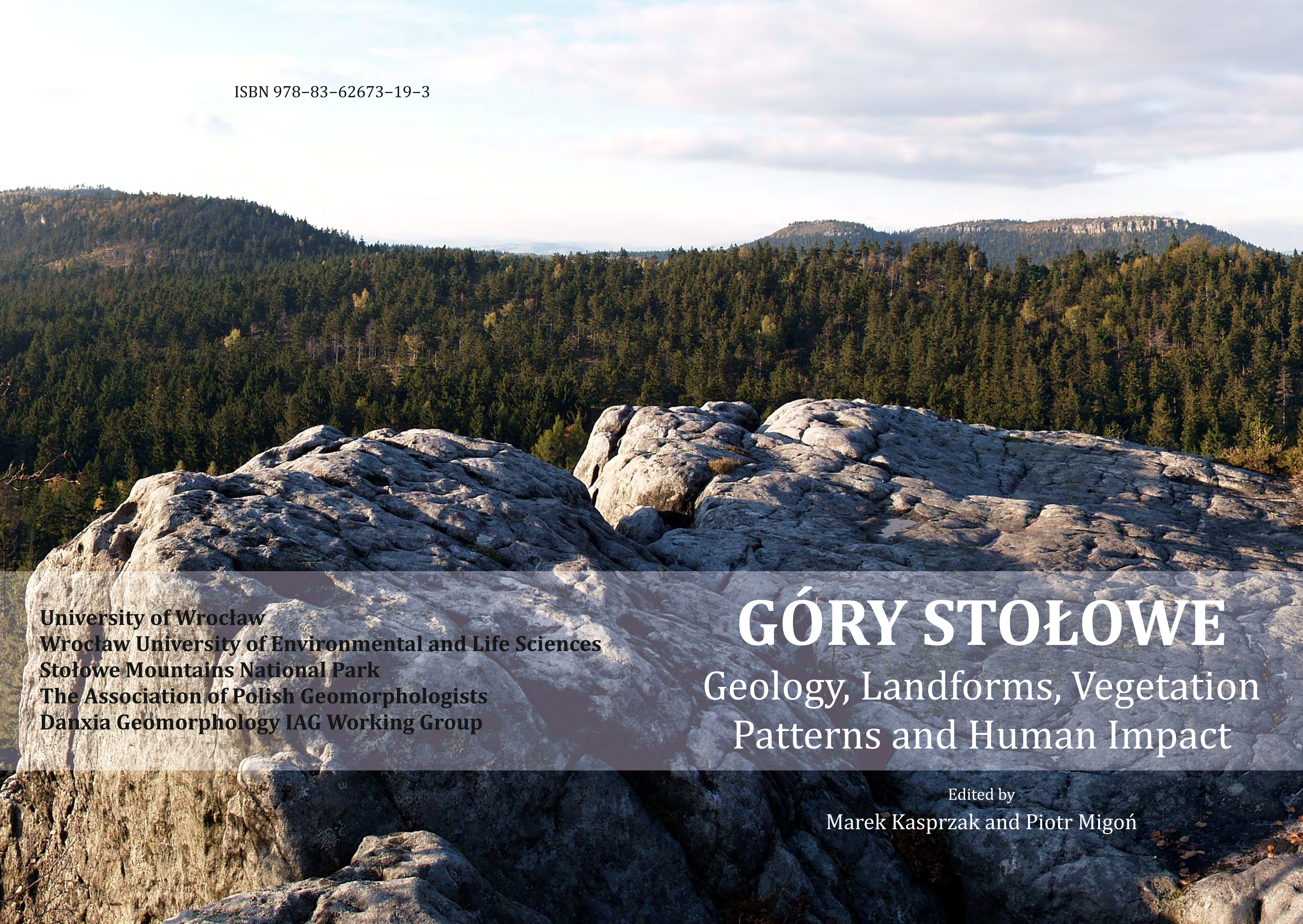

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University of Wrocław
Wrocław University of Environmental and Life Sciences
Stołowe Mountains National Park
The Association of Polish Geomorphologists
Danxia Geomorphology IAG Working Group

GÓRY STOŁOWE

Geology, Landforms, Vegetation Patterns and Human Impact

Edited by
Marek Kasprzak and Piotr Migoń

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Geology, Landforms, Vegetation Patterns and Human Impact

Excursion Guidebook prepared in association with the Sandstone Landscapes III conference

Kudowa Zdrój, 25–28 April 2012

Edited by
Marek Kasprzak and Piotr Migoń

Uniwersytet Wrocławski

Danxia Geomorphology
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Spis treści

PART 1 GENERAL INFORMATION 5

Geographical setting and general landscape (*Piotr Migoń*) 5
Geology and geological history (*Jurand Wojewoda*) 7
Landforms and landform evolution (*Piotr Migoń*) 11
Major landforms 11
Minor landforms 14
Contemporary processes and landscape evolution 16
Soils (*Cezary Kabała*) 20
Hydrology (*Piotr Migoń*) 25
Plants, Vegetation Patterns and Fauna 27
Land use changes (*Agnieszka Latocha*) 30
Nature conservation (*Piotr Migoń*) 34
Tourism (*Piotr Migoń*) 35

PART 2 EXCURSION LOCALITIES 37

Karłów (*Piotr Migoń*) 37
Szczeliniec Wielki (*Piotr Migoń, Zbigniew Gołąb, Przemysław Zwaduch*) 38
Karłówek (*Agnieszka Latocha*) 42
Pośna cirque (*Zbigniew Gołąb, Piotr Migoń*) 46
Radkowskie Ściany (*Piotr Migoń, Jurand Wojewoda*) 47
Narożnik – Białe Skały (*Cezary Kabała*) 49
Sawanna Łężycka (*Piotr Migoń, Diana Mańkowska-Jurek*) 50
Rogowa Kopa (*Łukasz Pawlik, Piotr Migoń*) 51

PART 3 RELIEF OF THE STOŁOWE MOUNTAINS – A TEST AREA FOR STUDIES IN GEOMORPHOMETRY (*Marek Kasprzak*) 55

LiDAR data and research methods 55
Properties and quality of digital data and their relation to other sources of spatial information 57
General characteristics of Stołowe Mountains relief based on digital data 58
The landforms of the Stołowe Mountains in examples 66
Mesa of Mt Szczeliniec Wielki 70

STOŁOWE MOUNTAINS – SELECTED REFERENCES 74

Part 1
General Information

Geographical setting and general landscape (*Piotr Migoń*)

The Stołowe Mountains are a distinctive landscape unit in the central part of the mountain range of the Sudetes, which themselves are an extended tract of diverse relief, c. 300 x 80 km in dimension, that occurs along the north-eastern rim of the Bohemian Massif in Central Europe. The Sudetes are the highest mountain massif north of the Alps, reaching the altitude of 1,603 m a.s.l. at Mt Śnieżka in the nearby Karkonosze, some 40 km to the west of the Stołowe Mountains. In fact, the Sudetes are composed of more than 30 smaller geographical units (massifs and intramontane basins), each given its specific name, and distinguished on the basis of altitude, underlying geology, and general type of relief. Many have straight line boundaries which reflects the key control imposed by tectonic processes on the regional landscape (Fig. 1). The Sudetes constitute an important European watershed, with the southern part being drained to the North Sea via the river system of Labe and the Black Sea via Morava and then the Danube, and the northern part drained to the Baltic Sea via the river system of Odra. Politically, the Sudetes are shared by the Czech Republic in the south, Poland in the north, and Germany in the west. The political boundaries in some sections have a very long history, traced back to the medieval political divisions.

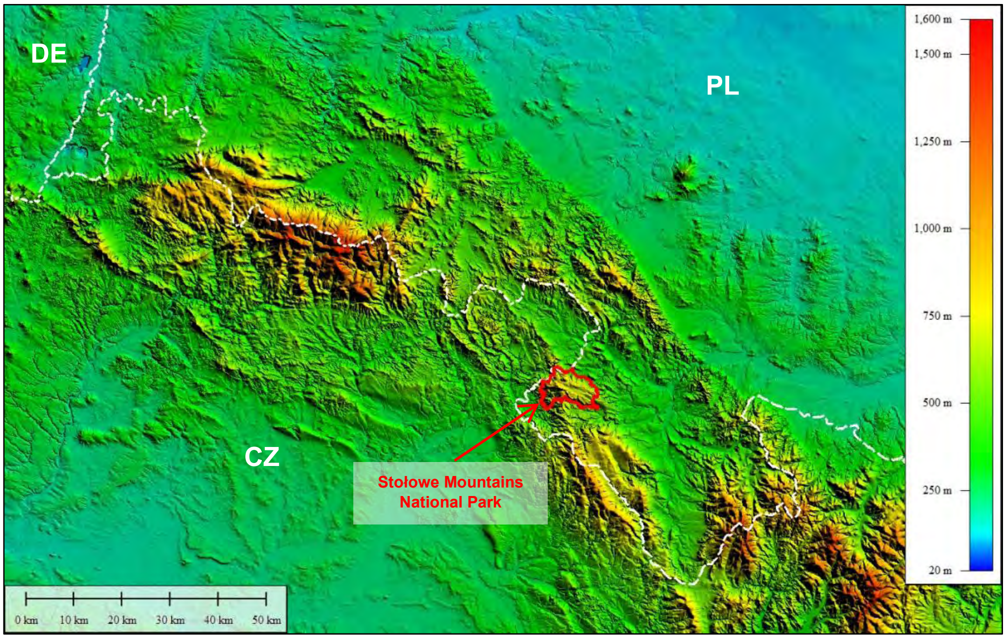

Fig. 1. Main features of relief of the Sudetes and the location of Stołowe Mountains National Park.

The unique appearance of the Stołowe Mountains, in stark contrast to many other mountain massifs in the Sudetes, is due to the presence of nearly flat-lying sandstone beds of Cretaceous age at relatively high elevation. Therefore, the overall morphology of the area is of stepped tableland type. Its major components are extensive surfaces of low relief and negligible gradient, separated from each other by steep escarpments. The latter are up to 300 m high and are crowned with sandstone precipices. Overall, the repetition of steep slopes and flat terrain at different altitudes, from c. 400 m a.s.l. to 919 m a.s.l. in the highest place, gives the mountain range a tiered geomorphological structure. A 'normal' mountain relief, with closely spaced deep valleys and narrow watersheds, occurs in the Stołowe Mountains too but is not associated with sandstone bedrock (Fig. 2). To the north of the area a wide, low-lying intramontane depression along the Ścinawka river drainage basin extends, hence the view of the plateau from the north is particularly impressive.

The Stołowe Mountains is the geographical name used in Poland that replaced the old German name of Heuscheuer-Gebirge. The area occupied by sandstones of Cretaceous age continues to the northwest, on the territory of the Czech Republic, but incidentally the political border nearly corresponds with the change in relief. The plateau gives way to the sequence of parallel morphological escarpments known in geomorphology as cuestas. They are characterized by distinctive slope asymmetry, with one side short and steep (20–40°) and another one long and much gentler (5–15°). Thus, the cuesta of Broumovské stěny is an extension of the northern escarpment of the Stołowe Mountains. This fundamental landscape change has reasons in geology and the changing attitude of sandstone strata, nearly horizontal under the plateau on the Polish side and inclined inward on the Czech side, forming

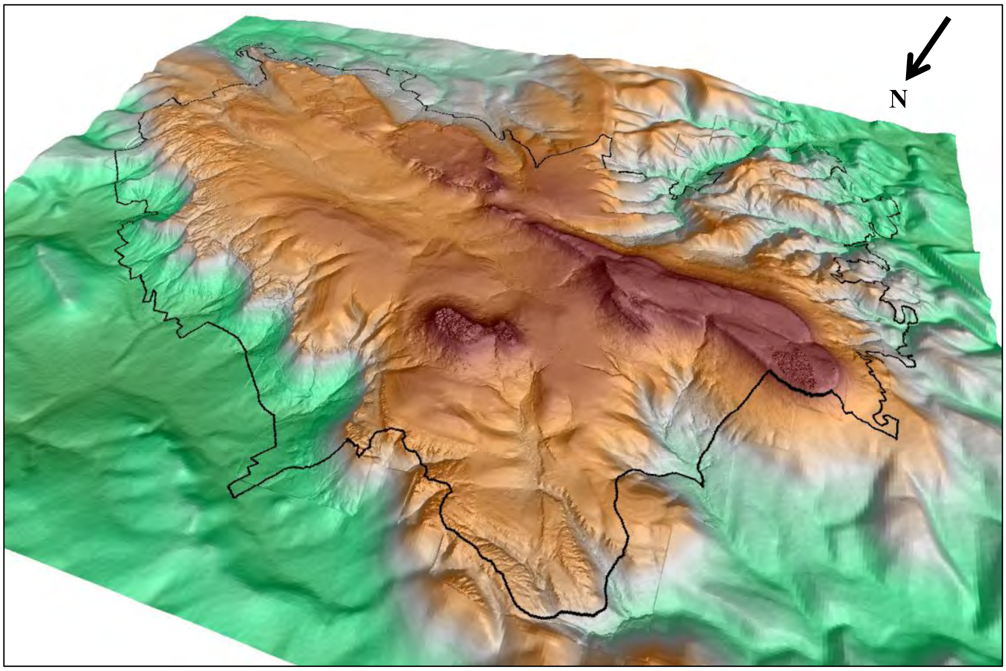

Fig. 2. 3D view of Stołowe Mountains (black line – boundaries of Stołowe Mountains National Park).

a large bowl-shaped basin known as Police Depression (Polická pánev). Its central part is occupied by rock labyrinths of Teplické and Adršpašské skály – arguably the finest sandstone terrain in the Sudetes.

Geology and geological history (*Jurand Wojewoda*)[1]

The area of the Stołowe Mountains is situated at the border of two prominent regional geological units: the Intra-Sudetic Synclinorium in the north and the Kudowa Massif in the south. They are separated by the Žd'arky – Jakubowice Fault, itself a continuation of the Pořiči – Hronov Fault Zone of regional significance. The Kudowa Massif is a tectonic block that mostly consists of intrusive granites and granodiorites of Carboniferous age (radiometric dates from this and the adjacent granite massif near Nový Hrádek ranging from 378 to 331 Ma). A dominant variant is medium-grained granite, brown-red colour, with frequent signs of cataclasis. Locally, weathering mantle of grus type has been documented in the Kudowa Massif, with thickness of a few meters at most. Regional geological and stratigraphic correlations allowed to suggest Westphalian B and C (313–311 Ma) as the most likely period of deep weathering of granite. Granites widely crop out in the south-western part of the Stołowe Mountains (Geological Map – Inset), although natural exposures are not frequent. Above the weathering mantle there occur Carboniferous sedimentary rocks. These are clastic deposists ranging from mudstones to most widespread conglomerates, with intercalations of coal, once mined in the vicinity of Pstrążna (nowadays an administrative unit of Kudowa-Zdrój). The uppermost Palaeozoic rocks are sedimentary rocks of Lower Permian age which occur locally in the vicinity of Kudowa-Zdrój, but mainly along the northern footslope of the Stołowe Mountains. They are represented mainly by conglomerates, with calcrete horizons, pointing out to their desert or semi-desert sedimentary environment. The boundary between Permian deposits and the overlying Cretaceous succession runs along the northern escarpment of the Stołowe Mountains, at the altitude of c. 500 m a.s.l.

The Cretaceous succession in the Stołowe Mountains is represented by a c. 350 m thick sequence that spans the period from late Cenomanian to late Turonian (possibly early Coniacian) (Fig. 3). The stratigraphy is essentially based on inoceramic fauna found mostly in fine-grained intervals, and partly aided by lithostratigraphic correlations of four mappable sandstone lithosomes which have diachronous bases. The lowermost part of the succession is represented by glauconitic, poorly sorted gravelly sandstone of upper Cenomanian (*Actinocamax plenus*). It overlies by an unconformity strongly weathered crystalline basement in the south (Kudowa granites) and lower Permian clastic sedimentary rocks in the north. The

[1] Geological history section is based on the following earlier publications: Wojewoda J., 1997, Upper Cretaceous littoral-to-shelf succession in the Intrasudetic Basin and Nysa Trough, Sudety Mts. [w:] Obszary źródłowe: zapis w osadach, J. Wojewoda (red.), Wind, Wrocław, pp. 81–96; Wojewoda J., 2008, Budowa geologiczna obszaru PNGS. [w:] Przyroda Parku Narodowego Gór Stołowych, A. Witkowski, B. M. Pokryszko, W. Ciężkowski (red.), Wydawnictwo Parku Narodowego Gór Stołowych, Kudowa-Zdrój, pp. 24-37; Wojewoda J. et al., 2011, Geologia Parku Narodowego Gór Stołowych – wybrane zagadnienia. [w:] Chodak T., Kabała C., Kaszubkiewicz J., Migoń P., Wojewoda J. (red.), Geoekologiczne warunki środowiska przyrodniczego Gór Stołowych, WIND, Wrocław, pp. 53–96.

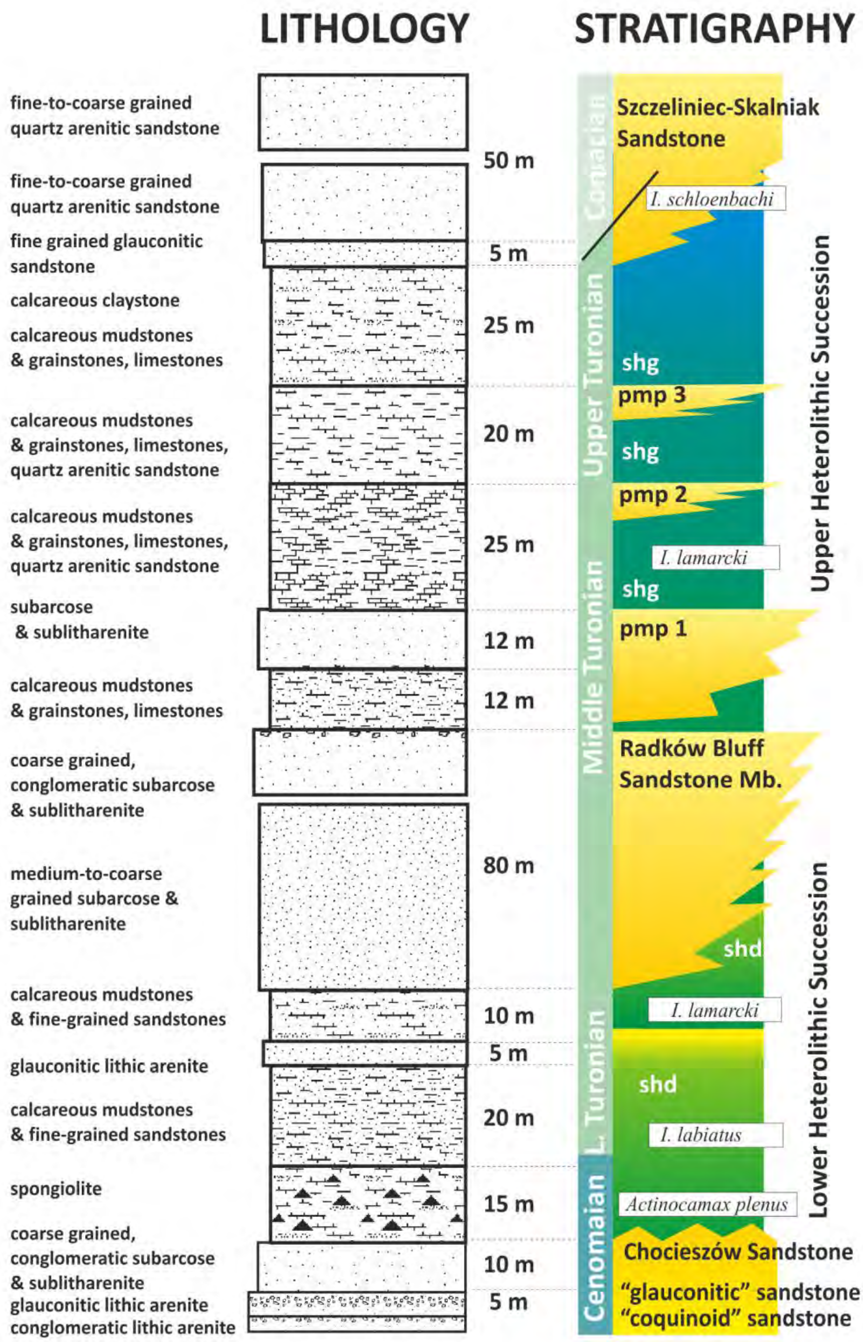

Fig. 3. Stratigraphic succession of Cretaceous sediments in the Stołowe Mountains.

sandstone is overlain by lower Turonian mudstones containing spongiolites (*Inoceramus labiatus* zone) which are gradually replaced by the Middle Turonian sandstones known as Radków Bluff Sandstone (RBS). In the north these sandstones are up to 80 m thick, whereas they wedge out towards the south. Locally, they can be subdivided into several smaller units, separated by calcareous mudstones ('marls') and claystones. Similar fine-grained, mostly calcareous sediments of Middle Turonian age rest above the Radków Bluff Sandstone (*Inoceramus lamarcki* zone). However, within these predominantly fine-grained sediments relatively thin (up to 15 m) sandstone series occur, passing gradually into finer deposits. The uppermost part of the sequence is made of quartz arenitic sandstone of upper Turonian to Coniacian (*Inoceramus schloenbachi* zone), known as Skalniak – Szczeliniec Sandstone (S–SS). All sandstone units, but the RBS and S–SS in particular, show distinctive rectangular joint pattern which divides the sandstone mass into cubic blocks (Fig. 4). Hence, since the 19^{th} century the three main sandstone series of the Stołowe Mountains have been labelled as Lower Jointed Sandstone, Middle Jointed Sandstone and Upper Jointed Sandstone respectively (Germ. *Quadersandstein*).

The Cretaceous sedimentary setting of the basin which has later become the Stołowe Mountains was typified by shallow marine processes dominated by wind-driven currents interrupted by storm events. Today, only the shelf and (off)nearshore facies are preserved. Sandstone bodies form progradational, coarsening-upwards units which consist mainly of various inner-shelf deposits. Sand deposition took place on a basin floor of scarp-

Fig. 4. Upper Jointed Sandstone exposed in cliffs of Mt Szczeliniec Wielki mesa.

like configuration produced by tectonic activity. Such a submarine topography induced peculiar depositional conditions in which giant bedforms originated, termed as accumulation terraces (Fig. 5). Progradation of the accumulation terraces left behind a characteristic assemblage of facies, including a giant-scale cross-bedded sandstone (GSpt facies) with the individual sets reaching up to 18 m in thickness, and sloping sets with tabular cross-beds (LSs-t facies). The small scatter of bed inclination in the GSpt facies (200–230°/25–40°) implies a constant trend of terrace slope during deposition of both RBS and S–SS. It followed the strike of neighbouring faults. The sediment transport was dominated by permanent shelf-along drift directed towards NW in the middle Turonian and SE in the Late Turonian. The GSpt facies is locally intercalated with homogeneous sandstone (HD facies) which represents various mass-flow deposits ranging from fluidized sediment flows to fluxoturbidites. These products of gravity flows fill inclined scours cut in the GSpt facies, are ungraded and reveal systems of fluid-escape dish structures. Further facies that can be observed in sandstones of the Stołowe Mountains are large-scale trough cross-bedded sandstone (Ltr facies) which commonly appear in the upper part of sandstone succession as 2–4 m deep channel fills, and proximal coquinoid tempestites (C facies) resulting from storm events. The latter form continuous layers, up to 1 m thick, underlain by an erosion surface of regional extent.

Sandy deposition in the Stołowe Mountains was interrupted by pulses of rapid subsidence, documented by abrupt contacts of sandstones with the overlying mudstones. These fine-grained sediments are mostly calcareous mudstones, siliceous mudstones and claystones in which the majority of inoceramic fauna was found. They represent distal equivalents of the sandstone facies. Two main facies groups can be distinguished in fine-grained deposits: heterolithic distal tempestites and homolithic calcareous micrite enriched with organic detritus and/or partly silicified.

Among small-scale structures observed in the Stołowe Mountains regular spherical caverns exposed in vertical sandstone cliffs have long aroused curiosity (Fig. 6). Despite superficial similarities to weathering features (tafoni), they are interpreted as primary fea-

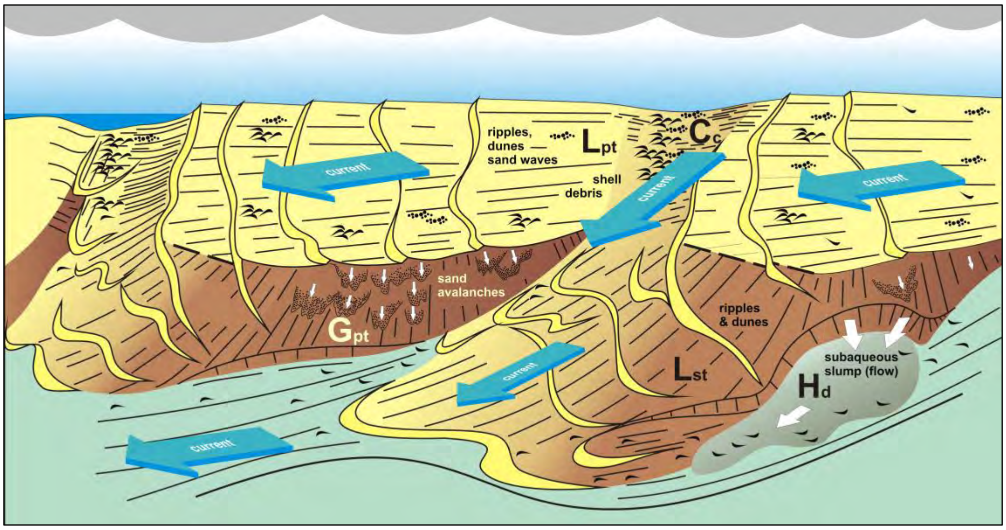

Fig. 5. Diagram to illustrate the origin of accummulation terraces.

