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Enigmatic clusters of sandstone boulders on plateaus of the Stołowe Mountains (Sudetes, south-west Poland) – their geoheritage and geotouristic value

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Abstract

Among sites of geomorphological interest in the tableland of the Stołowe Mountains, consisting of clastic sedimentary rocks of Late Cretaceous age, are enigmatic occurrences and clusters of sandstone boulders within plateau levels that are underlain by mudstones and marls. These boulders are allochthonous, having been derived from the quartz sandstone beds that support the upper plateau level and stratigraphically are in excess of 50 m above the altitudinal position of the boulders. Topographic conditions preclude long-distance transport from the escarpment slopes; boulders are hypothesised to be the last remnants of completely degraded outliers (mesas) of the upper plateau. Their present-day altitudinal position is explained by passive 'settling' following disintegration of caprock and denudation of the underlying weaker rocks. Two localities are here presented in detail, Łężyckie Skałki and Pustelnik, along with adjacent boulder trains in the valleys incised into the plateau. It is argued that both localities have considerable geoheritage value and both play the role of geosites, although on-site facilities are so far limited. However, the complex history of boulders sets a series of challenges for successful geo-interpretation.

Key words: sandstone landforms, tablelands, escarpment retreat, geo-interpretation

1. Introduction

The sedimentary tableland of the Stołowe Mountains in south-west Poland (Fig. 1) is widely known for its strangely shaped sandstone rock formations and can be considered a cradle of geotourism in the Sudetes range, of which it forms a part. The latter distinction is due to a visit by the famous German naturalist and writer, Johann Wolfgang Goethe, in 1790. Goethe was clearly motivated to see the newly discovered ruiniform relief (rock city) on the highest elevation of the tableland, the mesa of Szczeliniec Wielki (Migoń, 2016). In the following century, Mt. Szczeliniec Wielki strengthened its reputation as a prime tourist destination in the region; it has retained this role to the present day (Rogowski, 2020). A few other localities have also been developed to accommodate an ever-growing number of visitors, including the rock labyrinth of Błędne Skały (translatable as Errant Rocks) and, more recently, the group of picturesque pedestal rocks (hoodoos) known as Skalne Grzyby (translatable as Rock Mushrooms). All three localities undoubtedly rank among the most scenic and most impressive groups of rock-supported landforms, with a huge geoeducational potential, although it seems that, being subject to mass tourism, they are appreciated mainly for the scenery. On-site interpretative facilities are so far limited to the Skalne Grzyby area (Migoń & Duszyński, 2020), but a geotouristic guidebook (Duszyński et al., 2015) fills a niche and offers information about the other two places. However, even when considered collectively, these three sites do not provide a complete picture of longer-term landform evolution in sedimentary tablelands. Many more localities in the Stołowe Mountains can be considered as potential geosites, i.e., places important for our comprehension of Earth history (Reynard, 2004). They tell stories related to both the sedimentary history of the Cretaceous Period, recorded in rocks (Wojewoda, 2011), and subsequent evolution of landforms, including major (escarpments, tabular hills, rock cities), medium-sized (pedestal rocks, crags, boulder fields) and minor features (tafoni, weathering pits, sandy cones) (Duszyński et al., 2015). In the present paper, we focus on two apparently overlooked geosites, which both feature residual sandstone boulders scattered over plateau surfaces. Some aspects of their geomorphology were discussed in previous literature items (Migoń, 2010, 2012; Parzóch & Migoń, 2015), but not within the context of geoheritage and geotourism. Moreover, the inventory of boulders at the key locality of Łężyckie Skałki proved to be incomplete. The aims of the present contribution are thus to provide a comprehensive characteristic of these boulder clusters, to advance hypotheses of their origin, and to discuss their potential for geoscientific storytelling. For the purpose of this paper, boulders are here understood as separate rock compartments, not rooted in bedrock, whose minimum length (according to Wentworth's classification) is 256 mm (e.g., Boggs, 2009). In fact, boulders described here are more than 1 m long, with some exceeding 4 m (the lower limit of "megaclasts" according to Blair & McPherson, 1999 and Ruban et al., 2019), but given that their origin did not involve transport, further subdivision according to dimensions is not attempted here.

2. Study area – geomorphology and geology

The Stołowe Mountains tableland is a unique landscape type within the Sudetes range. It represents a multi-storey plateau, with several morphostructural levels separated by steep escarpments supported by more resistant sandstone beds (Pulinowa, 1989; Kasprzak & Migoń, 2015; Migoń & Duszyński, 2018). The upper plateau survived as erosional

