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The origin of sandstone boulder aprons along the escarpments of the Stołowe Mountains: are they all rockfall-derived? A new insight into an old problem using the CONEFALL 1.0 software

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Abstract. A characteristic feature of sandstone-capped escarpments in the Stołowe Mountains is the occurrence of extensive boulder mantles which extend from the rock face to the footslope over distances of 300–500 m. The hypothesis implying rockfall as the process of boulder release from the rock face and subsequent transport is tested by means of Conefall 1.0 software, designed to simulate run-out zones of rockfalls. The actual extent of boulder mantles is much larger than the simulated extent, which casts doubt on the applicability of rockfall scenario. Alternative hypotheses are briefly discussed and it is concluded that a similar morphological effect can be achieved by *in situ* caprock disintegration and sub-caprock slope lowering and retreat.

Key words:
sandstone boulders,
scarp retreat,
rockfall run-out zones,
Conefall program,
Stołowe Mountains

Introduction

Escarpment slopes in the Stołowe Mountains – a unique tableland relief in south-west Poland – are crowned with cliff faces of varying height and continuity. Slope sections below are mantled by large boulders, apparently derived from the cliff face, and these form extensive blankets down to the footslope. While rock falls were usually inferred as the origin of these boulders and the principal process involved in rock slope retreat (Dumanowski 1961; Pulinowa 1989; Migoń 2008), these hypotheses are yet to be tested against evidence. In this paper we offer an insight into this problem using one modelling approach that focuses on the possible extent of run-out zones.

Boulders on Escarpment Slopes in the Stołowe Mts

General outline of the geology and geomorphology of the Stołowe Mts

The Stołowe (i.e. 'Table') Mountains are located in south-west Poland and straddle the border with the Czech Republic (Fig. 1). They are mainly built of sedimentary rocks of the Late Cretaceous age, deposited in a shallow- to moderate-depth marine environment (Jerzykiewicz 1966, 1968; Wojewoda 1997, 2008), forming a succession of beds of variable lithology, nearly 400 m thick in total. Of particular geomorphological significance are thick sandstone beds which, by virtue of their much higher mechanical strength and the prevalence of quartz in their composition, are more resistant that the intervening fine-grained deposits (mudstones, marls, claystones, flaggy calcareous sandstones) and therefore support spectacular cliff lines (Fig. 1). The cliffs are of variable height, from less than 10 m to more than 40 m, and have developed in both the 'upper jointed sandstones' (Szczeliniec-Skalniak Sandstone after Wojewoda 2008), which are composed almost exclusively of quartz grains, and in the 'middle jointed sandstones' (Radków Bluff Sandstone), which are arkosic. Both variants are regularly jointed, although joint spacing varies along the escarpments. Nevertheless, spacing is generally very wide and cubic compartments 5 m long and 3 m wide are not uncommon.

