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ORIGINAL ARTICLE

From Plateau to Plain—Using Space-for-Time Substitution in Geoheritage Interpretation, Elbsandsteingebirge, Germany

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Abstract

The southern part of Elbsandsteingebirge in east Germany represents tableland morphology, with more than a dozen of residual tabular hills—plateaus, mesas and buttes. Their morphological diversity and close proximity to one another create an opportunity to use the ergodic principle (i.e. space-for-time substitution) as a framework for geoheritage interpretation and the development of a thematic geotourist trail. The virtual trail proposed here links eight localities, from the largest and least dissected plateau remnant (Grosser Zschirnstein) to the scatter of allochthonous boulders (Zeisighübel), claiming that they may illustrate the sequential development of erosional landforms in sandstone tablelands. It is argued that ergodic principle is a powerful explanatory tool designed for the general public and more advanced visitors, even though such an approach may not be an accurate reflection of the actual landscape evolution and does not take into account the rates of landform change. The concept is applicable to other localities, and there is usually an option to add further elements (sites) to the existing routes.

Keywords Sandstone · Tableland · Mesa · Escarpment retreat · Elbsandsteingebirge

Introduction

Interpretation of geoheritage and dissemination of knowledge about the Earth is accomplished by various means and techniques, both outdoor and indoor, and with or without personal interaction with an interpreter (Hose 2005). Among outdoor services, interpretation panels remain the most popular, despite a variety of problems associated with their design, erection and maintenance (Hughes and Ballantyne 2010; Macadam 2018). Nowadays, options to replace panels by mobile applications are explored as, despite various technical and perceptual problems, they are less intrusive (Reynard et al. 2015; Cayla and Martin 2018). However, the key issue is what should be the interpretation content provided at geosites, whether by a panel or a Web-based resource. Approaches vary hugely, and some authors argue that there is a limit of words beyond which the message is hardly absorbed (Macadam 2018). This is a questionable statement since it seems to ignore the needs of more interested groups, with some a priori knowledge who seek in-depth information (see Dowling 2011). In particular, developing a story is then difficult. One way of coping with the problem is to plan a series of panels along a predesigned route, i.e. building a trail. Panels would consequently explore a theme rather than simply provide factual information, unrelated to each other (e.g. Migoń and Pijet-Migoń 2017). Such a storytelling approach may seem straightforward, but it actually faces difficulties in choosing appropriate sites which could be visited in a certain order, so that particular issues would be logically linked with one another.

There are various options possible while choosing and following an overarching theme in geoscientific storytelling. The framework could be related to the passage of geological time (i.e. from the oldest to youngest events recorded in rocks); it could reflect pathways of sediment transfer and it could guide a visitor from natural features to examples of human use, etc. If landforms and scenery are the main subjects of interpretation, one can trace their evolution through time. In this way, the contemporary, usually fairly static landscape, can be shown in its dynamic dimension and various landforming events re-created in the minds of users. Having dates of landforms and sediments available would be particularly helpful since the whole story can be then reliably set in the temporal context, but for large-scale erosional landscapes, such dates are either very scarce, uncertain or even non-existent.

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Textbooks of geomorphology and physical geology often show the progress of erosion and dissection using tablelands (plateaus) and their assumed reduction towards isolated mesas and buttes, making use of space-for-time substitution, otherwise known as ‘ergodic principle’ (see Craig 1982; Paine 1985). We argue that despite reservations to the scientific rigour of this approach, it can serve as a powerful interpretative tool, and we will demonstrate its applicability to the scenic, mesa-dominated sandstone landscape of Elbsandsteingebirge in the eastern part of Germany. The virtual ‘mesa trail’, based on the principle of space-for-time substitution, will help to enliven the otherwise quite a static landscape.

Ergodic Principle

Ergodic principle (or transformation) is a concept developed in physics which holds that the average behaviour of many particles in one moment in time is equal to the average behaviour of one particle over a prolonged period. It was transferred to geomorphology to help unravel and visualize landform evolution through time, acknowledging that the timescales of landform evolution are typically much longer than our abilities to observe and monitor landform changes (Thornes and Brunsden 1977; Craig 1982). It was shown later that the understanding and application of the principle by geoscientists depart from the original meaning, and the expression ‘space-for-time substitution’ (Paine 1985; Thorn 1990) is more appropriate. In this approach, real-world examples of a landform of (assumed) identical origin, but in apparently different stages of decay, are collected and juxtaposed in such a way as to illustrate the temporal sequence which cannot be eyewitnessed. For instance, mountain fronts of variable geomorphic clarity are compared with one another to derive a model sequence of degradation of faulting-generated landforms through time. Thornes and Brunsden (1977), Paine (1985) and Thorn (1990) discussed at length the weaknesses of this approach and recommended caution in its use, but despite the criticism, it remains a frequently used teaching tool to show how landforms *may* evolve through time. The role of the research is then to validate such conceptual models.

Study Area

The study area is located in the eastern part of Germany, in the province of Saxony, c. 40 km south-east of the city of Dresden (Fig. 1). Geologically, it is dominated by flat-lying Cretaceous sedimentary rocks whereas their outcrop area is crossed by the Elbe river which forms a spectacular canyon. Hence, the whole region is known as Elbsandsteingebirge (Elbe Sandstone Mountains), even though it lacks most of geomorphic features of a mountain relief. The overall relief energy is only 300 m, and the scenery consists mainly of planar surfaces of plateaus, structural benches, plains and mesa tops (Fig. 2). However, these level surfaces are separated by steep escarpments, with the upper slope cliffs locally up to 60-m high. Deeply incised valleys, lined with cliffs and rock spurs, account for dissection of the escarpments and fragmentation of the plateaus.

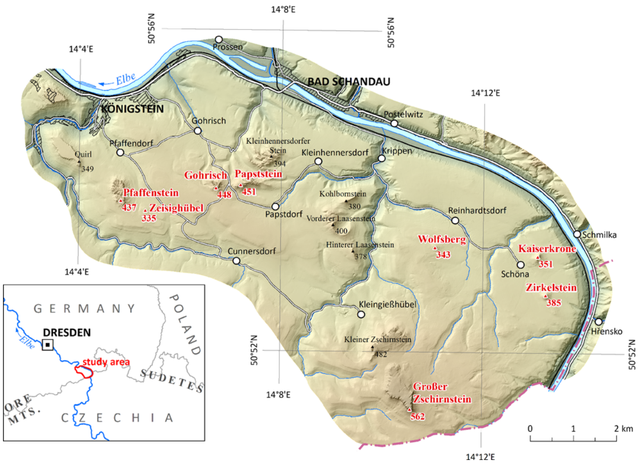

Fig. 1 The study area

The Elbe canyon divides Elbsandsteingebirge into two regions of contrasting morphology. The part north of the Elbe is mainly a heavily dissected plateau, with a labyrinth of minor canyons, gorges and ravines. By contrast, the southern part is dominated by isolated tabular hills—mesas and buttes. They range in altitude from 560 m (Grosser Zschirnstein) to barely above 300 m (Rauenstein) and vary in areal extent of the planar top surface, from 27.8 ha (Grosser Zschirnstein) to 0.09 ha (Zirkelstein).