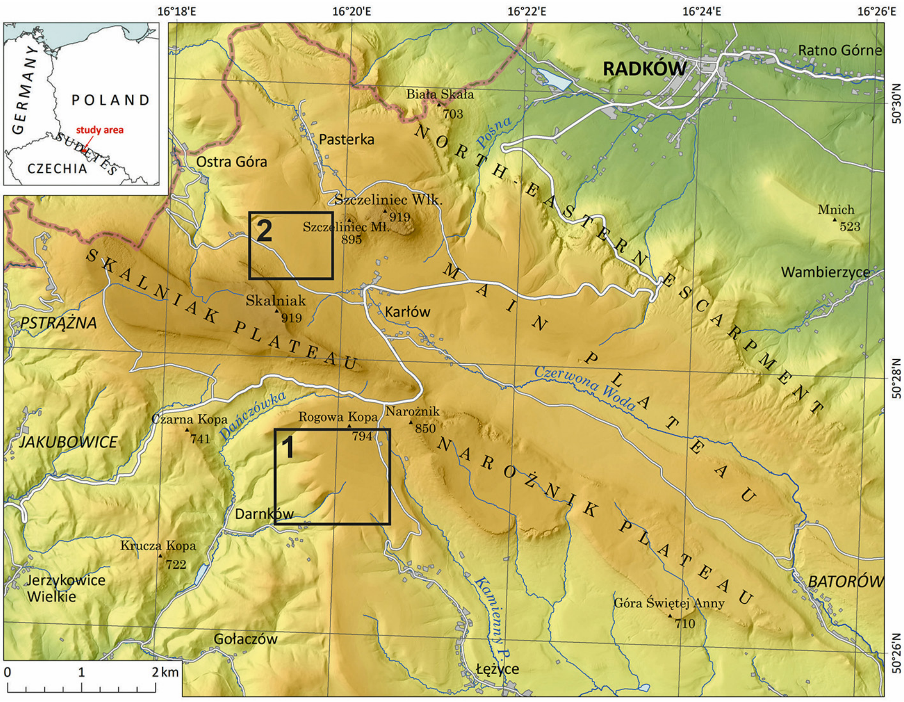

Fig. 1. Location of boulder clusters in the Stołowe Mountains tableland. 1 – Łężyckie Skałki (see Fig. 3); 2 – Pustelnik (see Fig. 7). The map is derived from a high-resolution (1 m × 1 m) digital relief model, available at www.geoportal.gov.pl.

remnants of various dimensions, rising to more than 900 m a.s.l. (Mt. Szczeliniec Wielki, Mt. Skalniak) above the more extensive main plateau which slopes eastwards and therefore covers a broad altitude range, from *c*. 600 m to 790 m a.s.l. (Fig. 1). Both planar tracts of relief are abruptly truncated by morphologically complex escarpment slopes, consisting of rocky cliffs in the uppermost section giving way to boulder-mantled middle slopes and generally concave lower slopes, which may still contain large boulders derived from the cliffs far above (Dumanowski, 1961b; Duszyński & Migoń, 2015; Migoń & Duszyński, 2018). The geomorphic history of the escarpments, including the origin of boulders, has long been considered to illustrate the principles of escarpment retreat through rock fall from the caprock level (Dumanowski, 1961b; Pulinowa, 1989); this has been revisited recently. It is now argued that rock falls with long runout distances actually played a negligible role in the evolution of the escarpments and that the bulk of the boulder mantle is due to *in-situ* disintegration of cliff lines driven by subsurface erosion, sand removal, and consequent loss of support to the overlying sandstone blocks (Duszyński & Migoń, 2015; Duszyński et al., 2016; Migoń, 2021). Below the main plateau, lower morphological levels are distinguished (Rogaliński & Słowiok, 1958; Pulinowa, 1989), but cliffed escarpments are no longer present.

The topography of the Stołowe Mountains is very much adjusted to the underlying geology and the area is considered to be an excellent example of structural relief, offering an opportunity to examine how lithology and structure underpin landforms and geomorphic processes (Pulinowa, 1989; Migoń & Duszyński, 2018). Except for the lower slopes of the northern escarpment, which truncate clastic beds of Early Permian age, the remaining area is entirely within the Upper Cretaceous succession that spans the interval from the late Cenomanian to the late Turonian, possibly early Coniacian, hence *c*. 6 myr (Wojewoda, 1997). This succession is of shallow-marine origin, *c*. 300 m thick, and contains alternating beds of sandstones and finer-grained sediments. In the vertical profile three main sandstone horizons occur: glauconitic sandstone and conglomerates at the base of the succession (*c*. 15 m thick), medium- to coarse-grained arkosic sandstones in the middle ('middle jointed sandstone', *c*. 80 m thick) and quartz sandstones capping the sequence ('upper jointed sandstone', *c*. 50 m thick) (Jerzykiewicz, 1968a; Wojewoda, 1997). Several minor sandstone bodies (up to 15 m thick) occur between the middle and upper major sandstone horizon in the northern part of the tableland. Between these sandstone units various fine-grained rocks occur, mainly mudstones and siliceous marls, with a subordinate presence of calcareous sandstones, claystones, spongiolites and gaizes (Wojewoda, 1997; Rotnicka, 2007).

From the perspective of rock factors controlling landform evolution the following differences between these two major components of lithological succession are important. First, sandstones show a higher intact strength as demonstrated by *in-situ* Schmidt hammer measurements (Migoń & Zwiernik, 2006; Placek, 2011; Duszyński & Migoń, 2015). Secondly, they are typified by more or less regular orthogonal jointing, with joint spacing from less than 1 m to, not uncommonly, more than 5 m (Jerzykiewicz, 1968b). These joints account for the production of large angular boulders that are released from cliff lines (Duszyński & Migoń, 2015). Thirdly, most sandstone units are thick bedded, whereas the finer-grained rock series show dense bedding, with 10–20 cm spacing (Rotnicka, 2007). Fourthly, and lastly, a common feature of fine-grained sediments is the poor permeability, which contrasts with the good permeability of the sandstones themselves as a result of both primary and secondary porosity (Kowalski, 1980). All these properties combined account for the much higher resistance of sandstones in comparison with mudstones and marls, their ability to support high cliffs of up to 40 m in height, and the longevity of sandstone boulders hypothesised from various lines of evidence (Migoń, 2012; Duszyński & Migoń, 2015).

3. Methods

The present study is primarily based on field work, aided by interpretation of high-resolution (1 m × 1 m) digital elevation models and ortophotomaps, freely available at www.geoportal.gov.pl. Field work included detailed geomorphological mapping of two boulder clusters and their immediate surroundings, measurements of each boulder larger than 1 m using laser rangefinder and tape, recording of minor weathering features on boulder surfaces and identification of evidence of former quarrying (smooth faces, debris leftovers, hollows left after complete removal of a boulder). Evaluation of potential geoheritage and geotouristic significance of boulder clusters was informed by a survey of the relevant literature focused on the geomorphological history of central European sedimentary tablelands.