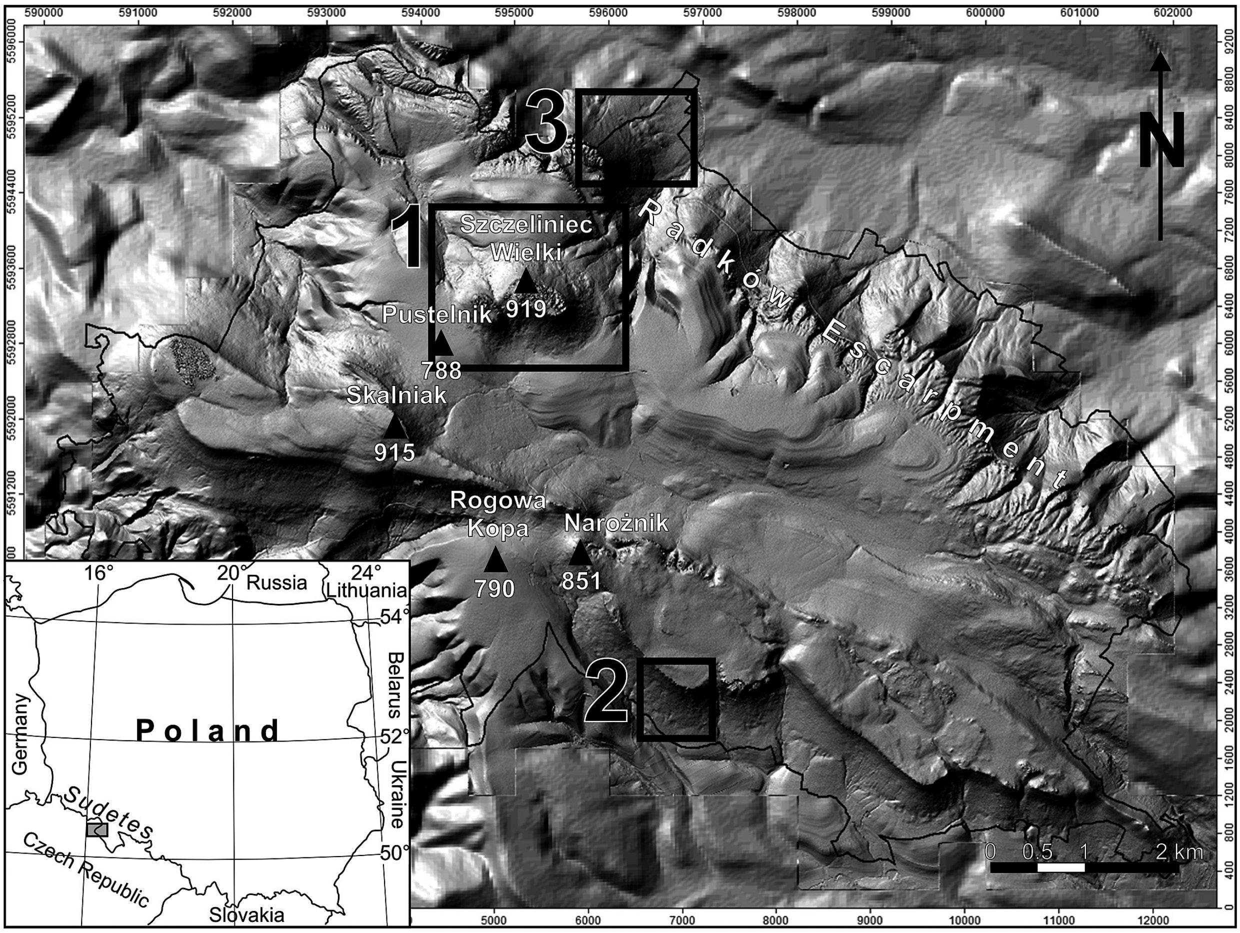

Fig. 1. Hillshade map of the Stołowe Mountains based in LiDAR data (courtesy of Marek Kasprzak). Black rectangles indicate location of the study sites: 1 – Mt Szczeliniec Wielki and Mały site, 2 – Mt Narożnik site, 3 – Biała Skała site

Escarpments, if looked at from a distance, appear as consistently concave-down, with the steep segment near the top. Therefore, early workers in the area compared them to 'classic' hillslope shapes as proposed by King (1953) divided into free face, debris slope, and wash slope segments, connected by a sediment cascade (Rogaliński, Słowiok 1958; Dumanowski 1961). Recent, detailed field mapping and interpretation of high-resolution LiDAR-based digital elevation models have revealed that hillslope topography is much more complicated, especially in the lower slope sections. A whole range of features previously unaccounted for, such as mid-slope benches, multiple steps, arcuate scarps, and lobate toes has been identified (Migoń, Kasprzak 2011, 2015). In addition, large sandstone boulders proved not to be restricted to the moderately steep (15–35°) debris slope but at a number of localities to extend well across the footslope (wash slope), where the incline does not exceed 5°.

Further on, the term 'caprock' will be used to describe the layer of resistant rock at the top of the slope (sandstone in this case), which prevents the less resistant rock layers below from being eroded, and is also a cliff former. The rock layers below the caprock are collectively called 'sub-caprock', although various lithologies occur below the sandstone cap (see above).

Previous views on the genesis of sandstone boulders in the Stołowe Mts

Loose sandstone boulders in the Stołowe Mountains occur in two settings. The vast majority of them are present within sandstone-capped escarpment slopes, below the level of the sandstone cap, and these are evidently derived from the caprock. The authors of earlier publications distinguished at least three types of mass-wasting processes which could have led to the creation of blocky talus. Czeppe (1952), Dumanowski (1961) and Pulinowa (1989) suggested that rock falls are the most common type of mass movement in the Stołowe Mountains, yet they also noticed some distinctive toppling features along the northern rim of Mt. Szczeliniec Wielki. Pulinowa (1972) recognized block slides too.

Both Dumanowski (1961) and Pulinowa (1989) highlighted the contribution of mass movements to the parallel scarp retreat as a consequence of geological conditions and offered the following explanation. The caprock is built of porous, jointed and hence, highly permeable sandstone, while it is underlain by a complex of poorly permeable mudstones and marls. Rainwater percolates through the sandstone discontinuities but cannot move further down as it reaches the impermeable level. Hence, it starts to drain horizontally until it emerges along a spring line below the caprock, destabilizing the slope above. This phenomenon is known as sapping and there is general agreement that it accelerates slope failure phenomena. Apart from sapping processes, Pulinowa (1972, 1989) paid attention to plastic deformations that occur in a mudstone-marl complex overlain by rigid sandstone. Toppling and block sliding that involve sandstone caprock are considered to be the consequence of these deformations.

However, previous authors rarely tried to explain the wide distribution of sandstone boulders within the slopes. Pulinowa (1989) suggested that distant boulders may bear witness to a greater extent of the sandstone plateau in the past, but she also emphasized creep as a means by which the most distant boulders were able to reach their present position. As far as the age of the boulder talus is concerned, Łoziński (1909), Czeppe (1952), Dumanowski (1961) and Pulinowa (1989) all believed that the boulder mantles result from mechanical breakdown and slope-failure processes in the periglacial conditions of the last glacial, but at the same time Pulinowa (1989) has also considered the possibility of further talus evolution under more humid conditions such as those of the Holocene period. The problem has remained unsolved until the present day.

Fig. 2. Giant sandstone boulders on a nearly flat level terrain at the eastern footslope of Mt Szczeliniec Wielki. Note standing persons for scale

In a few locations, sandstone boulders as big as 10 m long occur far away from escarpment slopes, on nearly flat surfaces which constitute the main plateau level of the Stołowe Mountains (Fig. 2), and at much lower elevation than their stratigraphic position would dictate. The best-known locality is Sawanna Łężycka, south of Mt Rogowa Kopa, where more than 30 boulders are dispersed over an area of c. 600 × 400 m. Their presence and allochthonous nature has long been noted (Walczak 1968), but attempts to explain their unusual position are much more recent (Parzóch et al. 2009; Migoń 2010, 2013a; Parzóch and Migoń 2015). These boulders are interpreted as remnants marking the position of upper plateau outliers (mesas, spurs) which have disappeared due to the complete breakdown of the caprock and further surface lowering in the order of tens of metres. This suggests considerable durability, longevity and ability of boulders to outlive the sandstone-capped residual hills themselves (Migoń 2010; Parzóch, Migoń 2015).