Cretaceous sediments of the mesa terrain are all of marine origin, with the period of deposition starting in the Cenomanian (99.5 Ma) and continuing at least to the Middle Coniacian (c. 85 Ma ago) as this is the age of the youngest preserved sandstone units (Tröger 2008; Wilmsen and Niebuhr 2014). The present-day mesa landscape was located in the proximal part of the Cretaceous sedimentary basin; hence, sandstone is the dominating lithology and is divided into five units, grouped into the lower Postelwitz Formation (units a, b and c1) and the upper Schrammstein Formation (units c2–3, d, e). Among them, units c3, d and e are thickly bedded and support rock cliffs which either crown the mesas or build rocky precipices in the middle slopes (Lamprecht 1927 (cited after Gerth 2012); Rast 1959). The thickness of these massive sandstone units varies from 20 to 80 m. Sandstones are quartz-dominated, with occasional kaolinised feldspars, medium to coarse-grained, typically cross-bedded. Sandstone beds are separated by thin (up to 4 m in thickness) horizons of poorly cemented fine-grained sandstones, glauconitic sandy marls and claystones, denoted as $\alpha3$, $\beta3$, $\gamma3$ and $\delta2$. These fine-grained sediments play an important geomorphic role, focusing interstrata weathering.

Fig. 2 General view of the sandstone tableland of Elbsandsteingebirge, with its numerous mesas (photo by P. Migoń)

Hence, they mark the boundary between cliffs and more gentle slope sections, underlie mid slope benches and support bedding caves (Rast 1959).

Whereas the general relationships between landforms and geological structure are fairly well recognized (Rast 1959; Lobst 1993), the evolution of sandstone landforms themselves is poorly known and the classic description by Hettner (1903) remains a useful reference. Rast (1959) included numerous comments about landforms, especially the minor ones (caves, overhangs, clefts, huge boulders), but was less focused on processes and landform change through time. Studies of the Pliocene–Quaternary history of the Elbe and Pleistocene glaciations (Wolf and Alexowsky 1994) provide context, but since their scope was different, they allow for only indirect inference about the evolution of escarpments. Therefore, the actual timescale of landscape evolution remains largely hypothetical. Preglacial gravel deposits scattered on plains at 250–270 m a.s.l., c. 40 m above the present-day Elbe channel, indicate that the river flowed over a wide planar surface and was entrenched only subsequently. However, this provides a little clue regarding the appearance of the interfluves. The Elsterian ice sheet reached the area, issuing a lobe flowing up the Elbe valley and terminating approximately north of the present-day German/Czech border, at c. 400 m a.s.l., but its impact on the sandstone tabular relief is unknown. The map by Lobst (1993) shows certain higher mesas (> 400 m a.s.l.) as nunataks but lacks consistency in this respect, and it is not clear what kind of evidence is available to support this cartographic presentation. The feasibility study of possible UNESCO World Heritage nomination asserted that 'by the end of the Tertiary, c. 2.6 million years ago, the general morphological features of the mesas were already shaped' (*Potentialanalyse*… 2006; our own translation), but the basis for this statement is unclear.

On the other hand, there is a large accumulated knowledge about rock slope failures from the nineteenth and twentieth centuries in the region, among them several rock falls affecting the mesas considered in this paper (*Wander*-… 2013). Likewise, caves of different origin have been documented throughout the region, providing evidence of various types of slope instability (Bellmann 2005; *Wander*-… 2013). Thus, while little temporal framework can be offered, geomorphological evidence seems sufficient to decipher the main pathways of escarpment evolution.

The Rationale of the Trail and Methods

The concept of the mesa trail utilizes the space-for-time substitution in the following way. It is assumed that geomorphic evolution of tablelands with prominent caprock proceeds through ongoing dissection of an original plateau and its fragmentation, whereas bounding escarpments retreat over time and they do so non-uniformly in space. Therefore, while the plateau is generally reduced in extent, tabular hills may be isolated in front of the main receding escarpment. They, in turn, reduce in extent too through the concurrent action of joint-guided weathering and erosion within the mesas and escarpment retreat at the perimeter of the mesas. Consequently, they may be divided into minor compartments or become buttes, i.e. hills crowned with only remnant caprock, where the height of the cliff is approximately the same as the width of the top surface. In the penultimate stage, only residual caprock blocks are left and they may persist in the landscape long after other evidence of existence of a hill disappears (Fig. 3).

Thus, within the mesa-and-butte landscape of Elbsandsteingebirge examples were sought which might illustrate consecutive phases of geomorphic evolution and are then presented in the order approximating this evolution. Grosser Zschirnstein, the largest and practically undissected, opens the sequence which ends with Zirkelstein—a classic example of a butte, and Wolfsberg, which almost lost its caprock. A boulder-covered gentle terrain swell of Zeisighübel—an ultimate stage of mesa evolution—complements the story. Distribution and distances between the hills (Fig. 1) preclude marking of a trail which would connect the examples in a geographically logical way and could be visited within 1 day. In fact, mesas such as Pfaffenstein are so diverse

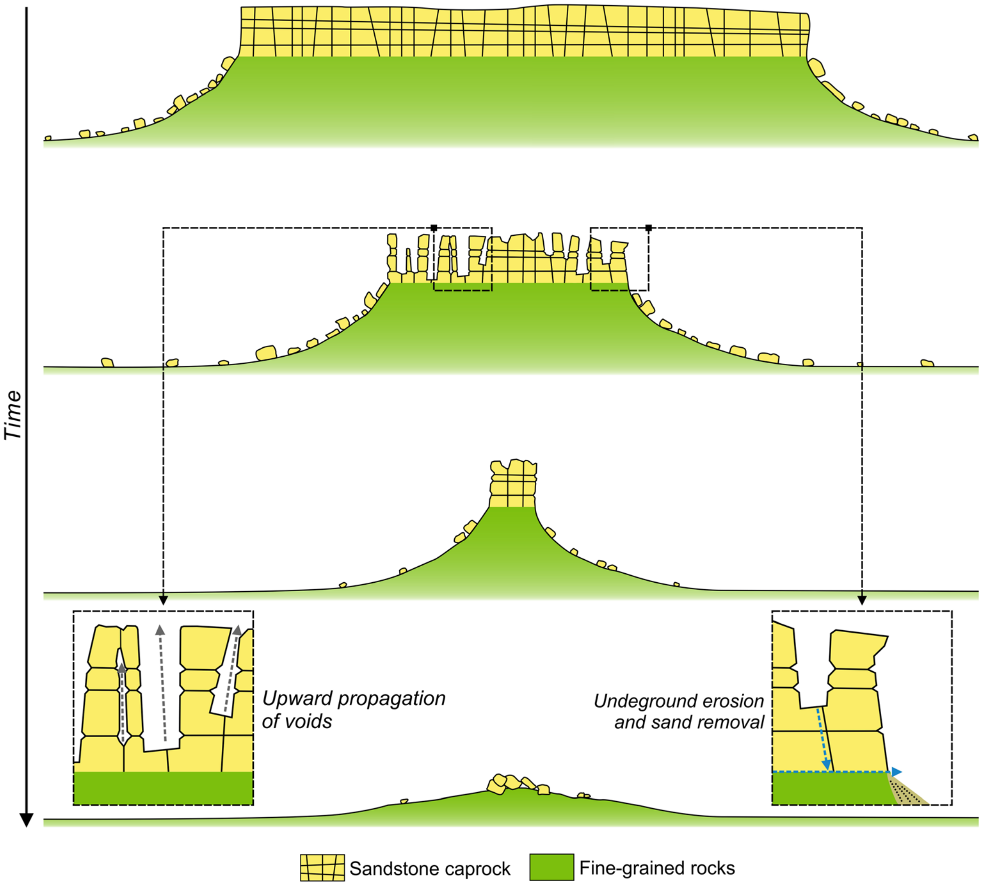

Fig. 3 Model representation of evolution of sandstone tabular hills, from plateau through mesa, butte, to a residual pile of boulders

morphologically and scenic that may easily fill half a day. Therefore, the trail is rather conceived as a virtual one and travelled by car, in combination with hiking.