4. Łężyckie Skałki

4.1. Geomorphological and geological setting

The locality of Łężyckie Skałki (= Łężyce Rocks) is situated in the south-western part of the tableland, next to the few remaining houses of the village of Łężyce Górne (Fig. 1). The main element of topography is a plateau covering *c.* 1.1 km^2, with an indistinct elevation of Rogowa Kopa (794 m a.s.l.) in the north and imperceptibly sloping surfaces towards the west and south (Fig. 2). On the western side the plateau terminates in a clear break of slope, beyond which surface inclinations increase to ~30°, and locally even to 50°, with bedrock cliffs exposed within the slopes. The western plateau rim is sinuous in plan, undercut by several deeply incised, V-shaped valleys, with permanent or periodic watercourses (Fig. 3). These streams are tributaries of the Dańczówka stream, which drains the area to the west, to the River Labe. The southern and eastern limits of the plateau are not so clear cut and the transition to fluvial valleys is gradual. These valleys drain to the Złotnowski Potok stream, which belongs to the drainage basin of the River Odra. Thus, the main drainage divide of the Sudetes that separates the catchments of the North Sea and the Baltic runs across the Rogowa Kopa plateau. The plateau itself is part of the middle morphostructural level of the Stołowe Mountains tableland ("Main Plateau"), although it is physically separated from its main area of occurrence by remnants of the upper plateau (Skalniak – 919 m a.s.l., Narożnik – 850 m a.s.l.).

Geologically, the plateau of Rogowa Kopa is underlain by fine-grained members of the Upper Cretaceous sedimentary succession of the Stołowe Mountains, which include marlstones and siliceous marls, calcareous, calcareous-siliceous and siliceous mudstones, silty limestones, calcareous spongiolites and thin intercalations of calcareous sandstones (Rotnicka, 2007). These thin-bedded rocks are not exposed on the plateau itself, but crop out locally in the channel beds, where they form low steps (<1 m high), and more impressively within the steep valley side of the Dańczówka stream in the north. This fine-grained series does not have any thick intercalations of quartz-rich sandstones which make up the boulders on the plateau.

Fig. 2. The locality of Łężyckie Skałki (Rogowa Kopa). **A –** view from the upper plateau towards Rogowa Kopa; arrows show individual boulders (not to be confused with haystacks). Note the absence of boulders in front and the ground sloping towards the viewer; **B –** ground view.

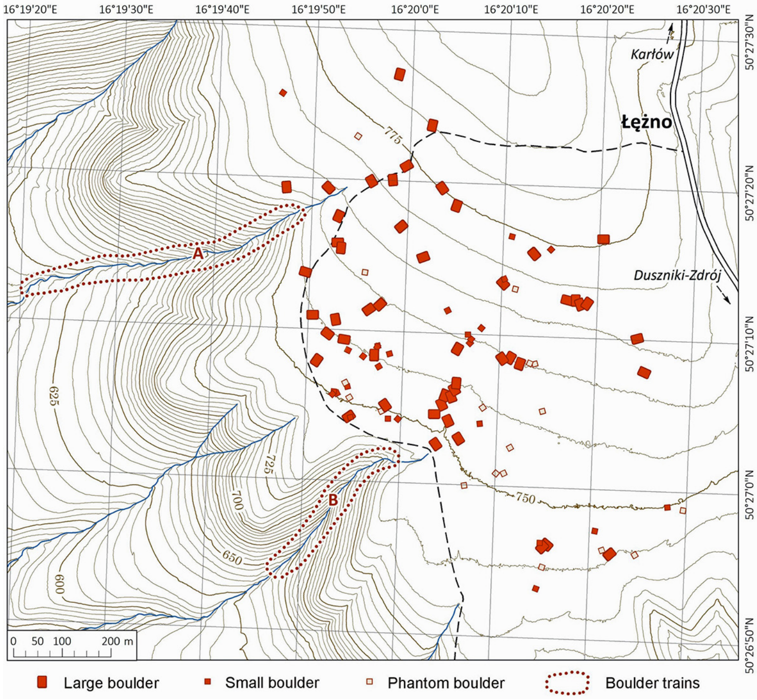

Fig. 3. Distribution of residual sandstone boulders on the Rogowa Kopa plateau (for location within the Stołowe Mountains, see Fig. 1). Contour lines are derived from a high-resolution (1 m × 1 m) digital relief model, available at www.geoportal.gov.pl.

The northern part of the plateau is currently an open ground, meadows being the dominant land cover. Deforestation and conversion to agricultural use probably occurred in the 18th century, when the hamlet of Łężyce Górne was founded (Staffa et al., 1992; Latocha, 2020); it may have had a larger extent than today. The southern part of the plateau is now covered by forest, but old topographic maps show a mosaic of pastures and arable land, with only one larger forest patch.

Allochthonous sandstone boulders, which are the main focus of the present paper and stratigraphically belong to the 'upper jointed sandstone' series, occur in two morphological positions. One includes boulders scattered over the plateau surface, with those in the north well visible due to open terrain conditions, whereas those in the south are hidden in young tree stands. The second position includes the floors of two deep valleys that incise into the plateau rim from the west. Here the boulders form trains of variable length, as long as 800 m. Interestingly, very few boulders occur in the slope position, between the plateau rim and the valley floors.