Fig. 6. Caverns and gas escape routes on the sandstones cliffs of Skalniak.

tures which originated due to the presence of gas (methane) saturated spaces within sediment. Later discovery of gas escape routes associated with caverns has given additional credit to this hypothesis. However, the origin of methane is unclear and its production from decaying living organisms on the sea floor is one of possibilities.

Landforms and landform evolution (*Piotr Migoń*)

Major landforms

From a geomorphological standpoint, and in clear relation to the regional geology, the Stołowe Mountains may be subdivided into two areas (although no formal names exist for any of these). The tableland with separating escarpments occurs in the central, south-eastern, and western part, and it is this part that represents ‘sandstone landscape’. The highly dissected south-western part, in close proximity to the town of Kudowa-Zdrój, has evolved on granite bedrock and will not be considered in subsequent description.

Planar surfaces are the dominant geomorphic feature of the Stołowe Mountains in terms of area occupied and four main levels are distinguished. The most evident and most extensive is the level II (counting from the top) that stretches from the border in the west to the vicinity of the town of Polanica-Zdrój in the east. Its extension is WNW–ESE, the length is c. 15 km, whereas the width varies from 2 to 6 km. The valley of Czerwona Woda (Red Water) constitutes the morphological axis of the level. The altitude diminishes to the east, from 700–750 m a.s.l. near the village of Pasterka to less than 500 m a.s.l. at the eastern end. The flat terrain of Sawanna Łężycka (see part 2 of the guidebook) belongs to the same morphological level, but is separated from it by a remnant of the level I. The level I, once continuous over the whole area, has been reduced to a few erosional outliers of different size (Fig. 2). It is best preserved south of the village of Karłów, where two elongated plateaus exist. The western one is higher (Skalniak – 915 m a.s.l.), whereas the eastern one, with the highest spot at Narożnik (851 m a.sl.) is more extensive and reaches as far east as the village of Batorów. North of Karłów the only remnants of the level I is the top surface of the twin mesa of Szczeliniec (Fig. 7). Its larger part is known as Szczeliniec Wielki and constitutes the highest spot in the Stołowe Mountains (919 m a.s.l.). Another highly isolated remnant of this level is the mesa of Szczytnik near Polanica-Zdrój (589 m a.s.l.). Surfaces belonging to the level III extend to the north-east and south of the level II, although the former only as fragmentary preserved water divides. The isolated hill of Mnich, north of the main escarpment of the Stołowe Mountains, is an erosional relict of this level too. The lowest level IV occurs only in the north-east.

The above named levels clearly correspond to the underlying geology. Level I has developed on the top surface of the Upper Jointed Sandstone of Late Turonian/Coniacian age. Level II truncates fine-grained series (mudstones, marls, calcareous sandstones) of Middle Turonian age that occurs between Upper Jointed Sandstones and Middle Jointed Sandstones, but in marginal parts coincides with the top surface of the Middle Jointed Sandstones. Geological foundation of Level III varies between the northern and southern part of the area. It has developed on the top of the Lower Jointed Sandstones of Cenomanian age in the former, but truncated the fine-grained series in the latter. Level IV truncates Permian sedimentary rocks which occur below the Cretaceous formations.

Plateau surfaces are separated by escarpments which, although occupy a smaller area, are the most visible landforms of the Stołowe Mountains (Fig. 8). Their height varies from less than 100 m, as along the contact of levels II and III in the easternmost part of the mountains, to nearly 300 m in the north, above the town of Radków. Here, the level III has been completely eliminated by erosion and the plateau of level II drops down to the piedmont surface of level IV. Escarpments separating the highest level I from the middle level II

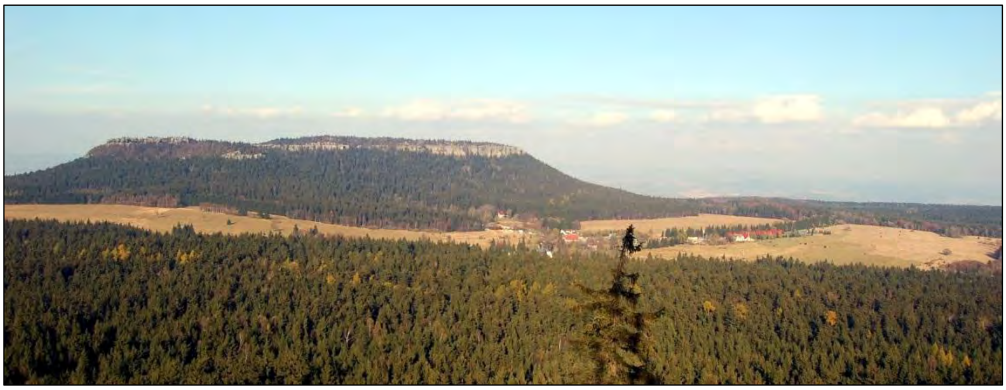

Fig. 7. The twin mesa of Mt Szczeliniec supported by the Upper Jointed Sandstone (Level I) rising above the extensive Level II cut across fine-grained inter-sandstone sediments.

Fig. 8. Northern escarpment of the Stołowe Mountains, seen from the hill above the town of Radków (in the foreground).

are 100–150 m high. In detail, the escarpments are concave features, with a sandstone rock face in the uppermost part, followed by a steep (30–40°) debris-covered hillslope and then a long, less inclined segment (10–15°) that finally grades into the undulating surface of the lower plateau level. However, rock slope segments are not universally present and in the eastern part of the area they are essentially lacking. Where they do occur, they attain variable height, from a few to c. 40 m. The latter figure characterizes the mesa of Szczeliniec Wielki, where vertical rock faces line almost the entire edge of the plateau remnant. Rock faces along the edge of Narożnik plateau are similar in appearance, although a little lower. Along the northern escarpment the continuity of cliff line is broken by the presence of numerous gorges and ravines. Escarpments are evidently lithologically controlled. A resistant sandstone layer invariably forms the rock face in the upper part, so called 'caprock', whereas the middle and lower slope truncates the fine-grained inter-sandstone series.

Another characteristic landform for the tableland of Stołowe Mountains is the amphitheatres. This is the name used to describe half-circular and half-elliptical recesses in the northern escarpments, separated from each other by protruding spurs. The largest amphitheatre is that drained by the Cedron creek above the village of Wambierzyce (see part 3, Fig. 54) followed by the amphitheatre of Pośna river south of Radków (see part 2 of the guidebook). These large slope hollows are interpreted as products of long-term complex erosion at spring lines, hence they are genetically akin to sapping cirques known from the Colorado Plateau. The absence of similar features along the south-facing escarpments is believed to be due to preferential subsurface drainage to the north and relatively low spring discharges in the south.

Minor landforms

On the major landform elements characterized above are superimposed various minor landforms, adding to the geodiversity of the Stołowe Mountains. Although a whole range of geomorphological features can be identified and mapped, a few are specific to sandstone morphology and will be described in more detail. These include:

- rock labyrinths, also known locally as 'rock cities', conform to the notion of 'ruiniform relief' described from many sandstone areas around the world. In general, these are fragments of sandstone slabs heavily fragmented along joints and other discontinuities, so that solid rock compartments are separated by narrow defiles and corridors, crossing each other at right or acute angles (Fig. 9). Depending on the degree of weathering, these compartments may be more or less cubic, with straight outer faces, or reduced to residuals with fantastic shapes (Fig. 10). Two best known sandstone labyrinths have developed on the top surface of Mt Szczeliniec Wielki (see part 2 of the guidebook) and in the westernmost extremity of Skalniak plateau, where they are called Błędne Skały (Errant Rocks). The 'rock city' on Mt Szczeliniec Wielki is more extensive, covering the entire surface of the mesa (c. 600 x 300 m), but also in a more advanced stage of degradation. Narrow alleys and cubic residual compartments occur in certain places only, while boulder fields and remnant tors typify most of the terrain. Height differences reach 20 m. By contrast, the 'rock city' of Błędne Skały has developed within a sandstone slab

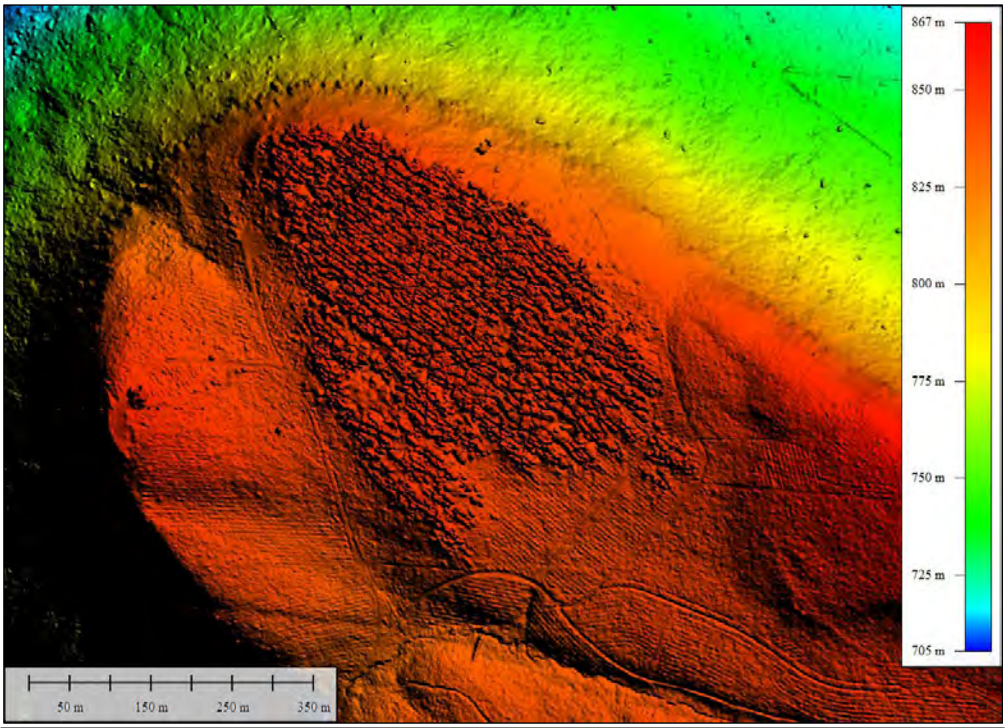

Fig. 9. The 'rock city' of Błędne Skały. Relief model generated from LiDAR-based DEM of 1 m resolution.

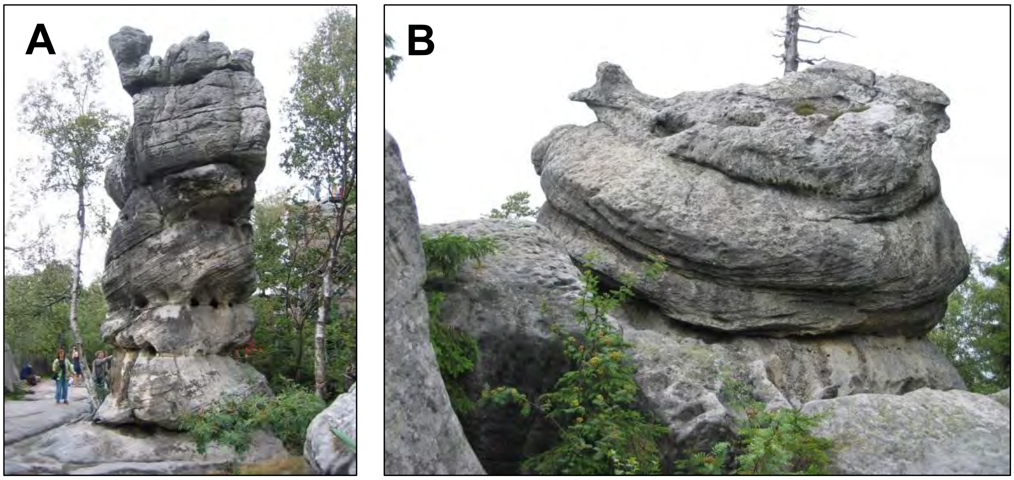

Fig. 10. Two examples of rock formations on the top of Mt Szczeliniec Wielki mesa: Wielbłąd (Camel) and Kwoka (Hen).

that is only 6–8 thick, but joint opening has been limited yet and joint-guided corridors are in places less than 1 m wide. Both rock labyrinths are supported by the Upper Jointed Sandstone.

There are further places in the Polish part of the Stołowe Mountains where rock labyrinths can be found but they occupy limited areas and are in an apparent more advanced stage of degradation, with no dense networks of criss-crossing, joint-aligned passages. Rather, they are reduced to clusters of free-standing residuals and loose boulders scattered around.

- hoodoo (mushroom) rocks – they are one of the symbolic features of the Stołowe Mountains and occur in many places within the area, but mainly along the north-eastern edge of the central plateau, north of Batorów. Here, more than one hundred peculiarly shaped sandstone tors can be found, although forest growth has recently obstructed the view of many of these. Hoodoo rocks are of variable height, from a mere 2 m to complex features 10–12 m high (Fig. 11). They consist of a narrow stem and a wider cap. Lithology is the prime control on the shape of these rock formations. The stem has evolved in densely bedded sandstone, hence containing more discontinuities and more prone to various weathering processes. The cap, in contrast, is supported by massive, homogeneous facies of sandstone which is essentially a product of advanced bioturbation in the shallow sea floor environment. Homogenization of the original deposit reduced primary porosity to 8% on aveage and made the bioturbated facies more resistant against weathering. Often, a <1 m thick layer of gravelly sandstone (tempestite) occurs between the two facies named above, which is highly porous, up to 50%. High water content in the porous layer enhances the efficacy of weathering processes, hence the origin of the stem (pillar). Hoodoo rocks are most common in the Middle Jointed Sandstone series, but similar landforms can be found within the Upper Jointed Sandstone too.
- block fields – extensive block covers occur on major escarpments, below the rock faces. The size of individual blocks can be huge: lengths up to 15 m are not uncommon. Imme-

Fig. 11. Hoodoo rocks.

diately below rock scarps block fields are apparently chaotic piles of big boulders stacked one upon another, with deep fissures in between, so that the terrain is virtually impassable. Going downslope, the density of block covers diminishes but blocks of enormous size, more than 10 m long, may occur even on the footslope. The origin of block fields is related to mass movement processes acting on caprock escarpments, especially rock fall and topple.

- isolated sandstone boulders – these are peculiar landforms found in two areas on the Level II, on a water divide between the villages of Karłów and Pasterka, and on Mt Rogowa Kopa, in a locality known as Sawanna Łężycka (see part 2 of the guidebook). In fact, in both places groups of scattered boulders can be seen (Fig. 12), a few tens of metres from each other. Individual blocks are from 2 to 10 m long and up to 5 m high, all rather heavily weathered. The peculiarity of these clusters of sandstone boulders derives from their allochthonous character. They rest on mudstone/marl substratum, which may suggest past transport, but on the other hand they occur on local elevations, far away from nearest sandstone escarpments, and there are no boulder trails leading towards block fields on the escarpments. Therefore, a hypothesis has been suggested that sees the boulders as relicts of a long gone sandstone slab, once present a few tens of metres above, that passively settled down concurrently with the lowering of mudstone/marl surface.

Contemporary processes and landscape evolution

The contemporary geomorphic system and the occurrence of individual landforming processes are clearly related to the major landform pattern, which in turn reflects the underlying geology. Permeability contrasts between sandstone versus mudstone and marl control groundwater circulation within the massif and bear on a range of subsurface and surface processes. Among them, suffosion and piping operate effectively within the sandstone and at

Fig. 12. Allochthonous sandstone boulders on the level II of Sawanna Łężycka.

the sandstone/mudstone(marl) boundary, affecting the stability of the overlying sandstone mass. Consequently, a variety of mass movement occurs along the escarpments, including joint opening, lateral spreading, sagging, large-scale toppling, rock fall, and shallow landslides and earth flows within the regolith-covered slopes. The latter are responsible for long-distance transport of sandstone blocks derived from caprock to footslope position, locally by as much as 500 m. Spectacular landforms related to mass movement processes are deep clefts parallel to the plateau margins, best developed along the edges of Mt Szczeliniec Wielki mesa (Fig. 13), continuous rock walls, and massive talus below, now mostly hidden by dense forest. Most of crevice caves are also related to joint opening due to high tensile stresses, whereas within talus and boulder fill along some valleys talus caves have been mapped.

Through the action of the above processes, steep slopes are subject to retreat in the long-term, so that the lower horizons enlarge at the expense of the upper ones. This is why the Level I is present as a group of spatially discontinuous plateaus in watershed positions rather than a one coherent geomorphic surface. The spatial pattern of scarp retreat is not uniform, hence escarpments are often sinuous in plan and composed of alternating spurs and embayments (amphitheatres). The latter are places of preferential groundwater outflow and most geomorphic activity. Another group of processes of critical importance for the relief evolution of the Stołowe Mountains is weathering, guided by discontinuities within the rock and unequal resistance of particular lithological units. It accounts for the origin of such spectacular landform assemblages as ruiniform relief on top of the sandstone mesas (e.g. on

Fig. 13. The deep cleft of Piekiełko near the northern rim of Mt Szczeliniec Wielki mesa.

Szczeliniec Wielki), joint-guided labyrinths (e.g. Błędne Skały), and mushroom-like tors, as well as distinctive microrelief of rock surfaces, with pans, honeycomb structures, tafoni, and karren (Fig. 14).

In contrast to escarpments, level surfaces of main morphological horizons show very little geomorphic activity. Extensive surfaces underlain by poorly permeable marls and mudstones are occupied by peat bogs, although in the past their area was even larger. Recent erosion is often induced by human impact and focused on some hiking trails and logging tracks.

The long-term geomorphic history of the Stołowe Mountains is poorly recognized, especially its temporal dimension. The altitude of the Cretaceous formations clearly indicates that they must have been subject to uplift to attain their current position of c. 900 m a.s.l., but there are little clues as to when the uplift commenced. Views expressed by different authors vary and ages from Oligocene/Miocene (c. 25 Ma ago) to Pliocene/Pleistocene (2 Ma ago) have been proposed. Likewise, little is known about rates of escarpment retreat. The pervasive control of geological structure and sandstone lithology on the course of surface processes makes it difficult (if not impossible altogether) to relate individual landforms to the history of environmental change. Thus, in contrast to many other mountain areas within the Sudetes, a distinct generation of cold-climate (periglacial) landforms cannot be safely identified. To establish a temporal framework of the geomorphological evolution of the Stołowe Mountains is one of the major research challenges for the future.

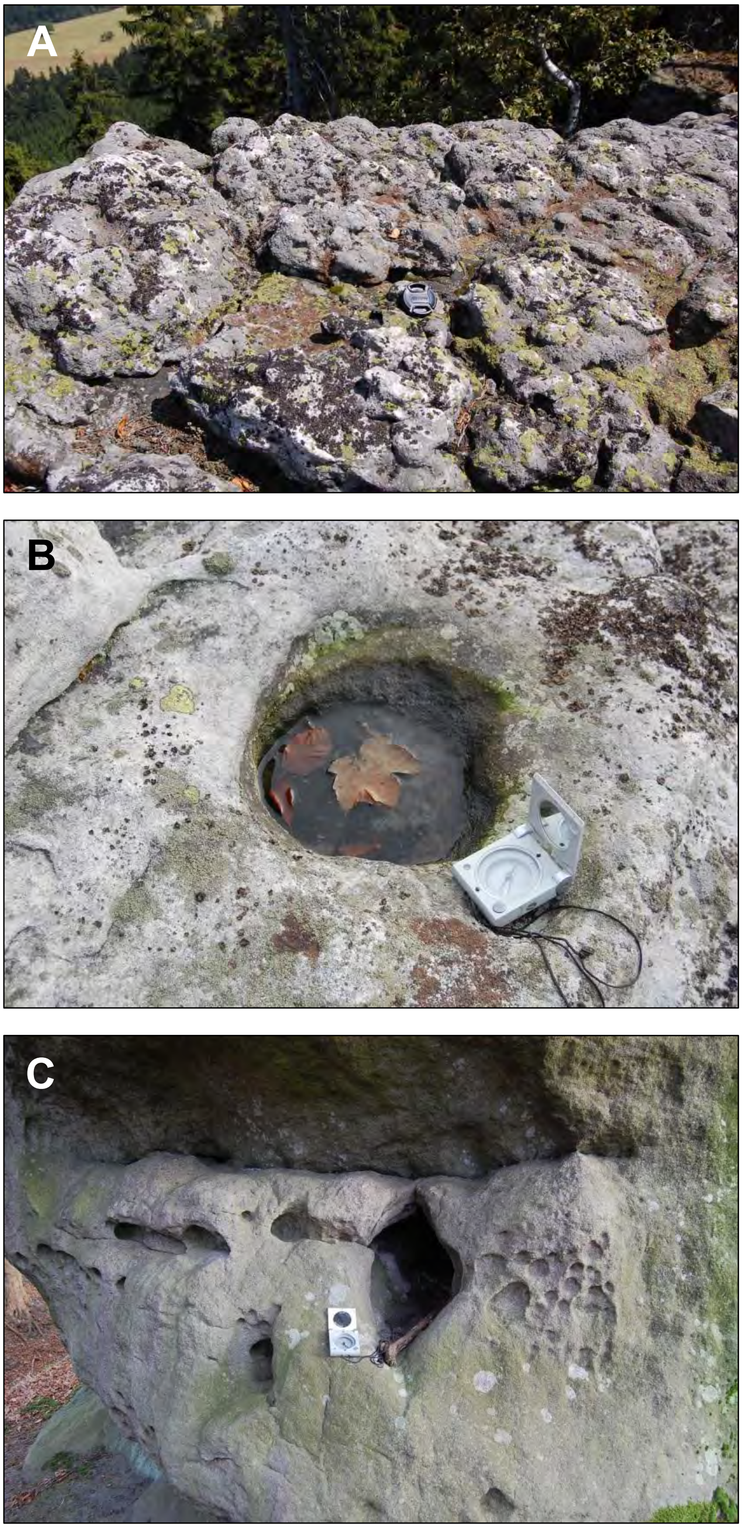

Fig. 14. Weathering features of sandstone in the Stołowe Mountains.
A – differential surface weathering,
B – weathering pits,
C – tafoni

Soils (*Cezary Kabała*)

Although soil is a shallow, most surface part of the lithosphere, it serves as a crucial link between geological substrate and living part of each terrestrial ecosystem. Many basic features of the soil are 'inherited' from the parent rock from which they are developed, but the direction and rate of the soil-forming processes depend on numerous other environmental factors: climate, water balance, land morphology, vegetation, and also on human impacts. Among the many functions of the soil, the most important one is to create conditions for growth and development of plant communities. The soil fertility and productivity is influenced mainly by the soil texture, water capacity, acidity, richness in macro- and micronutrients, humus content and other properties.

Contrary to the expectations associated with the nature of the terrain (mountainous area), very shallow and shallow soils (the depth of the soil profile less than 50 cm) occupy only about 10% of the area. More common are medium deep soil (the bedrock is at depths of 50–100 cm) – about 41% of the National Park, and deep soils (bedrock occurs at depths greater than 100 cm), which occupy over 48% of the park. The dominance of deep soil creates favorable conditions for tree growth, even for the deep-rooting species.

Texture of soils in the Stołowe Mountains is closely related to the type of parent rock and the degree of its weathering. Nearly 50% of soils have a sandy texture. These are soils developed from the Cretaceous and Permian sandstone and, in part, from granite. Loamy-textured soils cover about 27% of surface. Soils developed on granite have generally coarse texture of sandy loam, whereas soils formed from mudstone ('marl') have finer textures of loam and clay loam. Soils developed from mudstone weathering often have (on 20% of the surface) a specific texture of silt loam. Most mountain soils contain abundant skeletal fragments, also in the superficial layers. The soils located on the slopes at the contact of sandstone and marl often have bi-partial profiles. Loose surface layers are composed of sand and coarse sandy loam, while the underlying layers are loamy and compact.

The uppermost layer is characterized by a strongly acidic or acidic reaction in most soils of the Stołowe Mountains, and only some of the weathered marls (e.g. on the slopes of the Rogowa Kopa) give neutral or slightly alkaline regoliths and soils. High precipitation, positive water balance and forest vegetation lead to further soil leaching and decrease of soil pH. The strongest acidic reaction occurs in Podzols and some Cambisols ('acid brown earths') derived from sandstone (in the range pH 3.5–4.0). Somewhat higher pH is in the soils derived from granite, usually 4.2–4.4. Considerable pH variations occur in Cambisols formed from mudstone. Although the surface horizons are generally acid (pH not higher than 4.0–4.5), the underlying layer often have a pH above 5.5 or even near neutral (pH 6.5–6.9).

More than 15 soil types (Fig. 15) were distinguished based on the Polish Soil Classification [2011] and at least 12 major soil units if based on an international soil classification FAO–WRB [2006]. The most typical and unique soils in the Stołowe Mountains are Podzols (Fig. 16), developed from the Cretaceous sandstone. These soils have sandy texture, strongly acidic reaction, are poor in nutrients. In general, they are covered with spruce stands; however, in many sites they create more fertile habitats, appropriate rather for mixed forest. The largest area in the Stolowe Mountains (more than 40%) is covered by Cambisols ('brown earths') that occur in several subunits differing in morphology, texture and fertility (Fig. 17).