The proposal outlined in this paper is based on extensive field observations focused on landform recognition, mapping and establishing spatial relationships. Each presented mesa was visited and walked, both its upper surface and the perimeters, to identify geomorphic features indicative of cliff disintegration. Some additional observations were derived from examination of satellite images available at Google Earth, although the dense forest hides morphological details of the bounding escarpments. Landform recognition and mapping were substantially aided by the availability of high-resolution (2 × 2 m) LiDAR-based digital terrain model DGM2. The model was used while performing basic morphometric analysis of mesas and creating 3D visualizations in ArcGIS 10.2.2 environment.

Trail Stops—Phases of Landscape Evolution

Grosser Zschirnstein

The large table hill of Grosser Zschirnstein, representing due to its considerable surface area a transitional stage between a plateau and a mesa (Fig. 4a), has been selected to illustrate the early stage of mesa evolution. The plateau surface is more than 1.1-km long in NNW–SSE extension and 0.6 km wide in the central section, narrowing in both the southern and northern directions. It is inclined to the north, following the dip of sandstone beds. Consequently, the highest spot, 560 m a.s.l., is located at the southernmost tip of the mesa and the total height from the footslope is 110 m, contrasting with c. 40 m on the northern side. The top surface, underlain by sandstone of ‘d’ unit, is practically undissected, with only one, quite short re-entrant on the western side, and lacks rock outcrops. Sandstone cliffs bound the mesa along approximately two thirds of its perimeter, being absent only along a part of the eastern side. However, they vary in height, morphology and continuity. In the north, cliffs are up to 10 m high and form one step, with trough embayments separating sections of rock faces. In the south, the total height of rock cliffs reaches 50 m, with several steps and intervening benches, reflecting superposition of massive sandstone beds and the occurrence of weak, weathering-prone horizons in between. Major joint sets follow 40–45° and 125–130° directions (Fig. 4b).

Evidence of cliff disintegration and retreat is best observed around the southern end and the south–western section of the mesa rim. Numerous examples of columns and towers, up to 12 m high, separated from the main cliff line

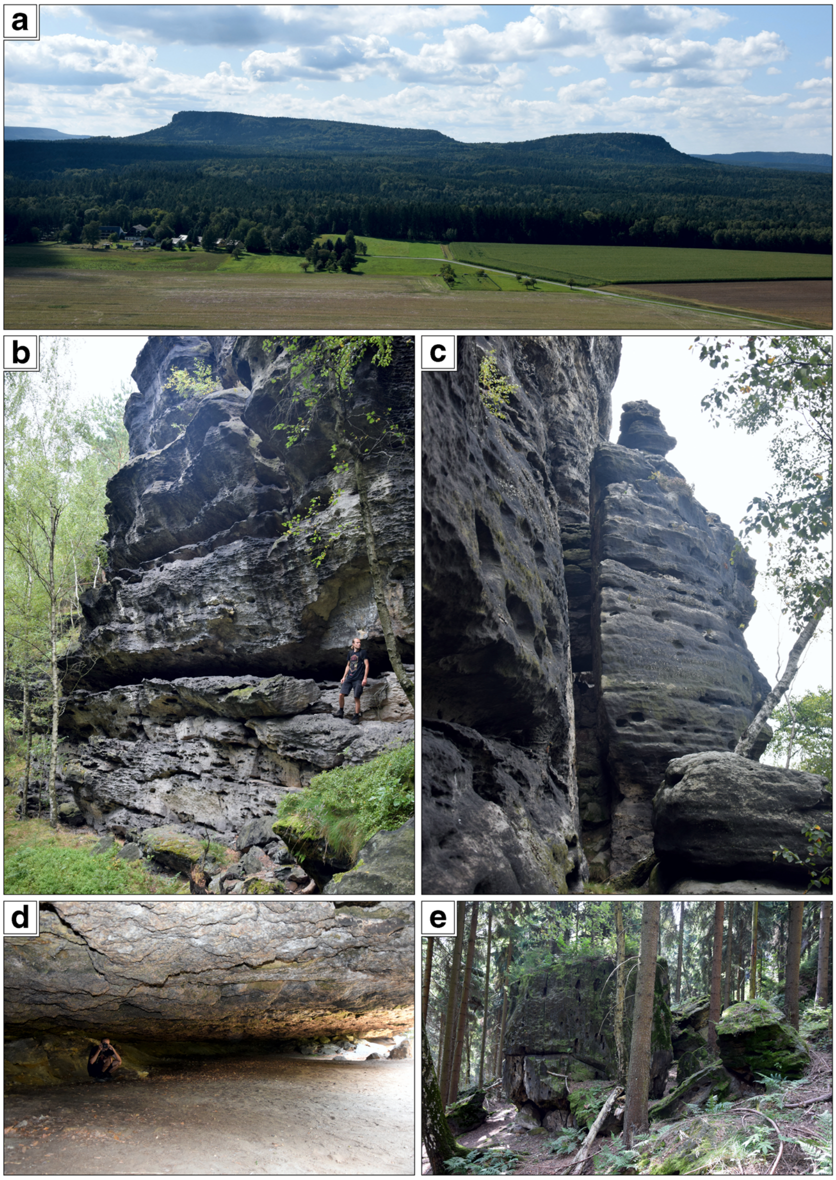

Fig. 4 Features of geomorphological interest at Grosser Zschirnstein. **a** General view of the mesa from Zirkelstein (smaller mesa of Kleiner Zschirnstein is adjacent to the right). **b** Heavily weathered cliffs, with ledges and overhangs along bedding planes. **c** Tower-like compartment separated from the main cliff line. **d** One of large bedding caves. **e** Block field in the middle slope (note the vertical attitude of originally horizontal bedding planes) (all photos by P. Migoń)

occur there (Fig. 4c), whereas large boulders in rotated position, up to 4-m high, as well as those roofing the clefts, testify to ultimate tower collapses. However, initial separation appears accomplished by preferential weathering of closely spaced joints rather than gliding and toppling. Cliffs of Grosser Zschirnstein are also hosts of numerous bedding caves, some as deep as 15 m into the rock, with the height of 1.5 m (Fig. 4d). They have developed along the thin, weak marly horizon $\gamma 3$ or 1st order bedding planes and cause undermining of the higher cliff sections and, probably, slow sagging rather than catastrophic collapse. Another indicator of rather slow evolution of cliff faces is the diverse surface microrelief due to selective weathering, with honeycombs and tafoni. Although their ages and rates of deepening cannot be constrained, they clearly show that considerable time intervals must have elapsed since the last rock falls.