Methods

Shadow and reach angle models as tools to determine the extent of run-out zones

Rockfall is a type of mass movement in which rock fragments are detached from the cliff face and by means of free fall, bouncing and rolling may travel across the middle and lower slope, or even beyond the base of the talus slope. Over the last decades, the problem has turned out to be of particular importance, as rockfall-derived blocks may constitute a significant threat for many inhabited areas at the foot of slopes. The need to define the maximum run-out zones and hence to delimit potentially endangered localities led researchers to study the maximum extent to which the boulders occur at footslopes. Copons et al. (2009) noticed four different approaches to the problem, based on (i) geomorphic mapping to study the most distant boulders, and on forecasting maximum run-out zones using (ii) heuristic, (iii) numerical and (iv) empirical models. These latter approaches have gained particular popularity and are applied in many studies. Basically, two empirical models are widespread in the literature – the reach angle model (e.g. Heim 1932; Corominas 1996) and the shadow angle model (e.g. Evans, Hungr 1993; Copons et al. 2009) (Fig. 3).

The reach angle model, also known as *Fahrböschung*, travel angle or travel distance angle is the arctangent of the line which connects the rockfall source area with the most distant boulder (Copons et al. 2009). The model assumes that the falling block will stop at the point of intersection of the above mentioned line with the slope topography (Fig. 3). On the contrary, the idea of Evans and Hungr (1993) that the falling block loses most of its kinetic energy just after free fall, when it hits the talus slope apex for the first time, makes the second approach – the shadow angle approach – especially useful in rockfall studies. The shadow angle is defined as the angle between the horizontal line and the line that connects the talus slope apex with the most distant block (also known as the energy line) (Fig. 3). Just like in the case of the reach angle approach, this model demonstrates that the falling block will stop within the intersection of the energy line with the local topography (Copons et al. 2009). In the last few decades several papers have been based on this approach (e.g. Copons et al. 2009; Jaboyedoff, Labiouse 2011; Blahůt et al. 2013) and the typical value of the shadow angle is around 27° (Copons et al. 2009).

Estimation of the position of sandstone boulders

To determine the distribution of sandstone boulders within the lower slopes of the Stołowe Mountains three sources of data have been used. In the first stage, following (Jaboyedoff et al. 2012), a Digital Elevation Model (DEM) based on high-resolution (1 × 1 m) airborne LiDAR data was studied in order to recognize geomorphic features potentially indicative of mass movements. In the case of two study sites, i.e. Mt Szczeliniec Wielki and Mały and Mt Narożnik, shaded relief maps helped specify the actual position of sandstone boulders quite accurately, but along the Radków Escarpment the results were unsatisfactory. Although the block accumulation at this locality is widespread, no individual boulders are visible on the DEM. Aerial photographs also proved to be of limited use since the boulders were invisible due to dense forest cover. Therefore, a need to verify data derived from the LiDAR model became evident, and field mapping was carried out in order to establish the maximum extent of the boulder mantle. The above real data were needed to compare the actual block cover with the extent simulated by means of the shadow angle approach.

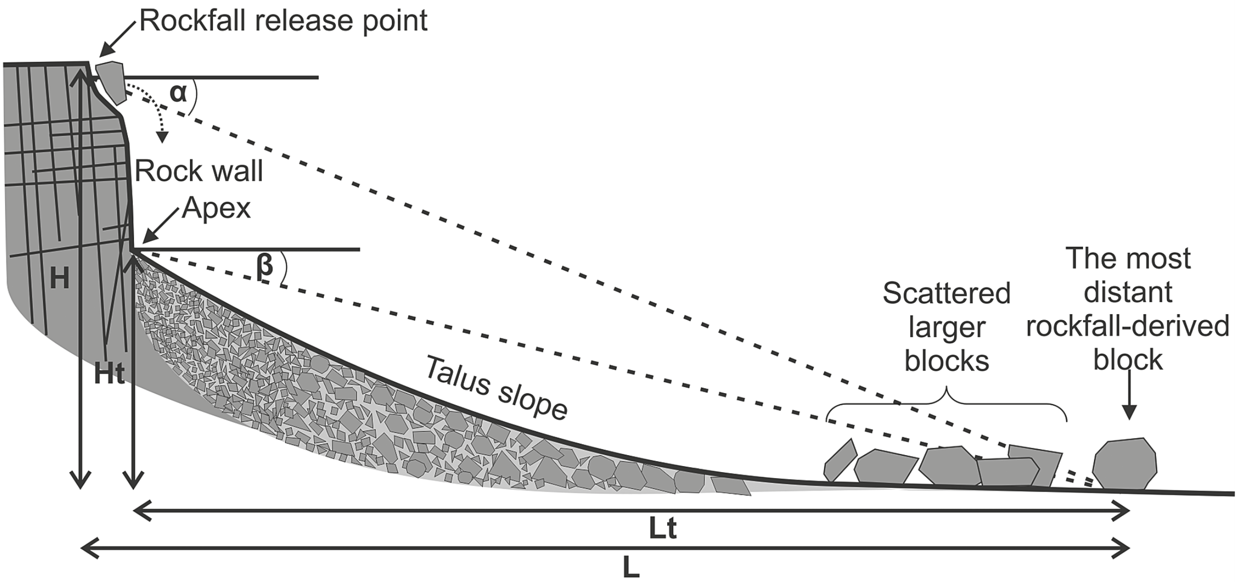

Fig. 3. Reach angle (α) and shadow angle (β) models presented on a sketch showing cross-profile of the rock wall and the talus slope. H indicates fall height, L indicates horizontal length of the landslide, Ht indicates height of fall on the talus slope and Lt indicates the travel distance on the talus slope (after Copons et al. (2009), modified)

Determining run-out distance by means of Conefall 1.0 software

The evaluation of maximum run-out distance zones, i.e. identification of areas which can be reached by boulders supplied by rockfall, is possible using purpose-designed computer programs. Among them is the CONEFALL 1.0 software, developed by Jaboyedoff (2003), which utilizes the concepts of reach and shadow angle (Heim 1932; Evans, Hungr 1993). CONEFALL locates the rockfall propagation zone within the area that is delimited by the intersection of the energy line with the slope surface. Jaboyedoff and Labiouse (2011) have reviewed the theoretical backgrounds of CONEFALL operation.