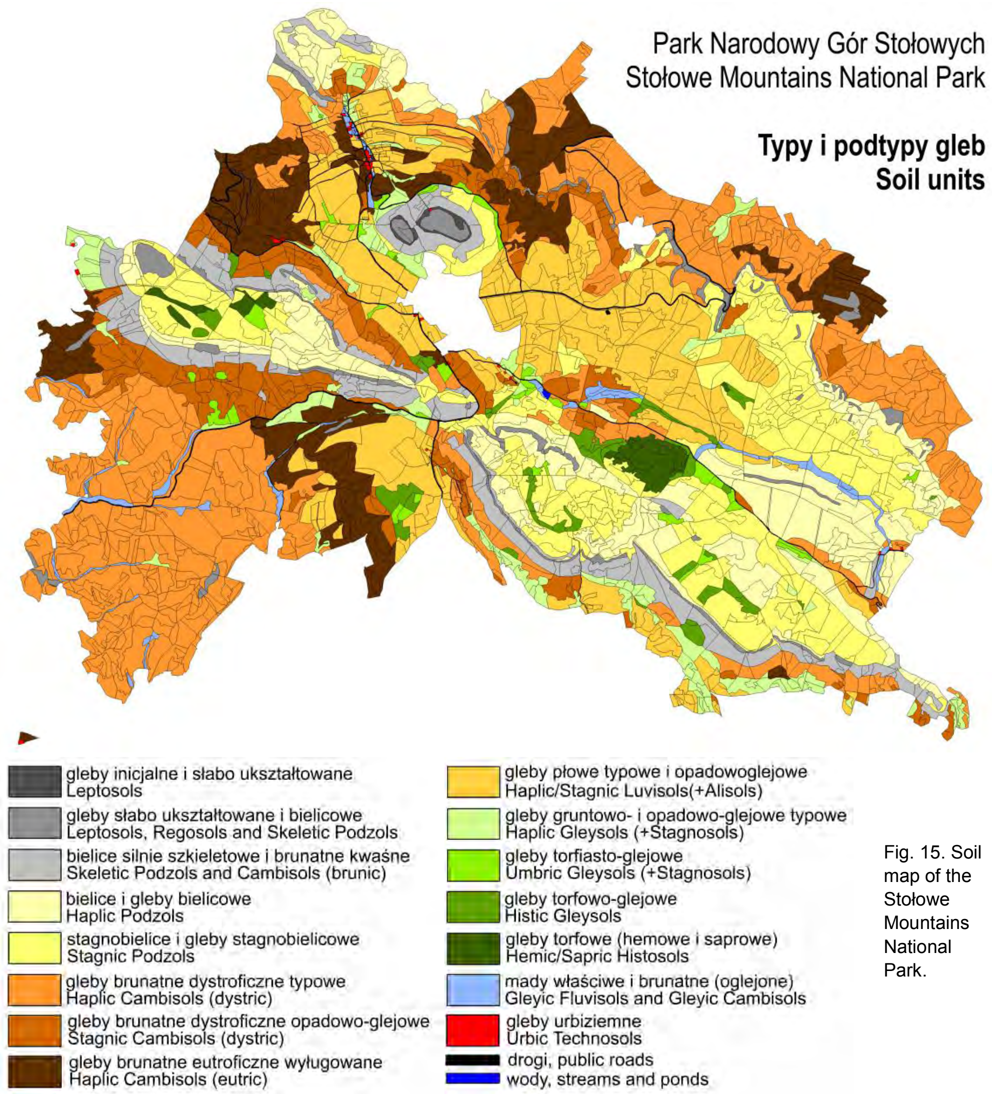

Fig. 15. Soil map of the Stołowe Mountains National Park.

The most fertile habitats form the Eutric Cambisols derived from mudstone on the slopes of the Rogowa Kopa, as well as around Ostra Góra, Pasterka and Wambierzyce. These are loamy (or silt loam) soils, neutral or slightly acidic, rich in magnesium, calcium and other nutrients. Other mudstone, strongly decalcified, was the parent material for 'acid brown earths' (Dystric Cambisols) that dominate in the northern part of the mountains. These soils have similar loamy texture, but are strongly acidic and poor in nutrients thus create habitat typical for the poorer ('acid') beech stands. Dystric Cambisols are also developed from the granite – near Kudowa – and from the Permian sandstone – near Radków. Although different in morphology (soils developed from granite are gray-brown, the soils from Permian sandstone are red-brown), they have also a lot in common: texture of loamy sand or sandy loam, low water-storage capacity, are acidic, and poor in macronutrients.

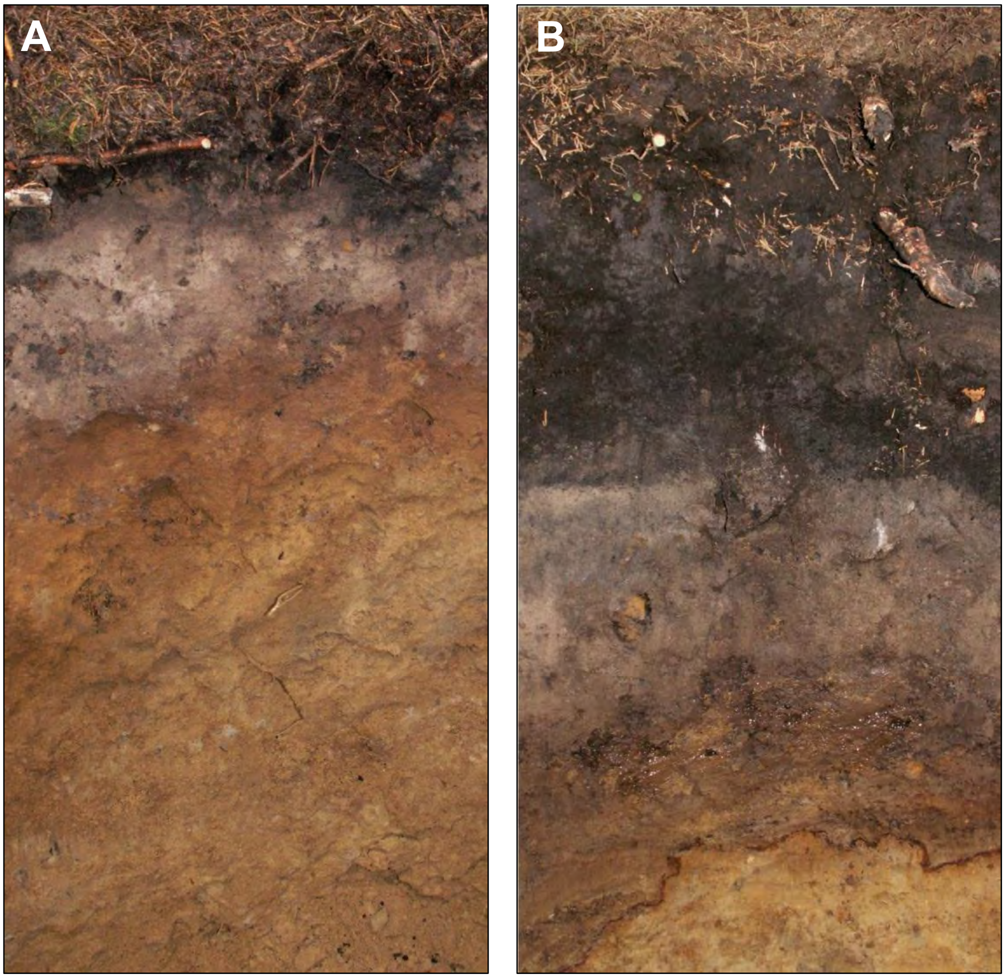

Fig. 16. Soils of the Stołowe Mountains: Albic Podzols (A) and Stagnic Podzols (B) developed from sandstone.

Central part of the mountains, the relatively flat plateau of Karłów and Pasterka, but also other summit and slope flattenings developed upon mudstones are covered by soils featured by clay translocation within the profile. According to FAO–WRB classification [2006] these are Luvisols, Albeluvisols and Alisols, depending on some morphological and chemical properties (Fig. 18). These soils have in general loamy or silty texture (coarser at the surface, finer in the underlying horizons), acidic, but not strongly acidic reaction and are of medium fertility, thus suitable for agricultural use. When afforested, they create habitats for more fertile varieties of beech stand. Textural differentiation that occurs in these soils may result in prolonged water stagnation in the upper horizons.

The highest parts of the hills, the cliffs and the larger sandstone outcrops are covered with initial or poorly developed soils, Leptosols. These are shallow sandy soils, acidic and poor in nutrients for plants, thus creating specific habitats suitable only for spruce or pine stands.

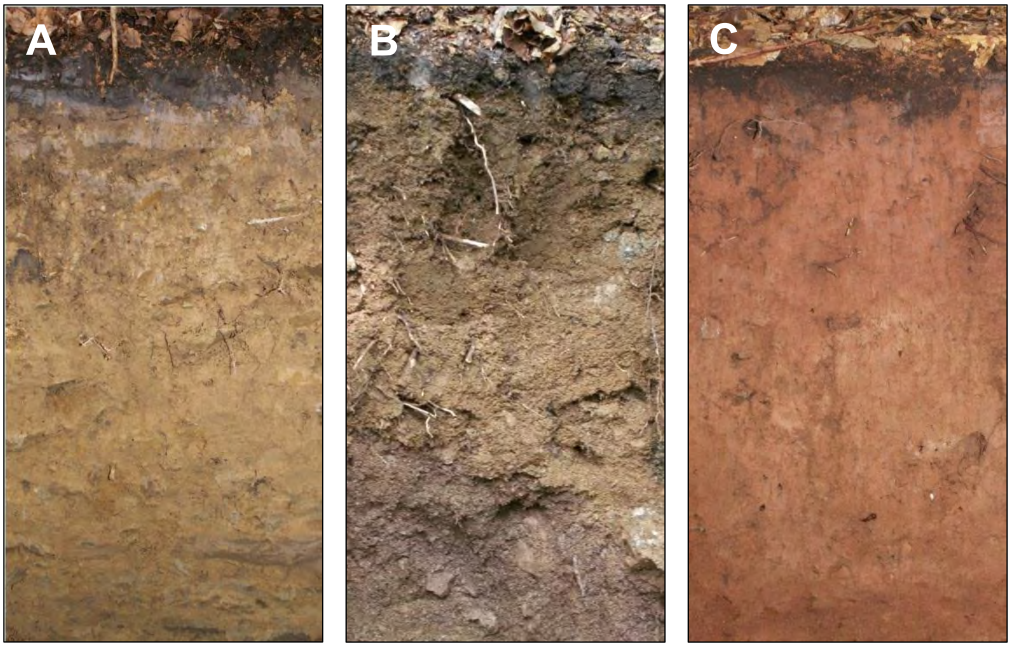

Fig. 17. Soils of the Stołowe Mountains: Eutric Cambisols developed of marl/mudstone (A), Dystric Cambisols developed of granite (B) and Permian sandstone (C).

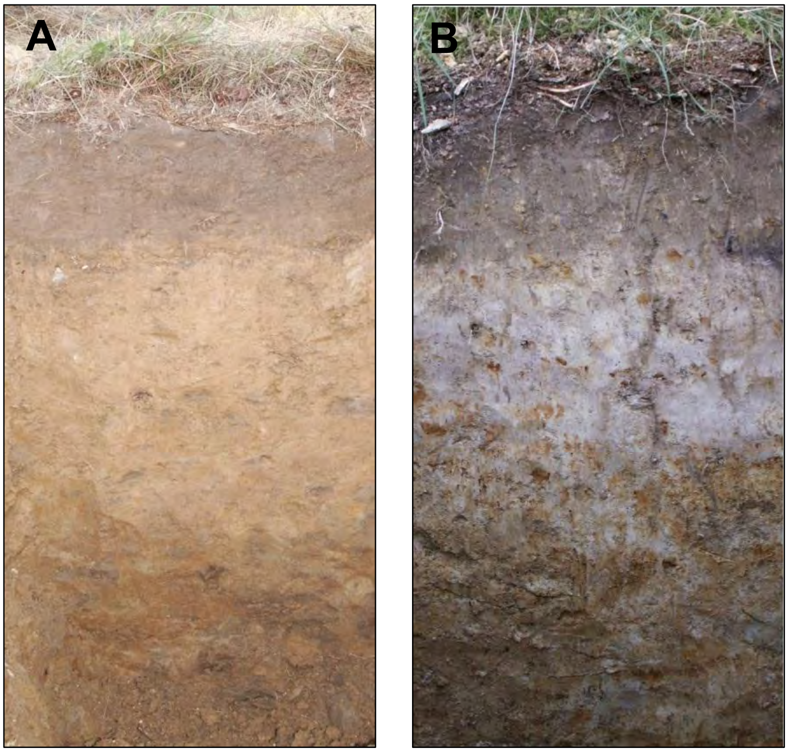

Fig. 18. Soils of the Stołowe Mountains: Albic Luvisols (A) and Stagnic Albeluvisols (B) developed of marl/mudstone.

Plain valleys of streams are covered with fine river sediments and appropriate soils, mainly Fluvisols and Gleysols. These are mainly loamy soils, often stratified with sand, neutral or slightly acidic, rich in humus and nutrients, but wet. They form fertile, specific habitats for forest and meadow vegetation. Among the other soil units, particularly important and interesting are organic soils (Histosols) that occur in the mire of Wielkie Torfowisko Batorowskie and several other bogs scattered through the mountains (Fig. 19).

The soil cover of the Stołowe Mountains reflects geological, morphological and climatic variability of the area, and creates a mosaic of different habitats. This affects the diversity of ecosystems in the Stołowe Mountains and extremely increases the scientific attractiveness of the national park as an area with a unique environmental variability.

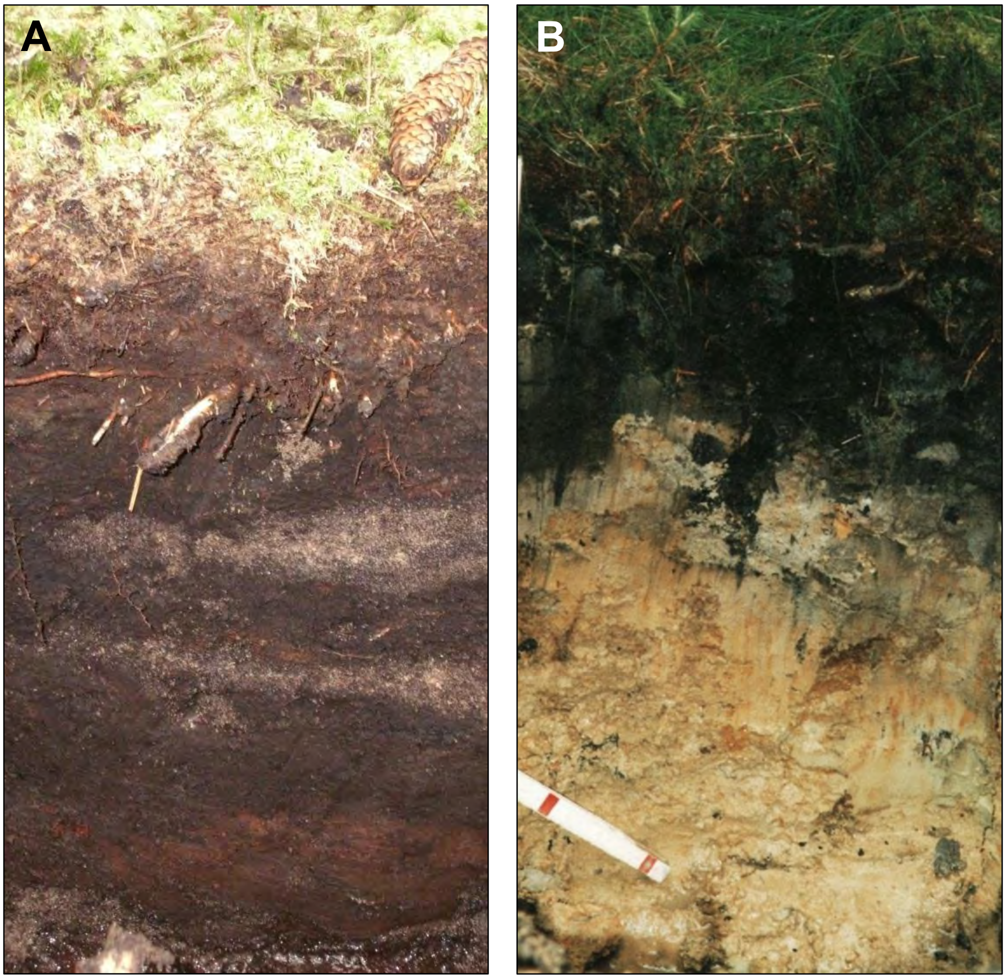

Fig. 19. Soils of the Stołowe Mountains: Fibric Histosols (A) stratified with sand and Histic Gleysols (B).

Hydrology (*Piotr Migoń*)

The area of the Stołowe Mountains sits on the European water divide. The south-western part of the sandstone terrain is drained towards the North Sea, whereas the remaining part belongs to the catchment area of the Baltic Sea. The divide goes across the most elevated part of the area, including the mesa of Szczeliniec Wielki. The main stream is Czerwona Woda that has its spring at the footslope of Skalnik plateau (fragment of Level I) and flows within the Level II in a shallow longitudinal valley as far east as Batorów, where it turns right and leaves the Stołowe Mountains (Fig. 20 – drainage network?). The northern escarpment is drained by a series of short streams of high slope, fed by springs located at the sandstone/underlying fine-grained rocks boundary. Very few streams (Kamienny Potok, Bobrówka) flow in the southerly direction, across the southern escarpment, which therefore remains straight over long distances. The western part of the main plateau (Level II) is dissected by deeply incised valleys of Židovka and Stekelnice, belonging to the hydrographical system of Labe and hence, to the North Sea catchment area. Overall drainage density within the boundaries of Góry Stołowe National Park is 2.7 km per 1 km^2.

An important component of the hydrological system of the Stołowe Mountains are mires. Their occurrence is facilitated by two interrelated factors: flatness of terrain and reduced permeability of mudstone and marl bedrock. The largest mire is Wielkie Torfowisko Batorowskie (Large Peatbog of Batorów) on the main plateau, which occupies over 60 hectares. Further mires are located in the northern part of the main plateau (Niknąca Łąka – Fig. 21) and on the higher plateau of Skalnik (Długie Mokradło, Krągłe Mokradło). Their area was significantly more widespread in the past, before extensive meliorations took place. It is estimated that more than 250 km of drainage ditches have been excavated to drain the mires and to allow the use of land as hay meadows, arable grounds, or as forest plantations. The disappearance of mires is regarded as a significant environmental problem in the Stołowe Mountains and various activities are now undertaken to reverse the trend, including introduction of man-made constructions across the former ditches, to slow down runoff and water the soils again.

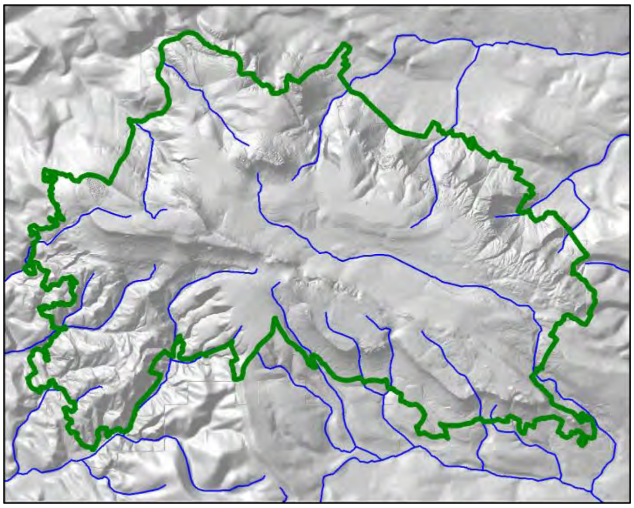

Fig. 20. Drainage network of the Stołowe Mountains.

Fig. 21. Niknąca Łąka (Vanishing Meadow) mire, with an educational trail.

In terms of hydrogeology, the Cretaceous strata have the highest water-bearing capacity and form the main aquifer, which is also best studied. Two separate water-bearing horizons have been distinguished. The upper horizon comprises the Upper Jointed Sandstones and the topomost part of the Middle Jointed Sandstone, whereas the lower one occurs in the Lower Jointed Sandstones, overlying mudstones, and the bottom part of the Middle Jointed Sandstone. The basal surface of this horizon is provided by the contact with underlying Permian deposits in the north and Carboniferous sedimentary rocks and Kudowa granites in the south. Water infiltration in sandstones is facilitated by a dense network of orthogonal fractures, the presence of faults, and general slope of sandstone plateau to the east and north. Springs tend to concentrate in the bottom parts of sandstone series, close to contact with poorly permeable mudstones and marls. Along the northern escarpment of the Stołowe Mountains they cluster to form spring lines, extended across hundreds of metres. Very few springs are characterized by high discharges (>5 $dm^3 s^{-1}$), which shows the rather uniformly high permeability within the whole area.

Plants, Vegetation Patterns and Fauna[2]

The great variety of habitat conditions promotes plant diversity in the Stołowe Mountains[3]. In the vegetation patterns of the area forests predominate, whose composition is determined by both local conditions of relief, soils and water availability, and the long-term history of human interference. Only small areas have preserved fragments of natural forests typical for the lower montane zone of the Sudetes. These are beech forests (*Dentario enneaphylli-Fagetum*, *Luzulo luzuloidis-Fagetum*) (Fig. 22), sycamore forests (*Lunario-Aceretum*) and riverine forests (*Carici remotae-Fraxinetum*). Extensive areas are covered by spruce forests, mainly planted. However, there are also meadow and wetland communities present which add to the vegetation diversity (Fig. 23).

Lichens[4]. At present, 250 lichen taxa are known to occur in the Stołowe Mountains. They include many species, varieties and forms which are rare in the region or in the country. Epilithic, sandstone-associated lichens form the most characteristic component of the

Fig. 22. Beech forest in the Pośna cirque grows partly on huge talus slope composed of sandstone boulders detached from the escarpment.

[2] This section of the guidebook has been prepared using English summaries from relevant chapters included in the scientific monograph of the Stołowe Mountains National Park (Przyroda Parku Narodowego Gór Stołowych, A. Witkowski, B. M. Pokryszko, W. Ciężkowski (eds), Wydawnictwo Parku Narodowego Gór Stołowych, Kudowa-Zdrój 2008), supplemented and edited wherever appropriate. Permission to re-use the text granted by the Stołowe Mountains National Park. Credit to individual authors is given in footnotes at the beginning of each subsection. Section on fauna prepared by Zbigniew Gołąb.

[3] Text adapted from Pender K., 2008, Plant communities (Summary). [in:] Przyroda Parku Narodowego Gór Stołowych, p. 191.

[4] Text adapted from Dimos-Zych M., 2008, Lichens (Summary). [in:] Przyroda Parku Narodowego Gór Stołowych, p. 155.

Fig. 23. Meadow communities in the vicinity of Pasterka village.

lichen flora. The typical species are *Arctoparmelia incurva*, *Cystocoleus ebeneus* and *Racodium rupestre*. The most interesting and rare epiphytic lichens in the Stołowe Mountains occur outside forest complexes, on the barks of roadside trees or on trees growing at the highest altitudes. Compared to the 1950s, considerable changes in lichen flora can be observed. They include decrease in frequency and abundance, disappearance of certain species and appearance of others. This pertains mainly to epilithic and epiphytic lichens, as the first to disappear are stenoecious species (*Lobaria pulmonaria*, *Menegazzia terebrata*, *Usnea rigida*). Some lichens regarded as common in the 1950s are now rare (*Arctoparmelia incurva*, *Melanelia stygia*, *Pertusaria corallina*). Instead, species well adapted to anthropogenic influences are becoming increasingly common.

Moss flora[5]. The moss flora of the Stołowe Mountains National Park comprises 190 species, which accounts for more than a quarter of the bryoflora of Poland. Terrestrial mosses constitute the majority, *Pleurozium schreberi* being one of the most common species. Numerous scarps have a rich moss flora, with *Dicranella heteromalla* and *Mnium hornum* as the most frequently appearing components. Mosses growing on rock substratum constitute the second biggest group. Many abundant populations of the montane *Cynodontium polycarpum* are present on huge boulders and rock outcrops, especially at higher altitudes. Much fewer mosses live on rotting timber and barks of living trees. The moss flora of the Stołowe Mountains includes numerous rare and interesting species (*Pohlia bulbifera*, *Leucobryum juniporideum*, *Schistostega pennata*, *Polytrichastrum pallidisetum*, *Plagiopus oederiana*,

[5] Text adapted from Berdowski W., 2008, Moss flora (Summary). [in:] Przyroda Parku Narodowego Gór Stołowych, p. 166.

Palustriella decipiens, *Orthodontium lineare*, *Dicranodontium asperulum*, *Polytrichastrum alpinum*, *Cynodontium polycarpum*, *Isothecium myosuroides*, *Oligotrichum hercynicum*). The most diverse moss communities can be found on rock faces of Mt Rogowa Kopa and Mt Szczeliniec Wielki, on the Wielkie Torfowisko Batorowskie mire, and in the valley of Pośna river, which are localities to be visited during the field excursions (except the mire).

Pteridophytes[6]. The pteridophyte flora of the Stołowe Mountains is diverse and fairly rich. It includes 33 species, with four species of club-mosses, seven species of horse-tails, and 22 ferns, which is nearly a half of pteridoflora of Poland. The club-mosses recorded in the National Park are *Hupezia selago*, *Lycopodium annotinum*, *L. clavatum* and the now extinct *Lycopodiella inundata*. Their surviving populations are very small. Among the seven recorded horse-tails the following are still present: *Equisetum arvense*, *E. sylvaticum*, *E. limosum* and *E. palustre*, whereas the existence of *E. hyemale*, *E. maximum* and *E. variegatum* could not have been confirmed in the recent research. Within the most numerous group of ferns, only *Ophioglossum vulgatum* is still present from evolutionarily old coarse-spored taxa. The best fern habitats are deep gorges within the calcareous mudstone terrain, where local enrichment of substratum in calcium carbonate occurs.

Vascular plants[7]. Currently, the flora of the region includes 868 taxa, representing 96 families and 389 genera. Nearly 12 per cent of the species have their northern and eastern distribution borders in Poland, which shows the south-western character of vegetation of the Stołowe Mountains. The presence of 77 montane and 50 xerothermic species, as well as of 160 anthropophytes has been recorded. The flora contains many rare and endangered species. Among them, 16 are included in the Red List of Poland, 99 in the Red List of Lower Silesia (the wider geographical region of SW Poland) and 96 in the Red List of the Sudetes. The most valuable plants are those critically endangered or endangered in Poland and in the Sudetes, e.g. *Saxifraga rosacea*, *Traunsteinera globosa*, *Goodyeara repens*, *Pinus* ^{X}*rhaetica*, *Orobanche elatior*, *Carex davalliana*, *C. pulicaris*, *Drosera rotundifolia*, *Dactylorhiza fuchsii*, *D. sambucina*, *Orchis mascula*, *Galium pumilum*, *Leucoium vernum* and *Lilium bulbiferum*.