The top surface of the mesa can be accessed using a marked trail which goes to the viewing point at the southern end of the mesa. This spot allows one to appreciate the position of the remnant plateau amidst an extensive lower plain and the sharp transition between the planar upper surface and high bounding cliffs. To see the evidence of cliff disintegration, however, one would have to reach the base of the mesa which is not possible from the top (Fig. 4e). An unmarked forest road traversing the western slope may be used for this purpose, and the undercliff can be explored since no restrictions regarding visitations exist at Grosser Zschirnstein.

Gohrisch

The mesa of Gohrisch may be considered as the next stage illustrating the sequential development of tabular hills, although it is considerably smaller in size than Pfaffenstein or Papststein. This positioning of Gohrish is due to limited fragmentation of its plateau surface, with only one short canyon penetrating into its interior from the west. The sandstone caprock is made of unit ‘e’, whereas the base of cliffs is largely connected with the fine-grained δ2 horizon (although, this is hardly exposed). The outline of the mesa follows the direction of two principal joint sets: 35° and 110°. These directions also control the extension of clefts, fissure caves and impenetrable slots breaking the continuity of the plateau.

The mesa is roughly triangular in plan and the plateau surface occupies c. 250 × 220 m, terminating with rock precipices all along its perimeter (Fig. 5a). These cliffs are up to 30-m high, distinctly joint-controlled and poorly dissected. Although one can identify narrow vertical zones of dense jointing (1–2 m wide), some with evidence of in situ disintegration (Fig. 5b), they are yet to be cleaned and widened by erosion to allow human penetration. In the northern part of the mesa, a rectangular system of clefts is cut into the plateau surface but they open high within the cliffs. The upper surface, except the few clefts and slots, is close to level, with residual relief of minor humps and steps up to a few metres high.

The most impressive examples of cliff degradation can be observed along the south–western part, where deep slots extend into the caprock (one was partly widened to allow construction of an alternative trail to the mesa top), clefts separate isolated towers from the main cliffs (Fig. 5c), and evidence of both forward and backward (rotational) toppling is visible. Boulder piles testify to occasional rock slope collapses (Fig. 5d). They are also common along the northern plateau rim, but this part is beyond marked trails and more difficult to access. A large overhang, > 20 m long and 5 m deep into the cliff, occurs in the north–eastern part of the mesa along the δ2 horizon, and the enlargement of such features is clearly another factor destabilizing the cliffs.

Gohrisch was developed for tourists in the 1880s (*Wander-*… 2013), as the last mesa in Elbsandsteingebirge, and the existing network of trails allows one to see most of

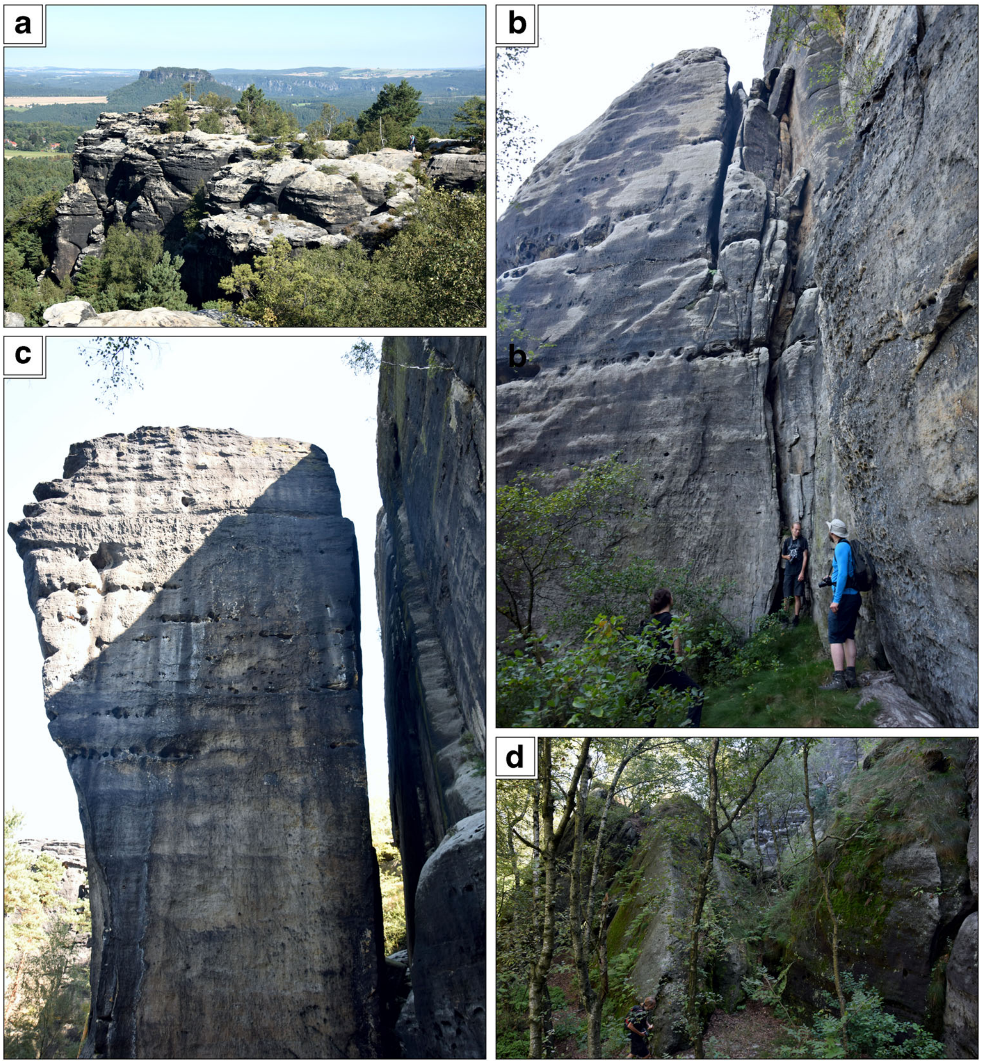

Fig. 5 Features of geomorphological interest at Gohrisch. **a** Heavily weathered and dissected top surface. **b** Cleft development along more densely jointed rock compartments. **c** High tower separated from the main cliff line. **d** Irregular accumulation of sandstone blocks below the cliff line (all photos by P. Migoń)

geomorphic features indicated above. There are paths across the plateau and into the hanging cleft system in the NE part, while three different trails can be used to ascend or descend the plateau. The Falkenschlucht (Falcon cleft) trail is particularly impressive, showing gravitational cleft opening and connecting to the foot of the cliffs where evidence of block detachment and collapse is abundant.

Pfaffenstein

The mesa of Pfaffenstein (437 m) (Fig. 6a) is morphologically the most diverse among tabular hills of the Elbsandsteingebirge, being shaped into a true rock city (Migoń et al. 2017) and probably the most visited, too. Being more than 650 m long and up to 300 m wide, it combines several distinctive sub-types of mesa morphology (Fig. 7). The northern part represents a relatively undissected top surface (1 in Fig. 7), whereas the northwestern part is a labyrinth of deep canyons and clefts which follow the grid pattern of 25° and 110° striking vertical joints (2). The southern tip of the plateau is sculpted into ruiniform relief (3), in stark contrast to Grosser Zschirnstein where the planar mesa top surface terminates against the cliff line. Finally, a deep gorge penetrates into the mesa from the west, nearly ending at its eastern rim (4), hence dividing the mesa into two compartments. Thus, Pfaffenstein is taken as an example of a mesa which partly retains its massiveness but is already subject to dissection and fragmentation. Sandstone caprock of Pfaffenstein belongs to ‘d’ and ‘e’ units, with the intervening δ2 horizon accounting for a distinctive bench in the southern and western part.