4.2. Plateau boulders

The boulders on the Rogowa Kopa plateau, nearly 100 in total number, are widely dispersed in its south-western part (Fig. 3). Their spatial distribution does not reveal any immediately evident clusters, although they seem to be more common in the less elevated part of the plateau. In particular, an elongated group consisting of nine large boulders may be identified in the upstream prolongation of valley 'B'. The plateau boulders are of widely varying sizes. The maximum values are 11 m in length, 8 m in width and 10.7 m in height, average values being 5 m, 3.5 m and 1.8 m, respectively. Two main categories of blocks can be distinguished on the basis of dimensions (Fig. 3). Large boulders measure at least 2.5 m along the longest axis, whereas in small boulders none of the dimensions exceeds 2.5 m. The former are the most common on the plateau (more than 50 individual objects). In several places small boulders are evidently an effect of disintegration and splitting of a large boulder (Fig. 4A,B). Although most boulders look intact, part of the 'population' consists of boulders which were used by the local inhabitants as a conveniently located source of stone material for domestic purposes. Therefore, the original size of some boulders could not be reconstructed due to complete excavation, or only partial reconstruction is possible (Fig. 4C, D). The former are referred to as 'phantom boulders' and are typically marked by the presence of post-mining pits, with clear boundaries, surrounded by embankments made of sandstone rubble or loosely scattered, sharp-edged leftovers. Exploitation of other boulders was terminated prior to complete excavation and these may have adjacent sides with contrasting microrelief, due to natural weathering and intentional cutting, respectively (Fig. 4D). This exploitation history also means that the density of boulders in the past may have been

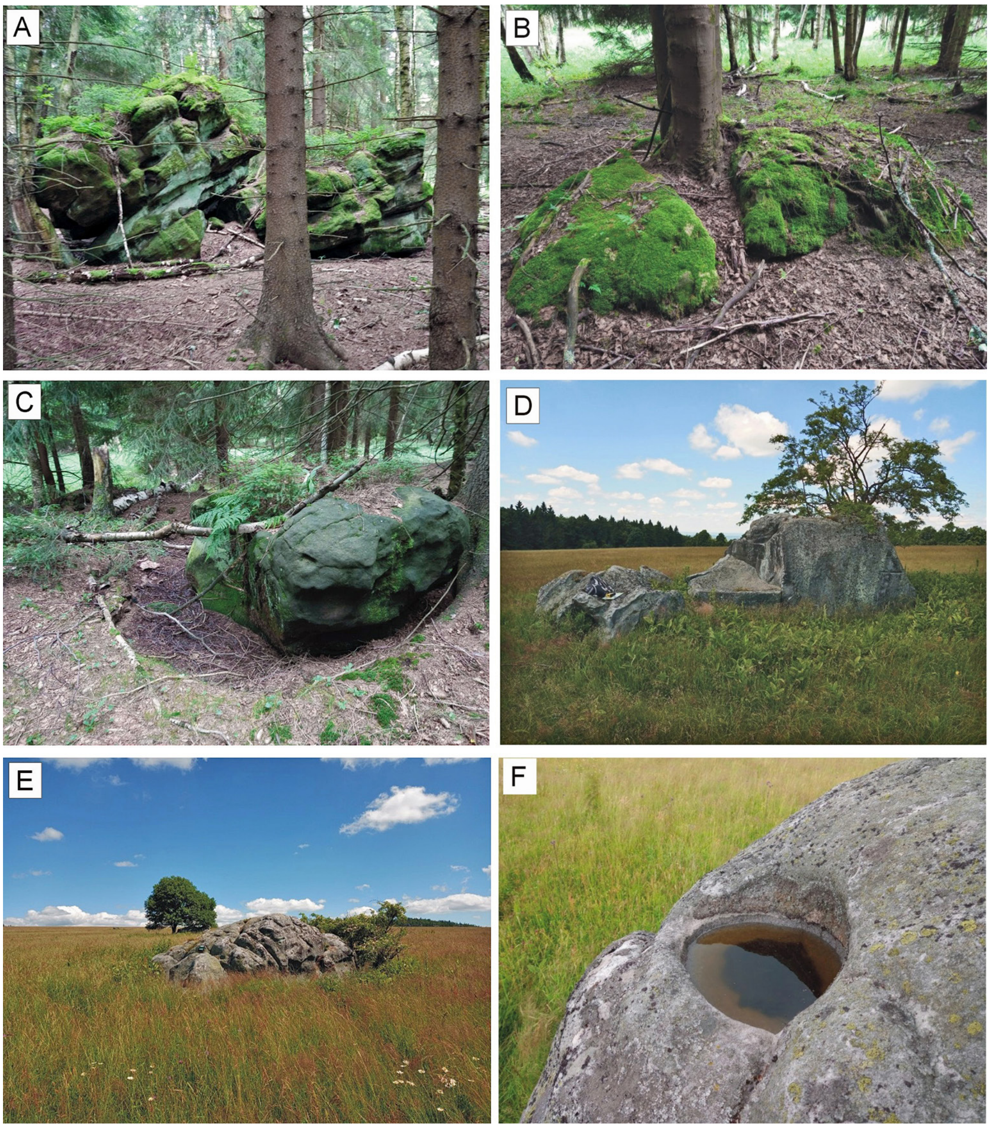

Fig. 4. Residual sandstone boulders on the plateau of Rogowa Kopa. **A, B –** split boulders resulting from the decay of the primary block through natural processes; **C –** a hollow left after partial excavation of a boulder, used to reconstruct the original dimensions of boulders; **D –** unfinished quarrying of a boulder; **E –** one of the intact boulders in open terrain, with diverse surface microrelief; **F –** weathering pit on a boulder.

higher. Most large boulders are characterised by distinct surface microrelief, in the form of hollows of varying depths on the upper surfaces, including regular weathering pits (gnammas), enlarged fissures along joints and incipient cavernous forms on the side walls (Fig. 4E, F). Small boulders typically lack microrelief.