Fauna. In the big forest complexes of the Stołowe Mountains we can easily come across deer (*Cervus elaphus*), roe deer (*Cervus capreolus*), wild boar (*Sus scrofa*), fox (*Vulpes vulpes*), squirrels (black and red variety) and small rodents. Among not so easily spotted are: muflon (*Ovis musimon*) – mountain sheep brought form Corsica and acclimatized in the Sudetes, badger (*Meles meles*), pine marten (*Martes martes*), weasel (*Mustela erminea*), stoad (*Mustela nivalis*) and fitchet (*Putorius putorius*). As for insectivora mammals hedgehog (*Erinaceus europeaus*) is rather commonly met, which is not the case with shrews (*Sorex*). The characteristic environment of cracks and crevices in sandstone massifs makes an ideal habitat for a number of bats. The most precious element of Park's mammal fauna are small, squirrel-like nocturnal animals, living mainly in broad-leaf forests: hazel dormouse (*Muscardinus avellanarius*), fat dormouse (*Dryomyces nitendula*) and dormouse (*Glis glis*). As for birds, in the Stolowe Mountains 98 breeding species have been recorded, including rare and endangered species. A characteristic feature of the mountains is relatively high

[6] Text adapted from Szczęśniak E., Świerkosz K., 2008, Pteridophytes (Summary). [in:] Przyroda Parku Narodowego Gór Stołowych, p. 172.

[7] Text adapted from Świerkosz K., Smoczyk M., Gołąb Z., 2008, Vascular plants (Summary). [in:] Przyroda Parku Narodowego Gór Stołowych, p. 181.

number of breeding pairs of rare owls, namely eagle owl (*Bubo bubo*), pigmy owl (*Glaucidium passerinum*), and Tengmalm's owl (*Aegolius funereus*). All three species are included into the Polish Red Data Book of Animals. From the conservation and faunistic point of view , breeding of black stork (*Ciconia nigra*), hazel grouse (*Tetrastes bonasia*) corncrake (*Crex crex*) and redpoll (*Carduelis flammea*) seems to be interesting. Among common reptiles on the teritory of the Stołowe Mountains we can meet common viper (*Vipera berus*), grass snake (*Natrix natrix*), sand lizard (*Lacerta agilis*) and slow worm (*Anguis fragilis*). As for rare amphibians salamander (*Salamandra salamandra*), smooth newt (*Triturus vulgaris*) and alpine newt (*Triturus alpestris*) can be sometimes spotted. The world of insects is still poorly investigated, but what attracts attention is rich in species long-horned beetles family and protected species of *Carabidae* family. Very interesting are snow insects and arachnids. The glacial relic of spider species (*Bathyphantes eumenis*) lives in cold wet sandstone fissures.

Land use changes (*Agnieszka Latocha*)[8]

The entire region of the Sudetes Mountains were subject to substantial changes of land use during the last 150 years. The changes referred mainly to settlement pattern, unpaved road network and type of land management, which were strongly connected with socio-economical and political changes. In the Stołowe Mountains, in the period of maximum population, which occurred at the turn of the 19th and 20th century, there were 62 settlement units, including colonies and hamlets. 12 settlements disappeared completely (19% of the total number) and 33 were subject to intense depopulation (54%). The process of land abandonment started as early as at the end of the 19th century and was intensified in the post-World War II period, which was a typical demographic process in the whole Sudetes. Depopulation was usually followed by considerable changes in land use, with secondary vegetation succession on abandoned arable grounds and an immense increase of forest stands. However, in the Stołowe Mountains, the increase of forested areas was not as spectacular as in other parts of the Sudetes – for the central part of the massif it changed only from 53 km² (based on topographic maps 1:25,000 from the 19/20th century *Messtischblatt*) to 57 km² nowadays. This phenomenon can be explained by natural environmental conditions of the area and its specific relief: rocky cliffs, numerous bedrock outcrops and very steep and debris-covered slopes did not support the development of agriculture. Therefore, the core area of the Stołowe Mountains remained forested for centuries and the agricultural land use and subsequent secondary vegetation succession were limited to the nearest vicinity of the villages. A much more widespread sign of land use change was the disappearance of arable grounds, usually turned into hay meadows and pastures (Table 1, Fig. 24).

Within the boundaries of the Góry Stołowe National Park there were six villages – two of them disappeared completely (Karłówek, Januszów), three remained in vestigial form (Ostra Góra, Łężno, Kociołek) and only one maintained its administrative status as a separate village (Pasterka), even though substantial depopulation was observed there as well (Table 1). All the villages were/are located in the upper parts of the valleys, usually in the source zones of streams.

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[8] The study was supported by the Ministry of Science and Higher Education by project no. NR09-0029-04/2008 and then by project no. N N306 384539 (4423/PB/IGRR/10).

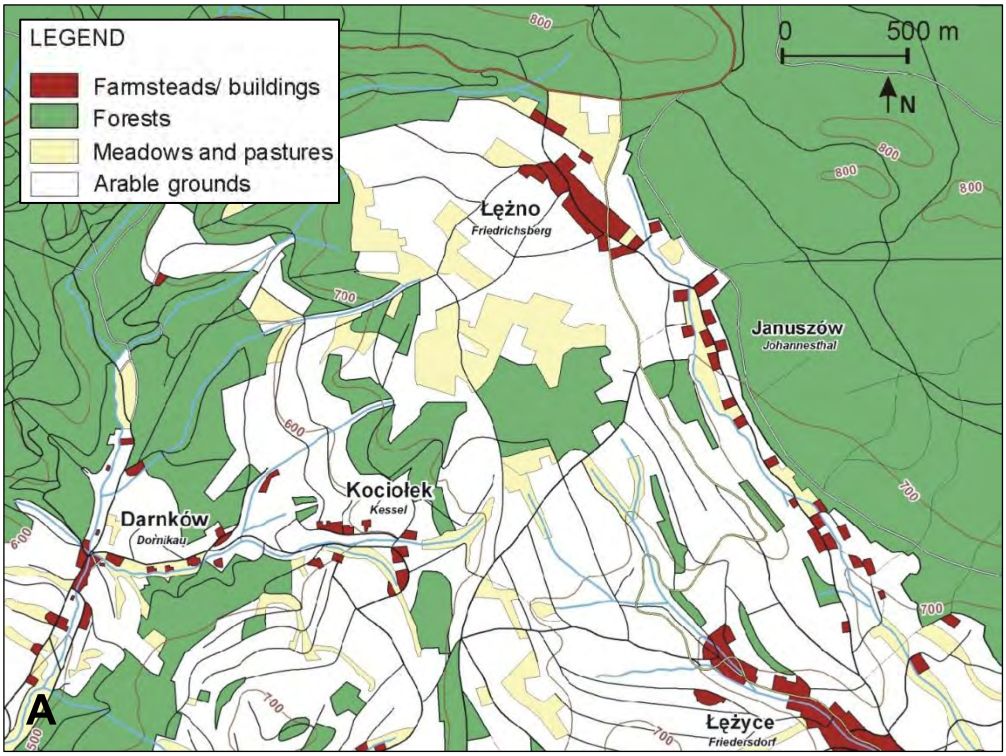
Tab. 1. General characteristics of depopulated catchments within the Stołowe Mountains National Park

Village	Catchment/ stream	Area km²	Underlying lithology	Altitude (m a.s.l).	Max. population	Present status	% of arable land in $19/20^{th}$ century and *at present*
Ostra Góra	Ostry Potok	2.2	marls, sandstone	530–745	207	included to another village*	60% *none*
Pasterka	Piekło (Pasterski Potok)	2.5	marls, sandstone	670–775	572	18 inhabitants	52% *none*
Karłówek	Kozi Potok + Pośna	0.6	marls, sandstone	660–765	49	vanished	39% *none*
Kociołek	No-name tributaries of Dańczówka	2.7	marls, sandstone, granite	520–760	74	included to another village*	52% *none*
Łężno	Złotnowski Potok	1.4	marls	750–790	160	included to another village*	56% *none*
Januszów			marls	600–750	104	vanished	

* no census data available but there are less than 5 permanent inhabitants in each of the village

The legacy of past human occupancy and intense activity in the depopulated areas is still readable in the contemporary landscape as various types of anthropogenic landforms and features. The main remains are ruins of buildings. Even though they are preserved in various conditions, the outlines of former farmsteads are clearly detectable, as they form artificial level surfaces (settlement terraces) within slopes and valley bottoms.

Landforms connected with former agricultural land use are the second group of anthropogenic features. They include the network of field access roads, which locally form road gullies. The morphometric parameters of gullies vary from catchment to catchment (20–720 m long, 0.4–4 m deep, with the usual depth between 0.8–1.5 m). More common than gullies are road scarps. They are from 0.5 m up to 4 m high (usually 1–2.5 m) and may continue for as much as 940 m. Most roads are no longer in use and road gullies are either partially filled up with mineral and organic matter or they become preserved due to overgrowth by dense grass and shrub cover. The density of old unpaved roads was 7–10.2 km/ km^2 in the $19/20^{th}$ century, while nowadays it is only 1.3–5 km/ km^2. Agricultural terraces, the evidence of former ploughing on contemporary hay meadows and pastures, are other anthropogenic scarps indicative of previous different land use. They are most common and best preserved around Pasterka village. The average height of terrace risers is 0.5–1.5 m. Other landforms connected with former agricultural land use are embankments and stone heaps collected by farmers from arable grounds to facilitate ploughing. Nowadays they are usually overgrown, mainly by xerophilous species, due to the high permeability of their loose, open-work structure. They are a common landscape feature and they vary in density and size. The height of these landforms ranges between 0.5 and 3 m, while the length of stone ramparts may reach up to 350 m. Some ramparts used to have a form of regular stone walls, however, in many places they collapsed and their previous structure has been obliterated.



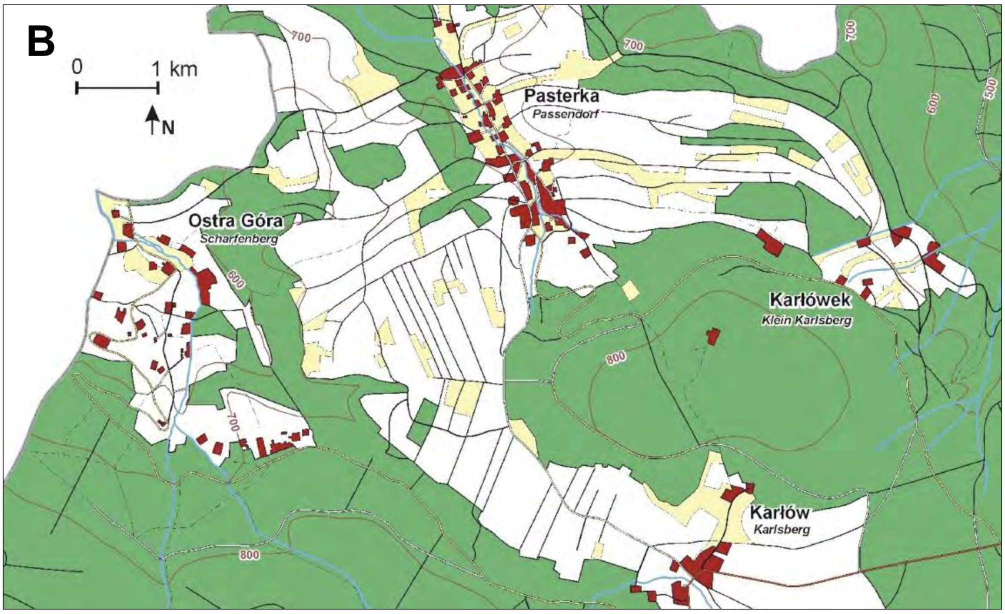
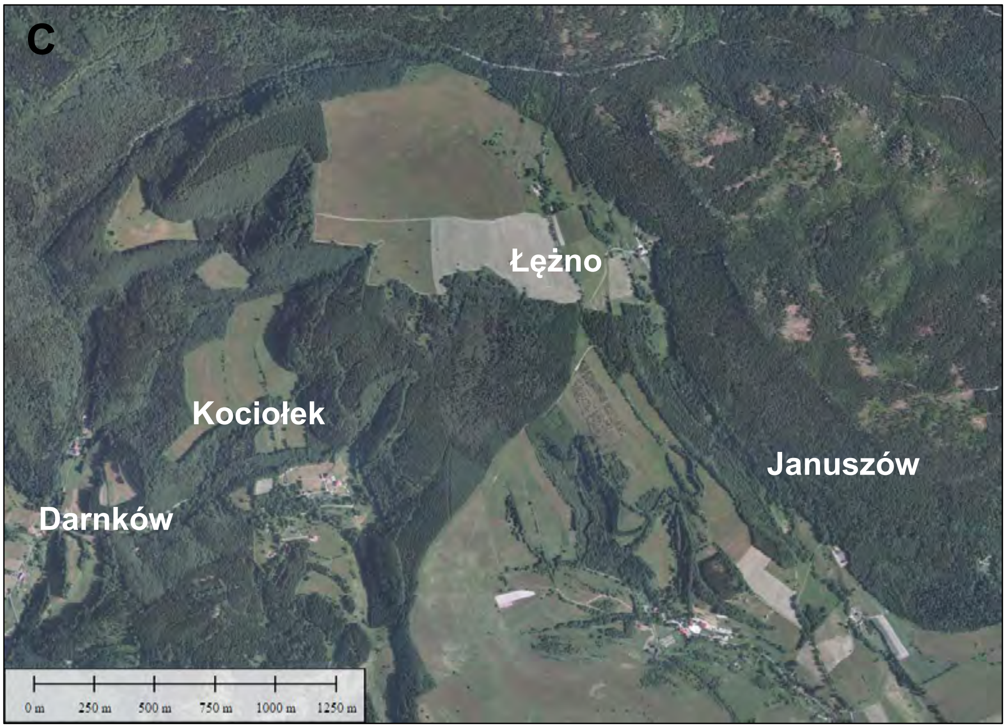


Figure 24 A,B,C,D. Land use changes around selected settlements in the Stołowe Mountains. Maps show land use in the early 20th century (interpreted from topographic maps 1:25,000 *Messtischblatt*), Orthophotomaps show the current state.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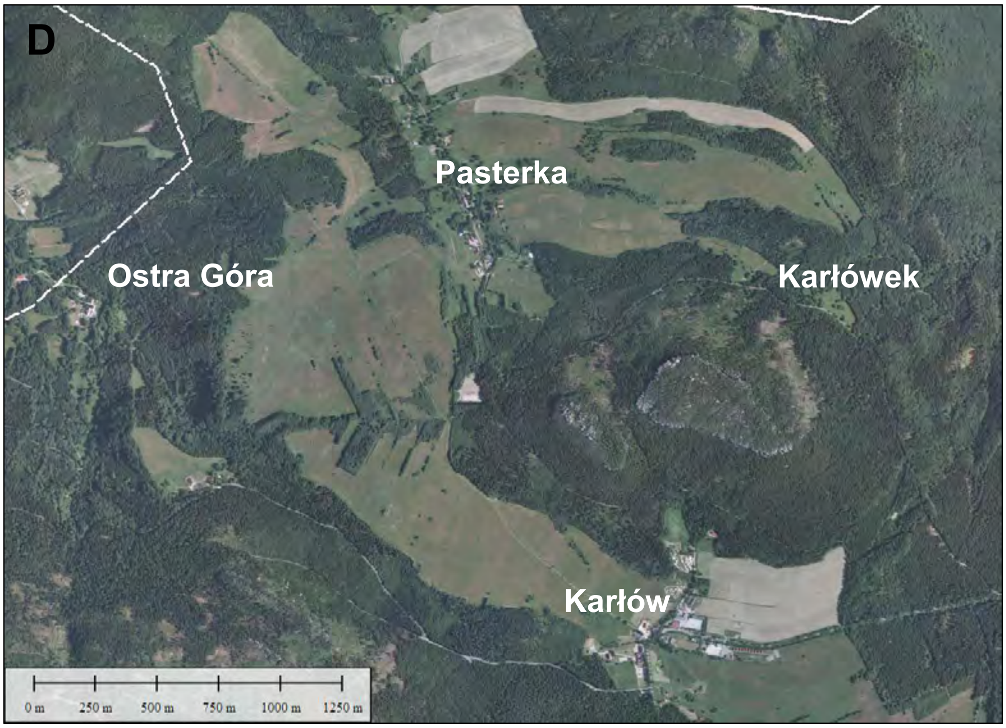
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1000 m
1250 m

The third group of anthropogenic features is connected with water management. They include various hydrotechnical constructions such as bridges (preserved or partly destroyed), subterrain water passages (culverts under the roads), stone- or concrete-cased riverbanks, flood-and-debris control dams. The latter ones were found only in one catchment (Januszów village), where there are two such constructions along the Złotnowski Stream. After depopulation of the area, the dams have not been cleaned and nowadays they are filled up with sediments. In spite of that, stone constructions of the dams are still well visible. The channel lining by stone or concrete was a common practice in mountain streams within all inhabited areas in the Sudetes. However, due to lack of maintenance, in most areas the remnants of former lining are preserved only fragmentary and locally. In the Stołowe Mountains the only exception is Pasterka, where channel lining has been preserved at numerous stretches along the stream, which is the axis of the village.

Nature conservation (*Piotr Migoń*)

Although the great natural value of the Stołowe Mountains has been appreciated since the end of the 18th century, formal action towards conservation and protection of their natural environment is of much more recent date. In the late 1930s the area of Wielkie Torfowisko Batorowskie (Great Batorów Mire), then already much degraded due to widespread meliorations, was declared as a protected area. However, after the Second World War nature reserves were first established on Mt Szczeliniec Wielki and Mt Szczeliniec Mały (1957, 50.26 ha) and in Błędne Skały (1957, 21.14 ha). Protection of the Batorów mire was formally re-established in 1958. In the subsequent years projects were under way to extend the network of nature reserves and to include selected deeply incised valley on mudstone/marl bedrock, the Pośna cirque, and beech forest communities. However, they were not concluded with an establishment of formal protection.

In 1981 a large area of the Stołowe Mountains was declared a Landscape Park (Stołowogórski Park Krajobrazowy) that included practically the entire mountain terrain between Kudowa-Zdrój in the south-west, Polanica-Zdrój in the south-east and Radków in the north. In 1993 a part of the Stołowe Góry Landscape Park, comprising most of the main sandstone/mudstone plateau with its northern and southern escarpments and the dissected granite terrain near Kudowa-Zdrój, was declared a National Park, the 19th in Poland. The area of the Stołowe Góry National Park occupies 63,41 km^2 and includes the three previously existing nature reserves, whereas two non-protected enclaves occur within the boundaries. These are the sandstone quarry cut into the northern escarpment above Radków and the area around Karłów. Within the National Park, c. 6.5% is subject to strict protection, mostly focused on relict and semi-natural forest communities and peat bogs. The entire area of the National Park is included in the Pan-European Natura 2000 network.

Tourism (*Piotr Migoń*)

The Stołowe Mountains belong to the most visited and most popular tourist destinations in south-west Poland. It is estimated that around 300,000 visitors yearly come to the area. There are two principal reasons for the ever-growing touristic interest. First, it is the scenic values of the landscape itself and the occurrence of landforms that are rare or non-existent elsewhere in Poland. The ‘rock city’ on the top of Mt Szczeliniec Wielki and the maze of Błędne Skały are unique in the country, whereas the number of oddly shaped ‘mushroom rocks’ far exceeds the respective number in the Polish Carpathians. Many view points located along the plateau edges offer wide vistas over the entire Sudetes. Second, in the close proximity of the Stołowe Mountains there occur three spa resorts: Polanica-Zdrój, Duszniki-Zdrój and Kudowa-Zdrój, popular since at least 100 years ago and catering for large numbers of visitors. In addition, around the mountains one can visit impressive cultural heritage sites, including the famous pilgrimage centre of Wambierzyce, the 16th century paper mill in Duszniki-Zdrój, the medieval old town and the imposing 18th century citadel in the town of Kłodzko, the bizarre ‘Chapel of Skulls’ in Kudowa-Zdrój, and many others. The Stołowe Mountains are easily accessible through a dense network of marked tourist trails (note than within national park only marked trails can be used while hiking) which connect nearly all interesting localities and provide links with towns and villages situated around the mountains. There is good road access, and the Road of One Hundred Curves, connecting Kudowa-Zdrój in the south and Radków in the north, built in 1867–1870, is an attraction in itself. The village of Karłów, situated in the heart of the Stołowe Mountains at the foot of Mt Szczeliniec Wielki, is the main tourist resort with good infrastructure.

However, it is worth noting the long history of tourism in the area. Although spas in the present-day Kudowa-Zdrój (formerly Bad Kudowa) and Polanica-Zdrój (formerly Bad Altheide) have been known since the 17th century, few if any people ventured into the forested, rock-riddled sandstone mountains for outdoor activities. This changed by the end of the 18th century when the unique labyrinth on the top of Mt Szczeliniec was discovered with seeking suitable locations for border military posts at the contemporaneous Austrian/Prussian boundary. Concurrently with the growing popularity of romantic affection for nature, the trail from Karłów to the top of Mt Szczeliniec Wielki became famous among visitors of neighbouring spas and soon made more accessible by providing steps and bridges over rock clefts. The fame of Mt Szczeliniec was augmented by the visit of Johann Wolfgang Goethe, a German poet and naturalist, in 1790, John Quincy Adams, later the President of the United States, in 1800, and kings of Prussia Friedrich Wilhelm II and Friedrich Wilhelm III. In 1813 Franz Pabel, a local forester from Karłów (then Carlsberg), received the official license of a guide to Mt Szczeliniec, one of the first distinctions of this kind in Europe. The trail through the ‘rock city’ is Pabel’s invention who himself made it suitable for visitors. In the mid-19th century the tourist lodge was built at the northern edge of the mesa, which – with little alterations – exists until today (Fig. 25). In the second half of the 19th century the local tourist organization, GGV (*Glatzer Gebirgsverein*), was active in marking hiking trails in the Stołowe Mountains and developing tourist infrastructure and in the beginning of the 20th century the area was already a well established tourist attraction.

Recently the changing nature of tourism contributes to growing environmental problems in the protected area of Góry Stołowe National Park. An increased use of private cars causes pollution along roads and congestions in most popular places such as Karłów. There is shortage of parking space at designated locations, especially during peak holiday season (July – August). Most popular hiking trails are under heavy pressure, with evident signs of erosion of light sandy soils on sloping ground. Illegal venturing into off-limits wilderness areas is another problem, difficult to deal with effectively. Heavy concentration of tourism in two most attractive places, Mt Szczeliniec Wielki and Błędne Skały, is a further matter of concern.

Fig. 25. Tourist lodge on Szczeliniec

Part 2
Excursion localities

Karłów (*Piotr Migoń*)

Karłów, once a small forest village on a meadow in the heart of the Stołowe Mountains, is now a major tourist centre of the area, with well-developed tourist infrastructure (accommodation, restaurants, parking places, services). Its history dates back to 1730 when a settlement was established around the forestry lodge. Shortly deforestation took place and the surroundings of Karłów acquired their present appearance of an extensive pasture and meadow terrain amidst forest. The village became popular by the end of the 18th century when the unusual scenic values of Mt Szczeliniec Wielki were discovered and first visitors climbed to its top, including the Prussian king Friedrich Wilhelm II and Johann Wolfgang Goethe, both in 1790. A few remains of traditional architecture survived in Karłów, including the former forestry house (now a hotel), post office, and one of mid-19th century tourist lodges.

Geographically, Karłów is located on the main plateau of the Stołowe Mountains (Level II), at the altitude of 720–760 m a.s.l., between the plateau of Skalniak in the south and the mesa of Mt Szczeliniec Wielki in the north (Fig. 26). The European water divide runs across a low elevation west of the village. The plateau is underlain by fine-grained sed-

Fig. 26 – Karłów seen from Mt Szczeliniec Wielki

imentary rocks, mudstones and calcareous mudstones. Sandstone debris from sandstone escarpments below the morphological Level I only reaches the footslopes of the escarpments. However, a peculiar group of isolated sandstone boulders occurs on the elevation of Pustelnik (790 m a.s.l.) west of the village (see Part 1 of the guidebook). They are probably remnants of a long gone mesa – another fragment of the Level I, completely consumed by erosion.

Szczeliniec Wielki (*Piotr Migoń, Zbigniew Gołąb, Przemysław Zwaduch*)

Rocks, landforms and processes. Mt Szczeliniec Wielki is an isolated mesa rising above the main plateau of the Stołowe Mountains – a remnant of a once continuous morphological surface supported by the Upper Jointed Sandstone (Skalniak – Szczeliniec Sandstone). The highest spot in the mountains (919 m a.s.l.) is located on one of summit tors, known as Fotel Pradziada (Great Grandfather's Chair). The European water divide runs across the mesa, so that its north-western slopes are drained to the North Sea, whereas the remaining ones to the Baltic Sea.

Geologically Mt Szczeliniec Wielki is built of a sandstone caprock overlying fine-grained deposits, mostly calcareous mudstone and mudstone. The thickness of caprock, i.e. of the Upper Jointed Sandstone, is c. 70 m, within which three lower-order units can be distinguished. The lower unit is composed of glauconitic sandstone, exposed only further away from the slopes of the mesa. The middle part of the succession is built of massive sandstone with sloping sets of tabular cross-beds dipping to SW. It is this unit that supports vertical cliffs up to 40 m high, seen from all around the mesa (Fig. 27). The upper unit is a large-scale trough cross-bedded sandstone from which the fantastic tor shapes on the summit surface of Mt Szczeliniec Wielki are carved (Fig. 10A).