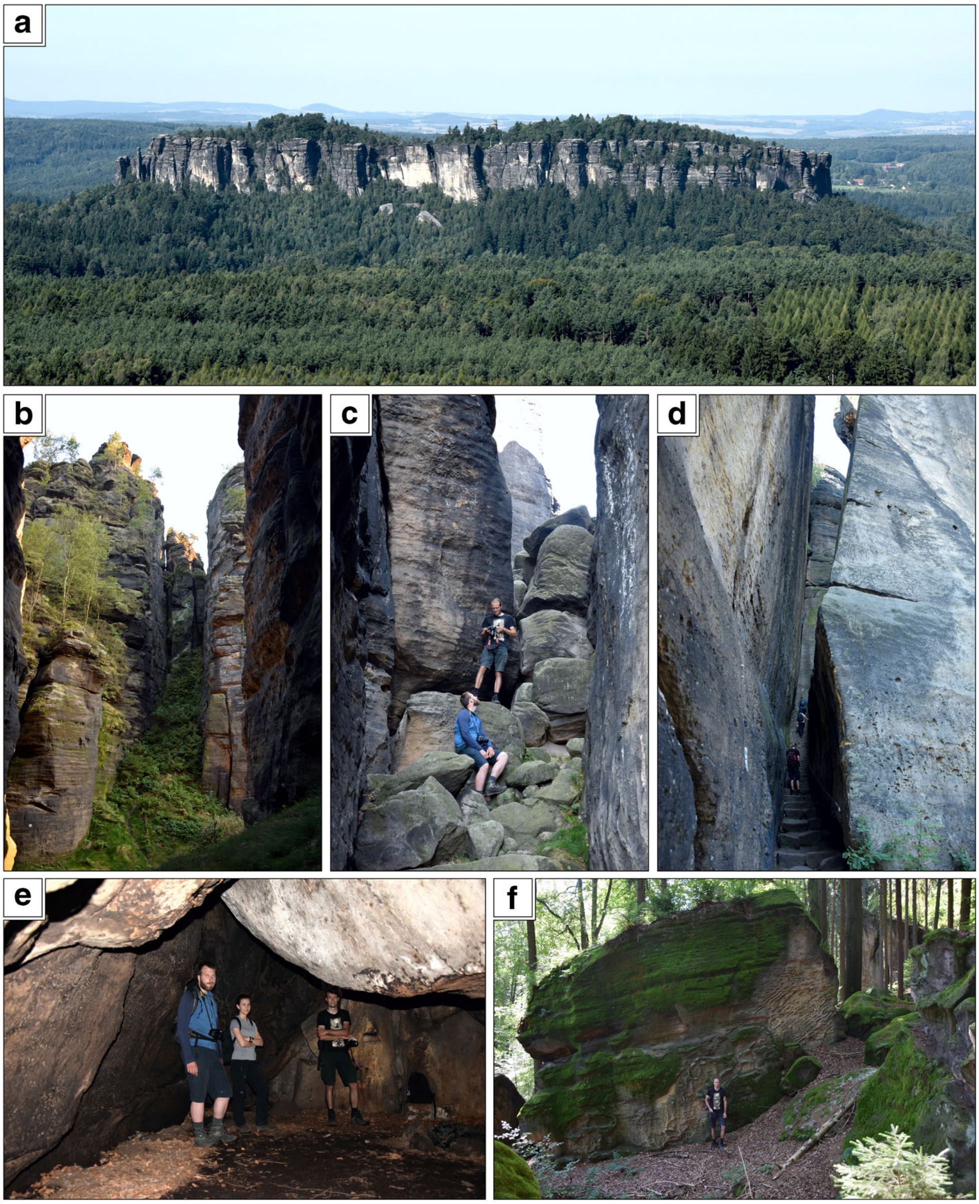

Fig. 6 Features of geomorphological interest at Pfaffenstein. **a** General view from Gohrisch. Note the scar left after the 1838 rock fall in the middle, with huge sandstone blocks in front and the displaced and back-tilted tower of Einsiedler in the right. **b** Canyon section in the NW part of the mesa. **c** Boulder fill of clefts testifies to in situ disintegration of more densely jointed parts. **d** Cleft opening due to slow gravity-driven movement of a rock tower. **e** Boulder cave inside one of the canyons. **f** Big blocks in the lower slope (all photos by P. Migoń)

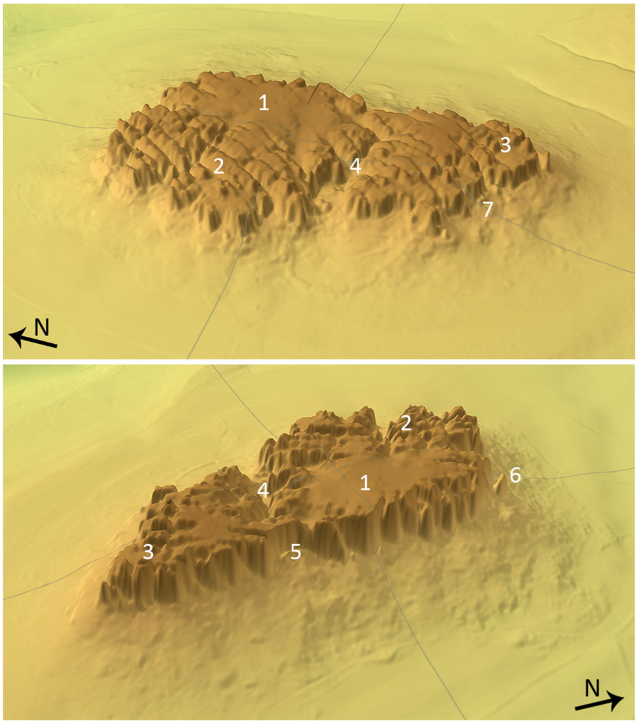

Fig. 7 Three-dimensional models of Pfaffenstein mesa, with key geomorphic features indicated by corresponding numbers (see text for explanation). Data source: high-resolution (2 × 2 m) LiDAR-based digital terrain model DGM2

The top surface is lined with vertical cliffs nearly all along its perimeter, with the cliffs facing east being continuous and the highest, up to 60 m. Those in the south tend to assume stepped profiles, with narrow ledges and benches separating vertical sections. On the western side, two major canyons break the continuity of the escarpment but several clefts developed at the expense of densely jointed linear zones also connect the middle slope with the top part of the mesa (Fig. 6b, c). The evidence of mass movement on Pfaffenstein is overwhelming and varied. The most impressive is the evidence of huge 1838 rockfall on the eastern side (5) which left three monolithic blocks, as long as 15 m, of Klamotte and plenty of minor debris (Fig. 6a). Other big blocks in upright rotated position in the middle slope may testify to previous events of this kind. Another important, but non-catastrophic process involved is detachment followed by backward tilting and then possibly downslope gliding. The tower of Einsiedler at the northern tip provides an example (6). Detachment and tilting occur also within canyons, and Jäckelfels is a 40-m-high tower slightly leaning towards the canyon floor (Fig. 6d). Abundant examples of tilted and collapsed sandstone towers are present along the base of south-facing cliffs (7), with several tunnels under collapsed blocks. On the other hand, some boulder caves may have originated through non-catastrophic processes of slow grain-by-grain disintegration of sandstone and removal of sand by episodic flow. In fact, there are plenty of caves of various origins at Pfaffenstein (Fig. 6e, f), indicating various pathways of cliff disintegration and collapse (Schneider 2004).