In this study, high-resolution DEM based on the airborne LiDAR was used as the input data. The resolution of the model was originally 1 × 1 m but was re-interpolated to a resolution of 5 × 5 m. The reason for such a procedure was threefold. Firstly, the adjustment of the size of the data set to the operational capabilities of personal computers was required. Secondly, it was much easier to delimit the rock face segment in the source file. Thirdly, the potential interference with isolated large boulders on the slope, whose effect would be shortening run-out distance, is largely eliminated. The source area file was created semi-automatically using GIS software. The procedure included the creation of a slope inclination layer and a shaded relief layer on the basis of DEM. The slope inclination layer was then reclassified into two classes, one approximating the cliff surface and another to cover the rest of the terrain, which is characterized by lower inclination values. The cells classified as the cliff face were considered as the source areas. The source file and the DEM derived in this way were loaded into the CONEFALL program. The source grid was additionally edited in order to show the cells below the cliff face, on the talus slope apex. The simulation was run using a shadow angle of 27°. The new grid was later used for further comparative analyses of the maximum run-out distance zones and the actual extent of the sandstone boulders within the slopes.

Although the paper is based on the well-known methodology for studying maximum run-out zones by means of the shadow angle approach, our aim is different than in the studies presented above. While the other studies used the shadow angle model to evaluate the potentially endangered areas in the mountainous settings, we intend to verify the hypothesis put forward by Rogaliński and Słowiok (1958) and Dumanowski (1961) that the boulders are derived mainly from rockfall, and the middle and lower parts of the slope are covered by typical talus. We use the shadow angle approach in order to determine whether it is possible for the falling blocks to travel for such long distances.

Study Sites

Mt Szczeliniec Wielki and Mały

Mt Szczeliniec Wielki (919 m a.s.l.) is the highest elevation of the Stołowe Mountains. Together with the neighbouring Szczeliniec Mały (895 m a.s.l.) it represents a typical mesa rising above the main plateau (Figs 1 and 4). The twin mesa is built of two rock types. The caprock is composed of the Skalniak–Szczeliniec Sandstone, whose total thickness is about 70 m, but the cliff faces themselves are up to 40 m high. The slopes beneath the cliffs ('sub-caprock' slope) are underlain by less resistant marls, mudstones, and thin-bedded sandstones. They are generally concave in profile and their inclination consequently decreases from c. 30° below the rock wall to less than 5°. However, the relief of the north-eastern slopes of Mt Szczeliniec Wielki is much more complex (Figs 1 and 4). Instead of being consistently concave, the slope becomes steeper at 830 m a.s.l., forming a 40-meter-high scarp inclined at around 35°. Below it, there is a distinctive, nearly flat bench, c. 80 m long and semicircular in plan. Lower segments of the slope are characterized by the occurrence of three lobate toes, extending down to the road. All these features were recently recognized as elements of a deep-seated rotational slide (Migoń, Kasprzak 2011).