Fig. 27. Sandstone cliffs around the mesa.

Weathering and mass movements are dominant geomorphic processes on the mesa. The former is highly selective and picks out mainly different discontinuities within the rock (bedding planes, joints, sub-horizontal boundary surfaces). However, typical features of sandstone microrelief known from elsewhere in the Bohemian Cretaceous Basin, such as honeycomb structures or ferruginous crusts, are largely absent. Most common are caverns in vertical surfaces (tafoni), but they rarely attain dimensions of 1 x 1 m. Long-term weathering contributed to excavation of narrow corridors and alleys between sandstone blocks, best seen in the central part of the summit plateau. Towards the margins of the mesa they give way to ruiniform relief, indicating inward progress of weathering.

Mass movements affect the outer slopes of the mesa and there is morphological evidence available for different phases of displacements. It is assumed that gravitational processes are initiated by processes operating close to and at the sandstone/calcareous mudstone boundary, including mechanical suffosion, chemical weathering, and responding to lithostatic stresses imposed by the heavy sandstone slab on deformable bedrock below. The latter induce squeezing out of deformable mudstone, which form unstable bulges in the lower slopes of the mesa. Along the edges of the mesa it can be observed that rigid sandstone blocks react to plastic deformations below by joint opening, outward movement and tilting towards the slope. Two deep clefts, up to 17 m deep, along the northern edge of the mesa show two stages of this process. Diabelska Kuchnia (Devil's Kitchen) is a narrow fissure with limited tilting of an outer block, while Piekiełko (Hell) is much wider and the outer block is inclined by c. 20° from vertical (Fig. 13, 28). Further movement of blocks makes them gravitationally unstable and results in toppling. Huge fallen blocks up to 20 m long below the sandstone cliffs are the testament of this process – unfortunately, they are barely seen from above.

Fig. 28. One of deep fissures along the northern rim of My Szczeliniec Wielki, with evidence of block outward movement.

Since a few tens of years joint opening and block displacements along the edges of the mesa are subject to monitoring as it can present considerable danger to visitors. Observations include repetitive geodetic surveying as well as registration of rock block displacements using extensometers and provide quantitative data about present stability conditions in three most exposed marginal zones of the Szczeliniec Wielki massif. The registered movements are partly of oscillatory nature, related to seasonal temperature changes, as those around the tourist lodge and on the adjacent observation terrace. However, progressive changes have also been observed. In Piekiełko recent horizontal movements up to 1.43 mm yr^{-1} and subsidence up to –0.87 mm yr^{-1} were recorded[9]. At the south-eastern corner of the mesa different blocks show different behaviours, with either inward or outward movement, as well as relative uplift or subsidence to +/– 1 mm yr^{-1}. Complex movements appear related mainly to precipitation extremes. Altogether, these data indicate that the margins of the mesa are far from stable which is a factor that has to be taken into account while managing tourist flows.

Montane pine forest. The flora of the Stołowe Mountains can be divided into two different groups, depending on the geological bedrock, i.e. acidophilous and basiphilous species. Montane pine forest of the association *Betulo carpatice-Pinetum* on the top of Szczeliniec Wielki represents an arrangement of species linked to an acid quartz sandstone (Fig. 29). This is why the pine forest with dominant relict variety of scots pine has very poor

Fig. 29. Montane pine forest in the vicinity of Piekiełko cleft.

[9] Numerical values from Cacoń S. et al., 2011, Badania przemieszczeń masowych bloków skalnych Szczelińca Wielkiego. [in:] Chodak T., Kabała C., Kaszubkiewicz J., Migoń P., Wojewoda J. (red.), Geoekologiczne warunki środowiska przyrodniczego Gór Stołowych, WIND, Wrocław, pp. 105–112.

undergrowth comprising bilberry (*Vaccinium mertillus*), red berry (*V. vitis-idaea*), heather (*Calluna vulgaris*) and crow berry (*Empertum nigrum*). In some recesses with stagnating water *V. uliginosum* can also be found. Apart from the pines (which, although small, are often quite old – even 200 years) the tree stand consists also of *Betula pubescens ssp. carpatica* and Norway spruce (*Picea abies*)

History. Mt Szczeliniec Wielki was discovered in late 18th century, and first visited as a possible location of a military outpost at the Prussian/Austrian border. After the Silesian Wars, the Prussians who overtook Lower Silesia from the Austrian-Hungarian Empire decided to fortify the newly established border. Friedrich Wilhelm II, the king of Prussia, came to Karłów (then Carlsberg) with the intention of building a fortress on the top of Mt Szczeliniec. He was guided to the top of the mesa by a local peasant, Franz Pabel. The king was so overwhelmed with the beauty of this rocky plateau that he decided to build a fortress elsewhere. He also decided to make the mountain open to visitors and made Franz Pabel responsible for making Mt Szczeliniec Wielki accessible to the tourists. The building of the stony stairs took 23 years to complete. When Friedrich III, next king of Prussia, came in 1813 to accept Pabel's work he made him the official guide and cashier of Mt Szczeliniec, which made Pabel the first licensed mountain guide in Europe (Fig. 30). Franz Pabel later became the landlord and mayor of Karłów and worked as a guide during 71 years leading groups of visitors to the top of Mt Szczeliniec Wielki. He is also credited with the creation of the route around the top of the massif and naming the rocky forms along it. In subsequent years further footpaths to the top surface of Mt Szczeliniec Wielki were built, and progressively the length of trails on the mesa surface was extended. In the second half of the 19th century the most difficult trail through the deep clefts along the northern edge was opened to the public, completing the network. Earlier on, in 1845, the tourist lodge at the northern terrace was built in the Swiss style which is used as a restaurant until today. Among many other mountain lodges in the Sudetes it occupies a special place as it was the oldest one purposefully built to serve tourists (others were converted from shepherd's houses).

Fig. 30. Commemorating plaque of Franz Pabel on Mt Szczeliniec Wielki.

Forest management. Although the Stołowe Mountains National Park was established primarily due to its geological value, most of activities of NP Service focus on forests. Forests cover about 90 % of National Park area. Most of them are coniferous forest with Norway spruce as the dominant species (about 78 % of the forest area). About 200 years ago the Stołowe Mountains, similarly to the rest of the Sudetes, were covered by mixed and broadleaf forests with beech (about 50 % of the all forest area), Silver fir (18-20%), spruce (26%) and some other tree species like as sycamore maple (*Acer pseudoplatanus*) or scotch elm (mountain elm, *Ulmus glabra*). In the 17th and 18th century the dynamic development of colonization and glass- and steel industry caused mass cutting of the natural forests. Huge amount of wood was needed so beech and fir became unpopular species (because of their slow growth) and only fast growing spruce was planted or sowed. Important is that seeds from different part of Europe were used, from spruce population not necessarily adjusted to the climatic and soil conditions of the Stołowe Mountains. Now, in the National Park forests consist of spruce (72 %) and some other tree species like beech (11%), larch (5%), sycamore (2%) and only 0.2% of Silver fir. The artificial spruce forests are unstable – responsive to wind and snow disasters, lack of rain, climate warming or insects (like as bark beetle) outbursts.

The National Park service, from the first day of NP existence, is trying to rebuild those artificial forests. Seedlings, mostly fir and beech seedlings, are planted. They have to be well protected because of big deer population. In other places, there were some natural renewals of beech, sycamore or fir, and these young trees are also protected. The seeds used to grow seedlings in NP nurseries came from NP forests. In artificial NP forests some of the spruce trees are cut to create optimal conditions for fir or beech seedlings.

One of the biggest problems in NP coniferous forests are outbursts of bark beetle. This small beetle can kill a lot of spruces in a very few days. It is difficult to plant seedlings of beech or especially fir in the open areas without trees. Although young trees need sun light to grow, beech or fir grow better under the canopy of grown trees so that NP forest service have to stop or slow down those beetle outbursts. Of course there are some strict protected areas (about 770 ha) with no human activity, also related to the bark beetle.

Karłówek (*Agnieszka Latocha*)

The village of Karłówek is a representative example of landscape and environmental transformation due to depopulation and land use changes in the Stołowe Mountains. It was was established in the middle of the 18th century, in the period of a general increase of settlement processes and increase of population in the entire Sudetes region. Many small settlements and hamlets were created at that time, encroaching on higher and steeper parts of the slopes and even towards watershed areas. Karłówek belonged to the larger village of Karłów and never developed into a large community. In the period of maximum population 11 farmsteads with 49 inhabitants (in year 1933) existed here. After the Second World War, the village was abandoned as the original German population was not replaced by the Polish one. It was mainly due to natural environmental constraints, making the location rather unfavourable for living. The site is situated at 660–765 m a.s.l., on steep slopes of NE aspect, in the shadow of the Szczeliniec Wielki plateau (919 m a.s.l). Such conditions did not support agricultural land use – nowadays there are no arable grounds in the vicinity of the former village, while at the turn of the 19/20th century they occupied around 40%. Former ploughing grounds are now turned into hay meadows and pastures or are overgrown by forest, which developed due to a spontaneous process of natural secondary vegetation succession on abandoned lands (Fig. 31).

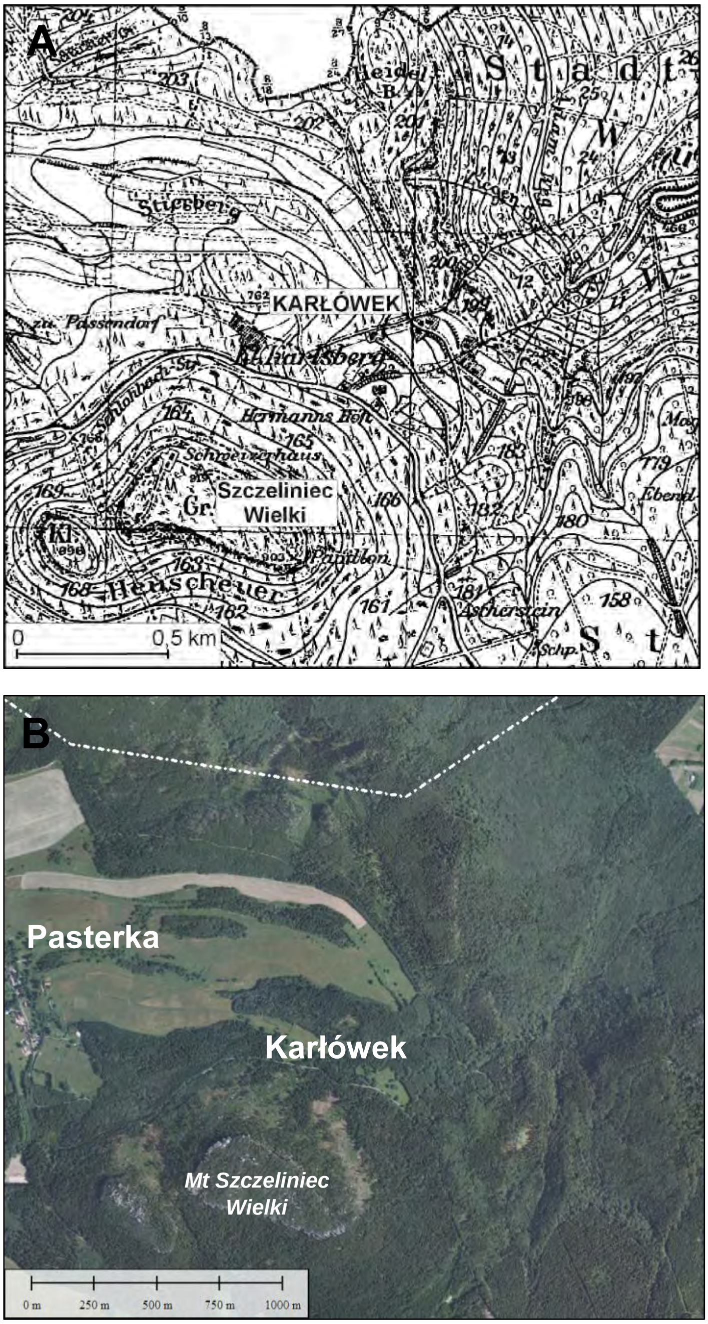

Fig. 31. The hamlet of Karłówek. (A) extract from 1:25,000, early 20th century topographic map; (B) orthophotomap.

Nowadays, the remains of old settlement are found mainly within the forested, while in the 19/20th century the village was famous for its open space and spectacular views, which could be admired from the rocky escarpment of the Stołowe Mountain plateau. The village was situated upslope of it. Therefore, Karłówek developed into a popular touristic place and an attractive overnight stop for tourists visiting also other, nearby attractions, such as Mt Szczeliniec Wielki or Pośna Waterfalls. There was even a guesthouse with accommodation and food service in the village. The touristic value of the place continues up to nowadays, as a few tourist trails (walking paths and cycling routes) lead through the site of past village. The modern tourist tracks follow old roads. In some places it is possible to distinguish the remains of old pavement (cobbling), which still act as an effective protection against linear erosion along the paths (Fig. 32). However, other roads, which are not in use nowadays, have disappeared. It was calculated, basing on comparison of old topographic maps and the present environment, that around 50% of old roads are not in use any longer. They become less and less visible due to their overgrown by vegetation and filling up with mineral and organic matter. This process is especially well developed in former road gullies, which can be found in the contemporary forested areas. Locally they are up to 1 m deep, however, their scarps are progressively degraded and mineral-organic material is accumulated within the gullies, which become progressively shallow (Fig. 33). Even though the occur-.

Fig. 32. Old cobbled road and remnants of house foundations in Karłówek.

Fig. 33. Road gully in the area of the former settlement of Karłówek.

rence of road gullies indicates that the linear erosion was an effective morphological process in the past, nowadays erosional features can be found only within the roads in use

The farmsteads of Karłówek were located along the upper parts of two deep, narrow valleys (Kozi and Pośna streams) and also on the watershed within the main plateau of the Stołowe Mountains (Fig. 31). Remains of former buildings are still visible. Their location can be also easily recognized by the anthropogenic levellings of slopes, which form settlement terraces (Fig. 32). Some ruins are preserved quite well, while in others only stone foundations are preserved (Fig. 34). Beside of buildings, also elements of stone strengthening of roads (stone walls) are locally visible, as well as fragments of former channel lining. The regulation of streams was a common activity within the inhabited areas. However, without constant renovation and maintenance, most stretches of the streams are now turning back to their natural, meandering pattern and artificial blocks eroded from lining or other hydrotechnical constructions can be found within the channels. Dilapidation of stone constructions (buildings, walls, channel lining) is fastened by vegetation growth, especially by tree roots, which loosen and wedge the stones out of the constructions (Fig. 34).

Fig. 34. Degradation of stone constructions made of local sandstone in Karłówek.

Pośna cirque (*Zbigniew Gołąb, Piotr Migoń*)

Pośna cirque is one of the amphitheatres (sapping cirques) within the northern escarpment of the Stołowe Mountains, located right above the town of Radków. With its size of 0.5 km^2 and depth of 220 m, it is exceed only by the Cedron amphitheatre further east. The cirque has developed through complex processes of spring erosion at the sandstone/mudstone boundary, fluvial erosion of streams flowing off the plateau of Level II of the Stołowe Mountains, and mass movement on the escarpment. The streams have cut deep ravines within the marginal parts of the Level II, then forming short gorges within the rocky upper part of the escarpment itself. Below, the distinctiveness of channel forms diminished and in dry periods surface flow may disappear altogether. Spring and stream discharges have been found high enough to tap water for consumption and water intake has been taking place since the 1960s. This severely altered surface hydrological conditions and caused the disappearance of picturesque Pośna Waterfalls (however, themselves partly artificial), which used to be one of the most visited tourist attractions in the Stołowe Mountains prior to the Second World War.

Most of the Stołowe Mountains territory is now covered with coniferous, planted spruce forests which have replaced the original fir-beech or spruce -beech forests. Natural broad-leaves forests of the lower montane belt have survived only in small fragments in nearly inaccessible areas (Fig. 35). The deep shadowy dale of Pośna stream is the example of such a fragment. Plant associations developed here can be classified as herb-rich beech forest (*Dentario enneaphylidis-Fagetum*) and in some places European sycamore forest (*Lunario-*

Fig. 35. Herb-rich beech forest in the Pośna cirque

Aceretum). Both of them are locally distributed in the marginal part of the Stołowe mountains cliff area and are linked to fertile soils. European sycamore forests prefer habitats rich in rock debris. The forests have a differentiated multi-storied structure. The tree stand is composed predominantly of beech (*Fagus sylvatica*) and European sycamore (*Acer pseudoplatanus*) sometimes accompanied by silver fir (*Abies alba*). The undergrowth is rich in many species; among them such significant vascular plants like: *Dentaria eneaphyllos*, *Lunaria rediviva*, *Asarum europaeum*, *Daphne mesereum*, *Actea spicata*, *Polystichum aculeatum*, *Galeoobdolon luteum*, *Corydalis cava*, *Lathyrus vernus*, *Pulmonaria obscura*, *Carex sylvatica*. The forest habitats in the dale of Pośna stream are included into strictly protected zone of the Stołowe Mountains National Park and into European ecological network Nature 2000.

Radkowskie Ściany (*Piotr Migoń, Jurand Wojewoda*)

Radkowskie Ściany (Radków Walls) is the name given to the most impressive part of the northern escarpment of the Stołowe Mountains, where sandstone cliffs up to 40 m high occur almost continuously over a distance of 2 km. The excursion stop is located on one of spurs protruding from the plateau level and offers excellent view of the escarpment, as well as the large morphological depression excavated in Permian sediments in front of the sandstone terrain (Fig. 36). The spur, locally known as Zbrojownia Herkulesa (Hercules Armoury), is undercut by vertical faces of 20–30 m high, but its upper surface abounds in sand

Fig. 36. A view from Radkowskie Ściany: northern escarpment of the Stołowe Mountains to the left, with the mesa of Mt Szczeliniec Wielki, and fragment of the wide Ścinawka Basin excavated in Permian sedimentary rocks to the right.

stone tors of different shapes, reflecting lithological control on geomorphological development (Fig. 37). Three distinctive sandstone layers of contrasting properties and resistance to weathering can be distinguished in vertical succession (Fig. 38). The lower layer is made of bedded sandstone ($LS_{x–b}$ facies), overlain by a thin but highly porous coquinoid conglomerate or sandstone (SC, CS facies). This in turn is capped by massive, bioturbated sandstone of $BL_{x–b}$ facies. The middle, conglomeratic layer is most affected by weathering, aided by high porosity, and forms recesses and narrow stems under overhanging caps. Tor shapes vary from slender vertical columns to massive blocks divided by narrow joint-guided clefts.

Fig. 37. Sandstone tors at Zbrojownia Herkulesa locality.

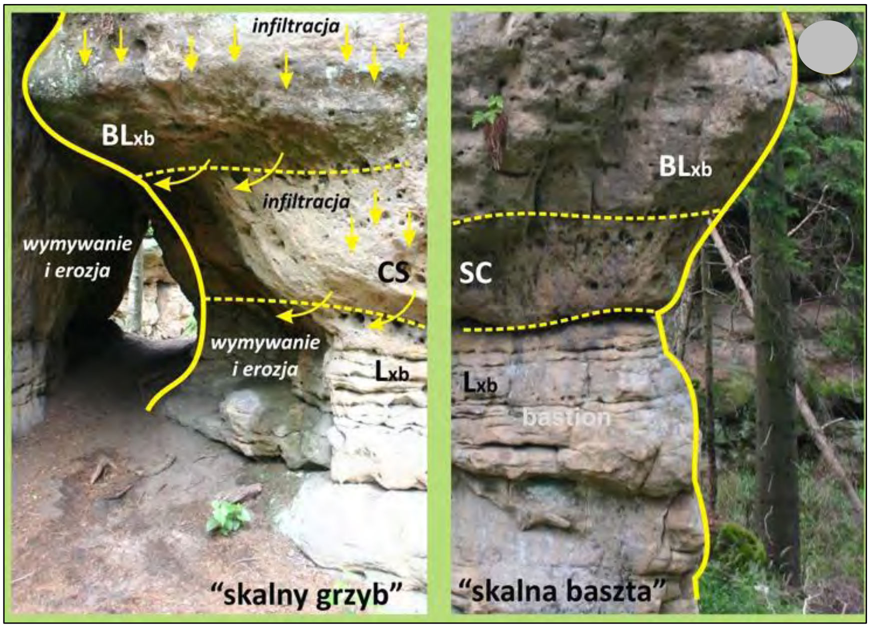

Fig. 38. Rock control on weathering processes and sandstone tor formation at Zbrojownia Herkulesa.

Narożnik – Białe Skały (*Cezary Kabała*)

The plateau and slopes of Mt Narożnik, including Białe Skały (White Rocks) area, is the part of the Stołowe Mountains where soil forming processes are most dynamic and where all varieties of soils developed from sandstone are present. The most common soil in the areas of sandstone occurrence is Podzol (in Polish: *bielica*). It has sandy texture throughout the soil profile and thus is permeable to water and water-soluble substances. Leached sands are poor in alkaline elements, so the Podzols are acid and dystrophic soils, creating habitats suitable for spruce forest or mixed forest with predominance of spruce. Surface layers of these soils have pH of 3.3–3.8, the sub-surface layers – usually 4.0–4.3. Base saturation fluctuates around 20% (the limit of dystrophic/eutrophic is at 50–60%). Two characteristic horizons are clearly marked in morphology of these soils: (i) a white-gray surface horizon (eluvial, E), and brown illuvial horizon (Bh, Bhs) enriched with humus, iron and aluminum. The amount of mobile iron and aluminum compounds in the illuvial horizon sometimes is even 100-fold higher than the amount of these elements in the eluvial horizon. The lower part of soil profile is generally yellow colored, caused by the presence of the highly dispersed, oxidized iron compounds. The soil is covered with an acid ectohumus of moder-mor or mor type, built of spruce needles and forest floor plant debris, partly decomposed.

However, such typical Podzols cover only patches of the area, in a mosaic with numerous other soils. In some locations, particularly below the rock outcrops and rock cliffs, Podzols are buried under the cover of yellowish-white sand those thickness rises up to 150 cm. Sand covers were formed by erosion triggered either by climate change, or, more likely, by human activity – forests cuttings, building of forest roads and paths, and mass tourism. Sand covers have variable thickness and are concentrated below the fissures in the larger rocks and sandstone walls. Thus, on most slopes, as in the area of Białe Skały, the Podzols having a thin surface sandy horizon occur in a mosaic with soils covered with a thick (or very thick) sand layer. It is clear that the thicker sand layer results in the lower fertility of the Podzol. Soils that have surface, loose sandy layer with a thickness of 50 cm are somewhat similar to poor Arenosols. Of course these are not Arenosols *sensu stricto*, but rather a sandy Regosols, because they contain a large admixture of sandstone boulders and finer rock debris. Often sand is only found in cracks between boulders, and the overall skeleton content soil exceeds 80% by volume. A characteristic feature of these soils is a large seasonal variability of soil moisture. During a few summer weeks these sandy soils may be completely dry, but most of the year they have high or even excessive water content. This is due to specific mountain climate, and surface or subsurface water runoff of the plateau. A visible effect of this excessive humidity is fairly high incidence of peaty ectohumus, often thicker than 10 cm.

In the lower parts of the slopes, at the foot of the sandstone cliffs, there are outcrops of mudstone (“marl”) regoliths covered with sandstone debris. Soils developed from such materials have bipartite texture: sandy at the surface (sand or loamy sand), and loamy in the subsoil (sandy loam, loam, or silt loam). The morphology of these soils is similar to the Podzols, but the B horizons often do not meet the quantitative requirements for this soil type (too small illuviation of the mobile aluminum, iron and organic carbon). Fine textured subsoil makes rainwater infiltration difficult and causes water stagnation in superficial soil layers.

These soils are therefore temporarily or permanently wet, which stimulates the development of hydrophilic or wetland vegetation. Alternating wetting and drying of these soils leads often to the formation of “thin iron pan” in the middle part of its profile. The layer is very compact and completely impermeable to water, which intensifies the effect of wetness in the surface soil layer. These soils, despite their Podzol-like morphology, have a higher content of plant-available nutrients, suitable for a broadleaf or mixed forest (typical or wet varieties).

Contemporary mobility of the cover sands raises the question of the age and origin of Podzols in the Stołowe Mountains. Numerous arguments were collected which show that at least some Podzols are polygenetic and bipartial soils ("welded soils"). The bottom, brown part, represents older acid brown earths, which have relatively recently been covered with cover sands, and then afforested with spruce stands, under which podzolization process started.

Sawanna Łężycka (*Piotr Migoń, Diana Mańkowska-Jurek*)

Sawanna Łężycka (Łężyce Savanna) is the informal name given to the nearly level terrain south of Mt Rogowa Kopa (790 m a.s.l.), in the south-western part of the Stołowe Mountains. Geologically, it cuts across mudstones which occur beneath the ‘Upper Sandstones’, whose outcrops are located to the north and the east, some 40 m higher than the surface of Sawanna Łężycka. The peculiar feature of the area is the occurrence of scattered sandstone blocks of ‘Upper Sandstone’ which are in allochthonous position and have unclear origin. More than 40 boulders can be found, from rather small examples 2–3 m long and rising by 1–1.5 m above the ground surface to massive elements up to 10 m long and 5–6 m high (Fig. 12). Variable orientation and dip of originally horizontal bedding planes indicated that boulders must have undergone significant change of original position, which appears odd given the flatness of the terrain.

The position of boulders on the local topographic high and the absence of boulder trails leading towards sandstone escarpments invalidate the hypothesis that boulders may have wandered to their current position due to slow creep away from talus slopes at the foot of the escarpments. Likewise, their wide scatter is difficult to explain by prolonged mass movement. The most likely hypothesis assumes that the source of boulders of Sawanna Łężycka is the long gone extension of the slab of ‘Upper Sandstone’ and that the boulders settled down concurrently with lowering of the marly/mudstone surface (Fig. 39). They owe their survival to the massiveness of the ‘Upper Sandstone’ and its much higher resistance compared to easily erodible mudstone.