Pfaffenstein is well developed for tourists, the history of tourism dating back to the mid-nineteenth century (Keiler et al. 2004), and most features indicated above can be observed while using the trails or from vantage points, looking down the cliffs or into the canyons. One can also visit several caves in different locations (cliff top, cliff base, inside canyons) and examine their significance for deciphering the pathways of cliff destruction.

Papststein

Papststein (451 m) was selected as a representative of a transitional stage between well preserved and much more degraded mesas. On the one hand, it is still of a large areal extent, being 511 m long and 215 m wide. On the other hand, however, it is dissected to a high degree, lacking roughly rectangular shape typical for Gohrisch and Pfaffenstein. From the west, Papststein is divided into three ridges that become a unity further to the est. The separation is the result of the presence of two dry valleys cutting the sandstone caprock (Fig. 8a). The morphology of the mesa proves an advanced level of decay not only in a plan view but also in a profile. Due to faster retreat of the upper sandstone unit ‘e’, Papststein became a two-storey mesa, with the lower sandstone unit ‘d’ forming continuous cliff lines up to 40 m high, and the overlying one appearing as a highly weathered terrain step, locally reaching impressive height of 25 m and giving rise to some outlying sandstone towers (Fig. 8b).

In a few localities along the mesa’s perimeter, the rock face is cut by penetrable clefts, which developed along widened vertical joints. The corridors are filled with sandy material derived from sandstone weathering. Some residual blocky compartments, more resistant to weathering processes, may be found in the clefts, indicating that this was rather in situ disintegration of sandstone than block tilting or lateral spreading that led to the development of passageways. Open clefts are a common feature in the upper sandstone unit, too.

The processes responsible for Papststein degradation are not limited to gradual disintegration. Morphological evidence of basal weathering and undercutting of sandstone is well visible both along mesa’s cliff lines and the upper sandstone step. Very deep overhangs indicate the important role of rock falls. In this context, the most convincing is the historical record. On 17 January 1972, a huge collapse of the south-eastern rock wall took place. It is estimated that during this catastrophic event, as much as 4000 m^3 of sandstone was detached (Gerth 2012). The cliff line looks particularly spectacular here and is very different from all other rock face sections within the described mesas (Fig. 8c). Rock fall deposits, appearing as a huge pile of boulders, may be observed

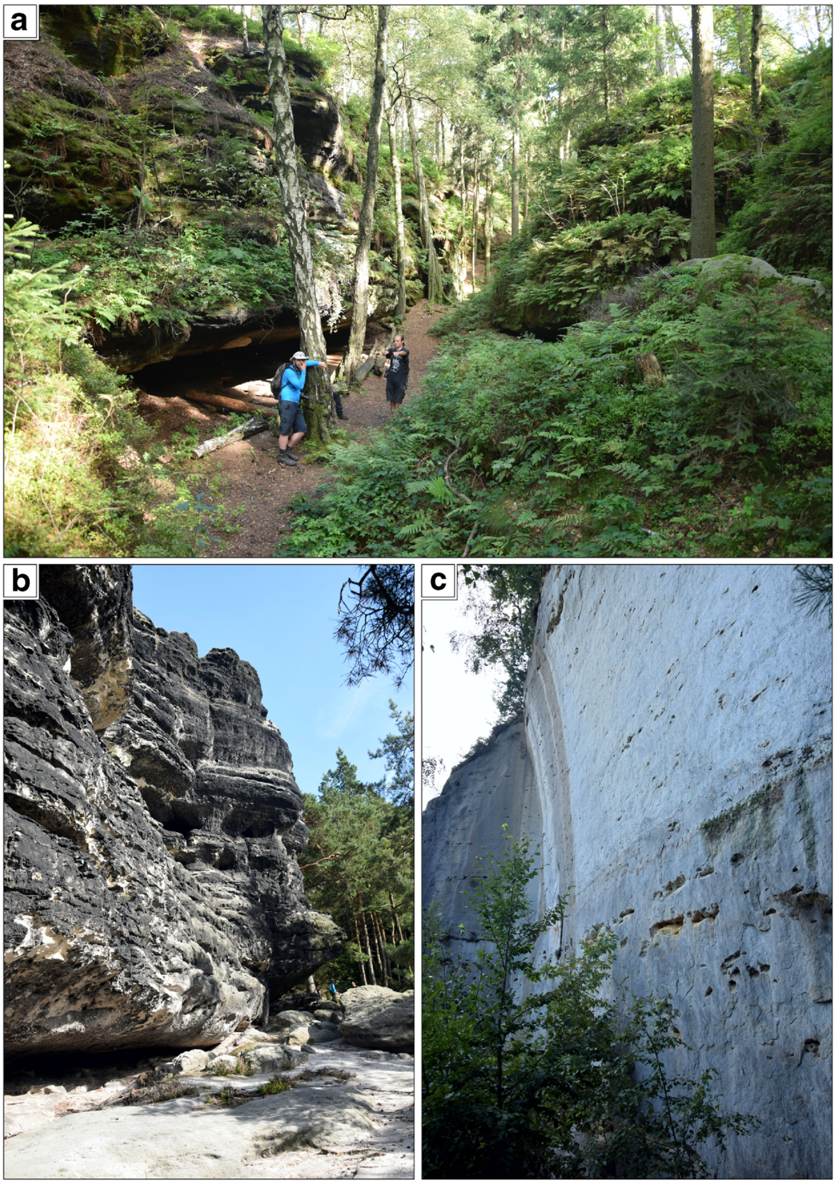

Fig. 8 Features of geomorphological interest at Papststein. **a** Dry valley in the upper part of the mesa. **b** Rock towers and structure-controlled benches. **c** Site of 1972 rock fall (all photos by P. Migoń)

right at the foot of the cliff. This locality is unfortunately away from the tourist trail.

Kaiserkrone

Kaiserkrone (351 m) represents the next stage in the mesa evolutionary pathway. In comparison to the previously described elevations, it is much more spatially limited—the top surface is only 135 × 24 m. The mesa is thus more than 30 times smaller than Papststein. Kaiserkrone is divided into two separate parts, with the southern one being about to split into two separate compartments along a cleft. The mesa is lined with precipitous rock walls supported by ‘c3’ and ‘d’ sandstone units, yet their height is not very spectacular—they reach up to 15 m. However, they continue along almost the entire mesa’s perimeter.