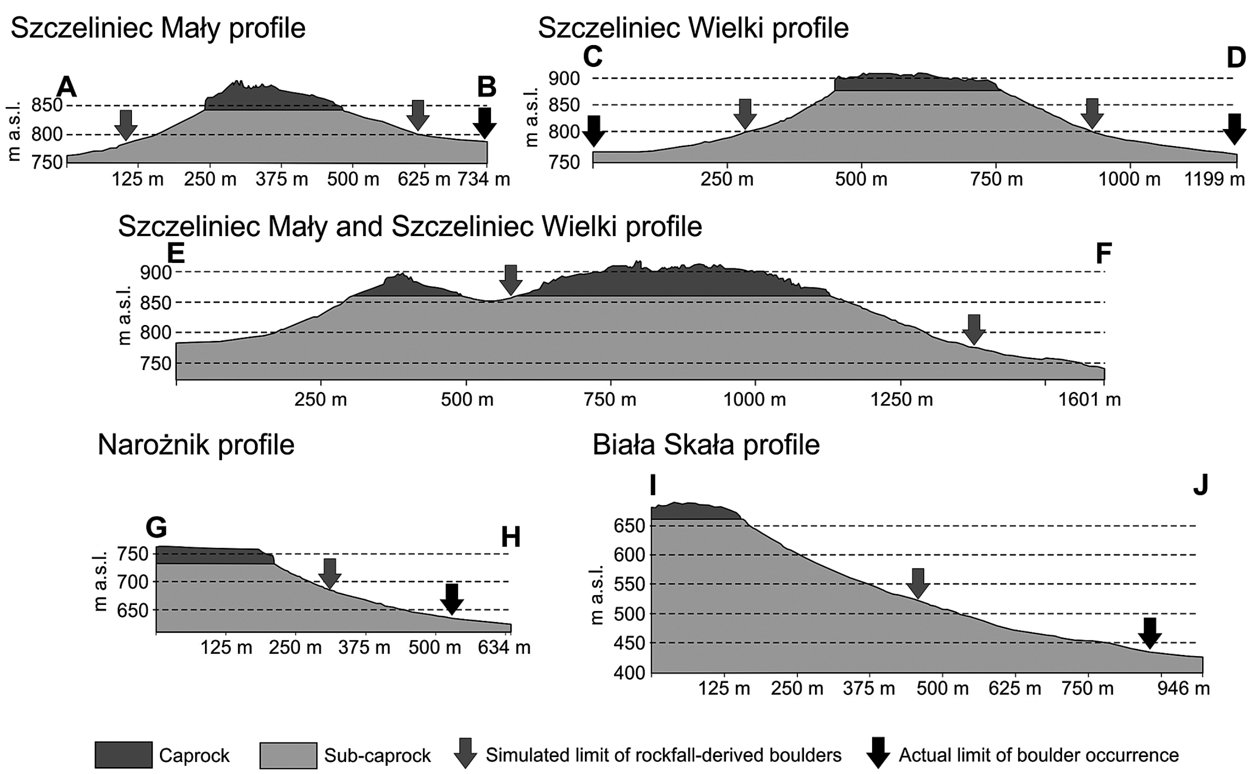

Fig. 4. Slope profiles across the study sites

Southern slopes of Mt Narożnik

Mt Narożnik (851 m a.s.l.) is the most elevated spot of an extensive plateau in the southern part of the Stołowe Mountains, elongated in a NW–SE direction (Fig. 1). Its northern, western and southern sections are rimmed by high cliff faces formed in the 'upper jointed sandstones'. The south-facing slopes are divided into two parts by the valley of the Kamienny Potok stream. To the east of the valley the sandstone was extensively quarried in the locality known as Skały Puchacza, but relatively little human intervention has left its signs on the escarpment in the westerly direction. The sub-caprock slope is built of the Upper Turonian complex of marls and calcareous mudstones. Longitudinal profiles of the slope are gently concave in a broad view (Fig. 4), but show the presence of minor irregularities at close-up. No unambiguous geomorphic evidence of significant remodelling by landslides has been identified yet, although shallow movements within the regolith may have occurred, leading to the origin of slope-parallel bulges (Kasprzak 2012).

Biała Skała

Biała Skała (i.e. 'White Rock', 703 m a.s.l.) is the name given to a prominent spur of the main plateau, within the northern escarpment supported by the Radków Bluff Sandstone unit (Fig. 1). Its upper surface represents a ruiniform type of relief, with numerous secondary rock elevations and troughs. The cliff face is typically 10–20 m high. The slope below is c. 30–40° steep and littered with sandstone boulders of various sizes. In the mid-slope the inclination decreases to 20–25°. Below c. 520 m a.s.l. the slope profile becomes wavy and irregular, with alternating segments of higher (15–20°) and lower (5–10°) inclination (Fig. 4). Benches are 50 to 100 m wide. Migoń and Kasprzak (2012) interpreted this tread-and-riser morphology as resulting from shallow landslides whose bodies are superimposed on one another. Transition into a nearly-level footslope surface occurs at an altitude of c. 425 m a.s.l., i.e. more than 750 m from the base of the cliff face. The lithological boundary between Permian sedimentary rocks below and the Upper Cretaceous succession above intersects the slope at around 520–530 m a.s.l., and landslide morphology can only be identified below this boundary.

Results: the Actual Position of Boulders vs. Maximum Modelled Run-out Zone

Mt Szczeliniec Wielki and Mt Szczeliniec Mały

Boulder cover within the slopes of Mt Szczeliniec Wielki and Mt Szczeliniec Mały forms a nearly continuous blanket, extending from the bottom of the rock wall down the footslope. The maximum distance to which the boulders can be traced is similar within the slopes of both mesas. It is around 400 m within the northern, eastern and southern slopes of Mt Szczeliniec Wielki and between 250 and 300 m on the Mt Szczeliniec Mały slopes (Fig. 5). In all these cases the most distal blocks occur on level or nearly-level footslope surfaces. The only apparent anomaly was found within the north-eastern slopes of Mt Szczeliniec Wielki, where boulders occur in a significantly more distant position than in the other slope sections. The blocks reach beyond the Mt Szczeliniec Wielki footslope, into the valley of the Kozi Potok stream. The most distant boulders occur within the southern part of the Pośna river amphitheatre, meaning that their distance to the cliff face is as much as about 700 m.

Size distribution of sandstone boulders within the lower slope of both mesas is not consistent. Huge boulders (~10 m long) are found on slopes of all aspects and in very different positions. Some occur immediately below the rock face, but they are also present on the footslope. In the mid-slope, the big boulders often occur in distinctive clusters consisting of a few to more than 10 individual blocks, very close to one another or in direct contact. Notable are giant solitary boulders in the vicinity of the Karłów – Pasterka road, both because of their size (up to 10 m long) and occurrence on nearly flat terrain, or even on the opposite slope (Fig. 2). On the slopes of Mt Szczeliniec Mały large sandstone blocks occur mainly within the upper, more inclined (> 20°) part. However, numerous shallow surface hollows in the lower slope suggest that former quarrying in this area, known from locations elsewhere in the Stołowe Mountains (Migoń 2013b), may be responsible for differences in the density of boulders. Smaller boulders (1–5 m long) are widespread across the slopes and do not seem to show any particular distribution pattern, although this needs to be tested.