4.3. In-valley boulder trains

Two boulder trains occur within the west-facing slopes of the Rogowa Kopa plateau (Parzóch & Migoń, 2015). The train in the valley, labelled 'A' (Fig. 3), is the longer one, with the most distant boulders located more than 800 m from the plateau rim. Closer inspection reveals that the boulders form three distinctive clusters which, going downstream, are 40 m, 44 m and 56 m long, respectively. The clusters are separated by valley floor sections with only occasional and generally small boulders. In addition, there are multiple boulders in the valley section located beyond the steep escarpment, below 650 m a.s.l., both in the channel and above it, within a 3–5 m high 'terrace'. In total, 99 boulders of more than 1 m in length have been mapped in the valley, including 80 in the channel itself (Fig. 5). Nine boulders are more than 5 m long. The number of boulders in each cluster varies, from 15 in cluster I to 34 in cluster II. Boulders in slope position

Fig. 5. In-valley boulder clusters within the escarpment of Rogowa Kopa. **A –** general view of the northern valley; **B –** upper cluster in the northern valley; **C –** solitary sandstone boulder resting on mudstone bedrock; **D –** boulders in the uppermost part of the southern valley.

rank among the largest ones and are comparable in terms of their dimensions with boulders on the plateau. The presence of shallow linear troughs upslope and minor swells on the downslope side is indicative of slow, gravity-driven movement of boulders, which will eventually reach the channel and join the clusters therein. Schmidt hammer tests (Parzóch & Migoń, 2015) have not revealed any evident differences between clusters, which – if present – might suggest different weathering histories and dissimilar exposure times.

In the next valley to the south only a few boulders are present, whereas a larger cluster occurs in valley 'B'. It consists of 47 rock elements, dispersed along a stretch of 300 m. In contrast to valley 'A', more boulders occupy the slopes in the headwater part. Furthermore, boulders are smaller on average, with only three exceeding a length of 5 m and the majority being less than 2 m long.

5. Pustelnik

5.1. Geomorphological and geological setting

Pustelnik (790 m a.s.l.) is situated in the western part of the Stołowe Mountains, approximately 1 to 1.5 km to the north-west of the village of Karłów (Fig. 1). It is a low terrain swell between the twin mesa of Szczeliniec Wielki/Szczeliniec Mały in the north-east and the plateau of Skalniak in the south-west, both belonging to the highest morphostructural level of the Stołowe Mountains, underlain by massive quartz sandstones belonging to the 'upper jointed sandstone' series. The swell itself is part of the middle morphostructural level. Shallow troughs separate the swell from the footslopes of both adjacent elevations, with the one at the foot of the Skalniak plateau being occupied by a watercourse – the headwater of Machovský Potok stream. The Pustelnik plateau is also crossed by the main water divide of the Sudetes. Slopes are less than 5° and in many places close to 0. In the north-west, however, the plateau is incised by two steep-sided valleys, whose depth with respect to the plateau level is 25 m.

Similar to the Rogowa Kopa plateau, the plateau of Pustelnik is also underlain by rock series belonging to the fine-grained heterolithic complex that occurs stratigraphically below the upper quartz sandstones (Wojewoda, 1997). These sandstones are exposed within the cliffed escarpments of Mt. Szczeliniec Mały and Ptasia Skała ridge, to the north-east and south-west, respectively, with the base at c. 840 m a.s.l., thus *c.* 50 m above the level of the plateau. Within the fine-grained complex marls, mudstones and thinly bedded calcareous sandstones occur and locally crop out within the steep valley sides to the north-west of the plateau level.

Fig. 6. Geomorphic setting of sandstone boulders on the plateau of Pustelnik. Two boulders on completely level surface in the foreground and the sandstone-capped mesa of Mt. Szczeliniec Mały in the background.

In terms of land cover the plateau of Pustelnik is also very similar to the surroundings of Rogowa Kopa. It is largely deforested and used as extensive meadows, with dispersed patches of woodland. Most sandstone boulders occur within an open terrain, although young trees tend to grow in their immediate vicinity (Fig. 6). A few are hidden in the woodland, whereas more of them litter the floor of a forested erosional incision in the north-west.

5.2. Boulder distribution and characteristics

As far as relief is concerned, sandstone boulders may be found in two positions, namely on the plateau itself and within the V-shaped incision to the north-west of it (Fig. 7). The plateau boulders are widely scattered, some more than 100 m from the nearest neighbour. However, they do form two groups. The eastern group occupies the highest part of the plateau and consists of one small cluster of four blocks and five other boulders. The western part includes eight solitary blocks and one small cluster (Fig. 8A, B). The dimensions of boulders are variable, with the largest ones measuring 10 m × 8.5 m × 2.5 m and 10 m × 4 m × 3.5 m. In terms of height, a block next to the channel of Machovský Potok stands out, measuring 6.5 m (Fig. 8C). A notable feature of many boulders is the presence of varied microrelief. Among specific weathering landforms are shallow pans on horizontal upper surfaces, some as large as 100 cm × 90 cm, as well as raised rims, arcades and elongated caverns within vertical surfaces, developed at the intersection with bedding planes.