The top surface is mostly a bare rock floor, with minor steps and joint-bounded compartments (Fig. 9a). The effects of cavernous weathering, such as honeycombs and tafoni, are present mainly within the cliff lines (Fig. 9b). The rock walls are dissected by vertical fissures which locally evolved into partly penetrable corridors and tunnels. These forms are the natural trails of sand evacuation from the inner parts of sandstone caprock as evidence by large volumes of sand at the outlets of corridors. Another way of gradual sandstone decay at Kaiserkrone is through destruction of protective crust covering large portions of cliffs. Where the crust is not present, the sandstone is crumbling and disintegrating grain by grain.

Although it appears that gradual rather than catastrophic processes have dominated in the evolution of Kaiserkrone, one may find many examples of overhangs along the cliffs, which are sites particularly prone to future collapses. There is

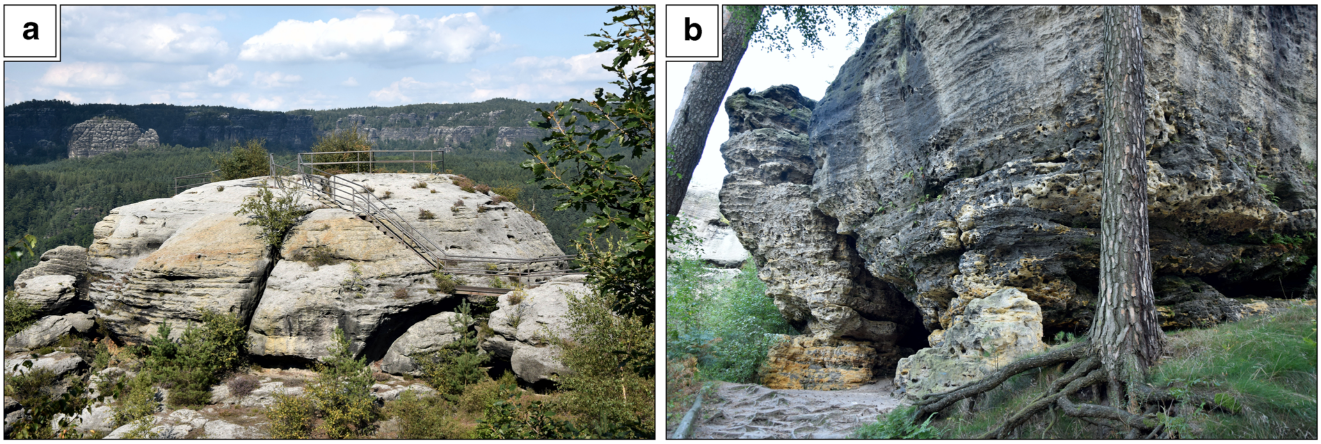

Fig. 9 Features of geomorphological interest at Kaiserkrone. **a** Top surface of the mesa. **b** Heavily weathered sandstone cliffs, with overhangs, joint-guided clefts and honeycomb weathering (all photos by P. Migoń)

no reason to doubt that similar processes occurred in the past, and boulders scattered within the middle and lower slope sections testify to this scenario.

Similarly to the other residual hills, Kaiserkrone is easily accessible via a network of paths, partly engineered within rock cliffs. The viewpoint at the mesa's highest spot is a perfect place to observe Zirkelstein, considered as the next evolutionary stage.

Zirkelstein

The residual hill of Zirkelstein (384 m) is an example of a very advanced stage of evolution, when the escarpments have worn back to such a degree that the hill appears an isolated sandstone tower rising high above the plinth and the flatlands around (Fig. 10). The top surface of the butte is only 40 m long and 30 m wide, but surrounded by precipitous cliff lines up to 35 m high. The rock faces in 'c3' and 'd' sandstone units occur all around the summit surface and follow the dominant NW–SE and WSW–ENE striking vertical joints, as well as secondary joint directions. The lower slopes in thinly bedded 'c1' and 'c2' sandstone units are gently concave.

Unlike on Papststein or Pfaffenstein, no individual rock forms are present on the top surface of Zirkelstein, apparently due to its limited area. Instead, it is characterized by a nearly level bare platform, transforming into short convexity towards its western and southern edges. The convex section may consist of a few steps, clearly joint- and bedding-controlled.

Where sandstone is thinly bedded and cut by other horizontal discontinuities, rock face is highly weathered, with many examples of small overhangs, tafoni and honeycomb structures. However, only minor slots have developed along vertical joints and none of them are penetrable. The surface of sandstone is covered by a protective crust. In all places where it was lost for some reason, the sandstone is quickly disintegrating into individual grains. The process of removal of sandy residuum may also be traced at a number of outlets of vertical fissures, beneath which small cones of evacuated material are present. Examples of such forms are well visible from the tourist trail which goes to the very top of the butte, using rock-hewn steps and ladders.

Apart from gradual, grain-by-grain disintegration, evidence of episodic mass movements may be recorded. In the southern part of the mesa, the joint-bounded block lying right beneath an overhang of the same size belongs to the most convincing examples. The number of overhangs around the butte is substantial, indicating that rock falls may play an important role in cliff backwearing. In this context, the scarcity of boulders within mid- and lower scarp slope sections is intriguing.

Wolfsberg

The penultimate stage of mesa decay is exemplified by Wolfsberg (343 m). This residual hill, rising c. 30 m above the surrounding terrain, represents morphology very different from the previously described examples. The top part lacks a cliff-bound structural bench or a miniature rock city. The presence of sandstone outcrops, belonging to 'c3' unit, is limited to only a few minor tor-like forms and loose boulders, in places piled one upon another (Fig. 11). They are interpreted as the only remnants of once existent sandstone caprock which was disintegrated by weathering processes and mass movements, and nearly completely removed. The common presence of honeycombs within all rock surfaces of Wolfsberg indicates that weathering is an important agent also in the contemporary environmental conditions. The tubes exposed at rock walls in the old quarry below the summit confirm the contribution of subsurface erosion in underground removal of sandy detritus.

Although the educational role of Wolfsberg as representing the nearly terminal stage of mesa evolution is clear, it remains poorly known and is not popular with tourists. No marked

Fig. 10 The butte of Zirkelstein (photo by P. Migoń)

tourist trails cross this elevation, and summit tors and boulders are hidden in the forest. Nevertheless, there is a hotel on the eastern side of the hill and a road makes the hill easily available.

Zeisighübel

The inconspicuous elevation of Zeisighübel, located 0.5 km to the ESE from the southern tip of Pfaffenstein, represents the final stage of mesa evolution. It reaches 335 m a.s.l. (hence, 100 m lower than Pfaffenstein) and geomorphologically is a broadly convex terrain swell, with slope inclinations less than 5° over most of the elevation (except the northern slopes). It is built by sandstones belonging to the 'c1' unit. The 'c1' sandstones do not act as caprock in the study area but underlie gently rolling plains between individual tabular hills. However, over the surface of the swell, around 40 large boulders of thick-bedded sandstone are scattered. The most impressive ones are nearly 10 m long and 4–5 m high (Fig. 12). Orientation of bedding planes is variable. While some boulders lie apparently horizontally, others are tilted up to 30°. Most boulders are far from one another, but others form small clusters of three to five. The most distant ones are more than 100 m apart. None of the boulders is rooted in bedrock, and they are all allochthonous, but not in the sense of surface transport from the nearby Pfaffenstein. There is no

Fig. 11 Boulder pile in the summit part of Wolfsberg (photo by P. Migoń)

continuity of boulder scatter towards Pfaffenstein, and the size of boulders precludes detachment and transport by ice sheet. This may rather be interpreted as a 'ghost' of a sandstone-capped hill, which suffered from complete disintegration, and the remnant boulders sagged along with denudation of the sandstone strata beneath.