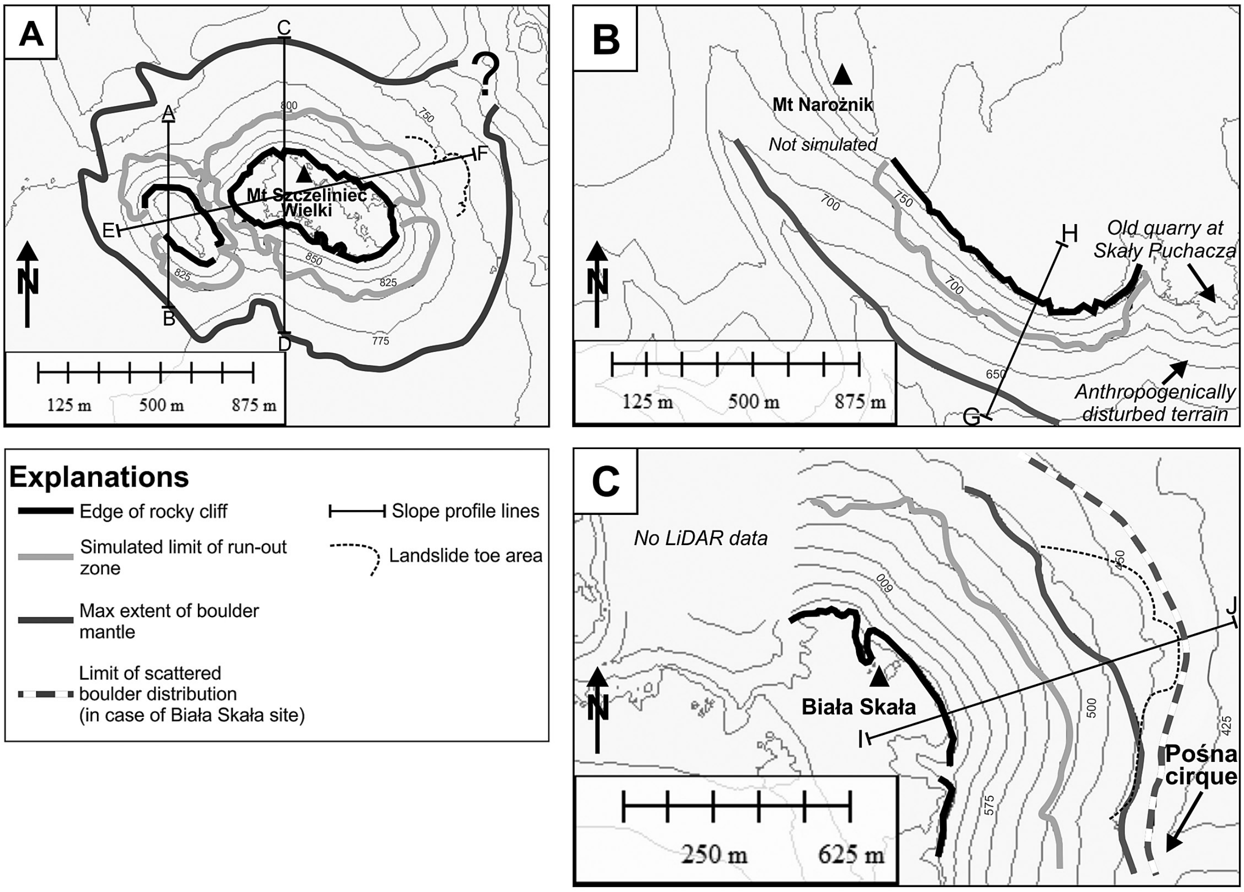

Fig. 5. Actual limit of sandstone boulders distribution within the studied sites vs. simulated limit of run-out zones. For location of slope profile lines see Fig. 4

The results of simulation in the Conefall 1.0 software revealed that the maximum limit to which boulders detached from the rock face can travel is up to 200 m in the case of the Mt Szczeliniec Wielki slopes and around 160 m in the case of Mt Szczeliniec Mały (Fig. 5). Over much of the perimeter of the twin mesa the maximum run-out zones are even shorter. If the results of the simulation are compared with the factual position of sandstone boulders, it becomes clear that the calculated distance is about two times shorter than the actual extent of boulder blanket, and up to three times shorter than that at the eastern foot of Mt Szczeliniec Wielki.

Mt Narożnik

Slope surfaces below the cliff face at Mt Narożnik are covered by a large number of boulders of different sizes. Although giants up to 10 m long occasionally occur, boulders are typically less than 5 m long. They are unevenly distributed, with densely-covered parts of the slope occurring side by side with sections where boulders occur sparsely. The relationship between slope inclination and size distribution of blocks is not consistent. Huge boulders appear scattered within the whole slope profile, from settings very close to the rock face to lower slopes of low inclination (<10°). However, within the flat footslope huge boulders no longer occur. In this part of the escarpment an additional complication is introduced by former quarrying, and we therefore limited our study to the sector west of the Kamienny Potok valley.

The maximum limit of boulder occurrence is around 350 m from the cliff face, though sandstone elements smaller than 1 m can be found even further (Fig. 5). The results of the simulation in the Conefall 1.0 software indicate that the maximum extent of run-out zones in case of potential rock falls is around 160 m from the cliff face, which is less than half the factual position of boulders within the south-western slopes of Mt Narożnik.

Biała Skała

In contrast to the other two localities, sandstone boulders present on the slopes below Biała Skała do not form a continuous cover throughout the sub-caprock slope profile, but show a general relationship with the gradient. However, the slope here is significantly longer and higher (Fig. 4). In its steep upper part, the block accumulation is densely packed, whereas along with a decreasing gradient, boulders occur less and less frequently and diminish in size. The most distant, isolated sandstone boulders occur at altitudes as low as 445 m a.s.l. and more than 700 m from the cliff face base (Fig. 5). They can be still quite large, up to 4 m long, and some are evidently half-buried in the colluvial deposits, thus their actual dimensions may be even larger. The density of the boulder cover observed nowadays is clearly less than it was originally. Shallow, semi-circular hollows, frequent heaps of small, angular, dressed stones, and partially-worked faces of large boulders and split boulders indicate widespread boulder quarrying in the past (Migoń 2013b), which implies that the contemporary boulder occurrence in the lower slope is but a remnant of the original cover.