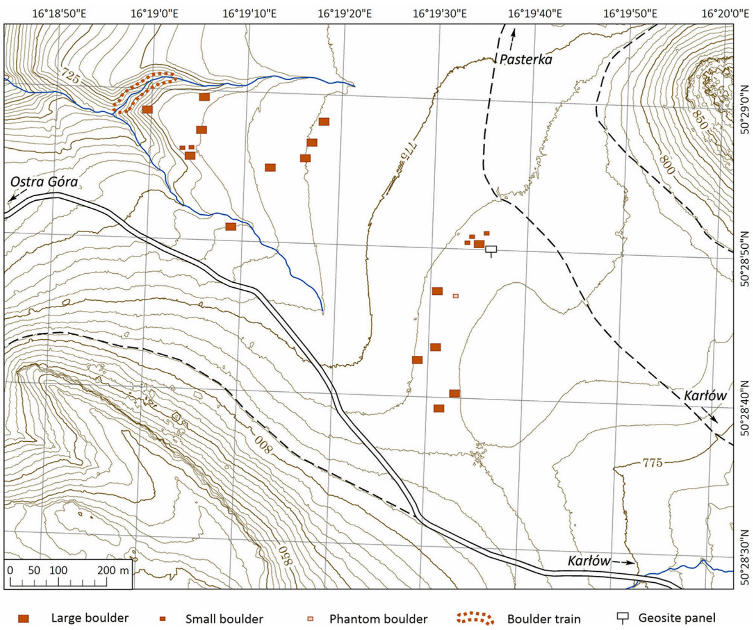

Fig. 7. Spatial distribution of sandstone boulders on the plateau of Pustelnik. Contour lines are derived from a high-resolution (1 m × 1 m) digital relief model, available at www.geoportal.gov.pl

Fig. 8. Various aspects of sandstone boulders on the plateau of Pustelnik. **A –** cluster of several boulders; **B –** solitary boulder on completely level terrain; **C, D –** large boulders rotated to near-vertical positions; **E –** boulders on the bottom of fluvial incision to the north-west of the plateau; **F –** remnants of boulder quarrying.

Wavy textures are likely exposed boundary surfaces separating sandstone beds, with hollows indicating places where lithification was incomplete and loose sand could have been removed, possibly with an additional role played by gas bubbles (see Dumanowski, 1961a). Whereas some boulders are massive and the recognition of bedding planes is not possible, others show these structural surfaces fairly clearly. In some boulders they are close to horizontal, as in the parent rock *in situ*, but in others bedding planes dip at various angles, from 20–40° to 80–90°, indicating considerable rotation in respect to the original position (Fig. 8C, D). Boulders inside the incision are generally smaller than those on the plateau (Fig. 8E). The largest one is 6 m × 4 m × 3.5 m, followed by 5 m × 4 m × 2.5 m. Altogether, 14 boulders longer than 1.5 m occur on the valley floor. As at the previous locality, boulder quarrying was practised for domestic purposes (Fig. 8F) and it is possible that the number of boulders on the plateau was higher in the past, as also suggested by shallow pits and debris leftovers.

6. Origin of boulders

For a long time, isolated sandstone boulders on the main plateau of the Stołowe Mountains were overlooked in geomorphological research. In fact, similar localities elsewhere (e.g., Elbsandsteingebirge, Germany) also escaped attention (Migoń et al., 2020; Migoń, 2021). Boulders at Rogowa Kopa were erroneously interpreted as simple *in-situ* remnants of the upper jointed sandstone (Walczak, 1968), ignoring the fact that the lower boundary of this rock series occurs more than 50 m above the morphological surface, on which the boulders rest. The presence of sandstone boulders inside poorly accessible deep incisions to the west of the plateau was never reported prior to the recent intensification of geomorphic research in the Stołowe Mountains. Parzóch et al. (2009) first drew attention to the enigma of these boulders and linked them with long-term escarpment retreat and undercutting of the Rogowa Kopa plateau, so that boulders originally positioned on the plateau began to move downslope, eventually reaching the valley floors where they came to rest. However, they did not discuss the origin of the boulders themselves. This conceptual model was subsequently developed by Parzóch & Migoń (2015), who also suggested that plateau boulders testified to the past existence of a detached outlier of the main plateau that had completely disintegrated, leaving only scattered caprock remnants in allochthonous positions. Residual boulders at Pustelnik were not mentioned at all until the publication by Migoń (2010) in a local natural history journal.

Any attempt to explain the origin of scattered sandstone boulders on the mudstone-underlain main plateau needs to consider that: (a) boulders are not rooted in bedrock, i.e., they are not in original position, (b) *in-situ* outcrops of quartz sandstone are both far away from the boulders (a minimum of 450 m at Pustelnik and 1 km at Rogowa Kopa) and stratigraphically more than 50 m above the elevation at which boulders occur. Local relief and the presence of escarpment-parallel valleys rules out the scenario that boulders may be the products of long-term, gravity-driven transport from the escarpments as movement against the gravity and over horizontal surfaces would then have been involved. There is also a notable lack of continuity of boulders towards the boulder-mantled slopes of the escarpments, expected if there were any causal connection. The rotated position of some boulders, even up to vertical, is also significant and suggests an episode of displacement from the original position. Duszyński et al. (2016) argued that progressive boulder rotation was one of consequences of sand removal by subterranean flows, apparently common in the sandstone caprock and at its contact with much less permeable fine-grained rocks beneath. Various stages of block displacement due to the removal of vertical support have recently been documented in a geologically and geomorphologically similar setting in the German Elbsandsteingebirge (Migoń et al., 2020).