In the past, sandstone boulders of Sawanna Łężycka were quarried for local purposes as the easy accessible source of material. A few blocks still show signs of this activity and it is possible that some may have disappeared completely.

In terms of vegetation, Sawanna Łężycka represents one of meadow communities within the territory of the Stołowe Mountains National Park. Various meadows cover an area of over 300 ha within the Park. Although this is only 5 per cent of the NP area, meadows are decisive for its biodiversity as they are sites for over 40% of vascular flora species. The meadows richest in the species on fertile drier soils are called Sudeten orchid meadows;

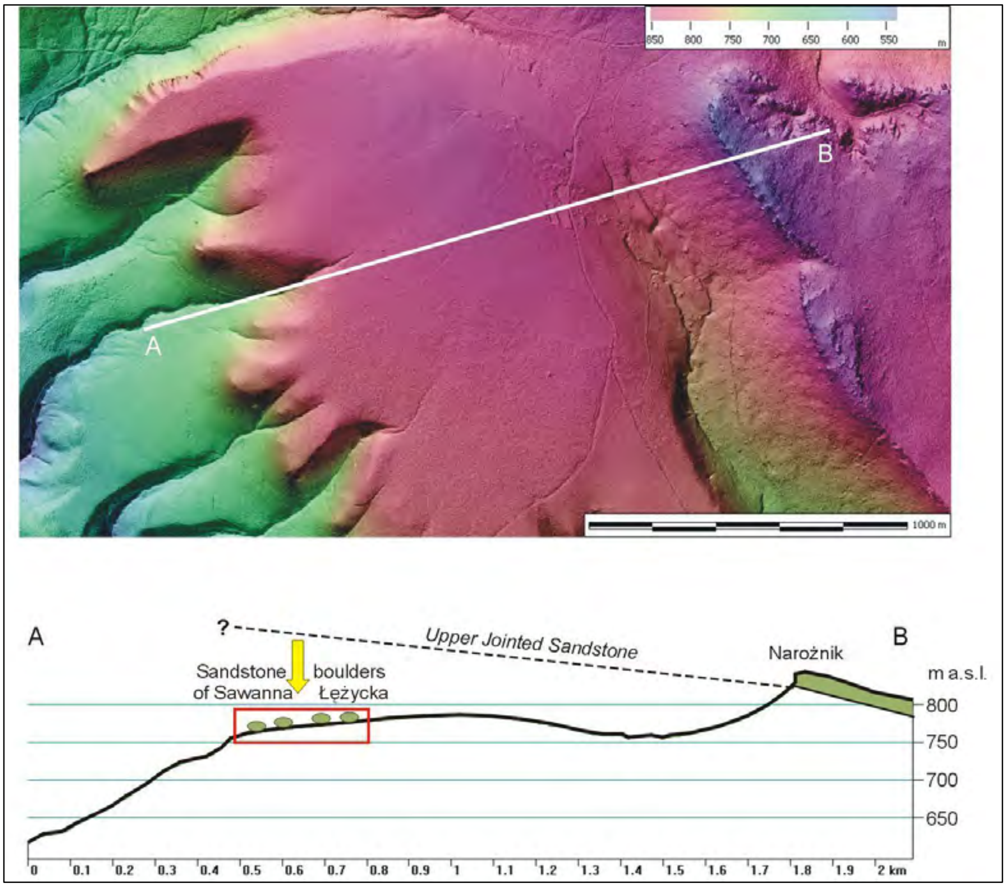

Fig. 39. A model to explain the origin of sandstone blocks on the plateau of Sawanna Łężycka.

many orchids flower there such as Fregrant Orchid *Gymnadenia conpsea*, Western Marsh Orchid *Dactylorhiza majalis*, Tway Blade *Listera ovate*, on the only site in Sudeten – *Traustainera globosa* and the only one of vascular plants in the NP territory having its own special protected areas out of pan-European Nature 2000 network – *Gentianella bohemica*. Furthermore, the meadows are an essential element of the cultural landscape of the Stołowe Mountains. Therefore, they must be maintained. Nowadays, most of them have been leased to local farmers who carry traditional pasture or hay–making management under the NP control.

Rogowa Kopa (*Łukasz Pawlik, Piotr Migoń*)

To the west of Sawanna Łężycka the plateau is abruptly terminated by a clear slope break, below which very steep hillslopes (locally up to 40°) extend down to the valley of Dańczówka river. The slopes truncate the thick complex of mudstones and calcareous marls of middle to late Turonian age. These fine-grained sedimentary rocks, in contrast to sandstones, do not form a distinct superficial relief with tors, rock 'mushrooms' or rock cliffs. On such bedrock Haplic Cambisols (eutric) developed with prevailing texture of silt loam (0–25 cm horizon) and loam (25–50 cm horizon). The weathering mantles of mudstones, although locally very diversified, form the most compacted and impermeable soils in the Góry Stołowe National Park. These features – compactness and impermeability – lead in favourable topographical conditions to gleization due to rainfall.

The steep slopes of Mt Rogowa Kopa are noteworthy from at least three reasons: its botanical value, the presence of distinctive pit-and-mound microtopography, and the strange occurrence of huge sandstone boulders along floors of a few ravines dissecting the slopes. As stated previously, fragments of natural forest have survived only in small areas in the Stołowe Mountains and the south-western slopes of the Rogowa Kopa are one of these areas. They are covered by European beech forest (*Fagus silvatica* L.) (Fig. 40). The age structure of trees is differential. On steeper slopes relatively young *Fagus silvatica* L. trees (to 100 years old), accompanied by single *Picea abies* (L.) Karst and *Acer pseudoplatanus (L.)* trees, are growing, whereas an older mixed forest occupies relatively gentle slopes on spurs. The single individuals of *Fagus silvatica* L. reach here the age of 180 years.

The pit-and-mound microtopography has been produced by widespread tree uprooting, a process most frequently induced by strong wind and called then *windthrow*, but other causes are also possible. Tree uprooting appears when a soil-weathering substrate is thrown intact together with a root system of a fallen tree in a form of root plate (as opposed to tree fall – tree stem breakage). Uprooting is seen as a major disturbance factor in most natural forests and simultaneously it is an important agent altering stability of hillslope surface and

Fig. 40. Beech forest on steep slopes of Mt Rogowa Kopa.

affecting other geomorphological processes. In a research polygon set on a slope facing the stream just below the sandstone boulders of Sawanna Łężycka, more than 100 pit-and-mound pairs have been documented, hence their density of 40 per 1 hectare. Altogether, 4.7 per cent of the study site is covered by pit-and-mound microtopography. Individual pits are from less than 3 m^2 to nearly 15 m^2 and their maximum volume is 4.2 m^3. The size of mounds is very similar. Uprooting disturbs the soil cover and is able to detach rock fragments up to 0.7 m long, as can be seen on some mounds. Considering the significance of pit-and-mound topography perhaps the most important feature is transformation of a planar slope into a step-like profile. Such a distinct microrelief provides additional roughness in the forest floor, affecting surface runoff and wash, as well as creates microhabitats.

Along the channel of an unnamed creek dissecting the slopes of Mt Rogowa Kopa there occur many sandstone boulders which are clearly allochthonous. Their dimension approach 5 m long and up to 3 m high, and they continue along 300 m downstream. They form a few distinct clusters in the valley floor (Fig. 41), but are nearly absent on slopes, except for two examples just at the convex slope break below the level of Sawanna Łężycka. A similar situation can be observed in the next valley to the south. The origin of these boulder trails is related to long-term retreat of the steep slope underlain by mudstones and marls. Undercutting of the plateau littered with huge sandstone boulders causes the latter to move downslope, by a presumably rapid gravity transport (hence their absence on slopes), to finally accumulate in the valley floor (Fig. 42). The large number of boulders gives and indication that the extent of Sawanna Łężycka must have been much larger in the past. Unfortunately, to date there are no clues to provide temporal framework for these complex processes.

Fig. 41. Sandstone boulder clusters in the floor of a ravine dissecting the slopes.

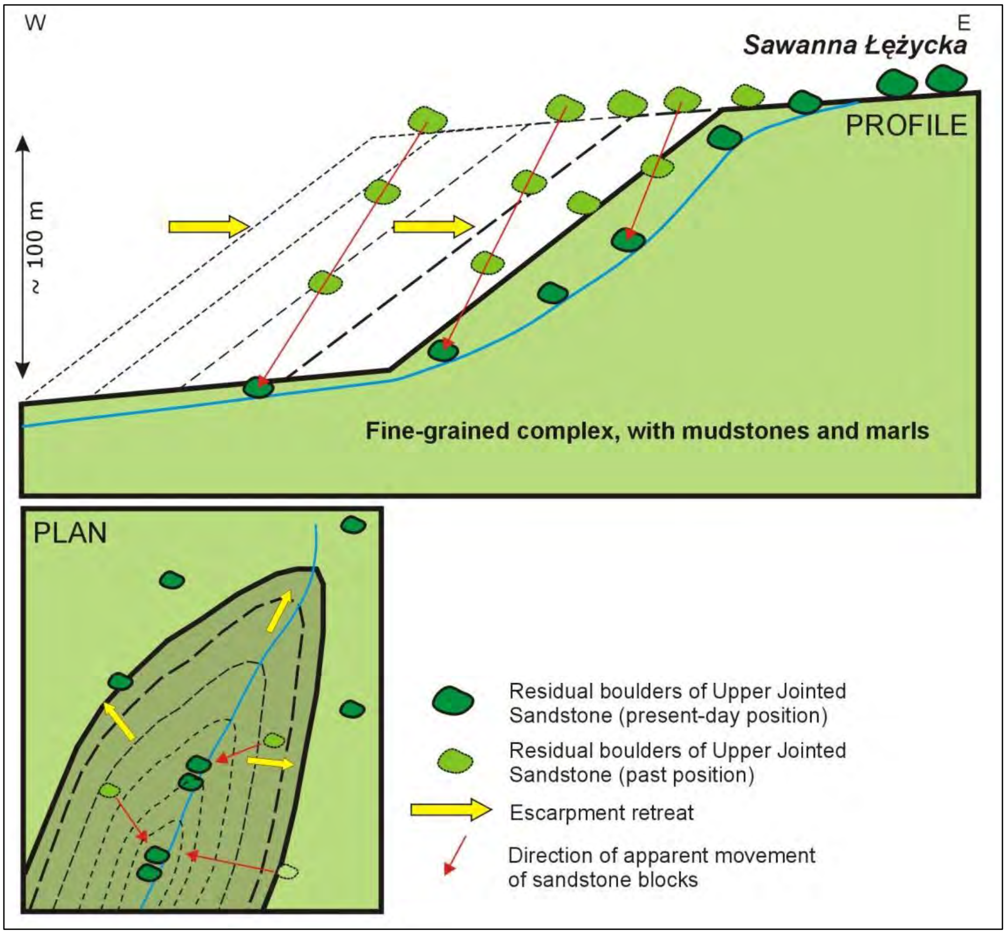

Fig. 42. Hypothesis to explain the origin of boulder trails in the valleys as a side-effect of long-term slope retreat.

Part 3
Relief of the Stołowe Mountains – a test area for studies in Geomorphometry (*Marek Kasprzak*)

Studies on the relief of the Stołowe Mountains have a long tradition because of the unique geomorphology of this massif, clear visibility of main relief elements and long tourist tradition. The best known and most valuable work in this topic are publications of Pulinowa (1989, 2008) and Migoń (2008), the latter two being the summaries of many years of previous research. In this text, terrain morphology will be analyzed quantitatively, with focus on new opportunities provided by DEM (Digital Elevation Model) developed from airborne laser scanning LiDAR (Light Detection and Ranging).

LiDAR data and research methods

The essence of LiDAR DEMs is to obtain information about the position in space of points of the test surface with laser scanning technology. During the airborne scanning (an optical remote sensing technology – LiDAR), the area is swept by a laser beams at different angles. Although there is beyond the scope of this paper to discuss in detail the measurement procedure, it should be mentioned that in final effect, after elimination of errors, it is possible to extract thematic layers from the model, which cover forest surface, undergrowth, ground surface or other objects (Devereux, Amable 2009) Normally the laser beam does not penetrate water, although the latest models of equipment, using a green laser, allow for this option as well.

The LiDAR model acquired by the Stołowe Mountains National Park (PNGS) is the most accurate current source of information about the relief of the Stołowe Mountains. DEM analysis completely replaces an analysis of topographic map. Sub-metric precision of DEM from LiDAR exceeds that of older existing models, e.g. DTED, which were used in selected previous publications (Fig. 43).

Digital elevation model from LiDAR covers only the area of PNGS and therefore relief analysis was limited to the National Park area. To fully analyze geomorphology of the Stołowe Mountains, complementary data from the rest of the area, including information from the territory of the Czech Republic, would be needed. At the time when this study was carried out, such data were not available.

LiDAR-derived DEM was used to geomorphometric analysis of the study area. The term *geomorphometry* means quantitative analysis of terrain surface using digital elevation models, run by computer applications, and therefore uses mathematical algorithms (Pike et al. 2008). Though it is now almost a separate branch of science, it does not present any novelty. Already in 1971 a textbook by Doornkamp and King (1971) was published which presented application of mathematical and statistical techniques in the study of relief and larger landscape units (catchments, basins).

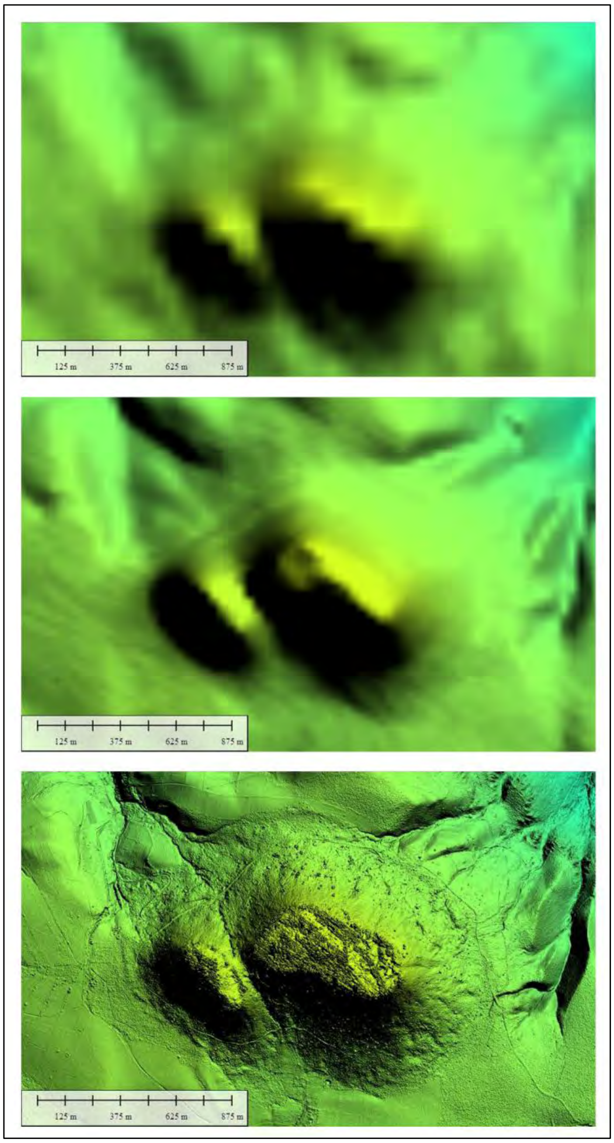

Fig. 43. Visual comparison of model resolutions. From top: SRTM-3, DTED-2 and LiDAR, Mt Szczeliniec Wielki example. Horizontal resolution of these models is, respectively 60 x 90, 32 x 32 and 0.6 x 0.6 m.

The research was carried out using GlobalMapper, MicroDEM and SAGA GIS software. The first one was used for transformation of files and recording of data. File record format was changed from .XYZ to the universal. ASC (arcASCII) with simultaneous interpolation and reduced resolution of raster model to 1x1 m, to allow further data processing by a personal 32-bit computer. Automatic procedure for changing the format of sequence file was made possible by a special algorithm (batch). The resulting files are combined into a single model (802 MB) with the addition of missing grid cells (fill holes procedure), which required about 20 hours of continual work of computer (CPU 3.2 GHz, 2 GB RAM). For the purposes of geomorphometrical analysis a DEM with cell resolution 5x5 m (381 MB) was also constructed. To obtain information on areas not covered by LiDAR data, the model was extended to include a part of the DTED-2 model, elaborated in the Institute of Geography and Regional Development a few years earlier, with horizontal resolution of approximately 50 m.

The analysis was based on primary and secondary geomorphometric parameters, which include Slope (incision), Exposure, Relief (relief energy) and Topographic Wetness Index (TWI). In addition, Topographic Grains (lineaments) were automatically determined. Understanding the first two parameters is not difficult, although for example in MicroDEM software up to 13 different algorithms to calculate the slope are implemented. Relief tool allows to highlight areas with the greatest energy of relief, and hence height difference within the predetermined distance from each raster cell (Guth 2009). In this work this distance was set at 250 m Topographical Wetness Index is a function of natural logarithm of ratio of local upslope contributing area and slope. In theory, TWI indicates spatial distribution of surface soil moisture saturation, and is one of the basic elements in hydrological modeling of slope and whole basin hydrology (Sørensen et al., 2006). Topographic Grains define the linear structure of the surface (ridges, axes and morphological edges of valleys etc.). The algorithm is implemented in the MicroDEM and allows to eliminate subjectivity in drawing relief lineaments (Kasprzak, Traczyk 2010). The final effect depends on determining the distance between the points to be calculated, surface, scale factor for the length of vectors and indicates the share of flat surfaces which are included in the final result (Guth 2003, 2009).

In the procedure of analyzing and visualizing spatial data, reclassification procedures were commonly used to receive grades of tested parameters. In the analysis of river channels a buffer zone 50 m along the water courses was designated. These activities were performed entirely in SAGA GIS. Raster data were supplemented with vector data, indicating the borders of the National Park and watercourses.

Properties and quality of digital data and their relation to other sources of spatial information

The morphometric analysis of the Stołowe Mountains area was based on digital data obtained from the Stołowe Mountains National Park. The volume of data used was approximately 175 GB. The sources of digital data were airborne LiDAR scanning and aerial photos (orthophotomaps). For analysis of surface topography LiDAR data were used, which are in fact a laser point cloud. The data package contained files with a cloud of non-filtered points, filtered to remove errors (files ending in. LAS) and filtered to extract thematic layers (files ending in. XYZ). Orthophotomaps were saved as GeoTIFFs. Horizontal resolution of these data in a grid record was about 0.56 x 0.56 m. All data was divided into sections / tiles of an area of 0.577 km^2, contained in separate files.

The orthophotomap was prepared in 8 and 12 bit color depth, both in the composition of infrared color (CIR – *color infrared*) to facilitate the analysis of botanical and geological contents, as well as RGB (red–green–blue) composition, reflecting views of the reality. Individual orthophotomap sections coincide with the topographic map of 1:10,000 scale and cover an area of 11.94 km^2. Image resolution reaches 0.15 x 0.15 m. Among the data there is also a continuous image, without division into sections. This orthophotomap covers an area of 194 km^2, and its resolution is 0.6 x 0.6 m.

All digital data were prepared in two coordinate systems: Poland 1992 (National Geodetic Coordinate System 1992 – EPSG 2180) and PUWG 2000 (zone 6, EPSG 2177). The first coordinate system was used for the most recent topographic map of 1:10,000 covering the area of the Stołowe Mountains. The second coordinate system is officially adopted for large scale mapping in Poland since 1 January 2010 and has replaced the previous PUWG 1965.

Among the abovementioned data, DEM is the most important in geomorphological analysis. However, before presentation of results, model errors and the accuracy of the mapping surface should be commented. DEM derived from LiDAR does not cover the entire surface of the PNGS, which is a major obstacle to proceed with morphometric and statistical modelling of geomorphological processes. Individual fields at the border of PNGS not covered by the model are located in the west, north and east. The largest of these has an area of approximately 0.23 km^2. The total loss is about 0.67 km^2. Because of many difficulties in interpolation, the model is not free of errors. It contain single points, which stand out from the surrounding surface as 'peaks', presenting a height of tree crowns rather than of the ground surface. Measurement errors are also result of changing raster model resolution used in morphometric analysis. For example, in the DEM of 0.6 x 0 0.6 m resolution, the maximum height 921.9 m a.s.l. was recorded on the top surface of Mt. Szczeliniec Wielki. When DEM was changed to cell size of 1 x 1 m, the height was reduced to 921 m a.s.l. and with the re-interpolation to 5x5 m, the height was only 919 m a.s.l. This situation was compared with geodetic data on topographic maps. Changes in value are due to specificity of re-interpolation algorithms in GIS software and will not be discussed here. Measurement of altitude on a DEM model always includes an error arising from the properties of a model and the size of raster cells. However, these errors are much smaller than the real distance corresponding to the resolution of the cell.

General characteristics of Stołowe Mountains relief based on digital data

Morphometric analysis, or better geomorphometric analysis, as it has been carried out almost exclusively on digital data in GIS software, will be divided into several steps, pertinent to the main relief parameters. The analysis was not made for whole area of the Stołowe Mountains, but only for the National Park area. According to the received digital data (file .SHP with the border of PNGS), the National Park covers an area of 6,440 hectares (64.40 km^2), which is almost identical with the area reported in the literature – 6,339.72 ha (Cacoń, Gołąb 2008). The centroid of the analyzed area is determined by a point at N 50.4651488 ° and E 16.3523493 ° (near the village of Łężyce Górne).

Elevation. DEM in the raster file contains information about the height of individual cells above the sea level. In the area of PNGS the highest point is located within the 'rock city' of Mt Szczeliniec Wielki. According to the DEM with horizontal resolution of 0.6 m, the culmination is at 921.9 m a.s.l., which exceeds a value determined by geodesy at 919.0 m a.s.l. (Staffa et al. 1992 pp. 231, 1:10,000 topographic map). The lowest point of PNGS has a height of 391.4 m a.s.l. The average height of PNGS is 680.6 m and standard deviation 98.4. The distribution of classes in 100 m wide classes is shown in Fig. 44. In the PNGS area absolute altitudes of 700–800 m a.s.l. dominate, occupying the entire central part of area (Tab. 2). Figures 45 and 46 provide more detailed picture about the elevation distribution in PNGS.

Topographic grains. Topographic grains set automatically in the MicroDEM are presented against hypsometry of PNGS in Fig. 47. Most lineaments refer to geomorphologically evident rock walls and ridges. This is particularly clear in the southern part of the area, such as along the escarpment of Ściany, Lisi Grzbiet, Urwisko Batorowskie and other morphological edges. In the south lineaments delineate long, straight reaches of Kudowski

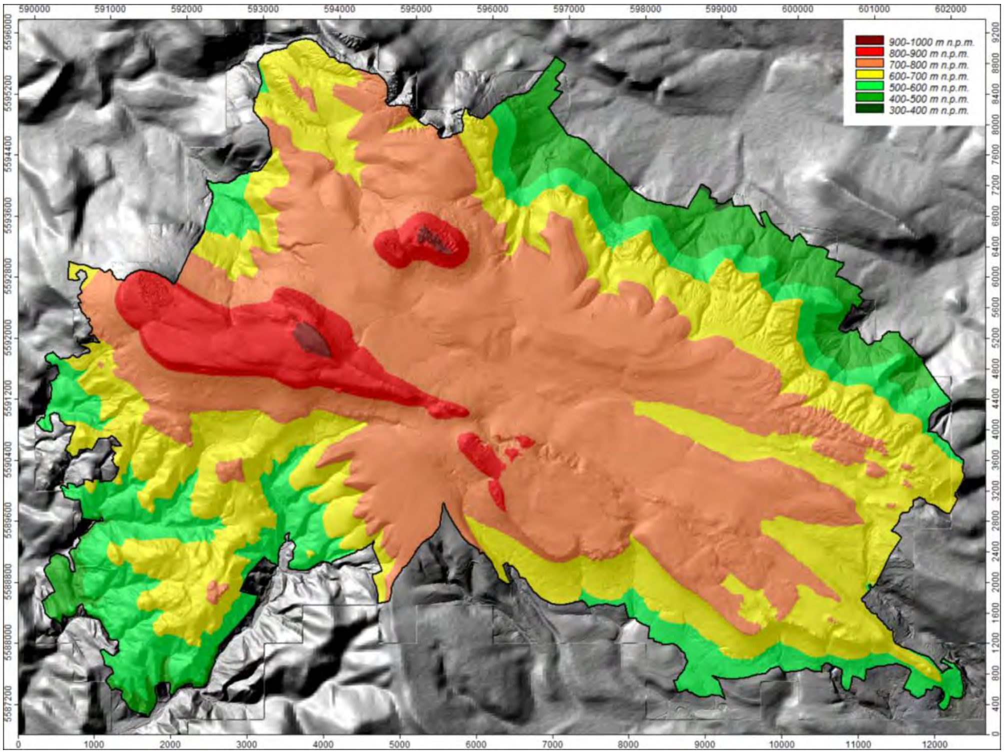

Fig. 44. Altitude classes in the area of Stołowe Mountains National Park.

Tab. 2. Altitude classes in the area of Stołowe Mountains National Park.