However, the simulation using Conefall 1.0 revealed that the maximum run-out zone for boulders detached from the cliff face is about 300 m (Fig. 5). Thus, the difference between the simulated and factual distance of boulders is more than 400 m, which is the second largest mismatch recorded among our sites, after that noted on the eastern slopes of Mt Szczeliniec Wielki.

Table 1. Mismatch between actual and simulated boulder limit at test sites in the Stołowe Mountains tableland

Site	Actual limit of boulder distribution [m]	Simulated limit of rockfall-derived boulders [m]	Actual area of boulder aprons [ha]	Simulated area of boulder aprons [ha]
Szczeliniec Wielki – N slope	448	143	28.25	8.40
Szczeliniec Wielki – E slope	460	165	25.78	4.80
Szczeliniec Wielki – S slope	420	160	23.43	7.18
Szczeliniec Mały – W slope	191	115	9.25	2.23
Narożnik – W slope	351	131	24.95	8.19
Narożnik – SW slope	416	172	19.70	5.46
Biała Skała	700	270	75.7	34.34

Discussion

Are the results of Conefall simulation to be trusted?

The comparison between the actual pattern of occurrence of caprock-derived boulders on the mid- and lower slopes of the escarpments and the results of rockfall simulation using Conefall 1.0 software indicates an evident and consistent mismatch at all investigated sites. Boulders occur at distances which are 2–3 times longer than suggested by the results of modelling (Table 1). Since the geological structure of the tableland rules out any other source of sandstone boulders than the cliff face in the upper slope, this discrepancy leads to consideration of the following alternative. Either assumptions inherent in Conefall modelling approach are flawed, or the geomorphic history of boulder mantles on escarpment slopes is significantly more complicated.

The assumption that Conefall simulation does not work in the particular setting of the Stołowe Mountains can be rejected. Firstly, while the procedure involves modelling, it is based on extensive empirical evidence from various localities worldwide about how far rockfall-derived boulders can travel. Second, in high-energy mountain environments the predicted run-out distances could have been validated by subsequent observations. Thus, there is no reason to claim that the modelling approach is incorrect. Although we acknowledge that individual boulders released catastrophically from the cliff face may have travelled to more distant locations on the footslope than the modelling predicts and they could have done so due to an unusual combination of processes, the scale and consistency of mismatch are too large to be explained by acceptable sporadic deviations from a general empirical relationship. In fact, it is densely-packed boulder aprons that continue for 100–200 m beyond the simulated reach, not just a few odd individuals, and scattered boulders occur further downslope. In addition, field evidence suggests that many distant boulders may have been completely quarried in the past and the original number of boulders was almost certainly higher.

Thus, the lesson learnt from Conefall simulations is that the role of rockfall in the escarpment evolution may have been overestimated in the past. In this context, it should be noted that only one case of a historic rockfall was reported in local history (in 1921) and even that involved only one block; otherwise, no catastrophic rock slope failures have been reasonably well-documented in the last 150 years or so.

Alternative scenarios

These circumstances encourage an exploration of alternative explanations for the origin of boulders, in addition to simple rockfall scenario. These may include: (a) a significant contribution of processes other than rockfall; (b) boulders being indeed related to rockfall, but not from the cliff faces in their present-day position; (c) there having been significant movement of boulders across the slope, subsequent to rockfall. Option (b) was mentioned by Pulinowa (1989) who, however, seemed to favour scenario (c) and referred to 'wandering blocks', especially on the slopes of Mt Szczeliniec Wielki. However, no solid evidence for this process to have been widespread (such as furrows left behind ploughing boulders) was provided, and while the position of some individual boulders could possibly be explained by long-term, slow movement (creep, gelifluction under periglacial conditions of the Pleistocene), densely-packed boulder aprons with blocks superimposed on one another require another explanation.

According to the literature, certain types of large-scale mass movements may be responsible for long-distance transport of caprock-derived boulders. Slumps are common in many tablelands and have been recognized to be one of the major mechanisms of scarp retreat (e.g. Reiche 1937; Peulvast, Bétard 2015). Their occurrence on the lower slopes, typically underlain by mudstones and claystones, is explained by the low shear strength of these rocks and poor drainage (Howard, Kochel 1988). In specific situations, large areas are remodelled by spectacular multiple-rotational slips, such as the Toreva blocks described by Reiche (1937). This indicates that boulders that were primarily detached during a rockfall event and came to rest within a relatively short distance from the cliff may subsequently travel for longer distances by means of landslide. In such circumstances the blocks are transported down the slope, all the time lying on the slope surface. However, this scenario is difficult to apply to the Stołowe Mountains. Until now only one rotational slide has been recognized in the area, to remodel a relatively small sector of north-eastern slopes of Mt Szczeliniec Wielki (Migoń, Kasprzak 2012), whereas distant sandstone boulders are scattered all along the lower slopes. Shallow translational landslides may have been more common, and in particular locations, such as the Radków Escarpment below Biała Skała, may explain the large extent of boulders as hypothesized by Migoń and Kasprzak (2012). However, long sections of the escarpments lack geomorphic evidence for shallow landslides. Slow movement under periglacial conditions (gelifluction) is another mechanism by which boulders could have been further transported from below cliff faces towards middle and lower slopes. However, while structural features of sandy-silty cover deposits indicate Pleistocene gelifluction (Waroszewski et al. 2015a, b), long-range transport of blocks more than 5 m long is difficult to visualize. Hall et al. (2001) described some of the largest boulders displaced downslope in a periglacial setting and none of them exceeded 5 m long, with the mean length being only 1.6 m and the mean height less than 1 m. Furthermore, they have been found on slopes with mean inclination in the range 18–24°, hence much more than the low-angle footslopes in the Stołowe Mountains. Finally, the geomorphic evidence of block ploughing is missing with the exception of just a few cases. Thus, while we do not deny that some movement in association with seasonal frost may have taken place, gelifluction does not seem to be a mechanism capable of explaining the position of very large boulders.