Thus, the most plausible scenario, valid for both localities presented herein, seems to involve the following steps (Fig. 9):

1. Dissection and non-uniform retreat of escarpments bounding the upper plateau led to the separation of minor sandstone-capped hills (mesas, buttes) (Fig. 9A). Two such hills are hypothesised to have been present at the locality of Pustelnik (south-eastern and north-western boulder clusters – see Fig. 7), whereas at the Rogowa Kopa site no similar spatial dispersal/clustering occurs. At a larger scale, the twin mesa of Szczeliniec Wielki/Szczeliniec Mały, detached from the Skalniak plateau, is an example of such separation.
2. Ongoing retreat of sandstone cliffs, whether by incremental events of rock fall/topple or slow *in-situ* disintegration, or both, transformed the mesas into ruiniform relief, consisting of disconnected sandstone blocks of varying dimensions (Fig. 9B). Rotation of some blocks may have occurred, whereas others settled down without rotation.
3. Exposure of less resistant fine-grained rock series resulted in their accelerated disintegration and decomposition (where the calcium-carbonate content was significant), whereas remnant caprock boulders survived by virtue of their massiveness and mineralogical composition (Fig. 9C). Further boulder displacement according to the local slope may have occurred.
4. Levelling of residual hills (‘ghosts’ of former mesas and buttes) to the general plateau level, with the current distribution of boulders reflecting both the original position of a residual hill and subsequent local displacements. Because of the negligible slope of the plateau boulders are essentially immobile (Fig. 9D).
5. Headward erosion undercuts the margins of the plateau, reducing its extent. Wherever the expanding incisions reach the boulders, they begin to move down the steep slopes towards the valley floors (Fig. 9E).
6. Boulders themselves are too large and heavy to be moved by low-discharge streams, but incision into weak bedrock may alter their balance of position and slow displacements down the valley are possible. The largest boulders are the most difficult to displace and these form barriers, inducing the development of boulder clusters.

This scenario is hypothetical and, unfortunately, currently unconstrained in terms of temporal

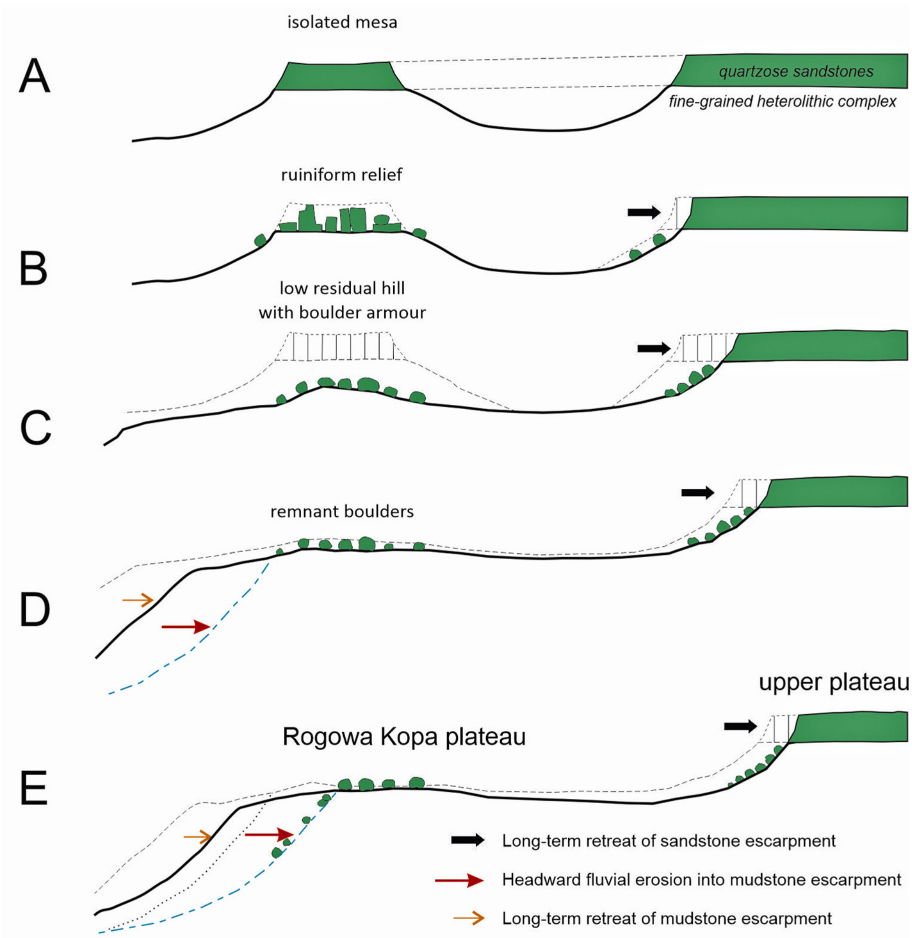

Fig. 9. Scenario of hypothetical evolution of tableland landscape leading to the occurrence of boulders on the plateau and boulder trains in the valleys incised into the plateau, based on Parzóch & Migoń (2015, modified).

scale, but it does overcome problems posed by alternative concepts involving considerable lateral displacements and is consistent with the geological structure of the tableland (i.e., stratigraphical position of quartz sandstone). The suggested intermediate phases within this scenario have been shown to occur as real landform assemblages elsewhere in the central European sandstone region, in the Elbsandsteingebirge of eastern Germany (Migoń et al., 2020).

7. Boulder clusters as geosites and problems of interpretation

Geoheritage may simply be defined as part of the rock and landform record that is of value and, hence, should be subject to conservation and protection (Brocx & Semeniuk, 2007; Brilha, 2018). As such, these records acquire educational value and may be used for the purposes of teaching and learning. A special role is played by localities that illustrate a given geological or geomorphological phenomenon in the best or most complete way, helping to understand a piece of Earth history. These are commonly known as geosites (Reynard, 2004), whose educational services are greatly facilitated by easy access. Therefore, the question is whether or not the boulder clusters in the Stołowe Mountains tableland can be considered as geosites and what are the challenges associated with their status as such.