Altitude classes [m a.s.l.	Area [km^2]	% of area
300–400	0.04	0.07
400–500	4.33	6.68
500–600	8.62	13.32
600–700	18.90	29.20
700–800	28.19	43.55
800–900	4.43	6.85
900–1000	0.21	0.33

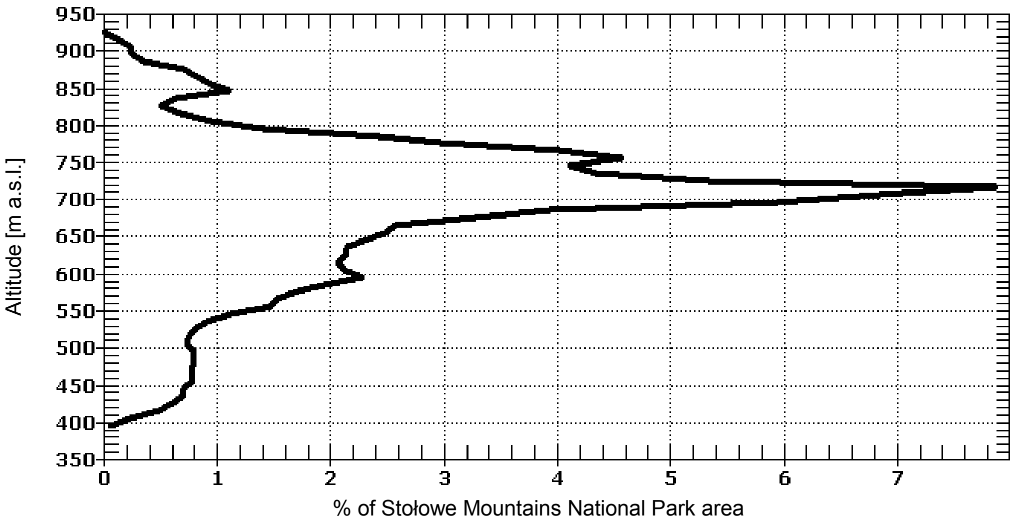

Fig. 45. Altitude - area relationships in the Stołowe Mountains National Park.

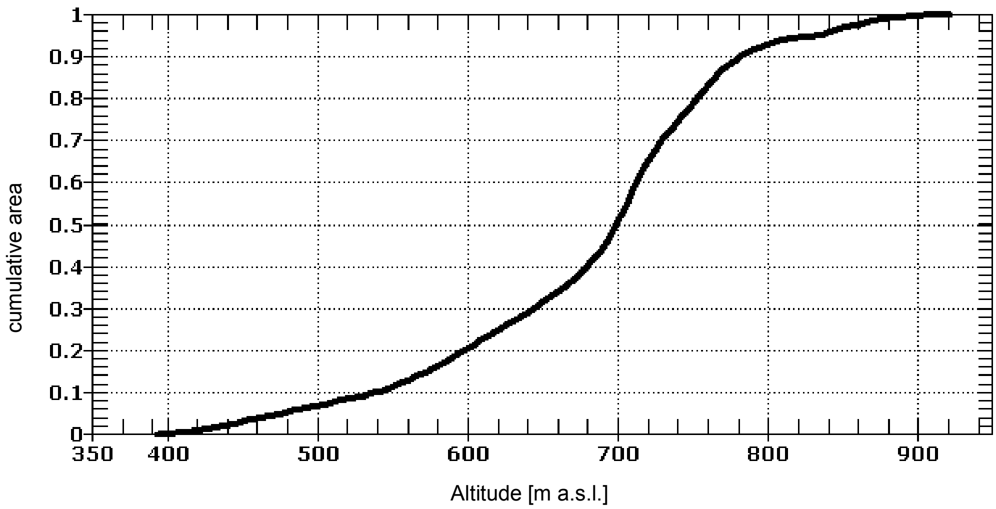

Fig. 46. Cumulative altitude diagram for the area of the Stołowe Mountains National Park.

Potok, Potok Złotnowski and the upper Czerwona Woda rivers. A relatively dense network of lineaments cuts the central part of PNGS, where they are arranged across the slopes whose curvature is determined by geological structure (stepped slopes). Against this background, the northern part of the area is completely different. Topographic grains are fewer, even along the escarpment of Radkowskie Ściany, which are so obvious in morphology. This results from a much more contorted line of slope edge. In the north and north-east there are also fewer straight, deeply incised valleys. Valleys are wider, assuming the shape of half-

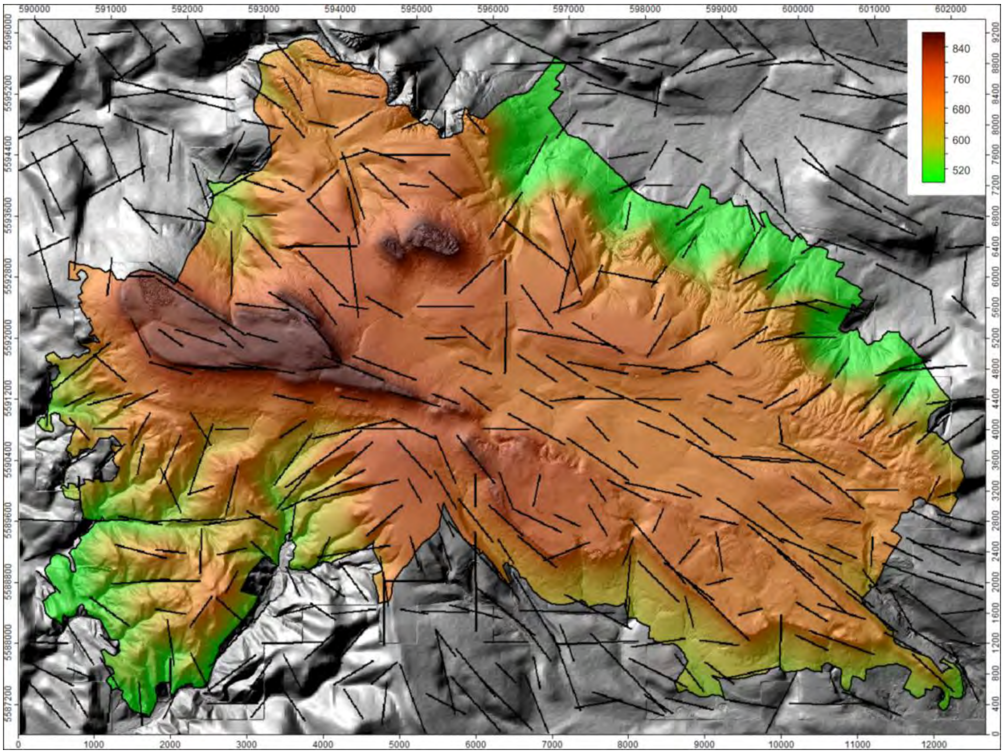

Fig. 47. Main relief lineaments in relation to hypsometry in the area of Stołowe Mountains National Park.

circular amphitheatrical within minor V-shaped valleys cut into their sides. The best example of this type of amphitheatrical lowering is the upper part of the Pośna river valley. Lineaments are slso missing within highly fragmented ('ruiniform') terrain, among rock labyrinths (Skalne Grzyby, Białe Skały) and within the peatbog of Wielkie Torfowisko Batorowskie. Interestingly, at predetermined parameters of the *topographic grain* function lineaments are not marked on the elevated level in the vicinity of Mt Szczeliniec Wielki and Mt Szczeliniec Mały. When parameters are changed and the density of lineaments increases, a line of this type may run between the two plateaus.

The resultant image sheds a new light on the course of major lineaments. These lines should not be associated with every one morphological edge. Topographic grains reflect ridges, depressions and slope breaks which continue over long distances. Relief lineaments are not present along clear morphological edges if these follow highly sinuous courses. Relief lineaments were determined on all altitudes levels in the analyzed area.

Aspect. Orientation of the Stołowe Mountains massif, strike and shape of slopes dictate that they are exposed in different directions with more or less similar frequency (Fig. 48). The total area is dominated by slopes exposed to the south (Table 3), followed by slope surfaces exposed to the north. Slope surfaces is directed towards the west have the smallest share. Areas with the most uniform exposure are characteristic for the central part of PNGS. The greatest diversity of exposure occurs in short, rough slopes in the west of the area and rocky parts of the surface in the north and north-east.

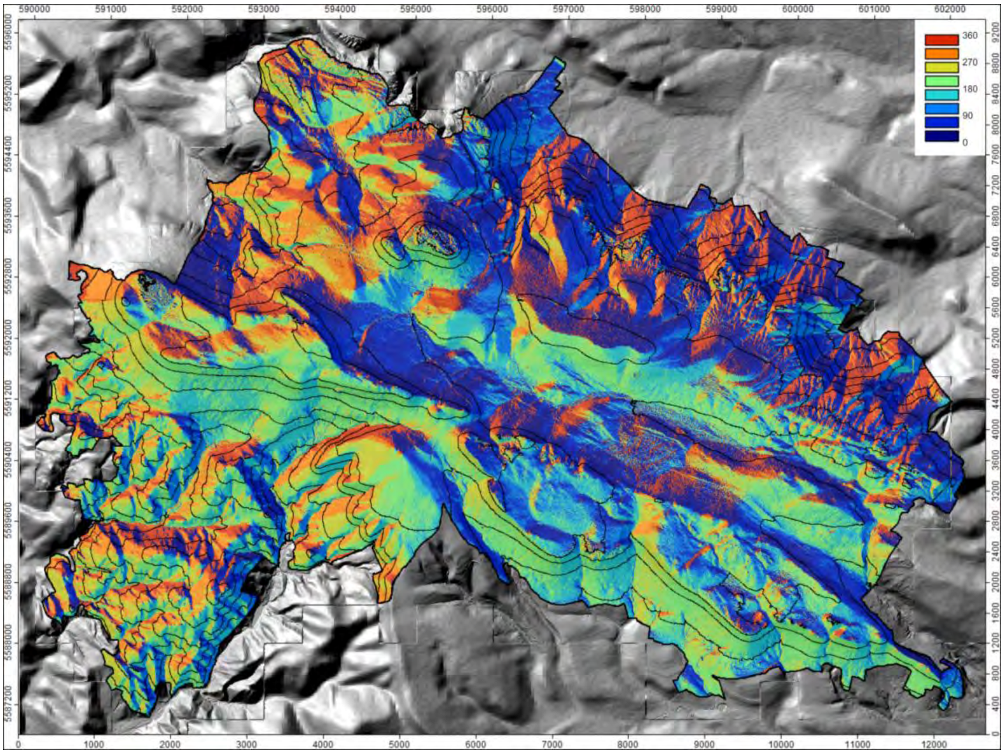

Fig. 48. Slope aspect in the area of Stołowe Mountains National Park. Azimuths in degrees. Contour lines every 50 m.

Tab. 3. Slope aspect in the area of Stołowe Mountains National Park.

Aspect – azimuth [degrees]	Aspect	% of aspect	Main aspect	% of main aspect
0–45	N–NE	16.49	N	27.76
45–90	NE–E	13.78	E	23.13
90–135	E–SE	9.34	E	
135–180	SE–S	11.90	S	29.93
180–225	S–SW	18.03	S	
225–270	SW–W	10.90	W	19.19
270–315	W–NW	8.29	W	
315–360	NW–N	11.27	N	27.76

Slope. The analyzed fragment of the Stołowe Mountains area represents a mosaic of extreme values of slope (Fig. 49). Due to structural pre-design of relief, flat slopes are identical with surfaces of the plateaus (morphological horizons). Steep slopes determine structural edges. Excluding rock walls, the maximum slope of the surface within the PNGS reaches 88.0°. The calculated value of average inclination is 13.1°, with standard deviation of 25.43%. The distribution in terms of slope in 5° classes is shown in Table 4

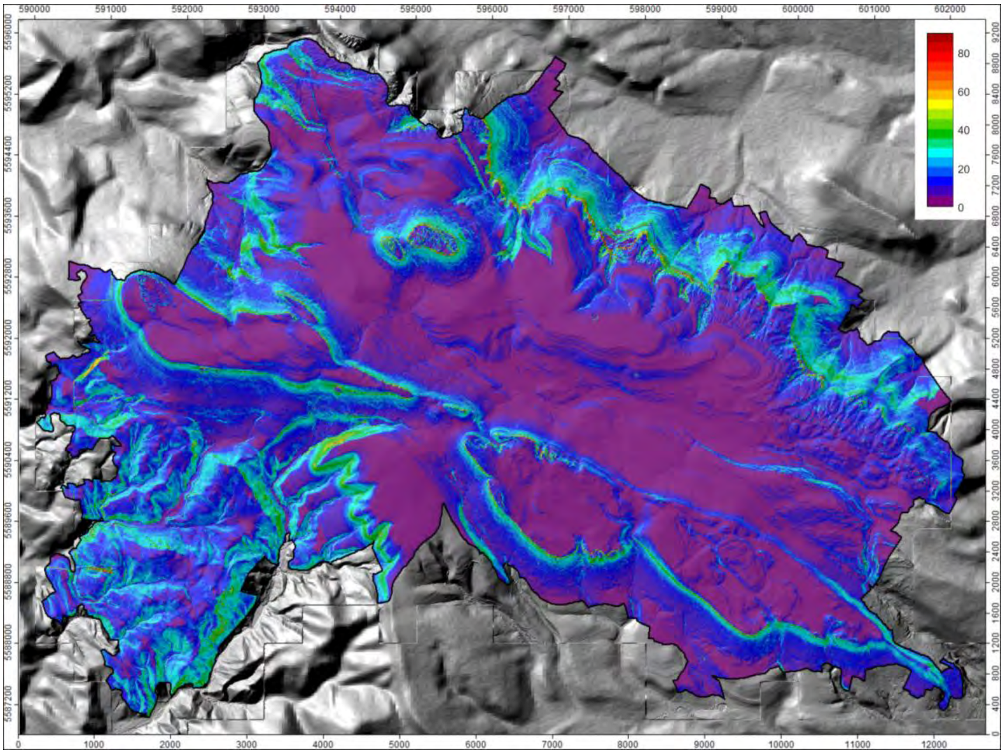

Fig. 49. Slope inclination in the area of Stołowe Mountains National Park. Scale in degrees.

Tab. 4. Slope inclination in the area of Stołowe Mountains National Park.

Slope [degrees]	Area [km^2]	% of area	% of area
0–5	18.968	29.304	52.415
5–10	14.959	23.111	
10–15	9.889	15.278	25.671
15–20	6.727	10.393	
20–25	5.051	7.803	13.998
25–30	4.010	6.195	
30–35	2.759	4.263	6.297
35–40	1.317	2.034	
40–45	0.499	0.770	1.103
45–50	0.215	0.333	
50–55	0.119	0.184	0.301
55–60	0.076	0.117	
60–65	0.053	0.082	0.144
65–70	0.040	0.062	
70–75	0.025	0.038	0.058
75–80	0.013	0.020	
80–85	0.006	0.009	0.013
85–90	0.002	0.004	

The PNGS surface is dominated by low values of slope. Slopes inclined less than 5° occupy nearly 1/3 of the total area, while the share of slopes greater than 60° is minimal. The steepest slopes are common at the northern boundary of the area. They are also characteristic for Mt Szczeliniec Wielki and escarpment edges (Fig. 50). The lowest inclinations appear in front of escarpments (footslopes) and behind the cliff lines.

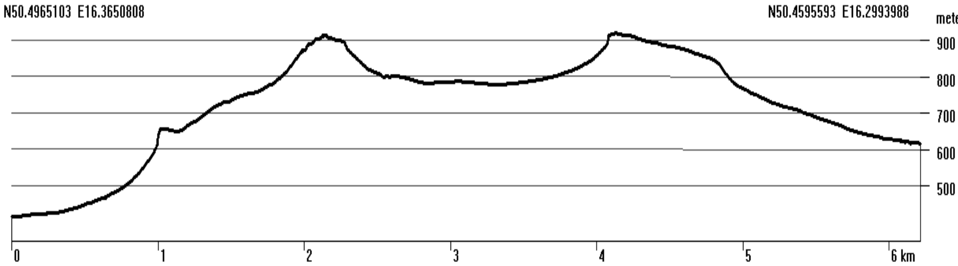

Fig. 50. Topographic profile (SW-NE) across the mesa of Szczeliniec Wielki and the plateau of Skalniak, to show characteristic slope shapes for the Stołowe Mountains.

Relief. Diversity of altitude and its spatial arrangement determine relief energy. This parameter, derived from *relief* function, is shown in Fig. 51. The analysis conducted for areas surrounding each raster cell, at a distance of 250 m, revealed zone of smallest and largest differences in relative height. This map supplements the picture obtained from the analysis of slopes. Parameter *relief* assumes the highest values on the northern escarpment of the Stołowe Mountains, where high rock cliffs and well developed sapping cirques (amphitheatres) occur. Rocks of Krucze Skały west of Darnków village, the slopes of Mt Rogowa Kopa facing north-west and the slopes of twin massif of Mt Szczeliniec are also evident. Areas of low-relief energy dominate in total area. They also form the most extensive, homogeneous surfaces (in terms of the analyzed parameter), mainly in the central part of PNGS.

Topographic Wetness Index. Discussed briefly in the 'Methods' section, the TWI parameter is one of the secondary parameters used in hydrological studies and in soil science. In geomorphology it is equally useful in giving an idea of most favorable conditions to the dynamics of hillslope processes. These processes are in fact often conditioned by the concentration of moisture.

The map of modeled parameter distribution indicates potential conditions for concentration of moisture at the foot of long slopes and flattenings of the Stołowe Mountains (Fig. 52). The most extensive area of this type coincides with location of peatbogs of Wielkie Torfowisko Batorowskie and other wetlands. The image of wetlands is artificially enriched by addition of buffer zones with a width of 50 m along river channels. Areas potentially dry are slopes usually convex in profile, especially around upper edges of escarpments. The shape of the slope forces rapid runoff down the slopes in this particular case.

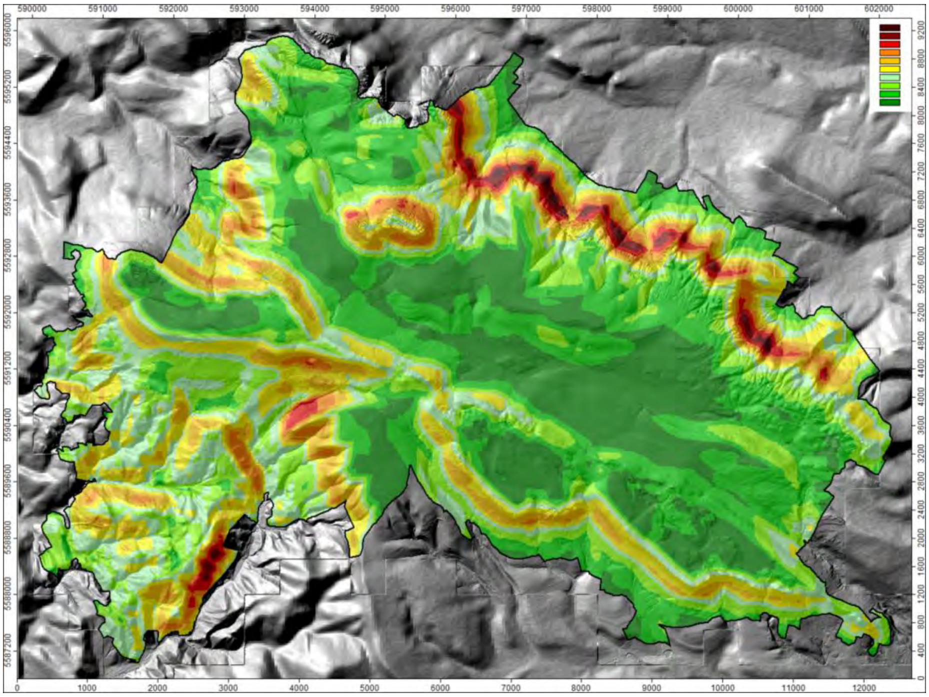

Fig. 51. Relief energy in the area of Stołowe Mountains National Park. Scale is non-dimensional. Warmer colours indicate higher relief energy.

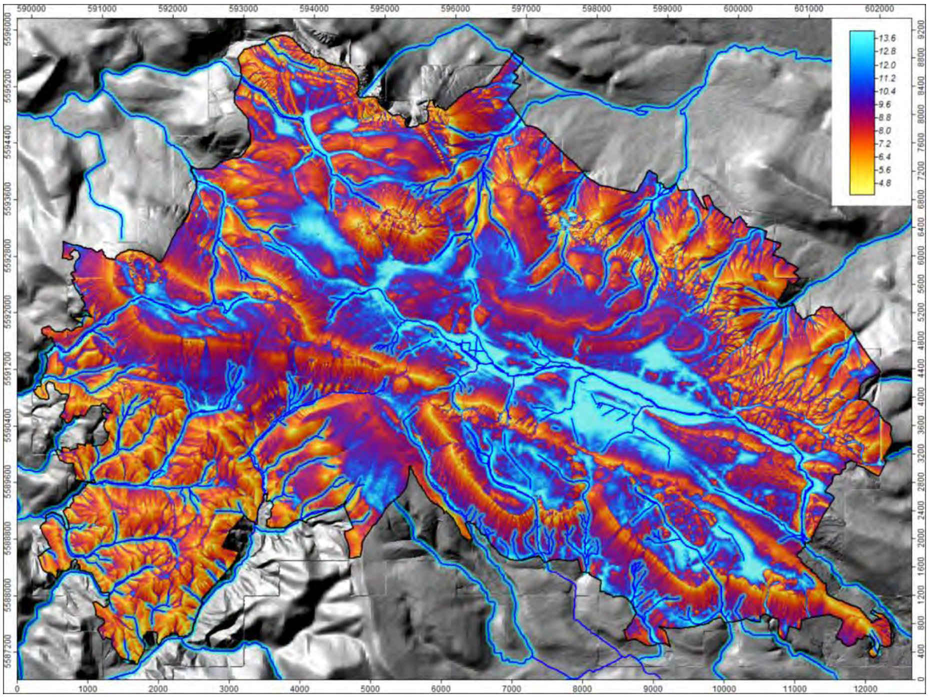

Fig. 52. Topographic Wetness Index (non-dimensional scale), including 50 m wide buffers along streams. Blue colour indicates areas predisposed by topography to be wet.

The distribution of TWI parameter highlights the situation of river valleys too. At the large scale, the drainage network is divergent, because the water is discharged in all directions away from the Stołowe Mountains massif. However, the individual parts of the area are characterized by a system of parallel valleys and taking small streams into account, the development of the river network towards a dendritic one can be inferred. Amphitheatre valley heads on the northern escarpment are interesting. Here, many continuous or discontinuous radial channels function, joining only at the base of the slope. Peat bog areas are presented separately. Within the Wielkie Torfowisko Batorowskie drainage system has a lattice shape.

The landforms of the Stołowe Mountains in examples

In this chapter spatial visualizations of selected landforms which are characteristic or significant in the geomorphic study of the Stołowe Mountains will be presented. Illustrations will be briefly discussed in terms of suitability of DEM in the study of particular forms of terrain. The 3D models were made using the DEM with 1x1 m horizontal resolution in MicroDEM.

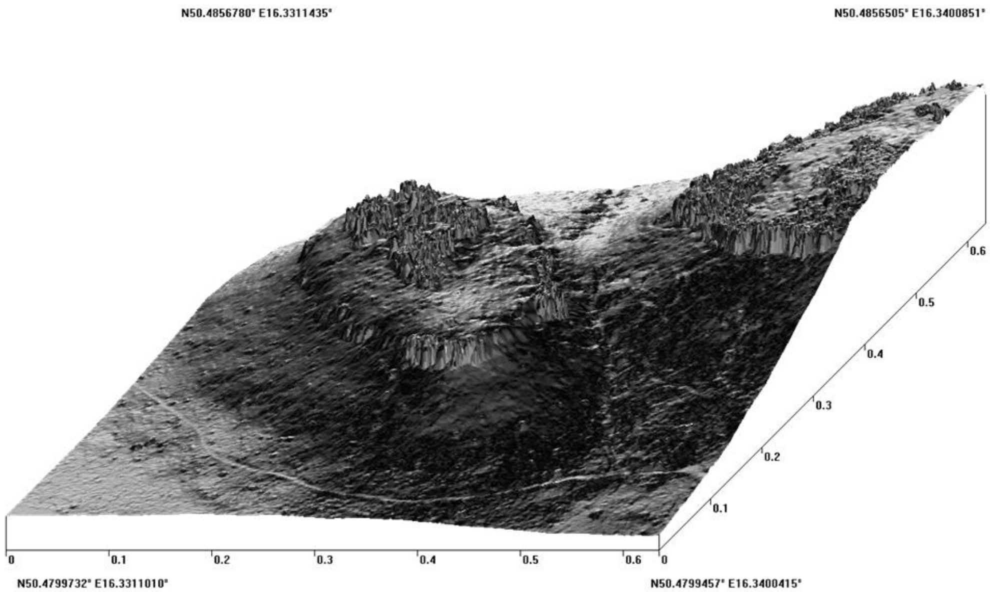

Fig. 53. Mt Szczeliniec Mały Mt. The smaller of the twin forms overlooking the main morphological level of the Stołowe Mountains. Based on the DEM it is not possible to accurately depict spaces between rocks and boulders, but the resultant image exceeds in accuracy all previous cartographic materials. In conjunction with the orthophotomap it can be used for relatively precise mapping of main features of the rock labyrinths. On the slopes of Mt Szczeliniec individual sandstone blocks can be seen. The line at the foot of slope is an unsurfaced road (tourist trail).