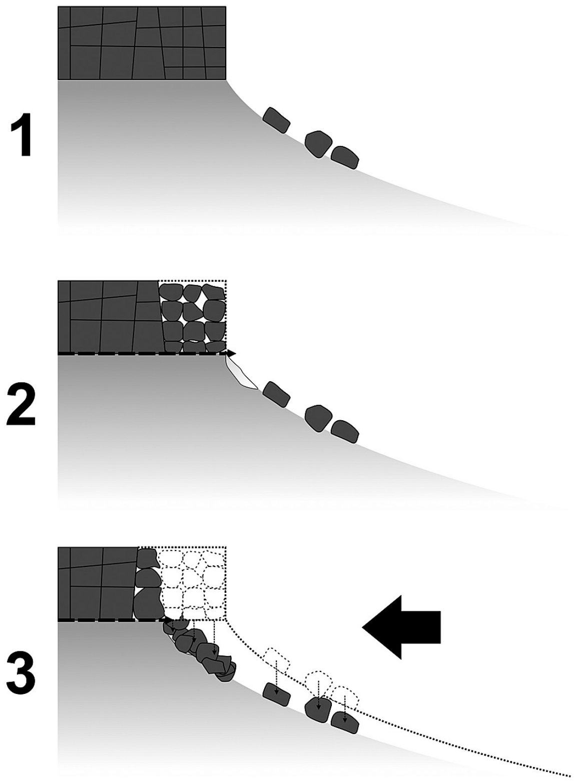

Fig. 6. An alternative scenario of the origin of boulder slope accumulations in the Stołowe Mountains, not involving rockfall: 1 – initial situation, with well-jointed sandstone overlying marls and mudstones forming sub-caprock slope; 2 – grain-by-grain disintegration of caprock along discontinuities. Sand particles are transported towards the slope (groundwater sapping) and deposited as cones and fans on the surface of sub-caprock slope. Sandstone blocks become separated from one another; 3 – lowering of sub-caprock slope and cliff retreat. The cluster of loosely lying blocks, formerly constituting the rocky cliff, is progressively lowered

Peulvast and Bétard (2015) found that the slopes of the Chapada do Araripe plateau (NE Brazil) are also influenced by debris flows arising from fluidization of slump toes. In the Stołowe Mountains, however, there are no erosional furrows or levees in the lower slopes that would indicate the contribution of this type of mass movement. The contemporary position of sandstone boulders on level or nearly-level surfaces far from the source rock area might suggest the contribution of high-energy processes capable of transporting the blocks over long distances, such as rock avalanches, which occur when the entire slope collapses (Govi, Turitto 1992, quoted after Dikau et al. 1996). An energy problem exists, though, as rock avalanches are generated on high and very steep slopes, with high potential energy, whereas the release zones in the Stołowe Mountains are a few tens of meters high at most. Additionally, in both cases (debris flows, rock avalanches) the presence of distinctive tongues of boulders extending onto the footslope would be expected, but such a pattern of boulder distribution does not exist. Rather, the limit of distant blocks follows a line roughly parallel to the cliff faces.

There is, however, another possible explanation which does not imply large-scale and/or catastrophic rock slope failures. Sandstones in the Stołowe Mountains are well jointed, which creates scope for efficient weathering to occur along discontinuities, as well as for underground removal of sand derived from rock breakdown – a process described by Dumanowski (1961) as 'suffosion' (i.e. groundwater sapping). Since the underlying marls and mudstones are impermeable, groundwater movement is preferentially towards the slope, and so is the transport of sand. Evidence for the widespread presence of this mechanism is provided by frequent cones and fans of redeposited sand below discontinuity/rock-face intersections, some a few metres high and long (Migoń et al. 2011). In due course, caprock blocks are separated from one another, lose support, and sag. Over long (though undetermined) time span, these processes would lead to *in situ* disintegration of the sandstone caprock along the former cliff line, without contribution of rockfall or other significant mass movement. The previous near-cliff caprock section becomes a cluster of loosely lying blocks, often one upon another. Simultaneously with caprock disintegration, the sub-caprock slope is lowered and the whole escarpment retreats. Blocks, which were originally at the height of the rock face, occupy progressively lower position within the retreating slopes, as if they were moved down under the influence of gravity-driven mass transport processes. However, in reality they testify to a sinking topography due to removal of material from inside the massif (Fig. 6). This is consistent with the interpretation of solitary boulders resting on planar surfaces of the Rogowa Kopa and Pustelnik which are still present in allochthonous position, although the entire retreating escarpment has been eroded away.

Final Remarks

In this paper we used the conceptual framework of run-out zone modelling to check if the observed distribution of boulders is consistent with the modelled distribution. The results were consistently negative, i.e. at each test site the model considerably underestimates the actual extent of caprock-derived boulders. The outcome of this exercise, coupled with the absence of geomorphic features indicative of other long run-out mass movements or only localized evidence for landsliding, imply that the present-day escarpment morphology in the Stołowe Mountains cannot be explained solely in terms of contemporary processes and hints at significant inheritance. There are several possible explanations of the distant position of large boulders, including those previously offered by Pulinowa (1989) in which, however, rockfall remained a necessary ingredient. We do not reject this possibility at the current stage of research, but we point out that an alternative scenario of 'sinking topography' exists that can help explaining the position of even the most distant boulders, without the involvement of catastrophic mass movements.

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