We argue that the simple answer to first question is 'yes'. Not only do the residual sandstone boulders on the main plateau enhance the scenery, as was appreciated already some time ago (Walczak, 1968), they are also key witnesses to long-term landform evolution in stepped tablelands and show the possible ultimate fate of residual tabular hills. Moreover, they illustrate the longevity of residual geomorphic elements and how these elements may influence the evolution of valley floor morphology, which may seem a very different, unrelated theme. Although inconspicuous at first sight, not easy to interpret and far less grand than adjacent ruiniformed mesa tops and rock labyrinths, these boulders are among the most significant elements of geomorphological heritage of the region. Their scientific value is enhanced by good access to at least some of the boulders and there is also an associated cultural value. In the distant past (19th and early 20th centuries), boulders were used as a local source of building stone and traces of these human activities can still be observed.

In fact, both localities have already been presented as valuable sites of interest for visitors who are willing to understand the story behind the scenery better, i.e., geotourists. Within the project that involved the erection of six geological interpretation panels at key spots, the Pustelnik locality was selected as one of these sites (Wojewoda, 2011). The panel includes a sketch showing alternative scenarios of how the boulders could have come to their current position and a special access path was marked (Fig. 10). The localities of Pustelnik and Łężyckie Skałki are both included in a geotourist guidebook for the Stołowe Mountains (Duszyński et al., 2015), whose updated edition (issued 2018) can be downloaded from the National Park website (https://www.pngs.com.pl/data/wydawnictwa/Przewodnik%20geomorfologiczny%20_Gory_Stolowe_2018.pdf). However, no on-site interpretation facilities are available at the Łężyckie Skałki locality and one may wonder how many tourists who pass by the boulders in actual fact realise that they find themselves in one of the most important sites for deciphering patterns of landform evolution in the tableland.

Legal access to boulders, regulated by rules applicable to national parks in Poland, is in fact quite limited and this does not help in our appreciation of their actual distribution. Only waymarked paths can be used and leaving the trails is forbidden. Moreover, the western escarpment of Mt. Rogowa Kopa is a strict protection area. Therefore, at Pustelnik tourists can only see part of the south-eastern cluster, whereas large boulders of the north-western cluster are off limits and cannot be seen from a distance. At Łężyckie Skałki boulders are more clustered and one can have a panoramic view of their distribution, although those hidden in the woodland remain out of sight. Unfortunately, impressive boulder clusters in fluvial incisions are completely inaccessible, although these are good localities to explain the phenomenon of ploughing blocks and conditions of fluvial transport. The development of 'virtual geosites' to be viewed through a dedicated webpage may be an option to consider in such circumstances, although this may also prompt people to ignore restrictions and try to reach the localities anyway.

Interpreting the boulders in an accessible way is also challenging and there are several associated problems. First, the history of boulders is interpreted from various complementary lines of evidence, whereas storytelling with too many uncertainties embedded may be in conflict with the expectations of the general public to read a simple, clear story on either on-site panels or in off-site resources. However, if the story is told in a more affirmative way, this may create discomfort among scientists who are involved in geo-interpretation. Secondly, the entire story is complex (see the scenario outlined in section 5) and will require a lengthy narrative, which is rather discouraged, especially for on-site interpretation panels (Macadam, 2018; Bruno & Wallace, 2019). Thirdly, visitors cannot be directed to other localities in the Stołowe Mountains that would illustrate intermediate phases of relief evolution, as they

Fig. 10. Geotourist facilities at the Pustelnik site. Information panel and railing at the panoramic viewpoint (in the background). Note that the panel does not obscure the view of the boulders.

do not exist. Thus, the space-for-time substitution concept, recently shown to be useful in interpretation of the mesa-dominated sandstone landscape of the Elbsandsteingebirge (Migoń et al., 2019), cannot be adopted. Fourthly, and lastly, the processes implied to occur are slow and not spectacular (as opposed to events such rock falls or landslides), thus with less potential to engage casual visitors whose background in geosciences is usually very limited.

8. Conclusions and final remarks

Two clusters of allochthonous sandstone boulders on the levelled surface of the main plateau of the Stołowe Mountains and boulder trains in the adjacent erosional incisions are sites of considerable significance for deciphering the long-term geomorphic history of sandstone tablelands. They originated through initial separation of sandstone-capped outliers from the upper plateau, followed by progressive caprock disintegration, minor displacements associated with rotation, surface lowering and concurrent sagging of boulders to the stage of a residual boulder blanket that is observed today. In-valley boulder trains result from fluvial undercutting of the main plateau and further relocation of residual boulders into expanding valley incisions.

This intriguing history of landform evolution sets the stage for assessment of the geoheritage and geotouristic potential of both localities. The Stołowe Mountains tableland is among the most visited tourist destinations in south-west Poland, with approximately 1 million visitors annually. They are attracted mainly by the scenic ruiniform relief on top of Mt. Szczeliniec Wielki mesa and the rock labyrinth of Błędne Skały, resulting in considerable congestion in the peak season, exhaustion of tourist-carrying capacity and a range of environmental and management problems. To address this issue, alternative tourist destinations are increasingly promoted in order to disperse tourist flows. However, in view of the fact that the core values of the Stołowe Mountains National Park reside in their exceptional geoheritage, geotourism with a strong educational component is considered an important part of the mission of the National Park. The two localities presented herein, albeit far less conspicuous at first sight than the star attractions of the area, have considerable geoheritage values and may become exciting geosites, especially if proper interpretation becomes available. Until now, they are visited by a minority of tourists and appreciated for their scenic rather than scientific values. However, they do tell a complex story of plateau and escarpment evolution and represent end-members of a long-term evolutionary pathway, with the nearest analogous examples in the Elbsandsteingebirge of Saxony, eastern Germany.

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