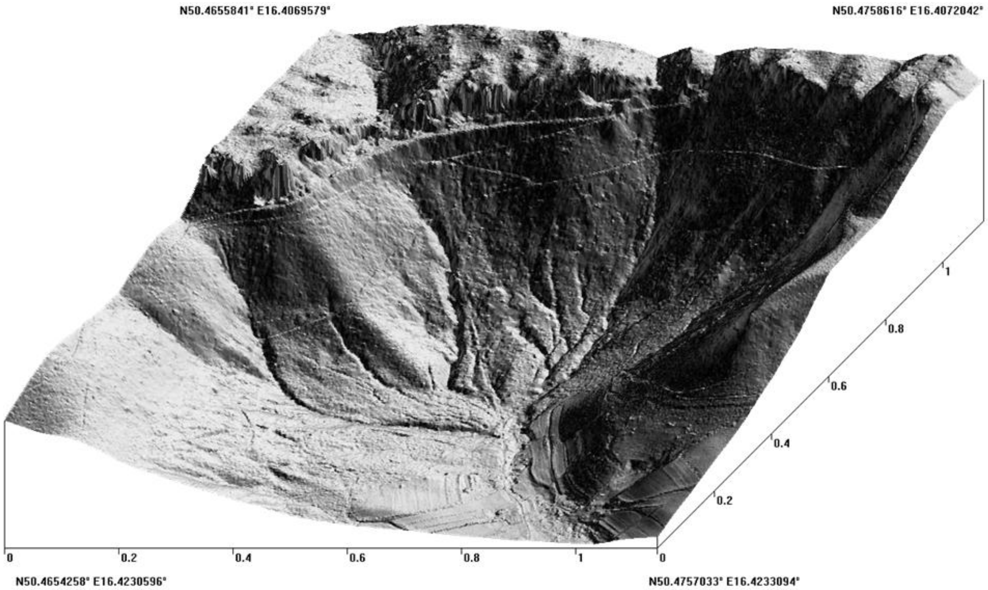

Fig. 54. Amphitheatre valley head in the headwaters of Cedron river near Wambierzyce Górne village. The presented form is typical for the northern escarpment of the Stołowe Mountains, where large sapping cirques occur. The convergent, concave slopes are incised by permanent and temporary rivers in a converging, radial arrangement. The model shows well the drainage network, difficult to detect and map on a steep, inaccessible, forested slopes.

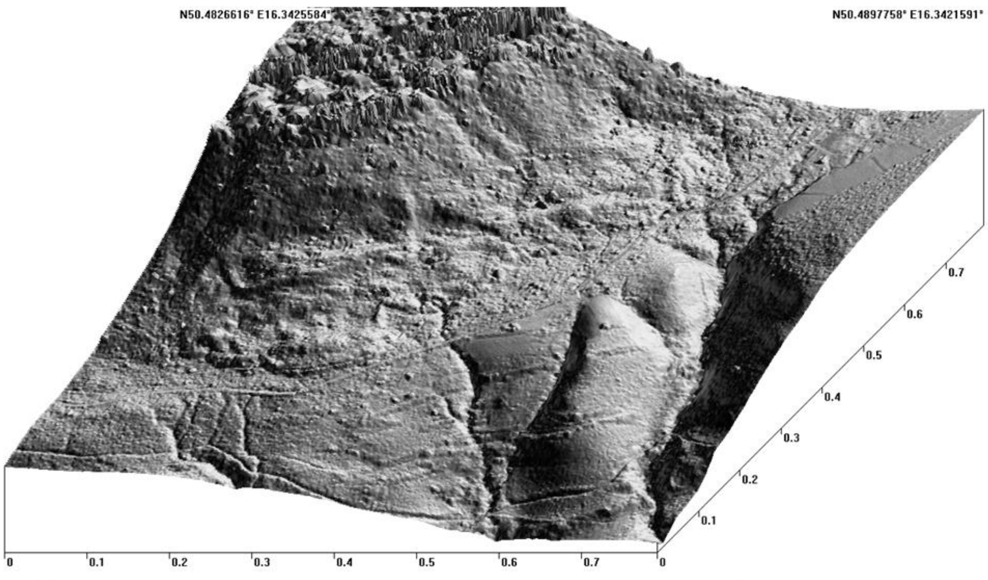

Fig. 55. The north-east slope of Mt Szczeliniec Wielki, the valley of Kozi Potok stream and headwaters of Pośna river. DEM reveals previously unknown hillslope relief. On the basis of this view one can conclude about instability of the surface and the presence of mass movements modelling of slopes. This area is very difficult to access due to lack of roads, steep slopes, uneven ground and dense undergrowth.

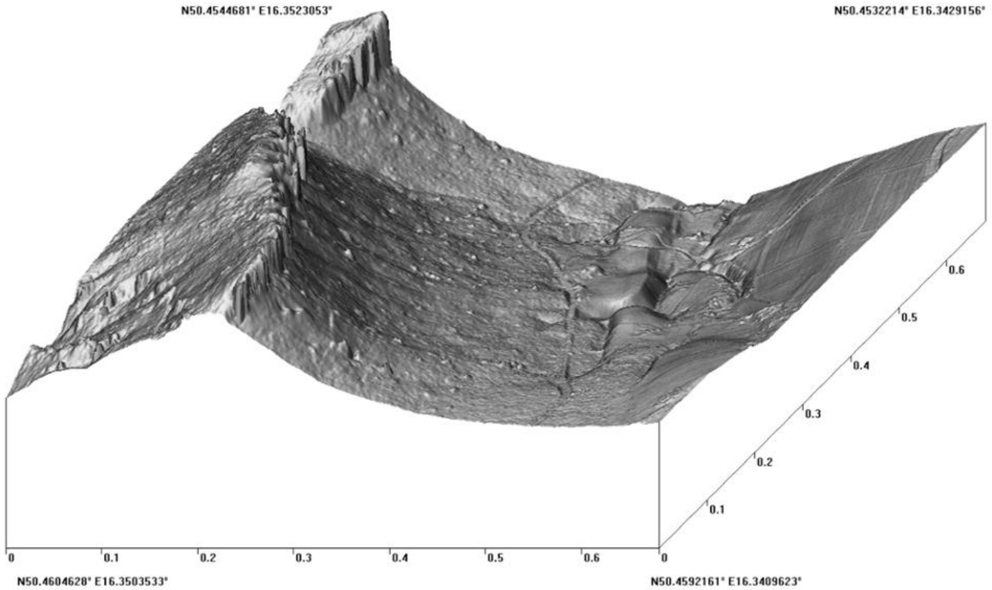

Fig. 56. The valley of Złotnowski Potok (Łężyce Górne), south of Lisia Przełęcz. The axis of the valley is marked by elevated levels imitating river terraces. Its smooth surface is due to human activities. Concave slope below the rock wall on the left side of the picture is littered with boulders and blocks creeping down the slope. Slopes on the right side of the valley are agriculturally used.

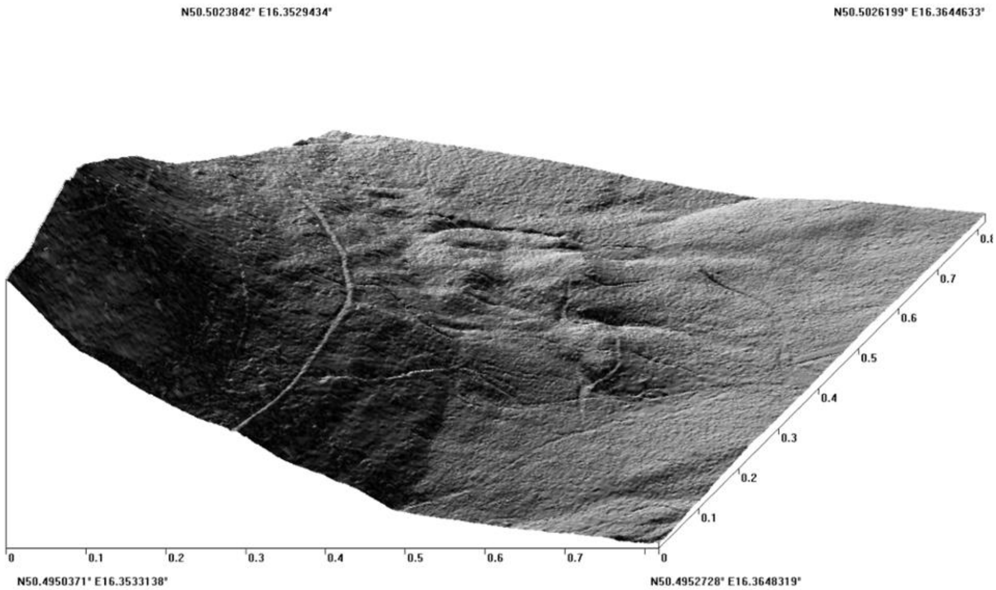

Fig. 57. The slope below the Biała Skała spur, west of Droga Stu Zakrętów (the Road of One Hundred Turns). The visualization shows interesting convex forms below the forestry road, interpreted as effects of mass movements. They are not found on similar slopes in the surrounding.

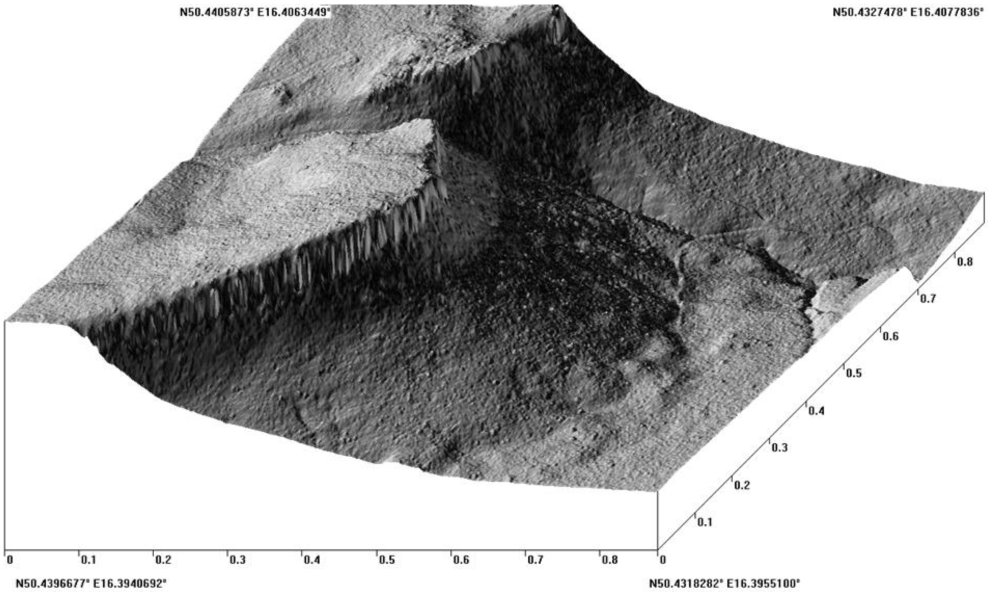

Fig. 58. Grodczy Dół valley in the southern escarpment of Urwisko Batorowskie – an incision of Bobrowa stream near the settlement of Szczytna-Ocieszów. This is another example of previously unknown forms on slopes. Below the cliffs, in the lower part of the slope there are lobes indicative of gravitational movement of slope covers.

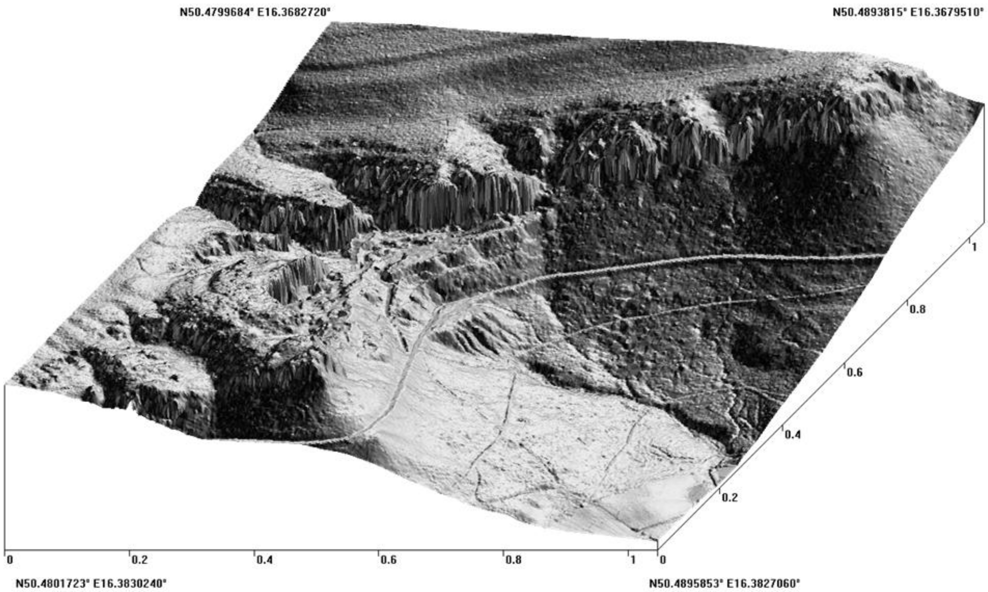

Fig. 59. Cliffed escarpment of the Radkowskie Skały above the Droga Stu Zakrętów road (Road of One Hundred Turns), the area of Głowa Króla (King's Head) rocks. In the area of Radkowskie Skały, individual rock formations are reproduced well enough to perform cartometric measurements. It is possible to distinguish single rocks groups and directions of further development of relief. Effects of rock fall and sediment deposition is indicated on the middle slopes. The varied shape of the surface above rock walls is structurally conditioned. The bench in the middle of the image is a quarry, while the dissected heap below is the quarry waste.

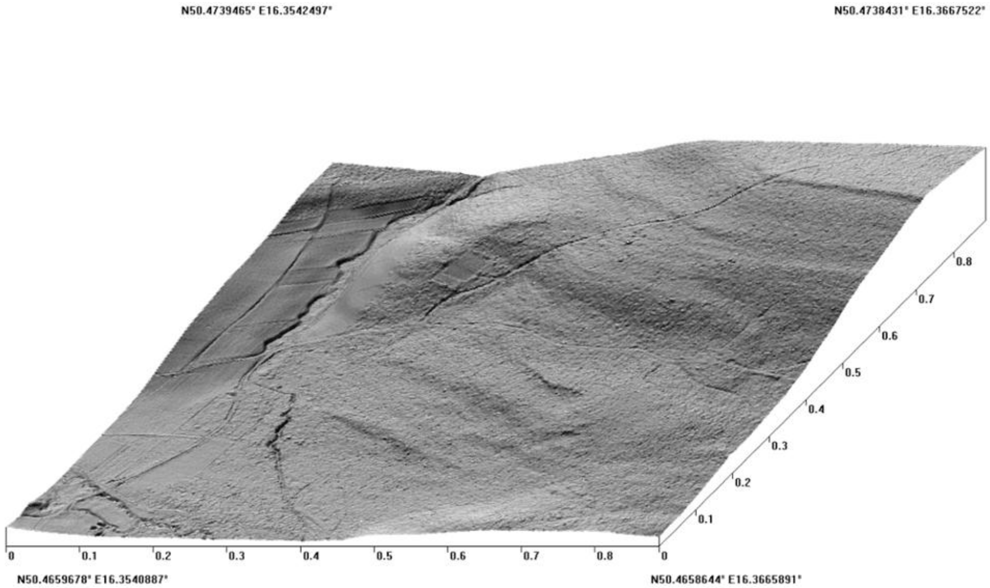

Fig. 60. The area at the junction of Czarny Trakt and Kręgielny Trakt roads, on the northern slope above a left tributary of the Czerwona Woda river. The typical stepped slope developed on rock layers with different strength and hence, resistance to weathering. Differences in surface texture are the result of contrasting land use (forest / meadow).

Mesa of Mt Szczeliniec Wielki

Mt Szczeliniec Wielki is the most recognizable landform within the Stołowe Mountains National Park (Fig. 61). It is a mesa elevated about 120–150 m above the surrounding area (Fig. 62). The area of mesa is 0.29 km^2. The highest point of Szczeliniec is located in its northern part. The upper part of Mt Szczeliniec Wielki is basically a ‘rock city’, or ruiniform relief. It consists of isolated rocks and groups of rocks separated by clefts and avenues. Some of the rocks have been given names reflecting their shapes, such as the Giant's Head, Mother-Hen, Cradle, Apeman, Throne of Praděd, Camel). The edges of the mesa are delimited by rock cliffs exceeding 20 m high (Fig 63). Slopes below cliffs have a concave shape and are covered by huge boulders delivered by a variety of mass movements. Just above the edges of rock cliffs there exist flattenings formed on the upper boundary of one horizon of sandstone rocks (e.g. large terraces near the tourist lodge). The deepest, linear cleft within the mesa is situated in its northern part – Piekiełko (Hell). Its base is surrounded by rock walls with heights exceeding 20 meters (Fig. 64). The longest, continuous chasms between the rocks have NW–SE course.

In the morphology of the study area, in the eastern corner, one can distinguish a level at lower altitude than in the rest of the mesa. This situation is probably a result of a large but complex mass movement, involving sagging and rotational outward movement. The shape and spatial arrangement of Mt Szczeliniec Wielki mesa were not shown correctly on the existing maps. Geodetic data in the past were not accurate, because difficult terrain pre-

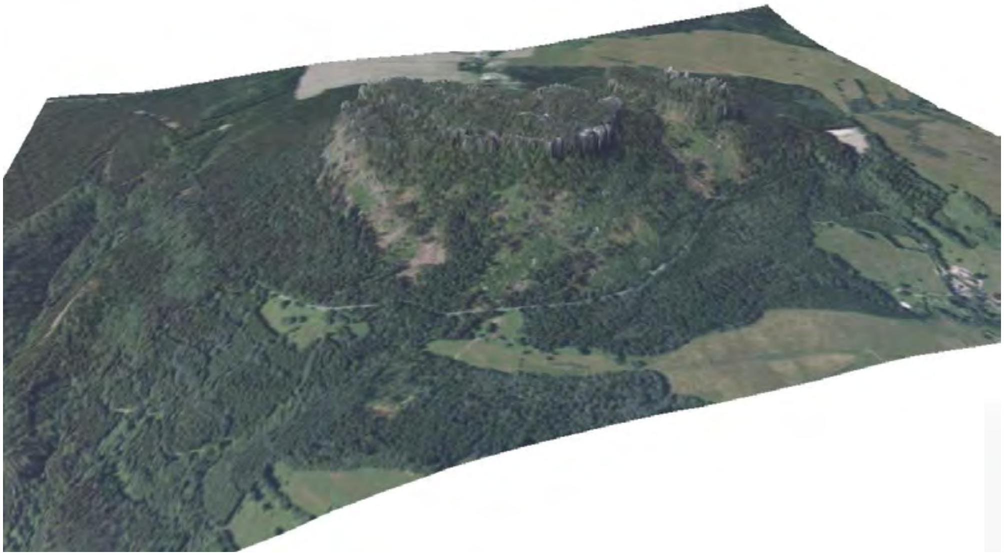

Fig. 61. The 3D view of Mt Szczeliniec Wielki. On the right the smaller elevation of Mt Szczeliniec Mały.

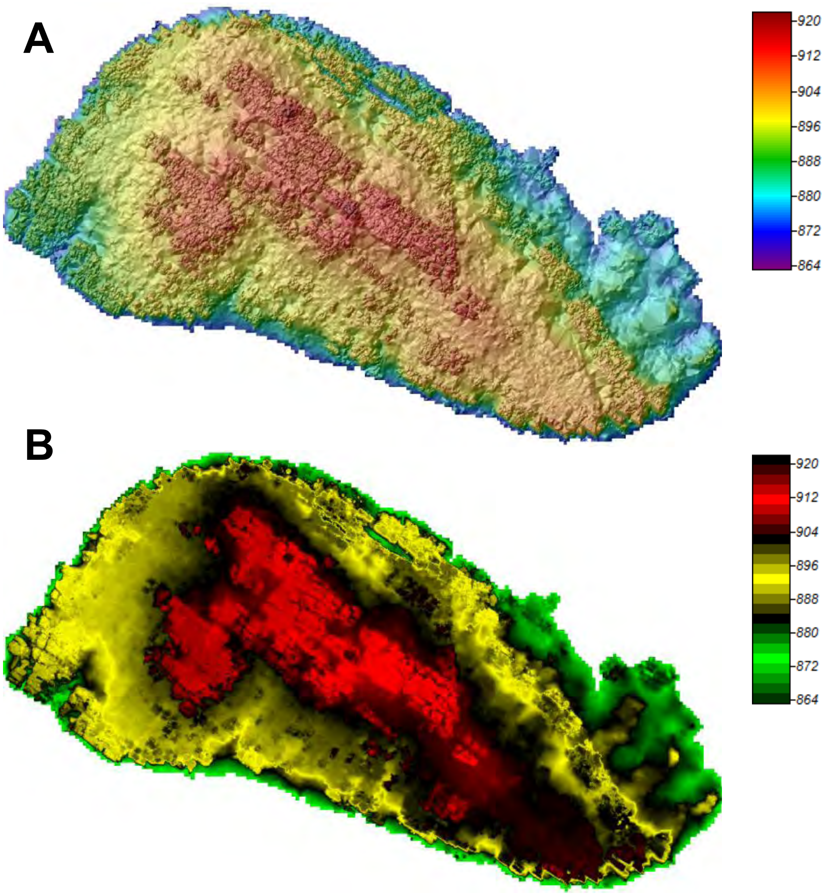

Fig 62 A,B. Two ways of expressing elevations of the Szczeliniec Wielki mesa, altitudes in m a.s.l.

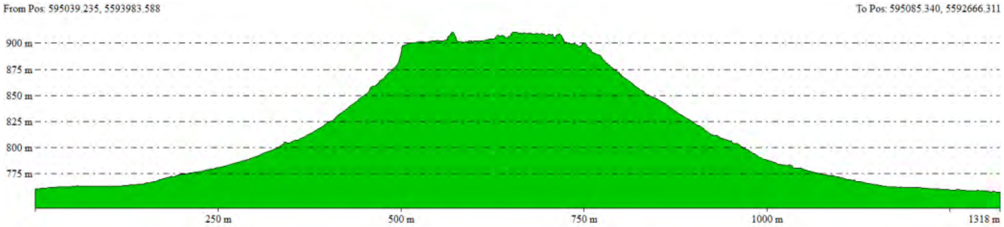

Fig. 63. The transverse profile across Mt Szczeliniec Wielki. Concave slopes, vertical rock cliffs and the surface of mesa are visible.

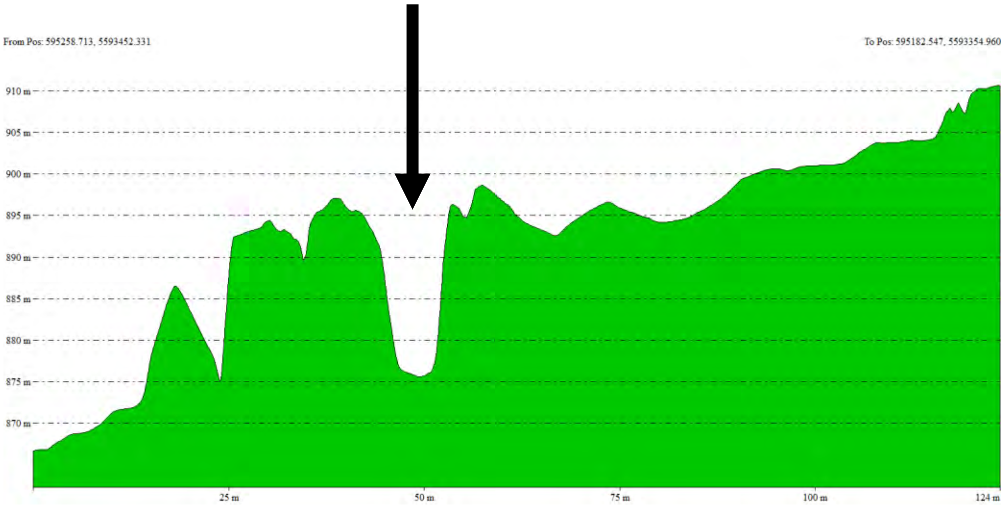

Fig. 64. Deep chasm of Piekiełko (marked by an arrow)

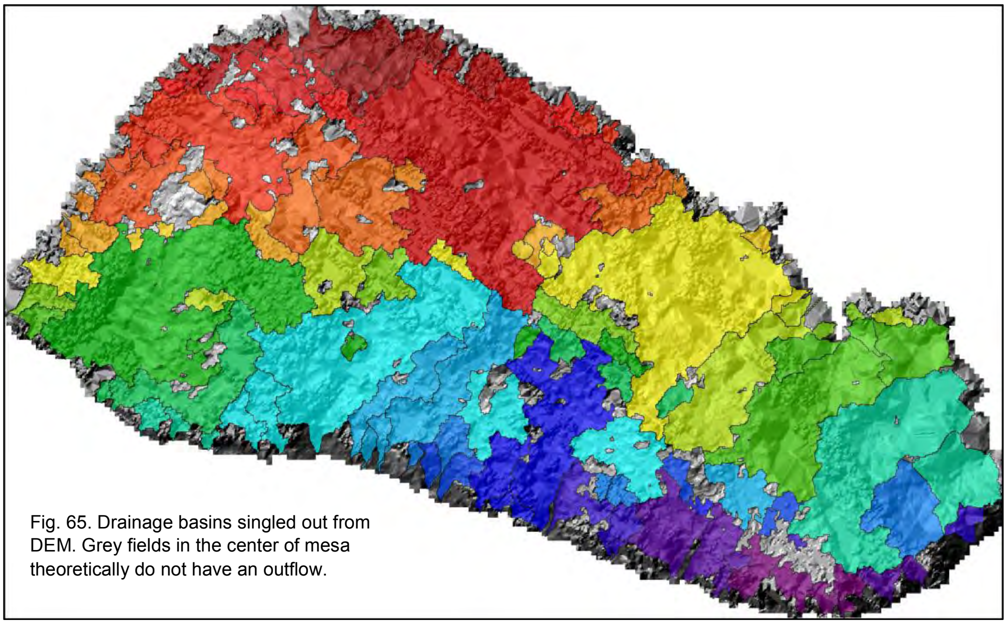

Fig. 65. Drainage basins singled out from DEM. Grey fields in the center of mesa theoretically do not have an outflow.

vented measurements. DEM derived from LiDAR shows that the existing topographic maps presented distorted and simplified situation.

The rocky labyrinth of Szczeliniec Mt. is drained concentrically in each direction. Fig. 65 shows a pattern of theoretical watersheds and catchments. This system has been generated automatically in the SAGA software and includes only the data from the DEM (function Drainage Basins). In the model there appear to exist somewhat isolated areas with no outflow. In reality they are drained under the surface, by suffosion long suspected to occur under the sandstone plataeus.

Acknowledgments

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Stołowe Mountains – selected references

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