Zeisighübel is entirely overlooked by tourist development in the area. However, a few boulders are clearly visible from the forest road that skirts the southern slope while the open forest allows visitors to appreciate the big boulders in isolation.

Summary

Table 1 summarizes key observations from the residual hills, which are supplemented by two quantitative measures derived from the analysis of high-resolution (2 × 2 m) digital terrain model. Jointly, they show the following trends in morphological evolution of the mesas: (a) increasing dissection of the upper tabular surfaces and evolution of ruiniform relief, with clefts, rock towers and caves; (b) increasing and decreasing steepness of slopes; and (c) decreasing role of large-scale mass movements (rock fall, toppling) in the evolution of mesas, with corresponding reduction of talus. In addition, the trend (a) may go towards separation of the original mesa into several disconnected compartments (e.g. Kaiserkrone) or reduction to a singular rock residual (as Zirkelstein). However, weathering processes acting upon exposed sandstone surfaces and subsurface removal of sand via joint-controlled groundwater flow are ubiquitous and play a part at every stage of mesa evolution.

Validity of the Approach—Discussion

The ergodic assumption applied to geomorphology has been criticized on several grounds (Paine 1985), both in relation to the general concept as well as its applicability to specific

Fig. 12 Scattered sandstone boulders on the Zeisighübel. **a** Two boulders in the top part of the hill, with bedding planes inclined in the opposite direction. **b** Large, heavily weathered boulder at the perimeter of the hill (photos by P. Migoń)

Table 1 Summary of morphological features of the mesas

	Form	Process	Slopes > 60° within mesa margins (%)	Slopes > 45° on top surface (%)
Grosser Zschirnstein	Undissected top surface Cliff lines (2/3) and steep slopes without cliffs (1/3) Bedding caves Blocky talus	Bedding-controlled weathering Honeycomb weathering Block sagging Tilting and block collapse	20	2
Gohrisch	Dissected top surface Continuous cliff lines Joint-aligned clefts, many roofed Detached rock towers Blocky talus	Bedding-controlled weathering Cleft opening Tilting and block collapse Subsurface removal of sand	33	19
Pfaffenstein	Heavily dissected top surface developing into ruiniform relief Continuous cliff lines Joint-aligned clefts and canyons Residual rock towers Caves Abundant blocky talus	Bedding-controlled weathering Cleft opening Tilting and block collapse Rock fall Rotational gliding Subsurface removal of sand	44	32
Papststein	Top surface reduced to narrow ridges Dry box valleys Mostly continuous cliff lines Residual rock towers Blocky talus	Bedding-controlled weathering Cleft opening Rock fall Subsurface removal of sand and sagging	22	20
Kaisrekrone	Fragmented top surface Heavily weathered continuous cliff lines Overhangs and joint-aligned clefts Scarce blocky talus	Cleft opening due to preferential weathering Bedding-controlled weathering	13.5	11
Zirkelstein	Remnant top surface Continuous cliff lines, heavily weathered Little blocky talus	Honeycomb and bedding-controlled weathering Rock disintegration and sand removal	38	16
Wolfsberg	Residual boulder pile on top No cliffs No talus	Slow gravity-driven boulder movement Subsurface removal of sand	0	0
Zeisighübel	Scattered boulders, not rooted in bedrock	Surface weathering Boulder undermining by burrowing animals	0	0

geomorphic settings or regions. These problematic issues emerge in the context of ‘mesa trail’, too. First and foremost, the sequence presented here may not be an accurate reflection of the actual evolution of erosional landscape in Elbsandsteingebirge which remains poorly constrained. It is not known what the mesas once looked like, and there seem to be no research methods allowing for a re-creation of the past topography. Moreover, it cannot be predicted how the current ones will develop in the future, although some pathways can be hypothesized with higher confidence. For example, it is very likely that fragmentation of the north-western part of Pfaffenstein will continue due to preferential weathering of dense jointing zones, whereas Papststein will probably separate into several ridges, evolving towards the present-day form of Kaiserkrone. Secondly, mesas and buttes were presented in a sequence, implying that one form evolves from another whereas, in fact, parallel pathways may be possible. Thus, a compact mesa represented by Gohrisch may reduce in extent on all sides to ultimately reach the stage of the Zirkelstein butte, without the stage of fragmentation represented by Papststein and Kaiserkrone. Thirdly, the scheme largely ignores minor lithological differences which may be locally important, simplifying geological structure to the layered succession of caprock-forming sandstone over weaker fine-grained rocks, whereas caprock on the mesas considered here is not identical. Finally, it does not consider the rates of processes and the temporal context of mesa evolution, although this is largely unknown anyway.

Nevertheless, the proposed approach has its values too, especially while bearing in mind that geointerpretation by necessity involves translation of specialist knowledge into a simplified format. Details and uncertainties crucial for scientific inquiry may not be so important if the goal is to achieve more general understanding of the environment. As long as the concept is physically and logically sound, and it is asserted that the one presented here is indeed sound, simplification can be defended. For instance, we do not see the likelihood of parallel pathways of mesa evolution as a factor invalidating the approach. The sequence outlined here is rather conceived as one reflecting the most complicated scenario. The three principal values of using ergodic assumption are the following. First, the sequence is easy to visualize and to show on panels, in guidebooks etc., which is of key importance in geoeducation where 'one picture is worth a thousand words' (Macadam 2018). Second, the sequence—wherever proposed—can be complemented by further examples, split into pathways, enlarged at both ends etc. Third, it shows that the Earth is dynamic even if it currently gives the impression of prolonged stability.

The concept of ergodic principle can easily be transferrable to other geomorphological settings where landforms of certain type and origin evidently change through time. Perhaps the most suitable one would be a volcanic terrain experiencing long-term activity, in which young cinder cones and lava flows would co-exist with their degraded counterparts. A sequence of raised marine cliffs and beaches would nicely illustrate the changing role of marine versus non-marine slope processes, set in the broader context of land uplift and sea/lake level change.

Conclusions

There has been an ongoing debate about how to explain geoheritage and geosciences most efficiently. This theme perpetuates through the recent compendium by Reynard and Brilha (2018), particularly in Macadam's (2018) discussion. But the issue was raised much earlier, since geotourism was first formally defined and its linkages with geoconservation were recognized (Hose 1995, 2012). Recent developments seem to focus on technological innovations, and their successful application (Cayla 2014; Martin 2014; Aldighieri et al. 2016; Cayla and Martin 2018) rather than on conceptual issues. In this paper, we bring the ergodic principle back into spotlight. Its relevance for geomorphology was debated particularly in the 1980s. The criticism, summarized by Thorn (1990), resulted in the abandonment of the concept in most geomorphological inquiries, but we argue that in specific geomorphic settings, it remains a valuable and powerful tool to interpret the physical landscape and its changes through time, particularly since visualization is relatively easy. Some types of geomorphology are better suited for this approach than others, and one has to be aware of constraints and limitations arising from scientific uncertainties, but nevertheless, the ergodic principle provides a good general framework to be filled by local examples.

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